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Hydrological Dynamics and Road Infrastructure Resilience: A Case Study of River Nile State, Sudan

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Abstract

This study explores the intricate relationship between hydrological processes, watershed management, and road infrastructure resilience, focusing on the impact of flooding on roads intersecting with streams in the River Nile State, Sudan. Located between 16.5°N to 18.5°N latitude and 33°E to 34°E longitude, this region, crucial to both ecological and economic aspects of the Nile River, faces significant challenges due to flooding. Utilizing precise Digital Elevation Models (DEMs) and advanced hydrological modeling techniques, the research aims to identify optimal solutions, such as overpass bridges, to mitigate flood risks. The total road length within the study area is quantified at 3572.279 kilometers, with stream orders categorized by length distribution: First Order at 2276.79 kilometers (50.7%), Second Order at 521.48 kilometers (11.6%), Third Order at 331.26 kilometers (7.4%), and Fourth Order at 1359.92 kilometers (30.3%). A notable flood event in 2020 disrupted approximately 120 meters of the Atbara - Shendi Road, revealing damage beyond initial expectations despite existing overpasses. This underscores the need for enhanced flood mitigation strategies and a reassessment of infrastructure resilience. The area where the flood caused the road cut had a watershed area of 214 square kilometers. The study identified 26 points where the watershed area is equal to or exceeds 214 square kilometers, indicating a higher risk of road disruption due to flooding. Enhanced scrutiny, potentially using high-resolution DEMs, is recommended for better assessment and management of these vulnerabilities. By integrating advanced DEM data and hydrological analysis, the study proposes tailored solutions to protect infrastructure while promoting sustainability and environmental stewardship.

Keywords: Hydrology dynamics; Road Infrastructure Resilience; River Nile State; Stream order; watershed

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INTRODUCTION

The complex interchange between stream order, watershed basins, and road infrastructure has become a focal point of study within the fields of hydrology and environmental planning. The concept of stream order, which plays a fundamental role in hydrology and geomorphology, was initially introduced by Horton in 1945 and subsequently refined by Strahler in 1957. It functions as a crucial tool for categorizing and examining river networks, providing valuable insights into their hierarchical structure and behavior. Horton's original work focused on organizing streams within watersheds, highlighting the process by which smaller streams merge to form larger ones [1]. Strahler expanded upon this by introducing a more organized method for assigning stream orders based on patterns of stream merging. According to Strahler's system, streams are assigned numerical orders according to their position within the hierarchy: small tributaries form first-order streams, and subsequent orders increase as streams merge, maintaining the highest order of the merging streams unless a higher-order stream is encountered [2]. This hierarchical framework allows researchers to investigate various aspects of river networks, such as drainage patterns, sediment transport, and ecological dynamics, across different spatial scales. Through this structured approach to understanding river systems, stream order classification enhances our comprehension of fluvial processes and their effects on landscapes and ecosystems. It's worth noting that streams can also act as barriers and channels for water, a characteristic that may increase flood risks under specific conditions [3], offers a tight approach to categorize streams within a watershed hierarchy. This classification system is helpful in elucidating the geomorphological and ecological processes within riverine systems [4]. Watershed basins, defined as areas where precipitation collects and flows toward a common outlet, are critical in managing water resources and maintaining ecological equilibrium [5]. The dynamics between watershed systems and road networks are intricate, as roadways can drastically modify the natural flow of water across landscapes, which may lead to inundation and deterioration of road infrastructure during flood incidents [6].

The design and configuration of roadways within a watershed are pivotal factors affecting hydrological phenomena, including surface runoff, sediment displacement, and stream connectivity [7]. Roads frequently serve dual roles as barriers and channels for water, a characteristic that can heighten flood risks under certain conditions [8]. The occurrence of roads being severed by floodwaters underscores the difficulties in sustaining infrastructure resilience and promoting environmental sustainability. Prior research has underscored the necessity of incorporating hydrological insights into road design and strategic planning to mitigate the detrimental effects of flooding [9], [10]. Additionally, the influence of road networks on hydrological processes within both urban and rural settings demonstrates that without proper drainage and strategic placement, roads can profoundly interrupt natural watercourses, thereby increasing flood hazards and causing ecological disturbances [11].

In addressing these challenges, contemporary advances in watershed management practices have championed the implementation of sustainable and robust road design principles that account for the hydrological and ecological attributes of watersheds [12]. These approaches not only strive to diminish the hydrological impacts of roads but also aim to bolster the overall vitality of watershed ecosystems. This research paper endeavors to examine the intersection among stream order, watershed basin management, and road infrastructure, with a specific focus on the impacts of flooding on roads. By integrating insights from extensive research and numerous case studies over the past decade, this study will propose strategies to alleviate flood impacts on road infrastructure while promoting watershed health and resilience.

Hydrology Analysis

Over the past ten years, advancements in technology and a deeper comprehension of watershed dynamics have substantially advanced hydrological modeling and analysis [13]. This paper presents a comprehensive review of the critical processes involved in hydrological analysis, encompassing precipitation interpolation, flow direction assessment, flow accumulation, stream order classification, and watershed delineation.

Precipitation Filling

Precipitation interpolation serves as a fundamental preliminary phase in hydrological modeling, aimed at rectifying deficiencies in precipitation data critical for precise hydrological simulations. Contemporary methods for addressing these data gaps have transitioned to employing advanced statistical methods and machine learning algorithms, which deliver enhanced accuracy in predicting missing data points [14], [15]. These techniques utilize patterns from historical data and spatial interpolation strategies to improve both the integrity and dependability of precipitation datasets.

Flow Direction

The calculation of flow direction over a landscape is essential in hydrological modeling. Typically, this process utilizes Digital Elevation Models (DEMs), where specialized algorithms predict the probable paths of water flow downhill at each dataset point [16]. Sophisticated algorithms like D8, MFD (Multiple Flow Direction), and D 8 [17] have been introduced to yield more refined and precise predictions of flow trajectories by considering variations in slope and terrain features.

