Impact of Structural and Non-Structural Measures on the Risk of Flash Floods in Arid and Semi-Arid Regions: A Case Study of the Gash River, Kassala, Eastern Sudan

Kamal Abdelrahim Mohamed Shuka *, Ke Wang *, Ghali Abdullahi Abubakar and Tianyue Xu

Institute of Agricultural Remote Sensing and Information Technology, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China; ghaliaa@zju.edu.cn (G.A.A.); 22014129@zju.edu.cn (T.X.)
* Correspondence: kassalakamal1978@gmail.com (K.A.M.S.); kwang@zju.edu.cn (K.W.); Tel.: +86-13067849238 (K.W.)

Abstract: Sediment precipitation in riverbeds influences the effectiveness of structural and non-structural measures for flash flood mitigation and increases the potential for flooding. This study aimed to disclose the effectiveness of the implemented measures for flood risk mitigation in Kassala town, eastern Sudan. We employed remote sensing (RS) and GIS techniques to determine the change in the Gash River riverbed, the morphology, and the leveling of both the eastern and western sides of the river. Flood model simulation and a 3D path profile were generated using the digital elevation model (DEM) with a data resolution of 12.5 m from the ALOS BILSAR satellite. The main purpose of this study is to extract the layer of elevation of the riverbed on both the western and eastern banks and to determine the variations and their relationship to flood occurrence and mitigation. The construction of dikes and spurs near Kassala town has led to sediment precipitation, causing the riverbed to rise. The results show that it is now 1.5 m above the eastern Kassala town level, with a steep slope of 2 m/km, and the cross-section area at Kassala bridge has shrunk, which indicates that the bridge body will partially impede the river’s high discharge and increase the potential for flood risk in the study area. The eastern part of Kassala town has a higher likelihood of flooding than the western side. This study suggests redesigning structural measures like widening the Gash River, extending Kassala bridge for normal water flow, strengthening early warning systems, and implementing soil conservation activities for normal water flow.

Keywords: flash flood; structural and non-structural measures; early warning system; land 3D profile; flood simulation; sediment precipitation; riverbed change; climate change

1. Introduction

Flash floods pose a significant hazard to many regions around the world, including the Gash River in eastern Sudan [1,2]. The Gash River catchments experience sudden and torrential rainfall events during the rainy season, leading to frequent flooding. These floods cause a considerable loss to urban facilities, including housing, infrastructure, livelihoods, and agricultural lands in the region [3]. Therefore, effective measures for flood risk mitigation are crucial to saving lives and assets [4]. To ensure the efficiency of flood risk mitigation measures in the Gash River at Kassala, it is important to assess the impact and results of both structural and non-structural measures [5]. The climate change implication of soil erosion in catchment areas affects the Gash River’s morphology, and potential ecological impacts have been considered [6]. Examining the Gash River’s hydrology and morphology and the causes of riverbed change, case studies, field observations, and hydrological models were utilized to evaluate the effectiveness of these measures in reducing flood risks [7].

There are few studies on the effects of structural and non-structural measures on flash floods overall. The biophysical and infrastructure-related aspects of flash floods were the focus of a few previous studies [8]. For instance, Frissell and Nawa (1992) explained how poor engineering practices, such as flimsy construction, inadequate design, and the
improper placement of buildings owing to the river meandering, contributed to the failure of structural measures projects in Baluchistan [9]. Structural measures are designed to mitigate the impact of flash floods and include the construction of infrastructure such as dams, levees, and stormwater drainage systems [10]. One notable example is the Three Gorges Dam in China, which is the world’s largest hydroelectric power station and flood control project. The dam has significantly reduced the risk of flash flooding in the Yangtze River basin and has helped prevent the loss of lives and property damage [11]. Another example is the construction of the Tunnel and Reservoir Plan (TARP) in Chicago, which aims to reduce the risk of flash flooding by capturing and storing excess stormwater in reservoirs [12]. Structural measures have proven to be effective in mitigating the impact of flash floods, but they require significant monitoring and ongoing maintenance to remain effective.

