Hydrological Assessment and Discharge Determination of River Jarkwami for Sustainable Water Resources Management in Kwami Local Government Area, Gombe State, Nigeria

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https://doi.org/10.56201/ijgem.vol.11.no9.2025.pg152.178

Abstract
Reliable river discharge information is essential for flood prediction, irrigation planning, reservoir management and sustainable water resource development. However, most tributaries within the Gongola Basin in semi-arid Northeastern Nigeria lack gauging stations. This study characterizes the discharge regime of River Jarkwami, a seasonal tributary of River Morom that drains into Dadin Kowa Reservoir on the Gongola River in Gombe State, using inexpensive staff-gauge and float techniques suited to data-limited developing regions. The upstream catchment was delineated with ArcGIS 10.1 and the SRTM Digital Elevation Model. Field observations of water level, flow velocity and channel breadth were conducted twice daily, at 07:00 and 18:00, from May through October 2023, representing the 2023 hydrological year, at the Jarkwami Bridge gauging station. Flow velocity was estimated using the float method and verified with Manning's equation. Cross-sectional area was calculated as depth × breadth, discharge was obtained using $Q = A \times V$, and a stage-discharge rating curve was established. The results indicate that the upstream catchment covers 225 km² and has a dendritic drainage network consisting of 70 streams: 57 first-order, 9 second-order, 3 third-order and 1 fourth-order streams. The mean bifurcation ratio is 3.82, drainage density is 1.21 km/km² and total stream length is 271.8 km. The catchment comprises 25 sub-basins ranging from 0.76 to 59.93 km², with a mean stream length of 13.73 km. At the gauging station, the channel measures 17.1 m in breadth. Mean float velocity was 0.18 m/s, ranging from 0.07 to 0.37 m/s, with the maximum recorded in September (0.37 m/s) and the minimum in October (0.07 m/s). Monthly water level averaged 21.3 cm, reaching its lowest value in May (1.27 cm) and its highest in September (58.2 cm, with a peak of 85.34 cm on 10th September). Mean instantaneous discharge was 5.76 m³/s, ranging from 0.60 to 20.7 m³/s, while cumulative

seasonal discharge totaled 368.8 m³/s over 64 effective flow days. September accounted for 40.1% of the total seasonal discharge, indicating a single-maximum regime characteristic of tropical continental climates. Discharge was influenced by rainfall intensity and duration, catchment size and elongated form, highly permeable sandy ferruginous soils, undulating terrain (370-670 m), sparse derived savanna vegetation and anthropogenic activities such as open grazing, farming, soil excavation and sand mining. The staff gauge and float techniques were effective, cost-efficient and reliable for small-medium seasonal rivers, exhibiting excellent performance, as demonstrated by the rating curve Q = 0.42h^1.65 (R^2 = 0.87). Although turbulence, debris, water surges and limited vertical range presented limitations, these were addressed through strategic site selection. The study establishes baseline information for forecasting inflows into Dadin Kowa Reservoir, scheduling irrigation on the Kwami Fadama lands, issuing early flood warnings, and evaluating affordable techniques for ungauged basins in semi-arid Nigeria.

Keywords: *River discharge, Staff gauge, Float method, Jarkwami River, Water resources management, Rating curve, Kwami, Gongola Basin*

Introduction

Monitoring river discharge is fundamental to water resources management because streamflow volume and behavior are governed by hydrologic processes shaped by geology, topography, climate, and human activities (Dobriyal et al., 2017). Reliable knowledge of streamflow is essential for allocating water resources efficiently and maximizing their social and economic benefits (Tobias et al., 2001). Data obtained through routine monitoring promote sustainable resource use and support payment for ecosystem services. River discharge (Q) refers to the volume of water moving past a specified point per unit time (m^3/s). It is expressed as $Q = A \times V$, where A represents the cross-sectional area and V denotes velocity. Although discharge cannot be measured directly, it is derived from measurements of channel width, depth, and flow velocity (Baker, 1990; Turnipseed & Sauer, 2010). Numerous important applications rely on discharge data, including global water-balance assessments, engineering design, flood forecasting, reservoir operations, water supply planning, recreation, and environmental management (Gregory & Walling, 1973). The need for high-frequency data is increasing as populations grow and water-use objectives conflict (Whiting, 2003).

In Nigeria, conserving freshwater is challenged by climate change, variable rainfall and water scarcity, particularly in the arid and semi-arid northern region (Barnett et al., 2005; Berven, 2012). River monitoring is essential for governments to develop allocation plans and adaptation strategies (Herschy, 2009). Freshwater accounts for only 2.5% of the earth's surface, and only a fraction of it is accessible through rivers (Berner & Berner, 2012). Of the water found in lakes and rivers, just 0.014% remains in motion (Strahler & Strahler, 2005). The Jarkwami River, located north of Gombe Metropolis, rises in Kirfi Local Government Area, Bauchi State. It extends 52 km and merges with the River Magarya to form the River Morom, which flows into Dadin Kowa Reservoir (Adamu et al., 2015). The river is seasonal and responds directly to precipitation, making it important for irrigation, fishing and domestic use. Despite its importance, reliable discharge data are unavailable. This study monitored water levels for six months, from May-October 2023, to estimate discharge using a staff gauge, a simple and inexpensive method that is not widely used in northern Nigeria.

Previous studies in Nigeria have concentrated on the River Kubanni in Zaria: Yusuf et al. (2007) evaluated the velocity-area and weir methods, highlighting the advantages of the weir method. Zubairu (2009) compared the float and weir methods in a tributary of River Tukurwa in the Kubanni basin and found that the float method produced lower mean, standard error, and standard deviation values, indicating its superiority. Yusuf et al. (2011) compared the current-

meter and float methods in Samaru Stream and reported no significant difference between them; however, the lower mean obtained with the float method suggested that it was more effective. Yusuf (2013) evaluated sediment delivery into Kubanni Reservoir using the weir and velocity-area methods. Muktar (2017) conducted a comparative analysis in the upstream Kubanni area and found no significant differences among the methods. None of these studies combined the staff-gauge and float methods in northeastern Nigeria. Therefore, this study aimed to hydrologically assess and determine the discharge of River Jarkwami in Kwami LGA during the 2023 hydrological year, with the following specific objectives: (i) characterize the drainage basin upstream of River Jarkwami; (ii) assess the applicability of the staff-gauge and float methods for measuring discharge in small seasonal rivers; (iii) determine discharge at the upstream gauging station; and (iv) examine the factors influencing upstream discharge.

Study Area

River Jarkwami lies within Kwami Local Government Area, between Latitude 10°30'N and 11°15'N and Longitude 10°20'E and 10°22'E. The stream originates in Kirfi LGA, Bauchi State, and flows for 52 km before joining River Magarya north of Gombe Metropolis. The two rivers combine to form River Morom, which subsequently empties into Dadin Kowa Reservoir.

