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Estimation of river flow properties using Arc-GIS, HEC-GEORAS, HEC-RAS, and gauge data in Northwest, Pakistan

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ABSTRACT

The accurate estimation of river discharge properties is challenging because of the lack of gauge data in inaccessible and remote regions, uneven distribution of gauge networks, and data-sharing complexities. To address these challenges, innovative integrated techniques must be evaluated. This study aimed to integrate geospatial (HEC-GEORAS), HEC-RAS, and river gauge data to quantify river flow properties, including the discharge rate, velocity, water level, and flow depth of a distributary of the Indus River in northwestern Pakistan. The study area is characterized by semi-arid conditions, experiencing water scarcity, and declining water levels. Such an integrated approach has never been used in the region, especially on any distributary of the Indus River, until now. The findings revealed that the peak flow velocity reached 1.8 m/s, and the spatial distribution varied from 0.3 to 1.3 m/s. The maximum depth was estimated at approximately 33 m in the upstream section and showed a declining trend of a few centimeters in the downstream section. River discharge decreases downstream (from 2.26 to 0.28 m^3/s) due to infiltration, tributary water distribution, evaporation, and agricultural water use. The estimation of hydraulic parameters provides meaningful information for sustainable water resource management, such as domestic, agricultural, and industrial water allocations. Furthermore, the results can support flood risk assessment, irrigation planning, and adaptation to climate change strategies by improving our understanding of water availability and flow dynamics in semi-arid river systems.

Keywords: *HEC-RAS, GEO-RAS, Discharge, GIS/RS, Manning values.*

1. Introduction

Hydrologists emphasize river discharge parameters as vital components of hydrologic studies and water resource management strategies [1]. However, challenges such as uneven and sparsely distributed river gauging stations installed globally [2] and issues with data collection [3] have encouraged the development of innovative methods and advanced technologies to address these issues. These include geospatial techniques that rely on remote sensing and satellite data, which enable the estimation of river discharge properties with large spatial and temporal variations in surface water on a large scale. The efficient management of natural resources using these advanced techniques is vital for effective agricultural production and strategies to mitigate hydrological extremes. Water is a vital resource for crop productivity and must be managed and utilized efficiently to achieve optimal yield.

Global water scarcity indicates that by 2025, nearly two-thirds of the world's population will exist in water-stressed regions [4]. Changes in climate, along with human activities, have caused fluctuations and periodic river flow changes and other hydrological processes globally, resulting in a disruption to irrigation systems [7]. These challenges highlight the need to manage water resources in the agricultural sector to maintain crop productivity and ensure food security [7, 8]. In this context, it is essential to operate and manage these resources with great attention to mitigate water-related issues such as water scarcity. Therefore, several studies have been conducted to combine ground- and satellite-based measurements using advanced techniques to enhance the accuracy of river discharge estimates. Combining satellite and in situ data in hydrological models provides a valuable way to understand better the processes that govern river flow and develop an effective strategy for mitigating the adverse effects of climate change on the hydrological cycle.

The reliable evaluation of river flow properties is an essential aspect of water resource management and hydrodynamic modeling [9]. The availability of time-series and spatially consistent discharge data is a major requirement for hydrological studies. Although gauge data are considered more authentic, they are often difficult to obtain because they are not widely available (2). Despite the limitations in the availability of ground data, satellite/remote sensing data present a valuable alternative with broader spatial and temporal coverage of rivers and other hydrological components of river basins. Some studies have highlighted the potential of remote sensing data for assessing river discharge properties with greater spatial and temporal resolutions [4, 5, 10, 11, 12].