Flooding incidents in Africa’s semi-arid and dry regions have not only resulted in physical harm, health effects, and financial losses but also in environmental degradation, homelessness, displacement, a shortage of food and water, disruption of social activities, and immobility [13,14]. Similarly, in the Gash River of Kassala, repeated flood events have had disastrous impacts, resulting in the loss of human life, destruction of property, and agricultural losses [15,16]. In Sudan, the Gash River, Khor Abu Habil, and Khor Baraka are the areas with the biggest flash flood rivers. The Gash River is a seasonal, flash-flooding river with high variations in flow during the wet season. The most damaging flood occurred in 2003, when almost half the city was submerged [17]. So far, limited impact studies have been carried out on the Gash River in Kassala to mitigate flash flood risk. It is crucial to comprehend how rivers behave hydrologically in order to prevent risks that could be brought on by extreme flooding [18].

We learned from the literature review that previous studies have not adequately addressed the effects of structural and non-structural measures for flash risk reduction in Kassala Town. Several experimental studies and assessments have examined the connection between the geometry of the sediment-retarding basin and the capability of the structure to control sediment flow [19]. The Gash River riverbed began to rise in the last three decades after the construction of embankments and dikes on the Gash River near Kassala city. Such changes influenced the cross-section area and channel bed of the river and the flow behavior, especially at Kassala bridge site [20]. Overland flow generation typically happens for steep and mountainous catchments, such as that of the Gash River, with very little plant cover with soil erosion and a high intensity of rainfall [21]. Unexpected torrential rains have been blamed for numerous large-scale sediment-related disasters (such as the Japan–Hiroshima heavy rain disaster in July 2018). The Gash River transports 40 mm of sediment, similar to that of the Yellow River suspended in China, for 80 to 100 days out of the year [22]. Resilience strategies were taken in the form of structural and non-structural measures to lessen flood risk in the study area [23,24].

The integration of remote sensing and GIS has received considerable attention in the field of hydrology in recent years [25]. Remote sensing technology provides essential data about objects at or near the Earth’s surface and the atmosphere based on radiation reflected or emitted from objects or areas in multiscale and multitemporal approaches. Remote sensing techniques use satellite and/or airborne sensors to collect information about a given object or area [26]. GIS methodologies represent a forefront approach to supporting conceptual site models and site investigations mapping, encompassing data analysis, visual analytics, and support design solutions. Remote sensing is obviously used for land surface hydrological fluxes and state variables, especially in areas with low in situ network coverage, which are mostly observed using this method [27].

Resolving hydrological issues is made much easier by combining remote sensing data with cutting-edge data processing, archiving, and visualization technologies. Hydrologic studies have evolved greatly [28]. Flood risk mapping is a crucial phase in the planning of effective flood mitigation measures and the preparation of mitigation strategies for various stakeholders in urban flood risk assessment. Hydrologic modeling is used in
traditional urban flood risk mapping to compute the depth and extent of an inundation using 1D–2D hydrodynamic models like SWMM, MIKE FLOOD, and HEC-RAS. Machine learning methods have recently been used to map flood risk and have demonstrated good performance in identifying flood-prone locations [29]. Any digital depiction of a continuous change in elevation in space that may be obtained from topographic maps and satellite images is known as a DEM [30]. It is the most significant source of information on topography and floods, both of which are crucial for much hydrological research. Flood management, watershed planning, development, design, operation, droughts, and water quality, as well as other economic and environmental concerns, are all dependent on hydraulic modeling [31].

The study objective of this research is to analyze and assess the effectiveness of the structural and non-structural measures for minimizing flood risk in the Gash River to Kassala town, eastern Sudan, through the utilization of RS and GIS technologies. This study focuses on investigating the impact of structural measures on minimizing flood risks, including the construction of embankments, dikes, bridges, and spur flood drain channels [32]. This study assessed the factors associated with flood hazards and the effectiveness of flash flood risk mitigation measures, such as sediment accumulation, a steep slope, and riverbed rise, as well as potential climate change effects on the river catchment. The findings of this study will enrich the concept of flash flood risk resilience in the Gash River region. The research results will support stakeholders, policymakers, and local authorities involved in flood hazard control and urban planning in making informed decisions for flood risk reduction.