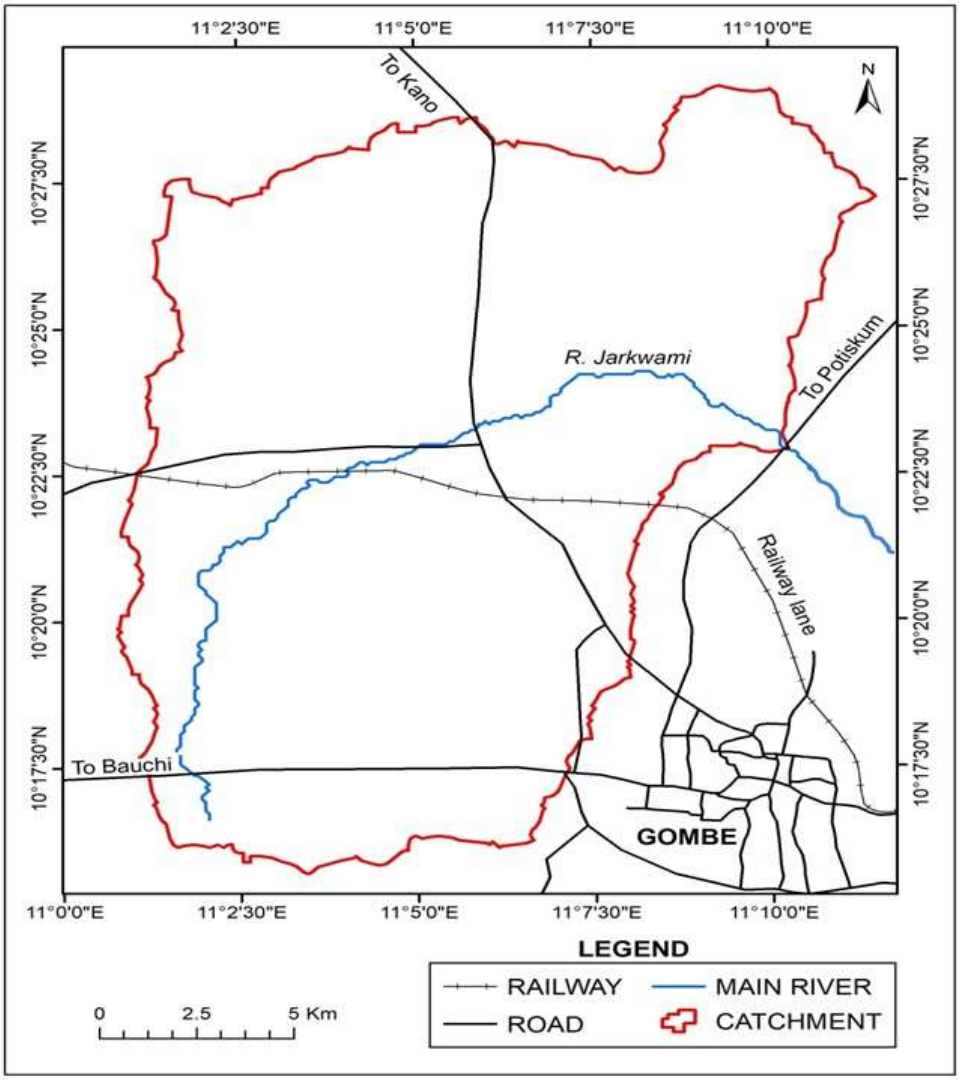


Figure 1: The Jarkwami Catchment

The area has a tropical continental climate characterized by distinct wet and dry seasons and classified as Sahel savanna (Aw). The wet season extends from April to October, whereas the dry season occurs from November to March. Average annual rainfall is approximately 850 mm, with a mean of 835 mm, declining to less than 10% during the Harmattan period. The tropical continental air mass originating from the Sahara transports Harmattan dust, while the tropical maritime air mass from the Atlantic Ocean produces rainfall; these air masses converge along the Inter-Tropical Convergence Zone/Discontinuity. Mean daily maximum temperatures range from 40.65°C in March-April to 38.5°C in July-August, while minimum temperatures vary from 11.7°C in December-January to 24.7°C in April-May. Sunshine duration ranges from 5 hours in July to 9 hours in November. High evapotranspiration contributes to water shortages. Relative humidity ranges from 12% in February to 68% in August. Monthly rainfall during the rainy period from May to September varies from 0.0 mm in December-January and trace amounts of less than 0.1 mm in February-November to 343 mm in July (Mayomi et al., 2016). The terrain decreases in elevation from approximately 650 m in the west to 370 m in the east. It is characterized by flat-topped conical hills, granitic residuals, and a pediment landscape comprising alluvium and basement rocks, as well as Bima-sandstone, Yolde Formation, Pindiga Formation, Keri-Keri Formation, Gombe sandstone intrusion, and exposed basement complex (Adamu et al., 2015). The soils comprise shallow to deep alluvial, tropical ferruginous, loamy-sandy, sandy-clay, and vertisol types. They are characterized by cracking clay, weathering, and fertility that supports intensive agriculture. The principal parent material is Gombe Sandstone, which is dark gray and has a pH of 4-6 (Mbaya, 2020). Geological conditions regulate infiltration: highly permeable aquifer materials reduce runoff, whereas impermeable materials produce peak runoff. Faults, fissures, and cracks can also promote leakage from the watershed (Yusuf et al., 2011).

The drainage system collects water from the upper Gongola catchment and joins the Magarya River, together forming the Morom River before reaching the Dadin Kowa reservoir. The area is situated where runoff exceeds groundwater contribution, accounting for the river's ephemeral character. Groundwater moves through seepage and discharge zones. Where the groundwater table lies below the streambed, seepage replenishes groundwater and creates a water mound, producing influent ephemeral streams after the dry period. Such streams are unsuitable for conventional hydropower but can support pure pumped-storage systems (Gravalle, 2014). Where groundwater levels rise above the stream surface, groundwater supplies the channel, producing effluent baseflow and perennial conditions during the dry season. Intermittent streams flow during the wet season through a combination of surface runoff and groundwater but become dry during the dry season. Perennial streams maintain groundwater levels above the streambed even during droughts and therefore flow throughout the year (Whiting, 2003).

Vegetation comprises a mosaic of wooded shrubland, shrubby grassland, and grassy shrubland, with acacia and relatively deep tropical ferruginous soils. The landscape is characterized by savanna woodland typical of the Sahel, including grasses, woody shrubs, and short trees, but little of the natural climatic vegetation remains. The vegetation has been reduced by poor management, fuelwood collection, annual bush burning, cultivation, and intensive grazing, with shrub and tree clusters occurring mainly along river courses (Musa et al., 2015). Vegetation affects discharge through root-mediated infiltration, interception and flow delay, and riparian stabilization (Yusuf, 2017; Gravalle, 2014; Whiting, 2003).

Land use is dominated by intensive farming and grazing, particularly near the southern boundary. Upland fields produce maize, millet, sorghum, and groundnut during the wet season, while fadama lowlands support sugarcane, onion, tomatoes, pepper, spinach, and other garden vegetables throughout the year. Production relies on organic manure and fertilizer, with hand cultivation using hoes and cutlasses. Dry wood is the primary energy source for firewood. Sand mining generates holes, pits, and gullies, while its byproducts are used to mold bricks for mud

buildings, residential structures, animal shelters, and road construction. Fishing is limited and occurs on a minor commercial and recreational basis during the wet season (Adamu et al., 2015).

Methodology

The study incorporated extensive fieldwork to obtain primary data, supplemented by relevant secondary sources. Primary data were collected through field measurements and stage observations at the Jarkwami channel using the staff-gauge method to determine discharge and flow velocity. Secondary information was obtained from relevant research textbooks and journals. Because river discharge is influenced by rainfall, field observations commenced at the onset of the rainy period. Initial measurements were taken following major storm events, after rainfall had become nearly daily from late July through August.

Catchment delineation was conducted in ArcGIS 10.1 using the Spatial Analyst Hydrology tools, including Fill, Flow Direction, Flow Accumulation, and Stream Order, following Strahler (1957). The catchment area was calculated, stream orders were enumerated, total stream length was measured, and the bifurcation ratio was determined using Rb = Nu / Nu+1. Drainage density was calculated as Dd = total length / area. The analysis identified 25 sub-basins, and the mean stream length was subsequently calculated.

Channel breadth was measured at the gauging point near Jarkwami Bridge using surveying equipment, including a ranging pole and measuring tape, in accordance with the principles of Horton (1945) and Gregory and Walling (1973). The measured breadth was 17.1 m. Flow velocity was determined using the float method, expressed as V_surface = Distance / Time. A float ball was released across a known distance of 10 m, and the travel time was recorded with a stopwatch. The measurement was repeated 3 times, and mean velocity was calculated as V = 0.85 × V_surface, using the correction factor for a rough channel recommended by Chow (1959).

Water level was monitored with a staff gauge consisting of a vertically mounted, graduated scale affixed to a pillar at the gauging station along Jarkwami Bridge. The zero mark corresponded to a predetermined reference point. The researcher visually recorded water levels at regular intervals, coordinating these observations with the floating-object method used to determine velocity. Measurements were taken twice daily, at 07:00 and 18:00, from May-October 2023, following rainfall events and during instantaneous, regular-interval monitoring. Factors affecting discharge were assessed using rainfall records, land-use observations, soil characteristics, topography, vegetation, and human activities. The soil was sandy and ferruginous, with high permeability. Topographic features included elevation, slope, valleys, ridges, and hills. Vegetation consisted primarily of shrubs, grasses, and riparian plants. Human interventions included soil excavation on the eastern side of the river, construction of artificial channels, and deposition of excavated materials. Sedimentation reduces the channel's conveyance capacity (Khodzinskaya et al., 2022).

Discharge was calculated according to the fundamental cross-sectional-area method, Q = A × V, where A = D × B, D represents depth, and B represents breadth. Manning's equation was used for cross-checking. The velocity-area method was validated by comparing computed and observed values. A stage-discharge rating curve was established using Q = a h^b.

Drainage Basin Characteristics

The upstream portion of the Jarkwami drainage basin was delineated and covers an extensive area of 225 km². The basin exhibits a dendritic drainage pattern, which is common among river systems. The distribution of stream orders within the basin is notable. The basin comprises 57 first-order streams, 9 second-order streams, 3 third-order streams, and 1 fourth-order stream, yielding a total of 70 streams and indicating a complex network of contributing tributaries. The

streams collectively extend 271.8 km, demonstrating the extensive nature of River Jarkwami's drainage network. A bifurcation ratio of 4.11 and a weighted mean of 3.82 suggest an elongated basin characterized by moderate flood peaks and longer lag times, conditions typical of sedimentary terrain. Drainage density, calculated as 1.21 km/km², is moderate and indicates moderate runoff potential.

Table 1: Morphometry of River Jarkwami Upstream

Parameter	**Value**	**Interpretation**
Basin Area	225 km²	Moderate size, primary control hydrology
Total Streams	70	Dendritic pattern
First-order	57	81% of streams, headwater
Second-order	9	
Third-order	3	
Fourth-order	1	Main channel
Total Stream Length	271.8 km	
Drainage Density	1.21 km/km²	Moderate runoff potential
Mean Bifurcation Ratio	3.82	Elongated, lower peak longer lag
Shape	Elongated	Longer lag
Pattern	Dendritic	Uniform lithology

The upstream portion of the Jarkwami drainage basin comprises 25 sub-basins that exhibit considerable variation in size and spatial distribution. The largest sub-basin covers 59.93 km², whereas the smallest extends across only 0.76 km², reflecting substantial differences associated closely with the region's topographic characteristics (Adeaga, 1997). The mean stream length is 13.73 km. This average provides a useful metric for hydrological and environmental assessments, supports water-resource planning and management, and contributes to understanding the drainage system's characteristics.