Flow Accumulation

Subsequent to determining flow direction, flow accumulation methodologies are utilized to estimate the volume of water amassing across a landscape, a critical step for delineating stream channels and potential flood areas [18]. Contemporary approaches leverage high-resolution Digital Elevation Models (DEMs) and remote sensing data, facilitating a more accurate mapping and evaluation of hydrological characteristics [19].

Stream Order

Stream order classification plays a pivotal role in comprehending the hierarchy of river networks and in watershed management endeavors. The widely utilized Strahler system assigns orders according to tributary structure [20]. Contemporary research frequently integrates traditional classification methods such as the Horton method and Strahler's system are foundational tools in the study of river networks and watershed management, with Geographic Information Systems (GIS) and remote sensing data to augment the precision and efficiency of stream network analyses [21].

Watershed Delineation

Watershed delineation is essential for effective water resource management and environmental planning. This process entails identifying the geographic boundaries of a watershed by tracing water flow to a shared outlet. Recent advancements have leveraged automated tools integrated within Geographic Information System (GIS) platforms, alongside high-resolution topographic data, to achieve more accurate and efficient watershed delineation [22].

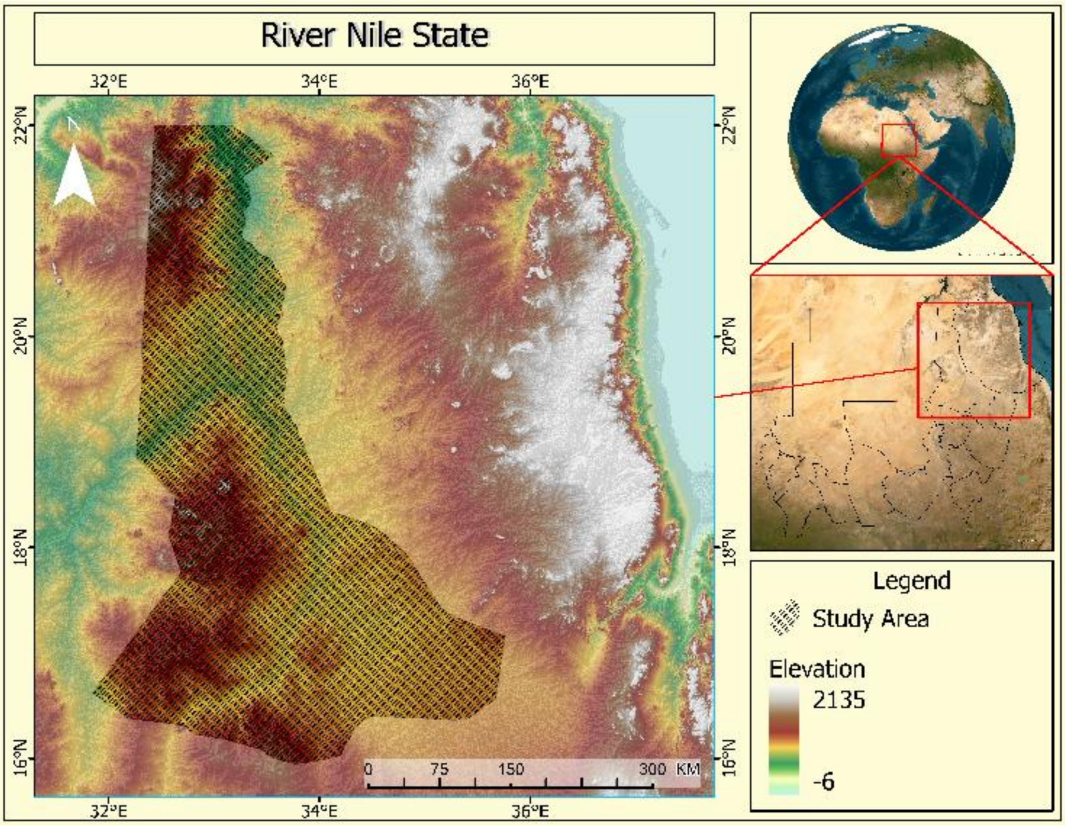
Basin

Basin analysis is fundamental for the sustainable management of water resources and environmental evaluations. This procedure entails delineating the physical boundaries of a drainage basin by tracking the convergence of water to a singular outflow point. Recent technological advancements have utilized automated tools within Geographic Information System (GIS) platforms, supplemented with high-resolution topographic data, to facilitate more accurate and efficient basin analysis [23].

Study Area

The research focuses on the River Nile State in Sudan, strategically located along the Nile as shown in Figure 1, the world's longest river, which progresses northward through the area before flowing into Egypt. Topographically, the region is primarily flat, interspersed with a few modest elevations that seldom rise more than a few hundred meters above sea level. The prevailing climate is characterized by aridity, with intense heat during the summers and relatively mild winters, typical of the Sahelian zone. Geographically, the River Nile State is positioned approximately between 16.5°N to 18.5°N latitude and 33°E to 34°E longitude, situated on a vital segment of the Nile River that is key to both its ecological and economic significance within the region.