Pakistan has diverse climatic conditions [13], and due to water scarcity problems, mainly in arid to semi-arid regions, monitoring river discharge properties is crucial. This is especially true in the southern parts of the Khyber Pakhtunkhwa (KP) province, where water scarcity affects crop production and irrigation. Moreover, discharge monitoring is essential for environmental protection and ensuring the quality of water and ecosystems that rely on water resources. The Teri Toye River, located in the District Karak of Khyber Pakhtunkhwa province, is a distributary of the Indus River with a confluence with the Kabul River in the southern parts of KP (Figure 1). Upstream of this confluence, the Indus River has a vast catchment area comprising the whole of northern Pakistan with many small to large river systems (Figure 1), making it significant to be monitored using the latest state-of-the-art data and techniques. The region encompasses a variety of climate zones, including semi-arid conditions [14]. Several factors,

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such as altitude, seasonal rainfall patterns, and proximity to mountain ranges, influence the local climate. The river traverses a narrow gorge characterized by minimal vegetation and a sparse human population, making it a vital component of the region's ecological and agricultural landscape.

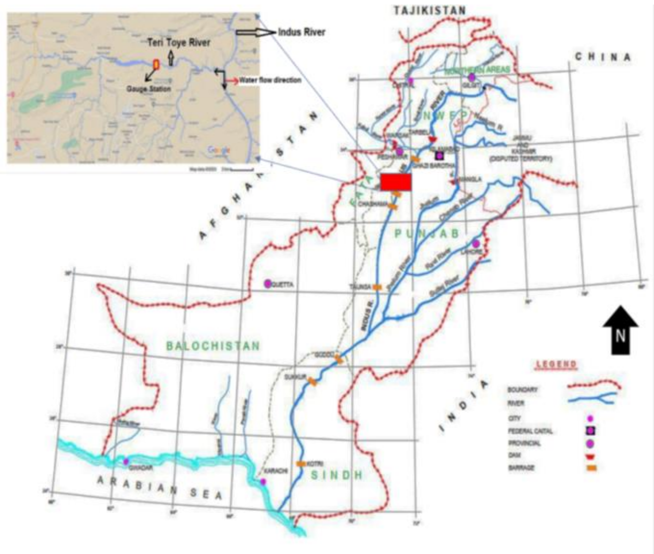

Fig. 1 Study area map showing the location of the Teri Toye River watershed (red polygon) in Pakistan, including the river network, gauge station, flow direction, and its connection to the Indus River.

In this study, the Teri Toye River was extensively monitored, particularly with respect to the hydraulic parameters in the upper, middle, and lower segments of the river. It introduces an innovative approach for discharge estimation for a river distributary by combining gauge stations with geospatial techniques, that is, the HEC-RAS-GEO. This method uses relevant datasets acquired through remote sensing techniques, including soil maps, digital elevation models, land use/land cover, roughness coefficients, and Manning's values, to evaluate river properties across a broader spatial extent, an approach not previously applied in the region. The methodology used in this study comprises four primary steps: (1) extraction of river geometry, such as discharge paths, centerlines, banks, and draw traverse for obtaining cross-sections at fixed intervals; (2) roughness coefficient (Manning's n) [15]; (3) using boundary conditions for conducting a steady state flow analysis and runoff modeling; and (4) simulating and estimating discharge rate, velocity, and depth at upstream, midstream, and downstream cross-sections. The HEC-RAS model, which is highly recognized for its accuracy and widespread application in river system investigations [16, 17], was used in this study. Specifically, HEC-RAS (version 5.0, 2016) was utilized and integrated with the Geospatial Hydrologic Modeling Extension (Arc-Hydro and HEC-GeoRAS). This software, available on the HEC website, includes the following 1-D hydraulic components: unsteady flow simulation, steady flow evaluations, sediment transportation, and determination of water quality, all based on the representation of geometric data and computational practices. This study focused on the steady-state flow component to evaluate the discharge properties of the Teri Toye River, a distributary of a large river such as the Indus River.

Materials and Methods

The Teri Toye River flows in an east-west direction with an approximate length of 33 km, and its average annual discharge is 30,166 m^3/s. This study focuses on the Teri Toye River, a distributary of the Indus River, which is considered the longest river in District Karak, Khyber Pakhtunkhwa (KP). To define the boundary conditions, discharge data (mean daily) were collected from the Irrigation Department of Khyber Pakhtunkhwa. River geometry was extracted using the DEM (ALOS PALSAR, 12.5 m resolution) (Figure 2).