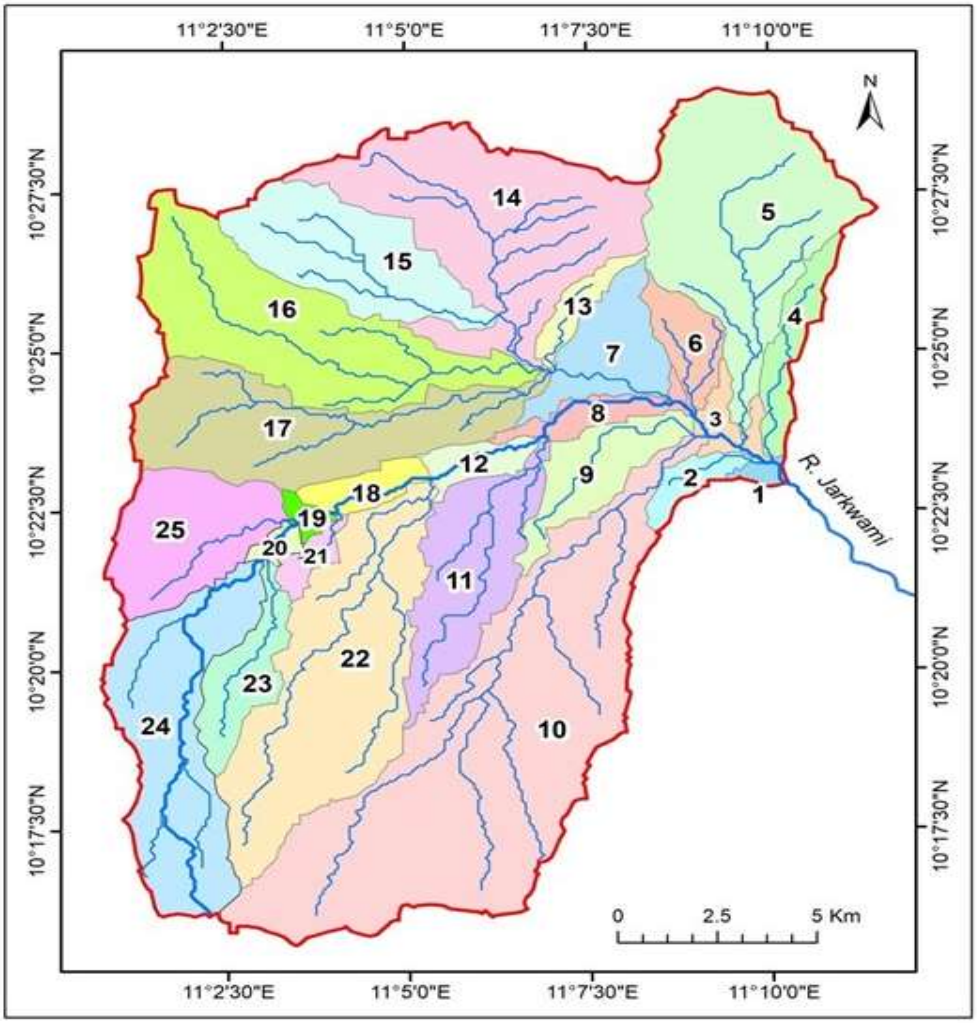


Figure 2: Drainage Basin Map and Sub-Basin Map - 25 sub-basins

The southwestern region is characterized by rugged, undulating terrain and higher elevations, producing a complex landscape (Figure 3). These conditions favor the development of longer sub-basins. In the western region, watercourses generally follow the contours of the land, generating meandering flows and more extensive sub-basins. The varied terrain reduces water movement and promotes accumulation, resulting in larger sub-basin areas. In contrast, the northeastern region has flatter, less undulating topography (Garcia & Martinez, 2018). This landscape supports the formation of smaller, more compact sub-basins. Because the terrain varies less, water flows more directly, leading to shorter sub-basins. The lack of substantial elevation differences and the flatter topography contribute to the prevalence of smaller sub-basins in the eastern region.

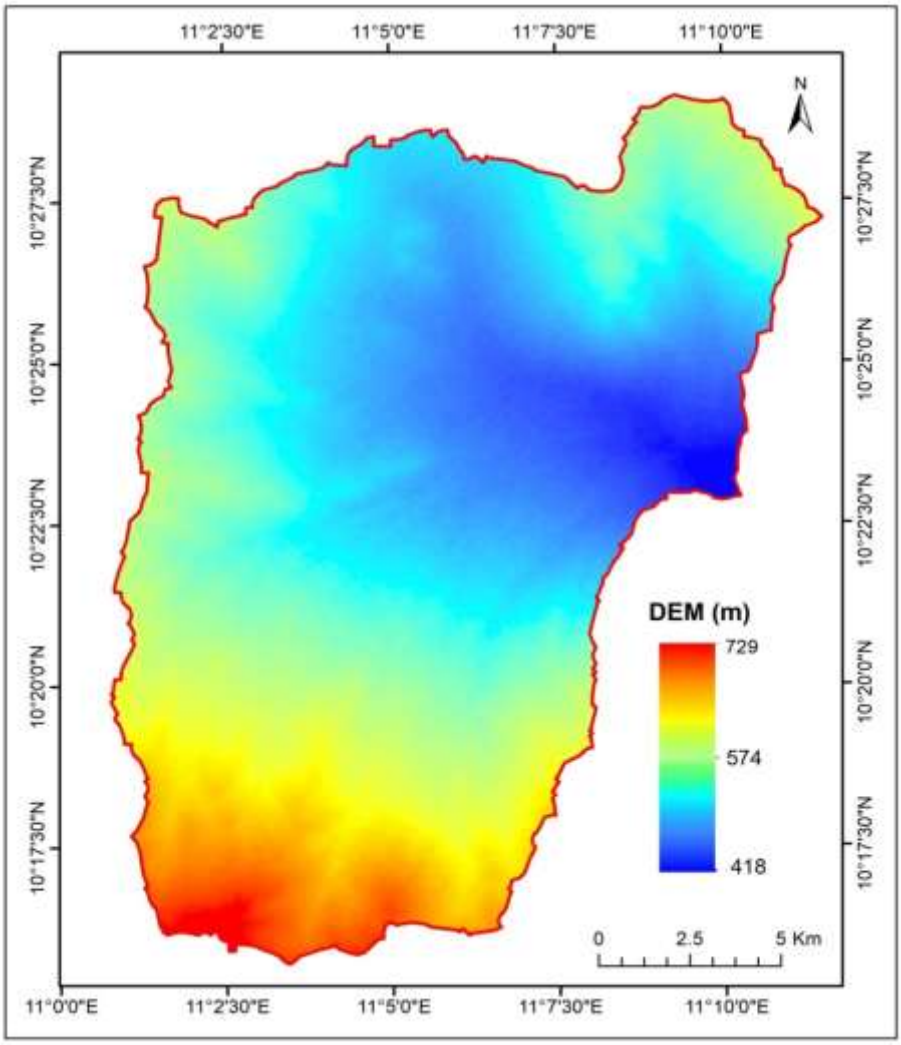


Figure 3: Relief of the Basin Upstream

Topographic differences have significant implications for hydrological behavior. In the western region, the longer sub-basins play an important role in slowing runoff, thereby promoting more effective water storage and distribution. These characteristics influence water-resource availability by regulating the timing and volume of flows entering larger rivers (Chow et al., 1988). In contrast, the eastern region contains smaller, more compact sub-basins that facilitate the efficient conveyance of water during periods of intense precipitation, although they may also contribute to flash flooding. The flatter terrain allows water to move rapidly, which can limit excessive surface runoff and help regulate sediment transport within the sub-basins.

Stream length within the basin is also a critical factor in determining the area available for interactions between water and the surrounding environment. Longer streams typically cross diverse landscapes and encounter varying land uses, vegetation communities, and geological formations. This spatial heterogeneity along the stream network creates a range of hydrological processes, including evaporation, transpiration, and infiltration, that collectively affect the basin's water balance. Understanding these processes throughout the stream network is essential for identifying the factors that regulate the quantity and timing of water reaching the Jarkwami River. Stream length also contributes to the temporal variability of flow. Long streams, particularly those originating at higher elevations, may display distinctive hydrographs characterized by delayed peak flows and extended recession periods. This

temporal variability is critical to the river's overall discharge regime, affecting both the magnitude and timing of peak flows. Recognizing the influence of stream length on the temporal characteristics of discharge is essential for effective water management, particularly under conditions in which seasonal variability and extreme weather events can substantially alter the river's flow regime.

Furthermore, stream length serves as an indicator of overall catchment area and the volume of water that may contribute to the Jarkwami River. Larger catchments are generally associated with longer streams and a greater capacity to collect and convey water to the main river channel. This relationship is especially relevant to understanding the basin's hydrological response to precipitation events, as stream length can function as a proxy for the scale of the contributing watershed. The significance of stream length to discharge in the Jarkwami basin is multifaceted and essential to understanding the complexities of its hydrological system. By shaping drainage-network connectivity and affecting the spatial and temporal variability of flow, stream length emerges as a key determinant of river-discharge dynamics. A detailed understanding of these relationships is crucial for sustainable water-resource management and ecosystem preservation within the Jarkwami basin.

A sub-basin functions as a critical catchment area that influences the quantity and quality of water reaching the river. Topography, land use, and vegetation cover directly affect surface runoff, infiltration rates, and sediment transport, thereby shaping the river's discharge patterns. Furthermore, the sub-basin plays a vital role in regulating the temporal and spatial distribution of water flow into the river. Through natural processes of groundwater recharge and storage, it functions as a buffer during periods of low precipitation and excessive runoff, helping sustain consistent and reliable river discharge. This regulatory function is particularly important for mitigating the effects of climate variability and anthropogenic pressures on the Jarkwami River. In addition, the sub-basin affects river water quality by serving as a natural filter that influences nutrient cycling and pollutant attenuation. Vegetation and soils within the sub-basin promote nutrient retention, preventing excessive nutrient loading in the river and thereby protecting downstream water quality and ecological integrity. This ecological filtration mechanism highlights the intricate relationship between the sub-basin and the overall health of the Jarkwami River. Biodiversity within the sub-basin enhances the resilience of the entire river ecosystem, as its diverse flora and fauna play essential roles in stabilizing the ecosystem, preventing soil erosion, and supporting the overall health of the watershed. Alterations and degradation within the sub-basin may produce cascading effects on the Jarkwami River, affecting discharge dynamics and overall ecological balance.