Figure 1. Study Area Location

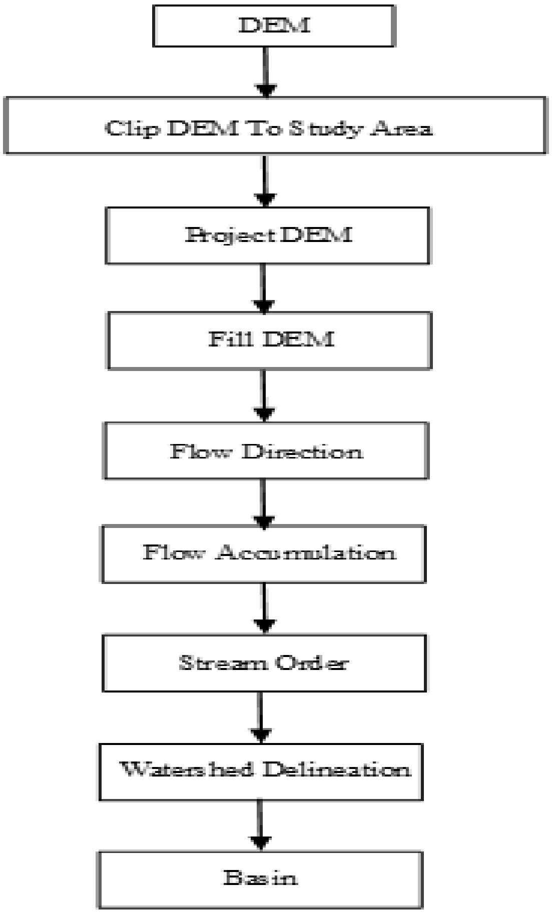


This paper aims to thoroughly analyze the hydrology of the River Nile State, focusing on streams, their orders, and watersheds. It also examines where roads and streams intersect to prevent road disruptions like those that occurred on the Atbara-Shendi roads in 2022. That year, the Nile River Road, an essential transportation route, faced major disruptions due to flooding at several points where it crosses streams. This analysis explores the hydrological dynamics and the resulting infrastructure damage observed at various intersections along the road.

RESEARCH METHODS

To delineate stream orders, watersheds, and basins using ArcGIS Pro 3.0.2, the methodology began with preparing and refining Digital Elevation Models (DEMs) by clipping the DEM for the study area and projecting the DEM as shown in Figure 2.

Figure 2. Hydrology Analysis Steps



The DEM used in this study is the Global Terrain Model (GTM) 2010, downloaded from the United States Geological Survey (USGS). The Hydrology toolset was then employed to calculate flow direction and accumulation, which supported the identification and segmentation of stream networks through a defined flow accumulation threshold. Stream segments were classified using the Strahler method via the Stream Order tool to elucidate the hierarchical structure of the network. Watershed delineation for each stream segment was conducted based on the flow direction raster using the Watershed tool, while larger drainage basins were identified using the Basin tool, which pinpoints all catchment areas converging to a unified outlet. This systematic approach in ArcGIS Pro 3.0.2 enabled a thorough and accurate hydrological analysis, critical for the effective management and planning of water resources and environmental considerations.

RESULT AND DISCUSSION

In summary, our investigation has revealed the intricate relationship between hydrological dynamics, watershed management, and the resilience of road infrastructure, particularly focusing on flood impacts at intersections of roads and streams within the River Nile State, Sudan. Through rigorous analysis, we have discerned that intersections with second-order streams are particularly vulnerable to flood-induced disruptions in road infrastructure.

To prevent future disasters, we advocate for a proactive strategy utilizing high-precision Digital Elevation Models (DEMs) to accurately evaluate runoff dynamics at all 45 intersections of roads and streams. Employing advanced hydrological modeling techniques enables us to identify optimal solutions, such as the installation of overpass bridges or other infrastructure enhancements, to effectively mitigate flood risks.

Furthermore, our recommendation underscores the importance of comprehensive evaluation and strategic planning to ensure the long-term resilience of transportation networks in flood-prone regions. Integration of cutting-edge DEM data and advanced hydrological analysis allows for the development of tailored solutions that not only protect critical infrastructure but also promote sustainability and environmental stewardship.

Ultimately, our research advocates for the integration of scientific rigor and innovative engineering methodologies to tackle the multifaceted challenges posed by hydrological hazards. Through collaborative efforts and forward-thinking initiatives, we can foster resilient communities and infrastructure systems capable of navigating the complexities of our ever-evolving natural environment.

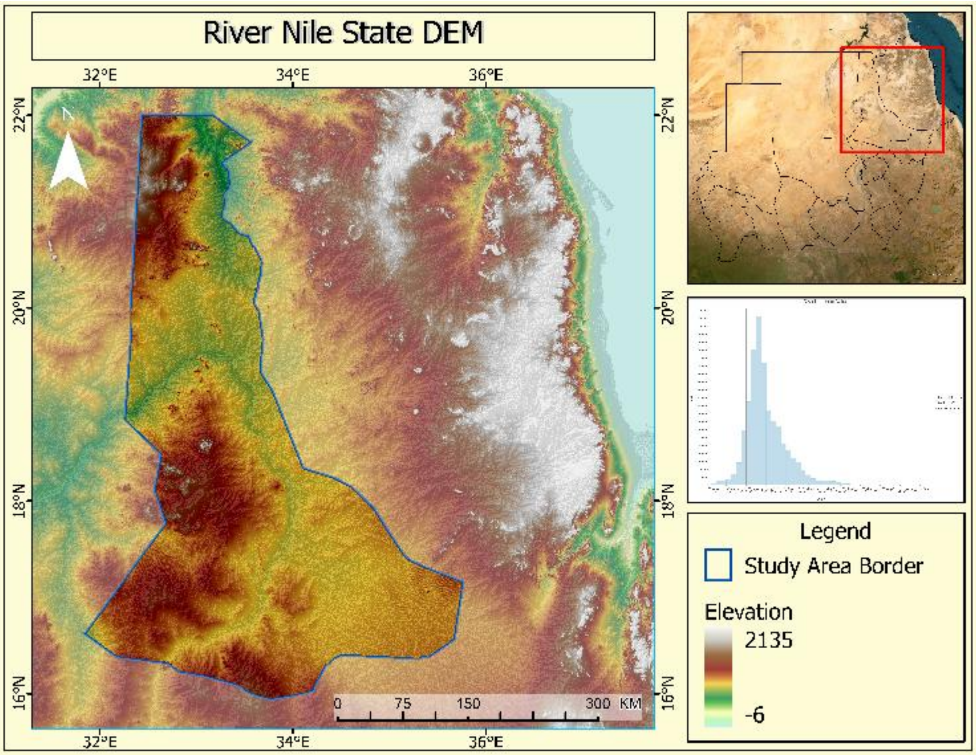
Situated in areas susceptible to seasonal flooding, the Nile River Road encounters heightened risk due to both localized and upstream precipitation patterns. The year 2022 witnessed exceptionally high rainfall during the monsoon season, which pushed river levels beyond normal limits, causing overflows at stream intersections. These hydrodynamic forces triggered erosion and partial destruction of the roadway infrastructure.