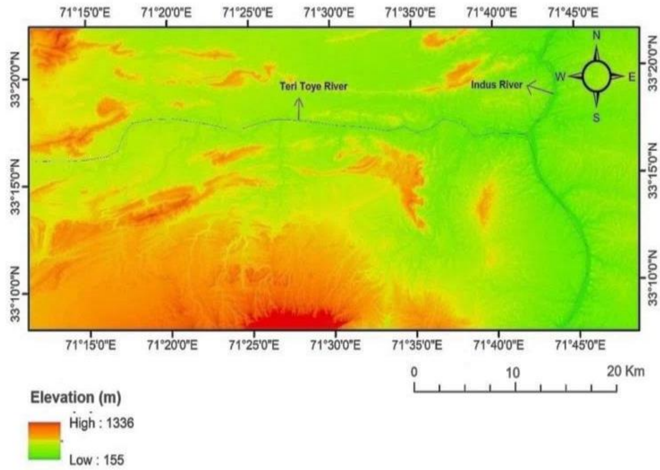

Fig. 2 Digital Elevation Model (DEM) of the study area illustrating terrain elevation gradients and the spatial relationship between the Teri Toye and Indus rivers.

Land use and land cover (LULC) data (Figure 3a) and soil texture maps (Figure 3b) were provided by the Soil and Water Conservation (SWC) Department of Khyber Pakhtunkhwa.

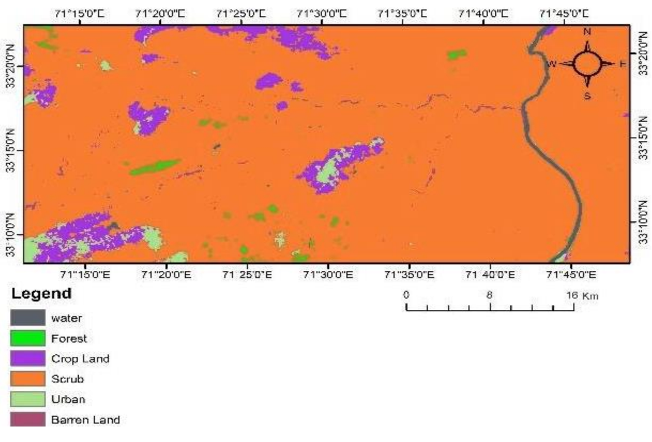

Fig. 3(a) Land use/land cover (LULC) classification map showing the spatial distribution of water, forest, cropland, scrubland, urban, and barren land within the study area

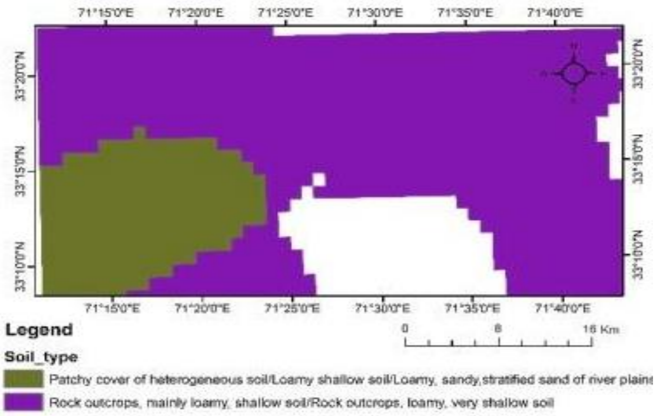

Fig. 3(b) Soil type map illustrating the spatial distribution of heterogeneous loamy soils and rock outcrop-dominated shallow loamy soils across the study area.

The methodological framework employed in this study is illustrated in Figure 4. The river geometry was delineated using HEC-GEO-RAS, a GIS-based extension of HEC-RAS. Following the extraction of river geometry, it was imported into HEC-RAS for further evaluation, which included the estimation of discharge, river velocity, and depth, as well as one-dimensional (1-D) runoff simulations and modeling.