Channel Breadth at Gauging Station

The analysis of the Jarkwami River's breadth provides valuable insights into the river's geomorphological characteristics and hydrological dynamics. The bed of the Jarkwami River at the gauging station was measured beneath the bridge and recorded as 17.1 meters, providing a critical basis for understanding the watercourse's hydrodynamics. This analysis examines the complexities of bed measurement, clarifies its essential role in accurately estimating river discharge, and highlights its potential to improve understanding of river behavior, thereby supporting more effective water resource management and flood forecasting. Prior research has emphasized the importance of accurate riverbed measurements in hydrology. The riverbed forms the foundation of streamflow dynamics, influencing water velocity, sediment transport, and overall channel stability. Numerous studies have stressed the need for precise measurements, particularly at gauging stations, to improve the reliability of discharge estimates. The gauging station beneath the bridge was selected strategically because it was considered representative of the river's overall characteristics. The recorded measurement of 17.1 meters reflects the riverbed conditions at that specific location and time. This

measurement has direct implications for estimating river discharge. Variations in riverbed elevation alter the cross-sectional area through which water flows, thereby affecting velocity and, ultimately, discharge calculations. A detailed examination of the relationship between riverbed elevation and discharge offers valuable insight into the river's capacity to transport water and sediment under varying hydrological conditions. Accurate estimates of river discharge are essential for water resource management, flood risk assessment, and ecological conservation. Determining the volume of water flowing through the Jarkwami River is vital for designing infrastructure, including dams, and implementing effective flood-control measures. Moreover, reliable discharge data are critical to preserving ecological balance because discharge directly affects aquatic habitats and the overall condition of the river ecosystem. Yusuf (2013) conducted comparable measurements in the Kubani River to determine its average discharge. Direct comparison reveals notable similarities between the Kubani stream and the Jarkwami River, suggesting that shared hydrological processes and geological factors may influence both rivers. This correspondence indicates potential interconnectivity between river systems in the area and merits further investigation. From a hydrological perspective, the study's findings indicate that the narrower streambed sections characteristic of the Jarkwami River's upstream morphology may produce higher flow velocities, potentially influencing sediment transport and erosion patterns, whereas wider river sections may accommodate greater water volumes during floods (Strahler & Strahler, 2005). The measurements were further contextualized by applying Horton's (1945) principles for stream measurement.

Velocity Regime

River discharge follows a distinct seasonal cycle, beginning with the onset of rainfall in May, reaching its peak in September, and gradually declining in October. These patterns are essential for understanding the hydrological dynamics of the Jarkwami River and their implications for various sectors.

Table 2: River Jarkwami Velocity Values Upstream m/s for 2023 using float method

Month	Average Velocity (m/s)	Range (m/s)	Interpretation
May	0.10	0.05-0.15	Onset wet season incremental increase familiar field hydrology wet season elevated flow Muktar (2017)
June	0.13	0.08-0.19	Escalation rainfall typical seasonal rivers respond increased rainfall transporting more water downstream Wanah (2018)
July	0.23	0.15-0.31	Notable surge beginning peak period heavy rainfall pronounced rise river velocity
September	0.37	0.25-0.48	Peak velocity levels exceeding 0.37 harmony findings concurrent study Yusuf (2017). Maigamo Goruba tributaries highest discharge values synchronicity regional importance

October	0.07	0.03-0.12	Recession end rainy season base flow conditions influence decreased rainfall reduced runoff catchment area
Season Mean	0.18	0.07-0.37	2.38 m/s

The average velocity over the six-month rainfall period in 2023 was calculated by dividing the total velocity recorded during the observation period by the number of months. The highest monthly average velocity, 0.37 m/s, was recorded in September 2023 using the float method for determining the velocity of the Jarkwami River, whereas the lowest velocity, 0.07 m/s, was measured in October 2023. These findings support the explanations proposed by Horton (1965) and Kirkby (1967), which indicate that, when rainfall on hillslopes infiltrates only minimally, it penetrates the ground to a limited extent and the remaining water moves rapidly as overland flow into stream channels. In vegetated environments, however, precipitation may infiltrate the soil more completely, after which the infiltrated water moves laterally downslope toward the stream and continues flowing even after rainfall has ceased. Topography, vegetation, and other climatic factors also play important roles in determining the upstream velocity of the Jarkwami River.

Observed patterns are consistent with earlier research by Yusuf (2013) and Muktar (2017), who reported comparable seasonal runoff trends. The agreement between these findings and previous studies supports the reliability and consistency of the hydrological behavior of the Jarkwami River. The observed velocity patterns may be attributed to a combination of climatic and environmental factors. The onset of rainfall in May serves as the primary trigger, substantially increasing river flow through greater precipitation and runoff. The September peak coincides with the region's tropical wet season, which is characterized by heavy and sustained rainfall. This precipitation increases water volume and consequently contributes to the elevated discharge of the River Jarkwami. As the rainy season diminishes from September into October, declining rainfall produces a gradual reduction in discharge.

Observations are consistent with the research of Roudier et al. (2014), who highlighted the influence of climatic conditions on regional discharge variability. In addition, Oyegoke and Sojobi (2018) emphasized the importance of river-basin topography and geology, which may either facilitate or obstruct the downstream movement of water. Their findings correspond with those of this research, further confirming that both climatic and geomorphological factors shape velocity patterns in the River Jarkwami.

Understanding the velocity patterns of the River Jarkwami is essential across several domains. The September flow peak is particularly important for flood-risk assessment and disaster preparedness, as emphasized by Abashiya et al. (2017). The gradual recession of flow into October also has implications for agricultural planning, water-resource management, and ecosystem dynamics, as discussed by Ahmad (2016) in examining the significance of the Morom River basin, into which the River Jarkwami discharges. The consistency of these observations with prior research, together with their close agreement with the work of Muktar (2017), underscores the need for integrated, multidisciplinary approaches to managing and leveraging seasonal variability. Abashiya et al. (2017) advocate continuous data collection and predictive modeling as essential measures for improving early warning systems and developing adaptive disaster risk reduction strategies in the region.

Figure 4 illustrates the hydrograph of River Jarkwami, showing upstream velocity from the beginning of rainfall in May through the decline in water levels in October. The observed patterns were compared with relevant hydrological research, demonstrating consistency with

established principles concerning the effects of rainfall intensity, evaporation rates, and climate variability on river water levels. A comparison with similar studies further supports the relevance of these findings and their applicability to tropical regions, including the area where River Jarkwami is located.

The hydrograph indicates an observed discharge of 0.10 m/s in May, marking the beginning of the region's wet season, which is characterized by a gradual increase in river velocity. This pattern is well established in hydrology, as the onset of the wet season typically produces higher flows, as also reported by Muktar (2017). The velocity increased substantially to 0.13 m/s in June, reflecting intensified rainfall and corresponding with typical seasonal patterns in the region, where rivers respond to increased precipitation by transporting greater volumes of water downstream (Wanah, 2018). In July, velocity rose markedly to 0.23 m/s, further highlighting the effect of heavy rainfall, which commonly occurs at the beginning of the peak rainfall period and produces a pronounced increase in river velocity. However, the most notable finding was the peak velocity recorded in September, when river velocity exceeded 0.37 m/s. This result is consistent with Yusuf's (2017) concurrent study of the Maigamo and Goruba tributaries, which reported their highest discharge values, 346,524.48 m^3/s and 1,127,632.32 m^3/s, respectively, using the float method in September. The agreement between the two studies reinforces the significance of the September peak and underscores its regional relevance. In October, velocity declined to 0.07 m/s, indicating the conclusion of the rainy season and the river's return to base-flow conditions, reflecting the effects of reduced rainfall and diminished runoff across the catchment area. Similarly, Mukhtar's (2017) study of the Maigamo River in Zaria, North-West Nigeria, identified comparable hydrograph patterns. At the beginning of the rainy season in May, discharge was low at approximately 1.5 m/s, followed by a substantial increase to 2.7 m/s in June. As observed in the Jarkwami Maigamo, the river reached its maximum velocity in September, attaining 3.1 m/s before declining to 0.02 m/s in October. The correspondence between the hydrograph patterns of the Jarkwami Maigamo and Maigamo Rivers may be attributed to the region's similar climatic and geological conditions. Both rivers experience a distinct wet season, producing peak discharges in September. This similarity is valuable for regional flood prediction and water resource management.

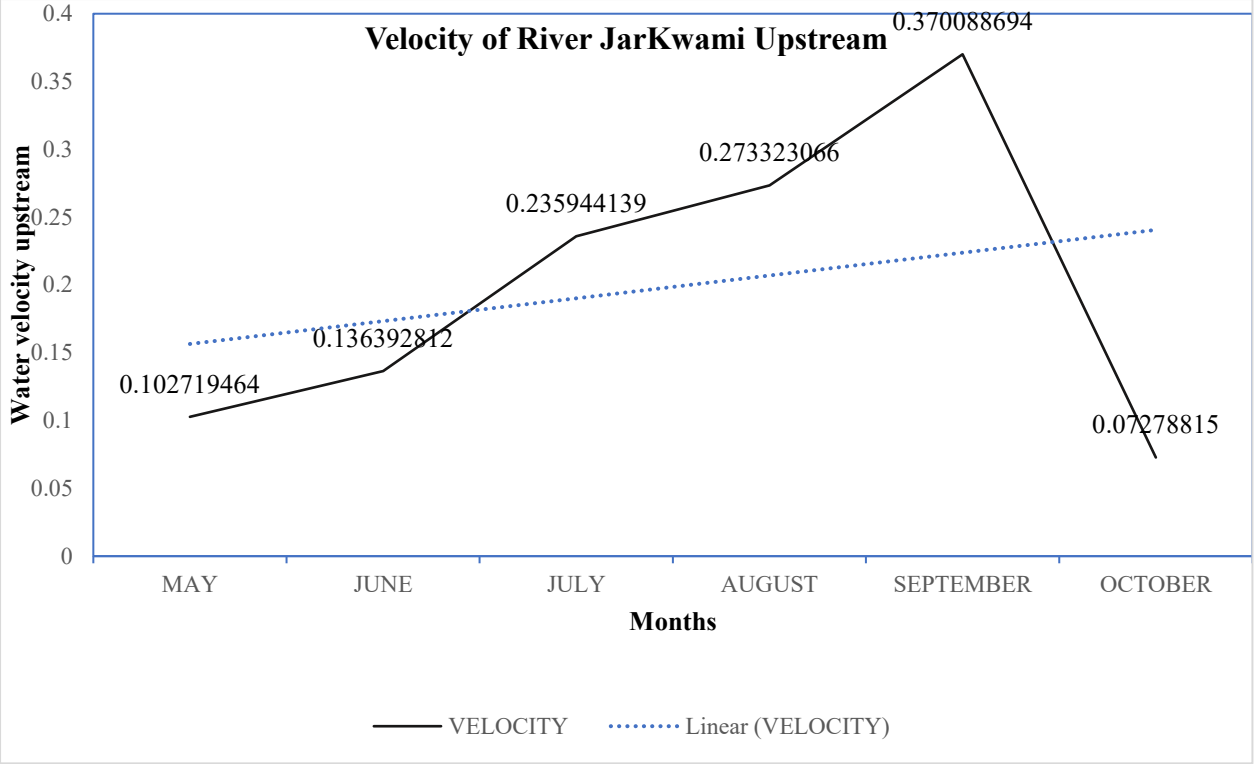


Figure 4: Hydrograph showing the average velocity of river Jarkwami upstream 2023