The vulnerability of the Nile River Road at its intersections with tributary streams arises from their specific geographical and hydrological configurations. An in-depth review of the flood incidents in 2022 revealed that 45 intersections were impacted: 30 intersections involved first-order streams, which are typically smaller, less complex stream channels that directly feed from the watershed. The interaction between these streams and the roadway often results in acute, localized damage due to sudden influxes of water and sediment.

13 intersections with second-order streams were documented. These are typically larger than first-order streams and can carry greater volumes of water and sediment, leading to more extensive erosive activities and structural damage to road infrastructures. Only two intersections with third-order streams were noted. Such streams represent a further increase in complexity and water flow, contributing to significant hydrodynamic pressures on road structures at their crossing points.

This detailed categorization of intersections by stream order highlights the scale and variety of the flood challenges faced, emphasizing the need for a differentiated approach in infrastructure planning and resilience building tailored to the hydrological characteristics of each stream type.

Fig. 3. Study Area DEM



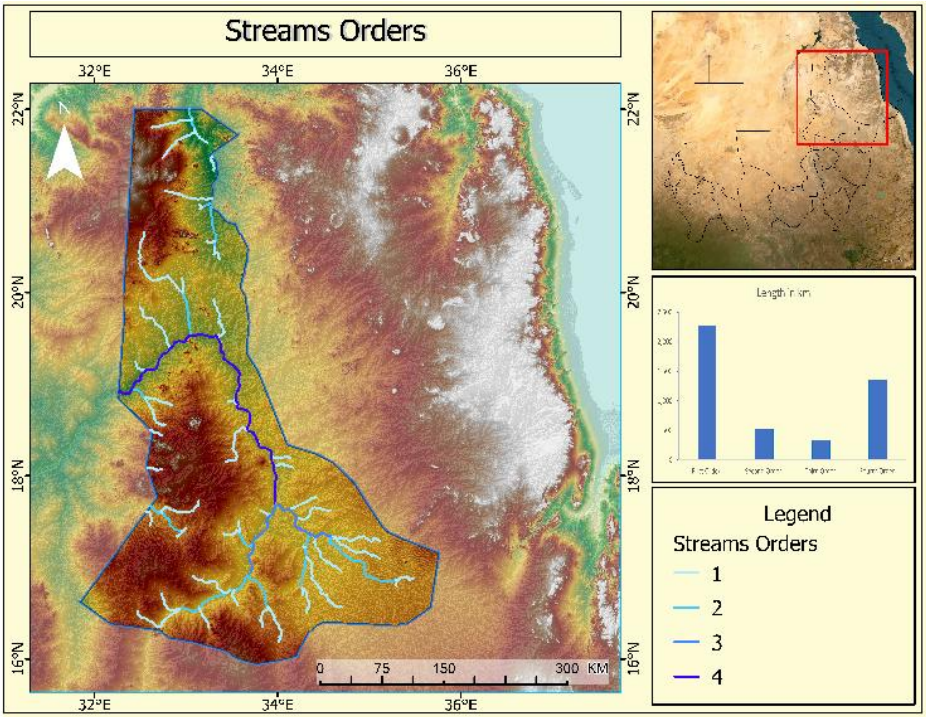
In this work, Figure 3 is depicted to provide a Digital Elevation Model (DEM) of the selected study area. This model offers a three-dimensional portrayal of terrain elevations essential for delineating geographical and hydrological features that are crucial for flood modeling and assessing infrastructure vulnerabilities.

Figure 4 is dedicated to showcasing the stream order, derived from a hydrological analysis of the study area. This classification system illuminates the hierarchical structure and connectivity of stream networks, which is instrumental in evaluating their potential impacts on road networks during flood conditions.

In Figure 6, the focus shifts to the layout of the road network within the study area. The visualization of this network is imperative for pinpointing critical infrastructure that may be susceptible to interruptions due to hydrological disturbances, thereby establishing a foundation for assessing infrastructural vulnerabilities. Figure 7 reveals the intersections of roads with streams, a critical factor in assessing the potential flood risks to the road network. Such figure pinpoints the exact locations where the infrastructural elements are most at risk of failure during flooding, highlighting the intersection points as critical areas for flood risk management.

Lastly, Figure 8 presents an intricate depiction of the road-stream intersections, complemented by the intersect values for stream orders. This granular view enhances the understanding of flood risks by correlating the frequency and severity of flood events with the stream orders at each intersection point. This level of detail is vital for formulating targeted strategies to mitigate risks and bolster infrastructure resilience against future hydrological threats.

Fig 4. Stream orders over study area



3.1 First Order Streams:

The total length of first order streams is approximately 2276.79 kilometers. These streams represent the smallest in the hierarchy, yet they contribute significantly to the overall network. They make up about 50.7 % of the total length of all streams as shown in Figure 5.

3.2 Second Order Streams:

Second order streams have a combined length of around 521.48 kilometers, representing the next level in the stream hierarchy. They account for about 11.6% of the total streams length.

3.3 Third Order Streams:

With a total length of approximately 331.26 kilometers, third order streams play a vital role in the watershed system. They constitute around 7.4% of the total streams length.