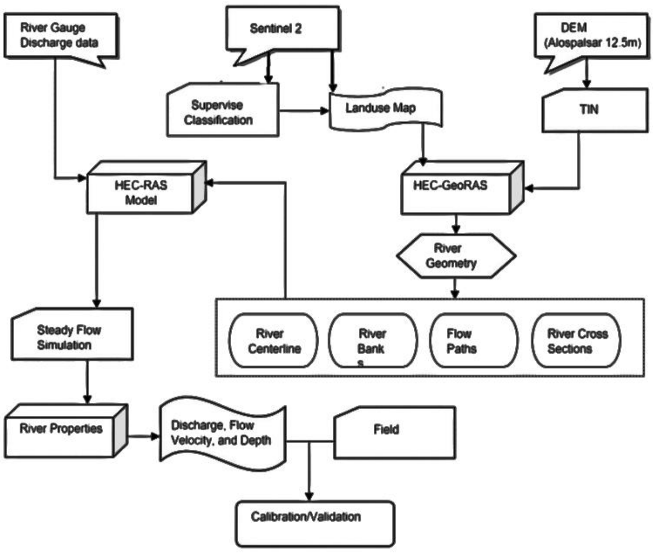

Fig. 4 Flowchart illustrating the methodology adopted in this study, including data acquisition, land-use classification, river geometry extraction, HEC-RAS hydraulic modeling, flow simulation, and calibration/validation of river discharge, velocity, and depth parameters.

These processes were important for analyzing the behavior of the Teri Toye River and generating significant insights into its hydrology. The key steps in this analysis are as follows:

2.1 Pre-processing (Arc-GIS & HEC-GEO-RAS)

Preprocessing is a fundamental step that involves extracting river geometry. The extraction process began by converting the DEM data into a triangulated irregular network (TIN), as shown in Figure 5.

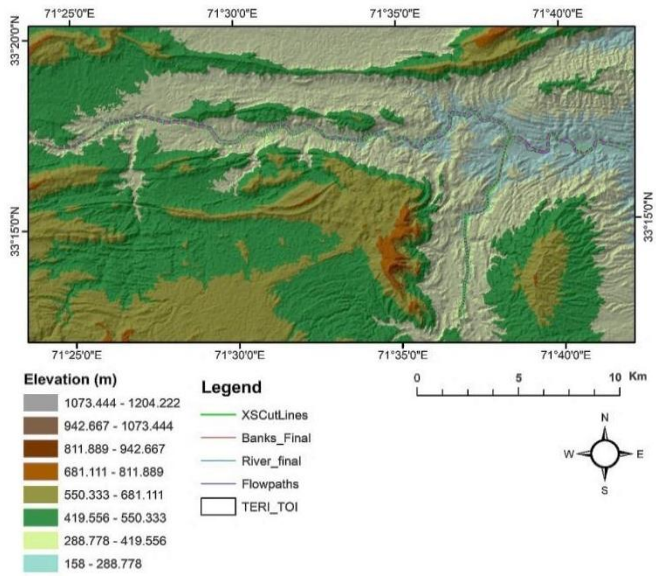

Fig. 5 Triangulated Irregular Network (TIN)-based terrain model of the study area showing the extracted river geometry, including river centerlines, banks, flow paths, and cross-sectional locations used for hydraulic analysis.

River geometry encompasses the attributes of a river, such as the centerline, paths, banks, and cross-sections, at specific intervals (Figure 6).

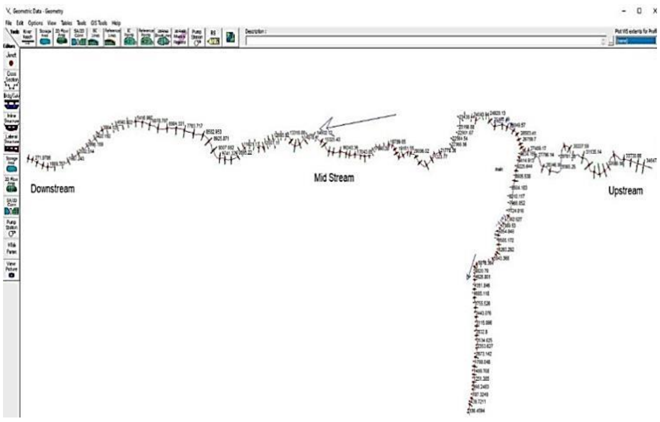

Fig. 6 Geometric representation of the Teri Toye River showing the river course and selected cross-sectional profiles along the upstream, midstream, and downstream reaches.