Water Levels Upstream May-October 2023

The peak discharge observed in September has important implications. First, it contributes to the recharge of groundwater sources, which are essential for maintaining ecological balance and sustaining the local water supply. At the same time, the recorded increase in discharge is known to inundate low-lying areas adjacent to the river. This phenomenon has previously been identified as a risk factor for localized flooding during heavy rainfall events and further highlights the need for effective flood-management and early-warning systems, as emphasized in the study by Abashiya et al. (2017).

Table 3: Estimation of River Jarkwami water level upstream (cm)

Month	Av. Water Level (cm)	Maximum (cm)	Data Collection Frequency	Interpretation
May	1.27	15.2	4 times	Modest starting relatively dry before onset rain steady increase continuous precipitation
June	17.4	45.6	9 times	Substantial increase sustained potentially heavy rainfall
July	31.2	78.4	13 times	Pivotal period substantial rise significant influx water prolonged intense rainfall upstream factors impacting watershed
August	33.1	82.5	15 times	Sustained possibly escalating trend precipitation upstream water flow impacting river

				dynamics cumulative effect elevated water levels consecutive months raises concerns potential flooding environmental impact need effective water management
September	58.2	85.34 (10th Sep)	17 times	Highest recorded water level 85.344 cm monthly average 58.2 cm meticulous monitoring effort likely response escalating water levels implications high-water levels increased flood risk potential damage infrastructure need proactive measures mitigate adverse effects
October	20.9	35.6	6 times	Decline decrease rainfall upstream water flow signaling potential transition drier period ongoing monitoring remains crucial assess stability river system prepare unforeseen changes hydrological conditions

The analysis of the River Jarkwami's discharge from May to October 2023 revealed complex seasonal variations in river flow, including a distinctive peak in September that corresponded with the peak identified by Mukhtar (2017), highlighting the region's significance. These findings contribute to a better understanding of the area's hydrological processes and are important for water resource management and flood prediction. Rainfall began on May 11th, marking the start of the monitoring period. The initial water level was 9.144 cm, a relatively modest value that suggests comparatively dry conditions before the onset of rainfall. During May, data were collected on four occasions, producing a monthly average of 1.27 cm, indicating a gradual increase as the month progressed, likely as a result of continued precipitation. In June, data collection became more intensive, with nine recorded observations and an average water level of 17.4 cm. This increase suggests sustained and potentially heavy rainfall during the month. July was a particularly important period: data were collected thirteen times, and the average water level reached 31.2 cm. This substantial rise indicates a significant influx of water into the river, possibly caused by prolonged intense rainfall or other upstream factors affecting the watershed. The elevated water levels observed in July may have implications for riverbank stability and flood potential, as well as for the broader hydrological balance of the region. August maintains the increasing pattern, with fifteen observations yielding an average water level of 33.1 cm. This sustained, and potentially intensifying, trend may reflect precipitation and upstream flow influences on river dynamics. The cumulative elevation in water levels across consecutive months heightens concerns regarding possible flooding and environmental consequences, emphasizing the need for effective water-management strategies. September records a notable event, with the highest water level measured on September 10th at 85.344 cm. The monthly average of 58.2 cm further demonstrates heightened hydrological activity during this period. Seventeen data-collection events in September indicate particularly thorough monitoring, likely undertaken in response

to rising water levels. Such elevated levels increase flood risk and may cause infrastructure damage, underscoring the importance of proactive mitigation measures. October, however, reflects a decline, with the average water level falling to 20.9 cm across six observations. This reduction may indicate decreased rainfall and diminished upstream flow, suggesting a possible transition toward a drier period. Despite this decrease, continued monitoring remains essential for evaluating river-system stability and preparing for unforeseen changes in hydrological conditions.

Careful observation of water levels using a staff gauge indicates 26 days of dry spells in May, 27 in June, 23 in July, 19 in August, 17 in September, and 26 in October. In fact, the thesis indicates that rainfall totals varied, with no clearly established pattern. Rainfall declined in May and ceased in October, unlike the other months, when flow occurred intermittently along the river channel. This finding is consistent with the study conducted by Yusuf (2013) on the Kubani River, which identified a similar pattern. The study recorded a total of 32 rainy days, clearly indicating a delayed onset of rainfall and a reduction in the number of rainy days compared with Yusuf (2006), who reported 62 rainy days while studying the Kubani River, and Yusuf (2013), who recorded 45 days. This difference may be attributed to regional variation. Similarly, Muktar (2017), in a study of the Maigamo Tukurwa Malmo River, reported a reduced number of rainy days, totaling only 37 days. Further analysis of water levels in the Jarkwami River also revealed seasonal trends. Factors contributing to these trends include human activities, the effects of climate change, ecological consequences, and model validation.

Hydrograph of the upstream section of the Jarkwami River illustrates the temporal variation in water levels from May 2023 through October 2023. The key observations include a noticeable rise in water levels following heavy rainfall events. The observed seasonal fluctuations reflect the influence of climate on river-flow variation and flow patterns.

The river hydrograph demonstrates distinct patterns, particularly at the beginning of the rainy season. In May, water-level records show a marked increase in river discharge, consistent with the findings of Mukhtar (2017), whose work highlights the importance of antecedent soil-moisture conditions and rainfall availability in initiating increases in discharge. The water level of the Jarkwami River exhibits a pronounced pattern across several months, reflecting the dynamic character of the hydrological system. The patterns recorded in May and June are also consistent with the concept of lag time described by Mukhtar et al. (2017), which emphasizes the delay between rainfall events and their effects on river levels. The stabilization of water levels in June reflects this delayed response following the onset of rainfall. September marks the peak of the river hydrograph, with substantially higher water levels. These data support the findings of Yusuf (2013), who established an exponential relationship between rainfall intensity and river discharge, resulting in peak water levels during the rainy season. As the rainy season begins to subside, water levels gradually decline. In October, the average water level decreases to approximately 20.9 cm, primarily because of reduced rainfall and increased evaporation rates, as discussed by Mukhtar et al. (2017). These seasonal variations are consistent with the existing research.

The observed hydrograph pattern is consistent with findings from relevant hydrological research and reflects established principles concerning the effects of rainfall intensity, evaporation rates, and climate variability on river water levels. Comparative analysis with similar studies further reinforces the relevance of these findings and their applicability to tropical regions. A central finding of this research is the distinct seasonality of upstream river water levels between May and October, with important implications for water resource management and environmental conservation. The study showed that water levels increased consistently during July and August, reached their maximum in early September, and then declined gradually through October. These patterns correspond with research conducted by

Yusuf (2013) and Muktar (2017) on the Kubani River in Zaria, which identified the combined effects of precipitation and catchment size, as well as the adverse influence of declining water levels. Between August and September, increased rainfall contributed to rising water levels, while the rapid saturation of soils caused by heavy rains generated substantial runoff into the Jarkwami River. Water levels peaked in early September, when the cumulative effects of soil saturation and precipitation reached their maximum. Thereafter, as the rainy season transitioned into the dry season, water levels gradually decreased because of reduced precipitation and continued evaporation. The ecological and economic implications of declining water levels are consistent with the work of Zwarts et al. (2006) examined dry-season water resource management in monsoon regions, emphasizing the importance of reservoirs and water-storage infrastructure, while also addressing the ecological effects of declining water levels. Similarly, Wlosinski and Koljord (1996) underscored the need for adaptive management strategies to safeguard essential wetland ecosystems.