3.4 Fourth Order Streams:

Fourth order streams, the largest in this dataset, have a combined length of about 1359.92 kilometers. Despite being fewer in number, they contribute significantly to the overall stream network, making up approximately 30.3% of the total length as shown in Table 1.

Total Streams Length:

When considering all stream orders, the total length of the streams amounts to approximately 4489.45 kilometers.

Table1: Stream Orders: Length and Percentage Distribution

Stream orders	Length in KM	Percentage
First Order	2276.79	50.7 %
Second Order	521.48	11.6%
Third Order	331.26	7.4%
Fourth Order	1359.92	30.3%

Fig. 5. Streams orders length

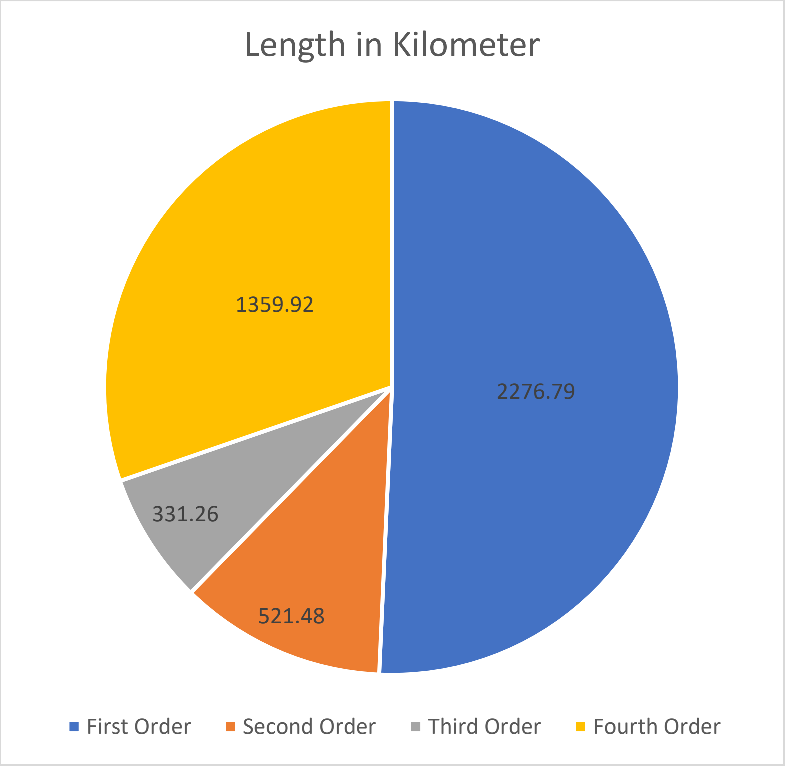
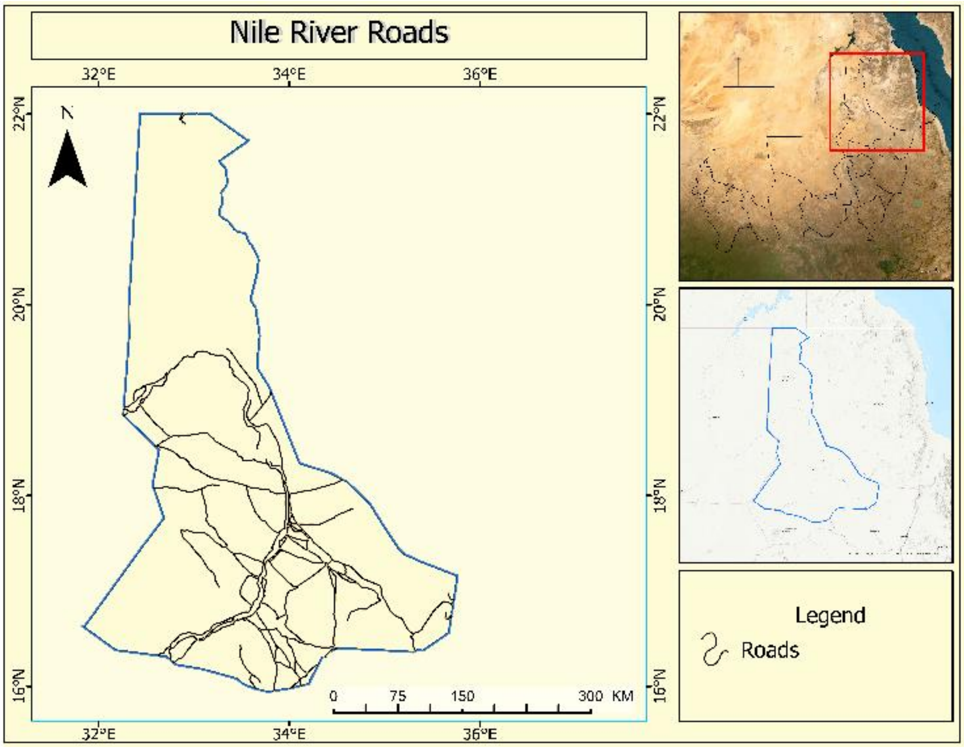