HEC-GEO-RAS runs a suite of different tools designed to facilitate the creation and management of river geometry data in GIS applications. HEC-GeoRAS enhances the reliability and precision of the data used for hydraulic modeling and simulations. These data were subsequently used to develop input data for the HEC-RAS application.

2.2 Processing

The HEC-GEO-RAS data were further evaluated in HEC-RAS to conduct hydraulic models and simulations that modeled the river's attributes. Prior to determining the river flow properties, several parameters, including flow rates, boundary conditions, and Manning's roughness coefficients, were set. The accurate collection of these constraints is crucial for confirming the reliability of the results, as they directly influence the outcomes of the hydraulic modeling. This study focused on determining various properties of the Teri Toye River, including discharge rate, water surface levels, flow velocity, and depth, and conducting one-dimensional (1D) modeling.

4. Result and Discussions

4.1 Hydraulic Properties of Teri Toye River

Hydraulic parameters, such as water depth, discharge rate, and runoff flow velocity, pertain to the physical characteristics of water flow within a river. Understanding these properties is crucial for several applications, including flood event prediction, infrastructure design (e.g., bridges), water resource management, dam construction for flood protection, ecosystem dynamics reliant on water flow, and water balance and agricultural productivity analysis. A detailed discussion of these properties is provided in this section.

4.1.1 Discharge estimations

Discharge refers to the water volume flowing through a specific point in the channel per unit time, commonly calculated in cubic meters per second (m^3/s) or cubic feet per second (cf/s). In HEC-RAS, the estimation of discharge requires specification of the river channel length, cross-sectional shape, and elevations of the riverbed and banks. Additionally, boundary conditions (such as flow rate and water level) and hydraulic properties, including roughness (Manning's value), were considered (Table 1).

Table 1: Manning's '*n*' values of land use classes

Landuse classes	LULC	Soil Type	Top width (m)
Main Channel	Barren Land	Loamy and shallow soil, and rocks outcrop	0.035
Left Bank	Scurb and Crop Land	Loam, shallow and heterogeneous soil	0.042
Right Bank	Scurb and Crop Land	Loam, shallow and heterogeneous soil	0.042

Discharge estimation was essential in this study for evaluating watershed boundaries and effective water resource and irrigation management. The discharge rates were assessed at the cross-sections along the downstream direction (Table 2).

Table 2: Discharge rate at upstream, midstream, and downstream

Location	River Station	Q left the bank (m^3/s)	Q Channel (m^3/s)	Q Right bank (m^3/s)	Top width (m)
Upstream	34647.25	0.37	2.31	0.71	141.31
Mid-stream	17492.23	0.19	1.23	0.56	88.07
Down Stream	271.9786	0.002	0.30	0.20	14.10

The Toy River channel primarily contains a rock outcrop along with loamy and shallow soil (Figure 3b). In contrast, land use and land cover (Figure 3a) indicated that the area was primarily characterized by barren land. These factors significantly affect the hydraulic behavior of rivers. To accurately determine the flow dynamics, boundary conditions were established as a roughness coefficient or Manning's value of 0.035 for the main channel and 0.042 assigned for the banks (Table 1). These values were selected to characterize the friction encountered by the water in the channel. The elevation profile of the channel plays an important role in influencing both the discharge rate and water level (Figure 7). The boundary conditions and other river characteristics contributed to the calculation of the water levels at each cross-section of the target distributary river (Figure 8). At the upstream (Figure 8-lower), the water level was observed to be 42.72 m, gradually decreasing to 23.46 m at the midstream (Figure 8-middle) and 1.62 m at the downstream (Figure 8-upper). The discharge rate was estimated at the respective cross-section to examine the spatial variations in the river discharge characteristics along the downstream direction. The results showed a pattern, with a larger discharge rate in the upstream section of 0.37 m^3/s at the left bank, 2.31 m^3/s in the channel, and 0.71 m^3/s at the right bank (Table 2).