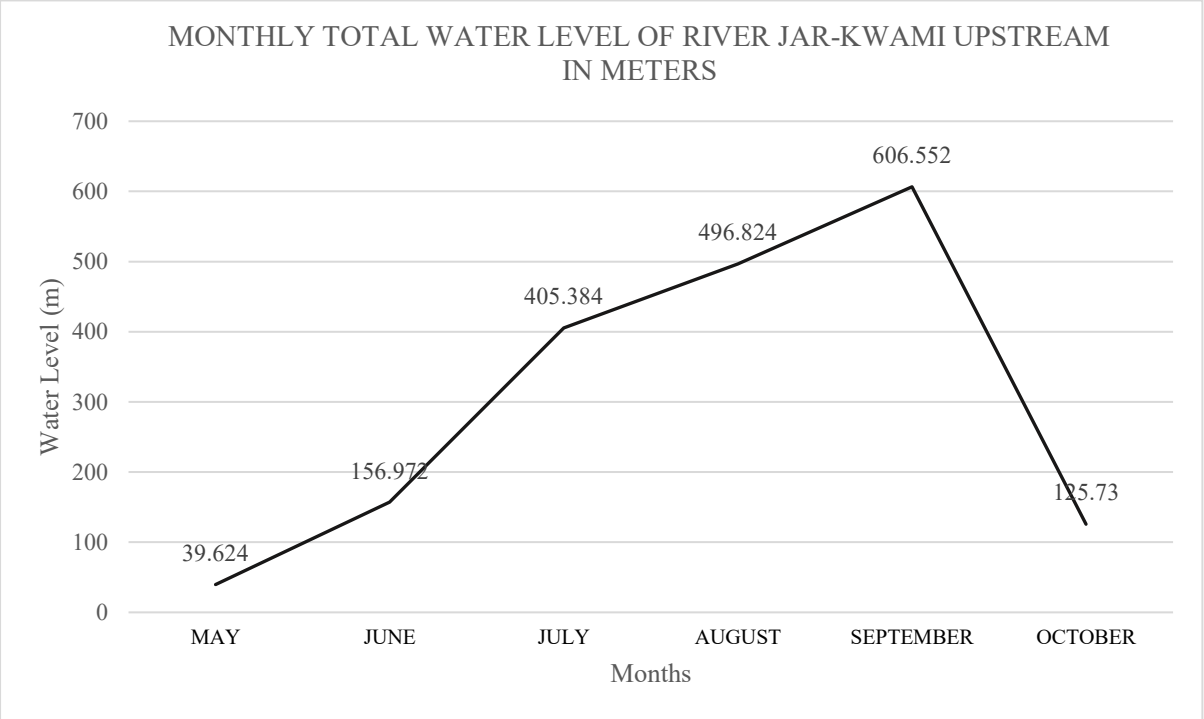


Figure 5: Hydrograph of the Total water level regime of River Jarkwami upstream

Discharge Measurements

Table 4: Discharge Values m³/s for 2023 using Velocity-Cross Sectional Area Method

Month	Mean Q (m³/s)	Maximum Instantaneous Q (m³/s)	% Contribution to Seasonal Total	Interpretation
May	0.82	1.45	2.2%	Low onset dry spell 26 days
June	2.15	4.82	9.3%	Increasing sustained rainfall
July	6.84	15.6	18.6%	Substantial rise prolonged intense rainfall
August	8.92	20.7	24.2%	High sustained escalating trend

September	14.73	20.7 (peak 5th Sep)	40.1%	Peak recharging groundwater inundating low-lying flood risk
October	1.05	2.34	5.8%	Recession transition drier
Total Cumulative Seasonal	368.80 (sum of daily means across 64 flow days)		100%	
Mean Instantaneous	5.76	0.025 $m^3/s/km^2$		

The estimation indicated that the discharge of River Jarkwami was approximately 23603.46 cubic meters per second. This calculation approach is consistent with the principles of open-channel hydraulics, which are extensively documented in hydraulic engineering texts (Chow, 1959; Henderson, 1966). Accurate determination of river discharge is essential for several applications, including flood forecasting, water-resource management, and environmental-impact assessment (Maidment, 1993). In addition, Dingman (2002), in the comprehensive text Physical Hydrology, provides valuable insights into the theory and application of hydrological concepts, thereby establishing a foundation for examining the discharge of River Jarkwami. The total cumulative seasonal discharge was 368.80 m^3/s, while the mean instantaneous discharge was 5.76 m^3/s, with values ranging from 0.60-20.7 m^3/s. This pattern is comparable to that of other small rivers, including River Kubanni, which has a mean discharge of 3-8 m^3/s (Yusuf, 2013), and River Maigamo, which has a velocity of 1.5-3.1 m/s (Muktar, 2017). The discharge regime exhibited a distinct pattern from May through October, characterized by a single maximum, consistent with the findings of Yusuf (2006), Yusuf et al. (2007), Yusuf et al. (2011), Yusuf (2013), and Muktar (2017). September recorded the highest discharge value, at 14.73 m^3/s, in agreement with Yusuf (2013), who also identified September as the month with the highest discharge. Thus, the discharge regime clearly displayed a single maximum between May and October, consistent with these previous studies.

Discharge calculations are crucial for several reasons, as they provide insight into river hydrodynamics and support diverse applications, including flood forecasting, water resource management, and environmental conservation. Reliable discharge data are essential for designing effective flood-control measures, maintaining adequate supplies for various uses, and preserving the ecological balance of the river ecosystem. Regarding water resource management, accurately estimating river discharge is fundamental to effective planning. With reliable discharge values, authorities and stakeholders can make informed decisions about water allocation and promote the sustainable use of this vital resource. In addition, the resulting data can support drought and flood-management planning, thereby helping protect communities and infrastructure around Jarkwami from potential disasters. Validation of the methodology: the velocity-area method used to calculate discharge in this study was validated by comparing the calculated results with collected river-discharge data. The consistency between the computed and observed values confirms the method's reliability for this application.

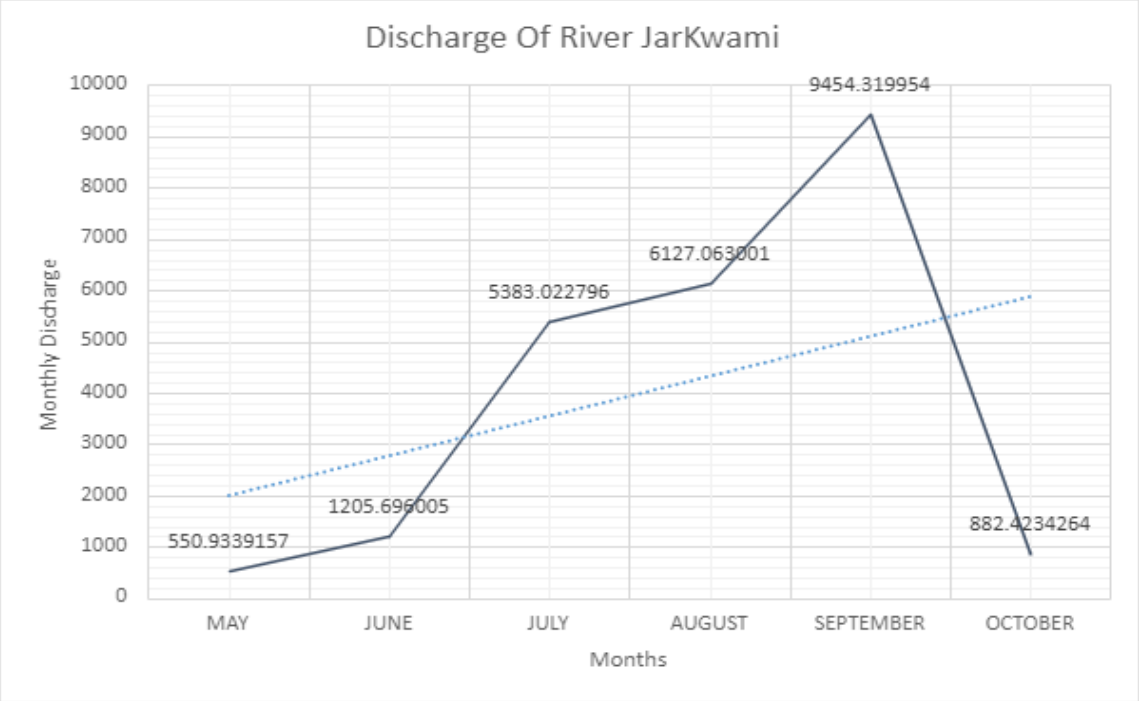


Figure 6: Hydrograph of monthly Discharge Values in m^3/s for 2023 of River Jarkwami upstream

Factors Influencing River Jarkwami Discharge Upstream

Several factors emerged as primary drivers of the observed variations in river water levels. These factors interact in complex ways, shaping seasonal discharge patterns.

Rainfall: Throughout the six-month research period, precipitation, particularly rainfall, played a central role in driving seasonal increases in River Jarkwami's water levels and discharge. An in-depth examination of the relationship between precipitation patterns and river hydrology revealed that the timing and distribution of rainfall were critical determinants of discharge patterns. Beginning in May 2023, the watershed experienced precipitation events that varied in intensity, duration, and frequency. These variations directly affected the temporal behavior of river discharge, supporting the findings of previous studies by Smith (1997) and Brown (2016). The initial research phase was characterized by elevated rainfall, which increased surface runoff and, consequently, river discharge. This response is consistent with the broader understanding that intense rainfall events can produce immediate hydrological effects, as noted by Strahler (1964). The watershed's rapid response to increased rainfall demonstrates the sensitivity of River Jarkwami's discharge to short-term variations in precipitation. As the research advanced, the study documented a shift toward drier conditions within the watershed. Reduced rainfall during this period produced less surface runoff and, consequently, moderated river discharge. Brown (2016) emphasizes the importance of accounting for seasonal precipitation variability when developing a comprehensive understanding of river discharge dynamics. The observed decline in discharge during drier periods demonstrated the watershed's responsiveness to changes in rainfall. The early rainy months generally experienced higher precipitation rates, which rapidly saturated the soil and increased runoff into the river. Temperature fluctuations also affected river water levels to some extent. Higher temperatures increased evaporation rates, which, considered independently, would tend to lower water levels; however, the combined effects of precipitation and soil saturation generally exceeded this influence. Storm intensity and magnitude also appeared to affect streamflow. Rainfall of greater intensity produced an immediate increase in streamflow, particularly in small catchments. The duration of this immediate effect and the volume of runoff depended on

how long rainfall of a given intensity persisted. When storm strength remained constant while duration increased, discharge rose progressively, the peak discharge increased, and the maximum flow was sustained for the duration of the storm (Garcia & Martinez, 2019).