Fig. 6. Study Area Roads

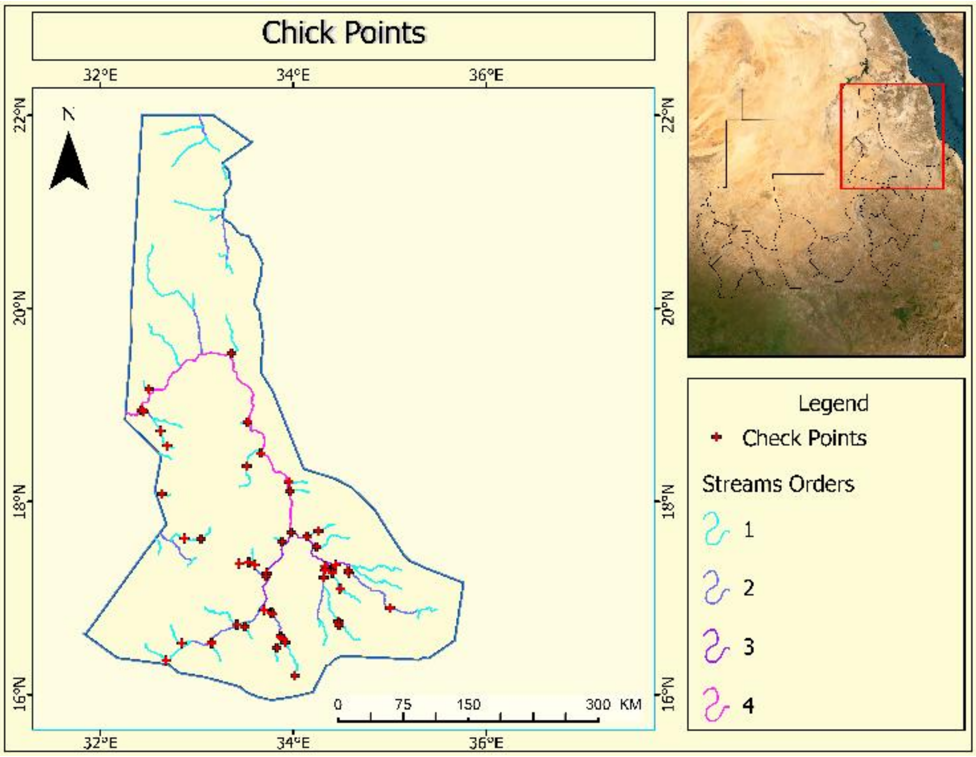


Streams of higher orders typically boast expanded drainage basins and augmented discharge capacities, thereby facilitating the conveyance of substantial water volumes during flood occurrences. Consequently, roads intersecting with such streams are subjected to heightened risks of inundation, erosion, and structural degradation due to the intensified hydrodynamic forces exerted by floodwaters.

Moreover, second and third order streams, distinguished by heightened flow velocities and channel intricacies, are predisposed to more pronounced sediment transportation and channel alterations during flood events. This heightened erosional propensity can exacerbate the impacts on adjacent road infrastructure, precipitating disruptions and potential safety hazards for vehicular traffic.

To summarize, roads intersecting with streams of higher order, particularly those classified as second and third order, are predisposed to experiencing flood-related hazards owing to their augmented discharge capacities and erosional tendencies. Comprehending these interrelations is imperative for guiding the formulation of efficacious mitigation measures and fortifying the resilience of transportation networks against flood events.

Fig. 7. Intersect of roads with Streams



In the realm of transportation infrastructure management, the accurate determination and evaluation of road length serve as fundamental metrics underpinning effective planning and operational strategies. In our investigation, we have meticulously quantified the total road length to be 3572.279 kilometers within the designated area under study.

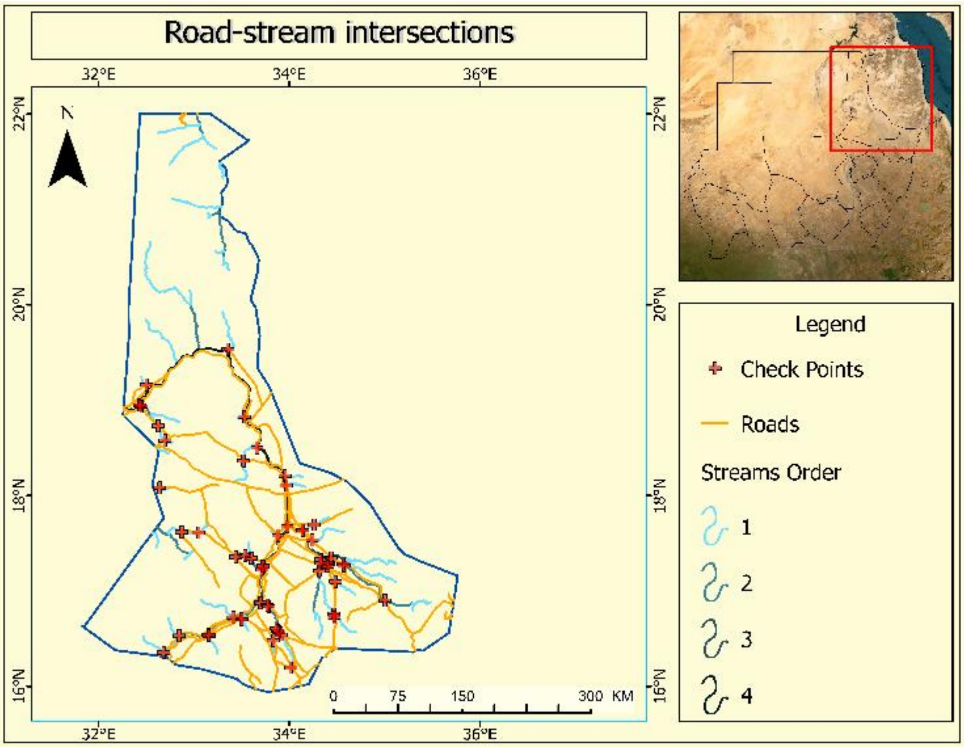
Furthermore, the intricate interplay between road networks and natural watercourses cannot be overstated. Our analysis has revealed that these roads intersect with streams at 45 distinct points. It is imperative to acknowledge that such intersections not only denote critical junctures in the transportation network but also entail potential environmental and engineering challenges.

In response to past incidents wherein flooding compromised road integrity, leading to significant disruptions, our research endeavors to proactively mitigate future occurrences of such disasters. By meticulously identifying intersect points and discerning the sequential order of streams, our aim is to develop a comprehensive understanding of the spatial dynamics influencing flood risk.