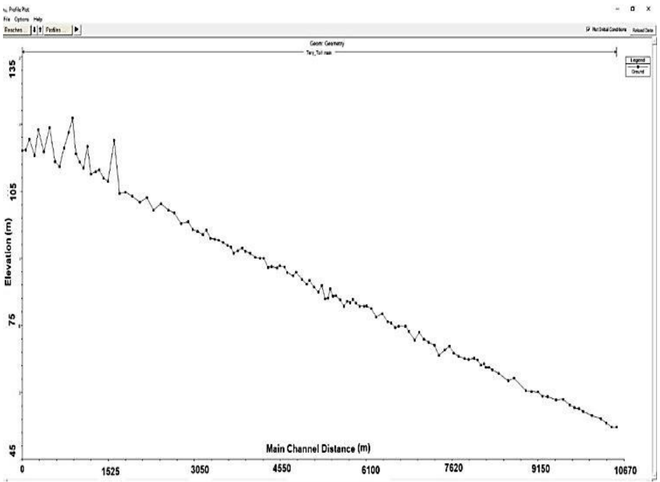

Fig. 7 Longitudinal stream profile showing the relationship between elevation and main channel distance along the watershed drainage network.

This larger discharge was due to the substantial volume of water entering the Indus River and other contributing sources. In the downstream direction, a gradual decrease in the discharge rate was observed, with values of 0.002 m^3/s at the left bank, 0.30 m^3/s in the channel, and 0.20 m^3/s at the right bank (Table 2). This reduction is associated with several factors, such as natural attenuation due to infiltration losses, water abstraction, and diversion into the irrigation canals. These findings emphasize the importance of considering the spatial attenuations of water levels and discharge rates along with river channel characteristics, such as roughness and soil type, when evaluating river systems.

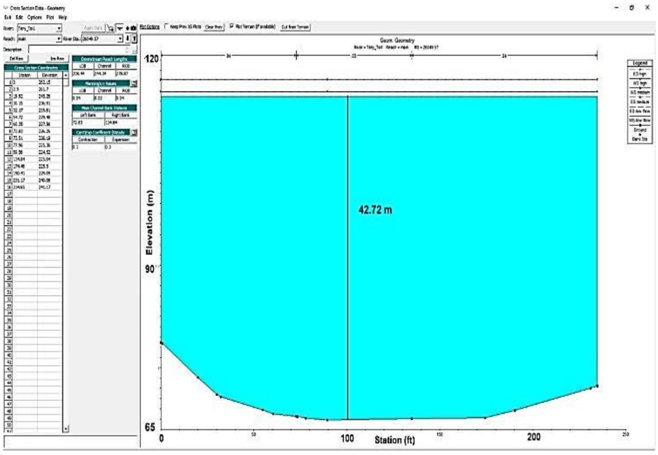

Fig. 8 Representative River cross-sections of the Teri Toye River at the downstream (upper panel), midstream (middle panel), and upstream (lower panel) reaches, illustrating channel geometry and variations in river morphology.

4.1.2 Calculation of Flow Depth and Velocity

Depth is the vertical distance from the water surface to the base of the river channel. It is usually measured in meters or feet and is affected by multiple factors, such as evaporation, precipitation, and water extraction. Velocity is the rate at which water moves through a river or channel and is commonly expressed in meters per second or in feet per second. This flow rate fluctuates with the gradient of the river channel, roughness coefficient, and other environmental factors. The standard method was used to determine the elevation of the water surface and the gradient between two adjacent cross-sections [18]. In the present study, the discharge parameters of steady-state movement, including flow velocity and depth at specific cross-sections of the Teri Toyo River, were evaluated using Equation (1):

$$Y1 + \frac{a1V1^2}{2g} + Z1 = Y2 + \frac{a2V2^2}{2g} + he \ldots\ldots\ldots (1)$$