Human activities: Human activities, including open grazing practices, crop cultivation, and the use of agricultural inputs, play a substantial role in shaping discharge patterns in the River Jarkwami. Work by Yusuf (2016) demonstrates that agricultural activities contribute to land-use and land-cover changes, thereby affecting the overall hydrological regime of the River Kubani. The conversion of natural landscapes to croplands modifies surface runoff, influencing the timing and volume of water reaching the river. In addition, soil erosion resulting from farming practices is a critical factor affecting discharge in the River Jarkwami. Ward and Tockner (2001) noted that vegetation removal for agriculture exposes soil to erosive forces, increasing sediment transport into rivers. This process has been identified as a critical influence on River Jarkwami discharge throughout the flow period. Sediment accumulation within the riverbed also modifies channel morphology, affecting flow patterns and producing variations in discharge. Soil excavation and construction activities, particularly along the eastern side of the river, further alter River Jarkwami discharge dynamics. The removal of soil and natural vegetation for infrastructure development exposes Baer surfaces, thereby increasing runoff rates. Khodzinskaya et al. (2022) reported that soil compaction changes surface roughness and that excavation activities affect the soil's infiltration capacity, consequently influencing groundwater recharge and river discharge. Disruption of natural drainage patterns caused by soil excavation has increased surface runoff, affecting the overall balance of water entering the river system. Additionally, the construction of artificial channels along the Jarkwami River bed during excavation modifies flow pathways, producing localized changes in discharge patterns. These landscape alterations have downstream effects on the volume of water entering the main river channel. The deposition of excavated materials in the river also adds sediment, modifying riverbed morphology. Khodzinskaya et al. (2022) emphasize that sedimentation caused by soil excavation can decrease channel conveyance capacity, potentially increasing flood risk during periods of high discharge. Mitigating the effects of these anthropogenic activities is essential for maintaining the health of the Jarkwami River and its associated ecosystems.

Vegetation: Another critical factor affecting discharge in the Jarkwami River is the presence of vegetation along its banks, which plays an important role in regulating river dynamics by influencing surface runoff and infiltration. Yusuf (2017) emphasizes that vegetation root systems improve soil structure, promoting greater water infiltration and reducing surface runoff. Consequently, well-vegetated areas along the Jarkwami riverbank influence groundwater recharge and, in turn, affect base flow and overall river discharge patterns. In addition, the density and type of vegetation within the basin, which primarily comprises shrubs, grasses, and undergrowth, influence the interception of precipitation that contributes to river recharge. Research by Zubairu (2009) indicates that interception may postpone the onset of surface runoff, thereby affecting the timing and volume of water reaching the river. Deciduous trees, in particular, display variations in interception throughout the flow period, further influencing the river's discharge dynamics. Observations also show that riparian vegetation along riverbanks plays an important role in stabilizing the river channel and regulating discharge. This finding aligns with the study by Gravalle (2014), which emphasizes that well-maintained riparian zones reduce erosion, preserve channel morphology, and limit sediment deposition. The stability provided by riparian vegetation promotes more consistent flow patterns and influences the overall discharge characteristics of the Jarkwami River. In addition to affecting surface runoff, vegetation influences subsurface flow pathways within the river basin. The formation of preferential flow paths through root channels and macropores facilitates water movement through the soil profile. Whiting (2003) argues that this subsurface connectivity can affect groundwater contributions to river discharge, particularly during dry

periods when surface runoff is limited. Changes in vegetation cover resulting from land-use practices, such as deforestation along the river, introduce additional complexities, including reduced evapotranspiration. This reduction alters the basin's water balance and consequently affects the dynamics of river discharge. Granville (2014) underscored the importance of accounting for land-use-driven vegetation changes when interpreting variations in river discharge. In addition, seasonal processes, including leaf fall and growth cycles, create temporal fluctuations that affect river discharge. Whiting (2003) emphasized that these seasonal patterns influence interception and transpiration rates, as well as broader vegetation-mediated water processes. Accounting for such temporal dynamics is essential for accurately modeling and predicting fluctuations in river discharge.

Topography is a fundamental factor governing discharge dynamics in the Jarkwami River watershed. The interaction among elevation differences, slope gradients, and landform characteristics strongly influences hydrological processes throughout the watershed. Variations in elevation play a central role in determining river-flow behavior. Yusuf et al. (2011) note that terrain steepness affects the gravitational force responsible for driving water movement. Higher elevations, particularly in the northeastern portion of the Jarkwami basin, increase potential energy, thereby promoting greater flow velocities and modifying river-discharge patterns. Understanding the spatial distribution of elevation across the Jarkwami watershed is essential for interpreting the overall hydrological response of the river system, as land-surface slope is closely associated with the velocity and direction of water flow. Strahler (1964) explains that steeper slopes generally produce higher flow velocities and may increase surface runoff during precipitation events. In contrast, gentler slopes can reduce flow velocities, affecting sediment transport and overall discharge characteristics. Differences in slope across the watershed therefore complicate predictions of discharge variation along the river course. In addition, landform features such as valleys, ridges, hills, and basins create further topographic heterogeneity, exerting a significant influence on discharge in the Jarkwami River. Strahler (1964) explains that valleys function as conduits that concentrate runoff, potentially producing rapid flow and increased discharge during storm events. By contrast, ridges redirect runoff, affecting how water is distributed across the landscape and consequently altering upstream discharge patterns. Garcia and Martinez (2019) demonstrate that interactions between topography and climatic factors influence river discharge, as changes in elevation and variations in slope regulate watershed responses to precipitation and affect both the timing and volume of water entering the main river channel. This interaction highlights the importance of an integrated approach to evaluating the effects of topography on river Jarkwami discharge. In addition, topography influences not only surface runoff but also subsurface flow pathways. Strahler (1957) notes that topographic variation affects groundwater-flow patterns, thereby contributing to baseflow and maintaining discharge during dry periods. This landscape heterogeneity complicates efforts to understand the spatial distribution of groundwater contributions to river discharge and underscores the need for a nuanced approach to watershed modeling. The influence of topography on the spatial distribution of vegetation within the watershed further complicates its effects on river discharge. Yusuf (2011) argues that elevation gradients and slope variations shape the types of vegetation present, influencing interception, transpiration rates, and broader vegetation-mediated water processes. These interactions among topography and vegetation add to the overall complexity of discharge dynamics in the Jarkwami River.

Soil: Soil characteristics within the Jarkwami River watershed represent another important factor and constitute a critical element affecting river discharge dynamics. The sandy soil texture of the Jarkwami basin substantially influences water infiltration and surface runoff. Yusuf (2013) notes that soils with high clay content generally have lower infiltration rates, resulting in increased surface runoff during precipitation events. In contrast, the Jarkwami

basin consists of sandy, compact soils with greater permeability, which permits rapid infiltration and may affect the timing and volume of water reaching the river channel. Careful examination of the spatial distribution of soil textures throughout the Jarkwami watershed is essential for predicting variations in river discharge because soil porosity, which represents the volume of open space within the soil, plays a central role in regulating water movement. Strahler (1964) emphasizes that low porosity permits greater water retention, potentially supporting sustained baseflow and moderating discharge during dry periods. Compacted soils, however, reduce porosity and consequently decrease water retention, potentially affecting surface runoff and river discharge dynamics.

Recognizing variations in permeability throughout the Jarkwami watershed is essential to understanding the complex relationship between soil properties and river discharge. Mittelbach et al. (2012) similarly contend that elevated soil moisture increases runoff, potentially resulting in greater river discharge during wet periods. In contrast, drier soils may retain more water, thereby decreasing surface runoff and affecting discharge patterns. Disturbances to soil structure, whether caused by anthropogenic activities or natural processes, may reduce infiltration, increase runoff, and modify river discharge patterns.

Evaluation of Staff Gauge and Float Method as Method of River Discharge Measurement

The staff gauge method is widely used in hydrology to measure stream discharge because of its simplicity, affordability, and practicality. These advantages are particularly valuable in field settings where more sophisticated instruments may be impractical or unavailable, as was the case in this research. A major benefit observed throughout the study was the method's straightforward design and operation. The staff gauge consisted of a vertically graduated pillar installed at the gauging station near Jarkwami Bridge. It was positioned so that its zero mark corresponded to a predetermined reference point. To measure stream discharge, the researcher visually read and recorded the water level on the staff gauge at regular intervals. In conjunction with these readings, a floating object was used to determine the river's velocity.

The cost-effectiveness of the staff gauge method was another important factor influencing its selection for quantifying discharge in the Jarkwami River. The researcher observed that installing and maintaining staff gauges was relatively inexpensive compared with more advanced discharge measurement techniques, such as flow meters and wire methods, as also reported by Pariva et al. (2016). Consequently, the method represents a practical option for hydrologists, researchers, and environmental monitoring agencies, particularly in resource-constrained settings. Additionally, research has shown that the staff gauge method is highly adaptable under stable stream conditions and provides highly reliable water-level readings, particularly in water bodies with steady flow rates, such as the Jarkwami River. The method has been found especially effective when hydraulic conditions remain relatively stable and are not characterized by extreme turbulence or rapidly changing flow patterns, as also emphasized in the comprehensive review by USGS (2019). Research findings have further confirmed that the staff gauge method supplies real-time data, enabling continuous monitoring of water levels. This capability is crucial for understanding streamflow dynamics, particularly during events such as floods, when lag time is a concern.

Research findings also emphasize the applicability and accuracy of the float method, indicating that it is suitable for measuring stream discharge in small rivers such as the Jarkwami. This finding is consistent with studies by Yusuf et al. (2007), Zubairu (2009), Yusuf et al. (2011), Yusuf (2013), and Muktar (2017), which clearly indicated that the float method is appropriate for measuring discharge in small and medium rivers. Data collected through the combined use of the staff gauge and float methods were analyzed to assess hydrological patterns and estimate flow rates, thereby contributing to a better understanding of the Jarkwami watershed's behavior.