To address these challenges, the implementation of specialized infrastructure solutions, such as underpasses or overpasses, emerges as a pivotal consideration. The design and deployment of these structures necessitate a nuanced approach, accounting for factors such as topographical constraints, traffic flow patterns, financial feasibility, and available space allocations.

By integrating advanced detection methodologies and leveraging spatial analytics, our research endeavors to offer actionable insights aimed at optimizing infrastructure resilience and safeguarding against potential calamities. Through the judicious application of data-driven decision-making, we aspire to foster sustainable and resilient transportation systems that effectively navigate the complex interplay between natural and built environments.

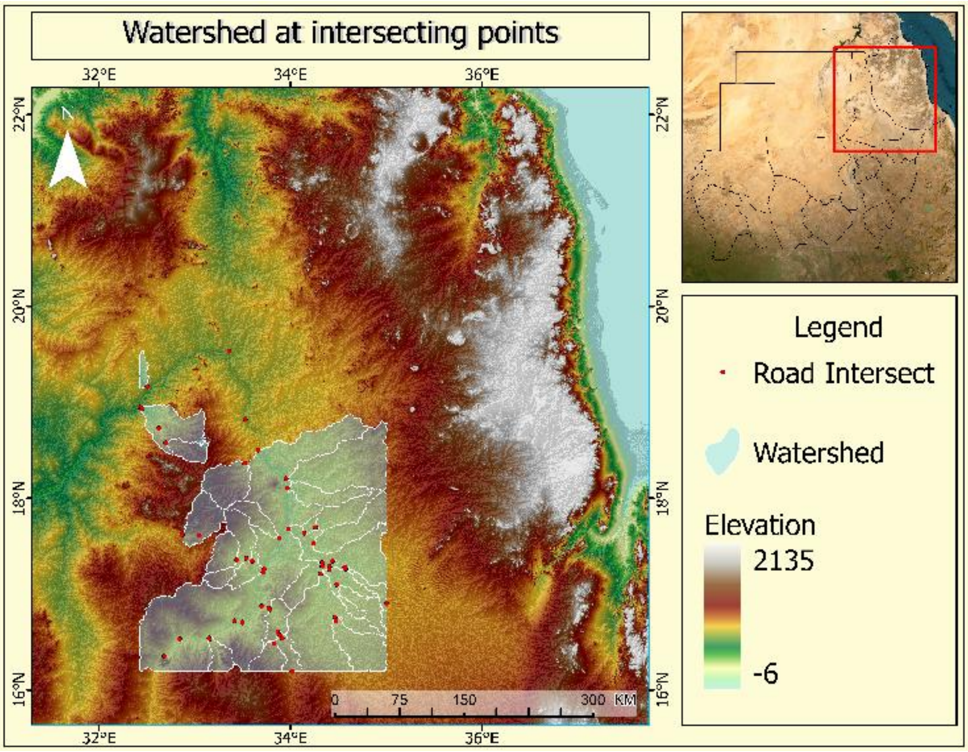
Fig 8. Depiction of the road-stream intersections



In the year 2020, a significant flooding event resulted in the severing of approximately 120 meters of the Atbara-Shendi road, as depicted in Figure 9 in this study. Notably, despite the existence of overpasses along this route, the floodwaters breached the infrastructure, causing damage exceeding the anticipated scale. This occurrence underscores the critical importance of robust flood mitigation strategies and prompts a thorough reevaluation of existing infrastructure resilience measures.

Fig. 9: Affected Area

Fig 10. Watershed at intersecting points

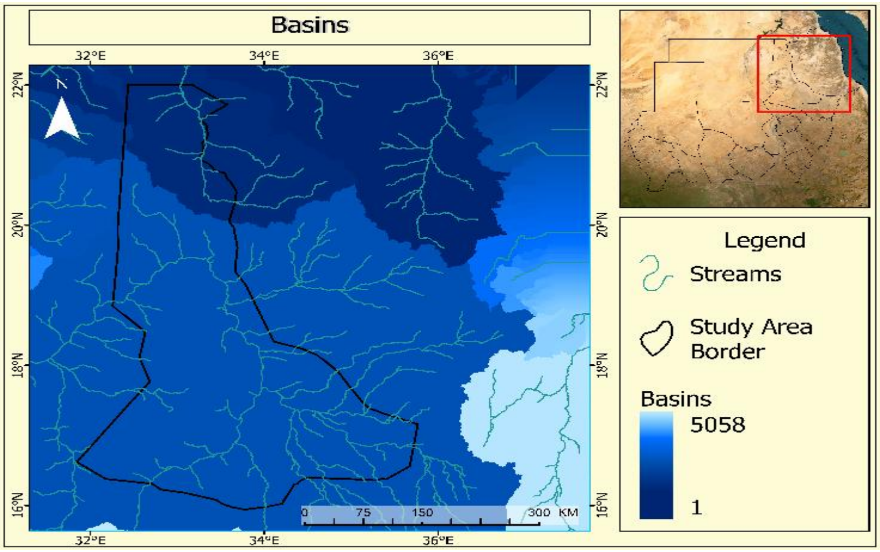


In delving into watershed domains, the use of key statistical parameters reveals deep insights into the complex spatial patterns and changing dynamics of hydrological phenomena. These metrics, likened to celestial navigation stars, encapsulate the vastness and depth of watershed dimensions within the examined area. The mean area acts as a guiding light, representing the typical size of observed watersheds as shown in Figure 10, while the range from minimum to maximum values delineates the spectrum of spatial extents, marking the transition from small catchments to large drainage basins. Beyond mere numbers, these ethereal statistical summaries become heralds of hydrological foresight, resonating through hydrological modeling to guide land use planners and water managers. By unveiling the intricate diversity of watersheds, these celestial metrics serve as navigational aids, directing efforts to enhance watershed resilience, mitigate hydrological risks, and preserve the integrity of water ecosystems.