Where Z1, Z2: channel elevation (m), Y1, Y2: Water depth (m), V1, V2: Average velocities (i.e., total discharge / total flow area) (measured in m/s), a1, a2: Velocity coefficients, g: Gravitational acceleration (m/s^2), and he: loss of Energy head (m)

These parameters are essential for evaluating irrigation areas delineated by watershed boundaries, which, in turn, contribute to estimating agricultural productivity. These factors also play a significant role in the effective water resource management of the study region. The visualization of the flow depth indicated a substantial increase in depth in the upstream region, as shown in Figure 9, where the depths ranged from 29 to 33 m. This greater depth is likely due to the significant contribution of water influx from the Indus River, which contributes to a higher flow volume at the upper reaches of the river. The notable decrease in water depth observed in the downstream direction highlights the dynamic behavior of river flow (Figure 9), where fluctuations have a significant impact on the surrounding areas.

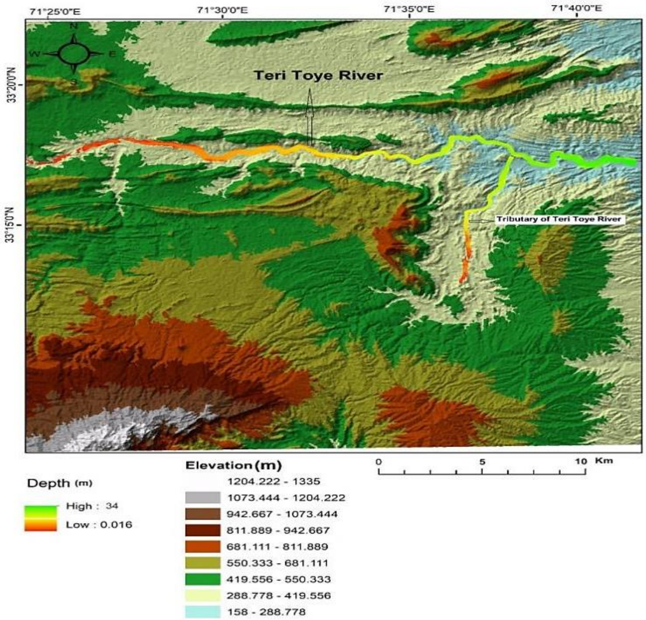

Fig. 9 Spatial distribution of water flow depth (m) along the Teri Toye River and its tributary, displayed over a terrain elevation model to illustrate channel depth variations across the river network.

At cross-section 34647.25 (Figure 6) located in the upstream region, the velocity was approximately 0.4 m/s (Figure 10). The broader channel also allowed the water to disperse, thereby decreasing the velocity. Conversely, a combination of the slope of the river and the gradual narrowing of the channel results in a steady increase in the flow velocity. At the downstream extremity (cross-section 271), the river velocity reached approximately 1.3 m/s (Figure 10). In certain sections, the water velocity was higher owing to channel narrowing and slope steepening (Figure 2). An increase in slope and narrowing of the channel accelerated the water flow.

5. Discussions

The hydraulic properties of the Teri Toye River were analyzed at three different locations (upstream, midstream, and downstream) by combining river gauge data with remote sensing data, such as the digital elevation model (DEM), geological maps, soil texture maps, and Manning's roughness coefficients. This study estimated flow properties such as discharge rate, river velocity, roughness coefficient, and depth using Manning's equation. The boundary conditions (e.g., flow regime and water surface elevation) and hydraulic parameters, such as Manning's roughness coefficient, must be defined to simulate the flow behavior of the river [19]. HEC-RAS with GIS has been applied to simulate river hydraulics and flood inundation mapping in Turkey, demonstrating a strong agreement between the modeled and observed water levels [20]. The findings indicated that a maximum discharge of 2.26 m^3/s was recorded at the upstream section, which gradually decreased to 0.28 m^3/s downstream. Notably, the highest flow velocity of 1.8 m/s was observed downstream; however, the velocity decreased upstream owing to variations in the gradient and geometry of the channel (Figure 10).