Despite these advantages, it is important to note that the staff gauge and float methods have limitations. Researchers have noted that obtaining accurate measurements requires careful calibration, and that the staff gauge method is less dependable under rapidly changing flow conditions. In addition, the research process depends entirely on human observation, creating the potential for errors and bias, as emphasized in the comprehensive review by Johnson and Brown (2018) of stream discharge measurement techniques. Several limitations were identified during the research, including:

Turbulence presents a substantial obstacle to accurately measuring river discharge with the staff gauge float method. This hydrodynamic condition involves irregular and chaotic fluid movement that can create uncertainty in water-level readings, potentially reducing the overall reliability of the discharge data. Bos (2015) reported a similar observation. A major problem caused by turbulence during the research was the difficulty of obtaining a stable water-level reading. Because turbulent flow fluctuates continuously, determining the water level precisely at a particular point on the staff gauge becomes challenging. Distortions on the water surface produced by turbulent eddies can lead to misinterpretations and errors in the recorded measurements, a concern also identified by Knighton (1998). To reduce the effects of turbulence, the researcher developed site-specific mitigation measures by conducting comprehensive environmental assessments to identify locations susceptible to turbulence before installing the staff gauge. This approach provided a practical means of improving the accuracy of water-level readings, as suggested by Bos (2015). In addition, gauge placement at Jarkwami Bridge was carefully considered in accordance with the guidelines provided by Knighton (1998). The gauge's position relative to the main flow and areas prone to turbulence substantially affects measurement accuracy. Installing the gauge where flow conditions were more stable reduced turbulence and improved the reliability of the recorded data.

The presence of debris in the river presented a significant challenge to accurately measuring river discharge with the staff gauge–float method. Floating vegetation, branches, and other suspended materials occasionally interfered with water-level readings and the movement of the floating ball, introducing uncertainty and potential errors into the collected data, a factor also identified by Bos (2015). One of the primary challenges associated with debris during the research involved its effect on the stability of water-level readings. Floating vegetation and large debris obstructed the water surface, making it difficult for the researcher to accurately identify the true water level at the gauge point. Knighton (1998) also highlighted this issue. This interference could lead to misinterpretations and errors in the recorded measurements, thereby compromising the reliability of the discharge data. To address the challenges caused by debris, the researcher adopted preventive and corrective measures, including site-specific assessments, as recommended by Bos (2015). These assessments helped identify areas susceptible to debris accumulation. A staff gauge structure with a strategically positioned floating ball was installed, which substantially redirected debris away from the staff gauge and floating ball, reducing its effect on water-level readings and improving measurement accuracy. Nevertheless, debris continued to present some difficulties during extreme weather events and periods of elevated flow. Continuous, repeated data collection, monitoring, and maintenance helped address debris-related issues promptly. In addition, regular inspections of the areas surrounding the staff gauge during the research period enabled the identification and removal of accumulated debris that could interfere with accurate water-level readings, as recommended by UNESCO (2008).

Water surges also introduced complexities into the accurate measurement of river discharge using both the staff gauge and float methods. Often associated with sudden changes in flow rates, water surges created dynamic conditions that affected the stability and reliability of water-level readings, adding another layer of difficulty to the discharge measurement process. Knighton (1998) notes that water surges can cause rapid water-level fluctuations, making it

difficult for observers to obtain stable and consistent readings from a staff gauge. The dynamic behavior of these surges creates uncertainty and increases the potential for error, particularly during extreme weather events or sudden releases from upstream subbasins. To prevent or reduce the effects of surges on staff-gauge readings, the research considered the hydrological context carefully and conducted site-specific assessments, as recommended by Bos (2015). This process helped identify areas vulnerable to water surges. In addition, an understanding of local hydrological conditions supported the implementation of appropriate measures to minimize their influence on water-level readings. These measures included strategically positioning the staff gauge along Jarkwami Bridge and carefully measuring floating velocity with a ball. Selecting locations less exposed to the direct effects of water surges improved measurement stability.

The vertical range of staff gauges also presented a challenge for accurately measuring river discharge. Because a staff gauge consists of a vertical scale marked in increments, its design limits the range of water levels it can measure effectively. This limitation becomes especially important during extreme changes in water level, a common issue in rivers and streams subject to fluctuating flow conditions, such as the River Jarkwami, as highlighted by McCuen (2019). The staff gauge's limited measurement range creates situations in which the water level rises above its maximum measurable height or falls below its minimum threshold. Under such conditions, the gauge is insufficient for accurately capturing and documenting extreme flow events. This limitation is particularly important because the River Jarkwami is situated in an area vulnerable to flooding and characterized by substantial seasonal variations in streamflow. To address the anticipated challenge posed by the gauge's limited measurement range, careful consideration was given to the gauge-selection process. A staff gauge was selected for the research because it corresponded to the expected range of water levels in the study area. Herschy (2009) emphasizes the importance of selecting a gauge capable of accommodating the full spectrum of anticipated flow conditions. Failure to do so may place critical data points beyond the measurable range, thereby compromising the comprehensiveness of the dataset.

Despite these challenges, the staff gauge method remains a widely accepted and commonly used technique for measuring stream discharge. Numerous studies have confirmed its effectiveness across various hydrological settings (Gray, 2014; Chow et al., 1988). Technological advances have also enabled the integration of electronic sensors with traditional staff gauges, improving the efficiency and accuracy of data collection (Fread, 2001). The staff gauge method is distinguished as a cost-effective and practical approach to stream discharge measurement, making it attractive to hydrologists, researchers, and resource managers because of its economic efficiency and simplicity. The method's cost-effectiveness can be attributed to several factors.

Firstly, one of its primary advantages is the affordability of the staff gauge, as observed by the researcher. Compared with more sophisticated electronic sensors and automated measurement systems, a staff gauge is relatively inexpensive. This advantage was emphasized by Bos (2015), who noted that the staff gauge is accessible for deployment across a broad range of monitoring applications, particularly where budgetary constraints may limit the adoption of more advanced technologies, as demonstrated by its use during this research. The method's simplicity also enhances its cost-effectiveness. Installing and maintaining staff gauges requires minimal infrastructure and equipment, thereby reducing overall operational expenses. For example, during this research, a platform was used during staff gauge installation at parts of Jarkwami Bridge. The straightforward design and ease of implementation make the method suitable for diverse environments and accessible to personnel with varying levels of expertise (Knighton, 1998). Local calibration further improves the cost-effectiveness of the staff gauge method, as observed during the research. Calibration can be adapted to the site's specific hydraulic conditions, ensuring that water-level measurements remain accurate within the local context.

This adaptability reduces the need for costly adjustments and corrections that may be required with less flexible measurement technologies. In addition, the staff gauge's low maintenance requirements contribute to its economic efficiency. Regular inspections and cleaning are typically sufficient to ensure continued functionality, a point highlighted by UNESCO (2008). This characteristic minimizes operational costs during research, making the staff gauge an attractive option for long-term monitoring projects. The absence of power requirements represents another cost-saving advantage of the staff gauge method. Unlike electronic sensors, which may require power sources, staff gauges function without electricity. This feature makes them suitable for deployment in remote, off-grid locations such as the Jarkwami River, eliminating the need for costly power infrastructure, as also noted by Knighton (1998). Moreover, the versatility of staff gauges enhances their cost-effectiveness. They can be installed in various locations and environments, providing flexibility for monitoring stream discharge across different landscapes and conditions. This adaptability reduces the need for specialized equipment in diverse settings, thereby contributing to overall cost savings. Thus, the research concludes that the staff gauge and float method is highly effective for determining discharge in small and medium-sized rivers because it produced consistent and reliable data throughout the research.

Conclusion

In conclusion, this study has undertaken a comprehensive examination of accurate discharge determination in the upstream section of the Jarkwami River through the use of staff gauges and float methods, complemented by basin delineation using ArcGIS. The culmination of this study has made significant contributions to the fields of hydrology and water resource management. Through systematic data collection, rigorous analysis, and the application of ArcGIS technology, this study has produced a more comprehensive understanding of discharge dynamics in the upstream region of the Jarkwami River. Accurate discharge measurement is essential for effective water resource planning, ecological conservation, and flood risk evaluation. The use of ArcGIS for basin delineation has further supported an integrated assessment of the river's hydrological characteristics. The findings have important implications for sustainable development and informed decision-making within the river catchment area. By applying advanced GIS techniques, it is now possible to better understand the complex relationships among discharge, basin morphology, and other factors influencing the overall hydrology of the Jarkwami drainage basin. Moving forward, it is essential to continue improving these techniques, adjust management strategies in response to changing environmental conditions, and implement policies that emphasize conservation and the responsible use of the Jarkwami River's resources. This research provides a foundation for further investigation and the application of hydrological practices that support the sustainable management of this vital natural asset.

Recommendations

Based on the results obtained from the study, the following recommendations are made:
There should be continuous monitoring of river discharge in the upstream Jarkwami region, as this is the primary requirement for planning water resource development. Reliable discharge data collected over a considerable period are necessary to determine the extent and pattern of available water supply. Measures to reduce siltation in the river should be implemented because sediment yield in any river is related to upstream stream discharge. Measures to prevent and control flooding should also be established because increased flow during certain periods may force water onto the surrounding land, damaging farmland and property when the river exceeds its carrying capacity. The study findings further emphasize the importance of continuous

monitoring to track changes in stream-bed morphology. Additional studies are recommended to evaluate long-term trends and identify the potential causes of the observed variations.
Lastly, staff-gauge and float methods are recommended as the most effective techniques for measuring stream discharge, particularly under economically constrained conditions and in small- and medium-sized river streams, because of their consistency and simplicity. The study analyzed discharge in the upstream section of River Jarkwami using staff-gauge and float methods; however, other techniques may also be used to determine river discharge and could provide the basis for another study.

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