Some watersheds, resulting from the intersection points of roads and streams, are too small to be displayed on the map.

From the dataset the following summary statistics are derived:
Mean area: Approximately 1,331.7 square kilometers
Minimum area: 0.034961 square kilometers.
Maximum area: 22,206 square kilometers.

Fig. 11. Basin map



The research area consists of eight distinct hydrological basins, each exerting a unique influence on the hydrological processes under scrutiny. These basins vary considerably in size, ranging from a nominal area of 0.049946235 square kilometers to the largest basin, which covers an extensive 107,852.9014 square kilometers, as depicted in Figure 11.

The location where the flood caused a road cut was found to have a watershed area of 214 square kilometers. This indicates that any point where the road intersects with a watershed area of 214 square kilometers or larger is at a higher risk of being affected by flooding. Therefore, it is essential to assess these points to prevent similar issues. A total of 26 such points were identified; however, not all of them are on the main road; some are on secondary or unpaved roads. Enhanced scrutiny, potentially using high-resolution digital elevation models (DEMs), is recommended for greater accuracy.

Comparative analyses with similar studies from various geographical contexts, such as those conducted in Louisiana, USA [24], Southeast Asia [25], and Jakarta, Indonesia [26], highlight the universal applicability of integrating hydrological data into infrastructure planning and design. For instance, the Louisiana study utilized high-resolution DEMs and GIS tools to evaluate flood risks on coastal road infrastructure, recommending elevated roadways and enhanced drainage systems as key mitigation strategies. Similarly, research in Southeast Asia, focusing on monsoon-induced floods in Thailand and Vietnam, underscored the significant role of DEMs and hydrological models in evaluating flood impacts and recommending optimal solutions, such as elevated roads and improved drainage systems. The study in Jakarta addressed urban flooding issues, emphasizing the necessity of sustainable urban drainage solutions and strategic planning to ensure the resilience of road infrastructure.

Table 2: Comparative Analysis of Methodologies and DEM Data Used in Hydrological Studies

Methodology Step	Louisiana, USA [24]	Southeast Asia [25]	Jakarta, Indonesia [26]	This study
Watershed Delineation	Yes	Yes	Yes	Yes
Stream Network Extraction	Yes	Yes	Yes	Yes
Stream Order Classification	No	Yes	Yes	Yes
High-Resolution DEM Analysis	Yes	Yes	Yes	No
Identification of High-Risk Points	Yes	Yes	Yes	Yes
Vertical Resolution	1m	20 m	16 m	16 m
Spatial Resolution	1m-10m	30 m	30 m	30 m

These comparative studies reinforce the necessity of employing elevated roadways, improved drainage systems, and sustainable urban drainage solutions as key strategies for enhancing infrastructure resilience. While specific solutions may vary depending on regional characteristics, the underlying principles of integrating hydrological data, enhancing drainage systems, and employing strategic planning are universally

applicable. Our results, aligned with these similar studies, demonstrate that comprehensive evaluations and strategic planning, supported by high-precision

DEMs and advanced hydrological modeling, are crucial for ensuring the long-term resilience of transportation networks in flood-prone areas.

The comparative analysis of studies from Louisiana, USA, Southeast Asia, Jakarta, Indonesia, and River Nile State, Sudan, underscores the universal importance of integrating hydrological data into infrastructure planning and design. All studies utilized Digital Elevation Models (DEMs) and hydrological models to assess flood risks and propose mitigation strategies. The Louisiana study and our study in River Nile State employed Medium-resolution DEMs (10m-20m) as shown in Table 2 for detailed analysis, focusing on elevated roadways and enhanced drainage systems. Southeast Asia's research used medium to high-resolution DEMs (10m-30m) to address monsoon-induced floods with similar mitigation recommendations. Jakarta's study, with medium-resolution DEMs (10m-30m), emphasized sustainable urban drainage solutions for urban flooding. Despite regional differences, the consistent use of high-precision DEMs, advanced hydrological modeling, and strategic planning highlights the global applicability of these methodologies to enhance infrastructure resilience against floods.

CONCLUSION

Our investigation into the "Hydrological Dynamics and Road Infrastructure Resilience: A Case Study of River Nile State, Sudan," elucidates a complex interplay between hydrological patterns, watershed management, and the vulnerability of road infrastructure to flood events. Our analysis identified 26 high-risk intersections where roads meet watersheds of 214 square kilometers or larger, particularly with second-order streams, making these areas susceptible to flood-induced disruptions. This underscores the necessity for enhanced scrutiny using high-resolution Digital Elevation Models (DEMs) for precise assessments.

We advocate for the proactive utilization of high-precision DEMs and advanced hydrological modeling techniques to evaluate runoff dynamics at all road-stream intersections within the study area. Implementing these technologies will facilitate the identification of optimal mitigation strategies, such as the installation of overpass bridges and other infrastructure enhancements, to effectively mitigate flood risks.

Our findings underscore the critical importance of integrating scientific rigor and innovative engineering methodologies to address the multifaceted challenges posed by hydrological hazards. Comprehensive evaluations and strategic planning can ensure the long-term resilience of transportation networks in flood-prone regions. The utilization of cutting-edge DEM data and advanced hydrological analysis enables the development of tailored solutions that protect critical infrastructure and promote sustainability and environmental stewardship.

Future research should focus on refining these strategies and exploring innovative solutions to further enhance the resilience of road infrastructure against hydrological hazards.

In conclusion, our research contributes to the growing body of knowledge on the resilience of road infrastructure in flood-prone areas. Identifying vulnerable points and proposing targeted mitigation strategies provide a foundation for future efforts aimed at refining these approaches and exploring innovative solutions. Through collaborative efforts and forward-thinking initiatives, we can foster resilient communities and infrastructure systems capable of navigating the complexities of our ever-evolving natural environment.

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