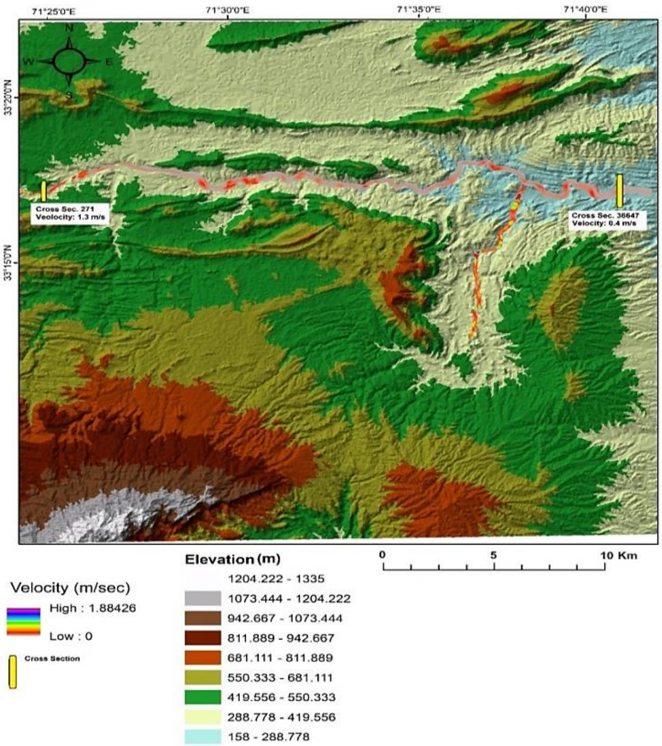

Fig. 10 Spatial distribution of water flow velocity (m/s) along the Teri Toye River overlaid on a Triangulated Irregular Network (TIN)-based terrain model, highlighting velocity variations across the river channel and surrounding topography.

By accurately extracting river geometry and slope, this study estimated river depth using empirical relationships derived from the data. The maximum water depth, ranging from 29 to 33 m, was observed in the upstream region, with a gradual decrease in the downstream direction (Figure 9). The discharge rate was higher upstream but reduced downstream (Table 2), which is consistent with the findings of [21], who reported significant downstream attenuations due to infiltration, abstraction, and lateral water losses in irrigation systems.

River flow contributes to groundwater recharge, which is an important source of water for domestic use [22]. The unique aspect of this study was its ability to estimate river discharge parameters over a broader spatial area by integrating point-based river gauge data, remotely sensed DEM, and organizational data (geology and soil), offering a promising approach for assessing river properties over larger spatial extents. Future research should apply this advanced HEC-RAS and GEO-RAS methodology to analyze river properties in diverse physiographic and climatological settings of major rivers.

6. Conclusions

The climatic and physiographic conditions of the Teri Toye River are vital aspects of the region related to water balance, ecology and agriculture. Ground-based data are point-restricted and insufficient for the detailed mapping of river properties, such as discharge rate, flow depth, and velocity, over a broader spatial extent. This study aimed to address this limitation by integrating geospatial techniques (HEC-RAS and HEC-GeoRAS) to evaluate the hydraulic properties of the Teri Toye River over a larger spatial area than previously studied areas. The integrated approach adopted in this study successfully produced the following findings, which have significant impacts on effective water resource management and flood control as a distributary of a large river system:

- Areas with greater river depths generally correspond to lower-flow velocities and higher discharge volumes.
- Discharge rates were higher in the upper reaches of the river and decreased downstream.
- An increased flow velocity was observed in sections where the river channel became steeper and narrower.
- A greater water depth was detected upstream, which was attributed to a larger channel incision, suggesting that these areas may be more suitable for groundwater recharge and irrigation.

These interpretations were correlated with the field data, confirming the reliability of the HEC-RAS and HEC-GeoRAS models in accurately mapping the hydraulic properties of rivers under semi-arid conditions. The results reveal that these techniques are valuable tools for water resource management, ecological studies, agricultural planning, and addressing hydrological extremes, such as floods and droughts.

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Authors' Contribution

Both authors contributed equally to the manuscript preparation.

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