2. Study Area

In the eastern part of Sudan, Kassala State is located between longitudes 35 and 37° E and latitudes 14.15 and 17.15° N (Figure 1). Kassala Town, the capital of Kassala State, is located 30 km from the border with Eritrea and around 400 km from Khartoum, which has an area of roughly 43,000 km², and there are 1.85 million people [33]. The city is divided into two sides on the western and eastern banks by the seasonal Gash River, which has a long history of flood threats.

Between the Ethiopian Plateau and the Eritrean Highlands is where the Gash River’s catchment region is located. The Gash River is barely 35 km away from the Sudanese–Eritrean border to Kassala town; hence, the flood wave arrived there without adequate time for warning or preparation (i.e., only around 4 h) [34]. Kassala was the town most affected by the Gash flooding. Several destructive high floods from Gash River had assaulted it, and most of them were very severe [35]. The annual flow of Gash River has a high variation; it is inconsistent even within the flow of one season. The flow for one day varies hour to hour; accordingly, Gash River is characterized as a flash flood river (Figure 2). Gash River’s flow can begin as a trickle and quickly increase to up to 850 m³/s. According to the records that are still in existence, there were devastating flood disasters in the years 2003, 1998, 1992, 1988, 1983, 1975, 1974, 1952, 1950, 1941, 1939, 1932, 1931, 1929, 1927, 1926, and 1921. One of the worst floods ever was the one that occurred in 1975. In contrast to the flood in 1975, the devastating flood was in 2003, when nearly half of Kassala city submerged [36].

The Gash River has a catchment area of around 23,000 km², with an average yearly rainfall of 280 mm, and 17,400 km² (or 76%) of the total area is located on Eritrean land, with a basin area of 31,000 km², a river length of 500 km, and a steep slope of approximately 2 m/km [37] (Figure 3). During the wet season, floods transport 40 million m³ of the sediments from the catchment area downstream to the Kassala area [38,39]. The average annual discharge was $1 \times 10^9$ m³, and flooding probability occurred around once every five years. Since 1907, the Gash River has frequently ended in the Gash delta due to a scheme known as the Gash Agricultural Scheme (GAS) in northern Kassala city, Kassala.
Figure 1. Study area and Gash River basin.

Figure 2. The Gash River’s annual flow of 106 m$^3$ indicates the likelihood that it will flood once every five years.

Figure 3. Longitudinal profile by extracting the slope of the main channel of the Gash River.
During the rainy season, the Gash River’s flows are highly variable. It is dry from November to June. The rainy season typically begins in June and ends with a succession of flash floods in September [40]. The steep and irregular topography of the upper third and, partially, the middle third of the basin, inadequate vegetation cover, and unfavorable geological formations, which are linked to poor soil formation and low infiltration rates, are the main causes of flash floods and high sediment load. Flooding has been occurring repeatedly in Kassala town in the downstream plains in the bottom third of the basin; for instance, it has been claimed that major floods occur every 1 to 5 years [41].

2.1. The Structural Measures and Non-Structural Flood Protection Measures

The frequent occurrence of flood damage in recent years has highlighted the need to avoid and mitigate urban flooding, which is one of the natural disasters that does the most harm to human life and property globally [42,43]. The Gash River protection efforts in and around Kassala town date back to the early 20th century [44]. To defend Kassala town, an embankment was built along both riverbanks for a distance of 10 km. Additionally, 500 m-spaced spurs were built to prevent lateral river flow movement and divert the river to deliver silt downstream to the protected area. Since 1931, these spurs and dikes have been particularly effective at maintaining the river channel in the Kassala reach when compared to other unprotected spans. The drainage canal was constructed south of Kassala city in 1945 to drain the high discharge of the river and irrigate the Kalahooat Agricultural Scheme (KAS) in western Kassaka city. In addition to that, Kassala bridge has been constructed to link the two sides of the east and west of Kassala city.

The main goal of these structures is to push the river to scour the bed by forcing the flow toward the center of the river course and away from the bank [45]. As a result, the water that has been held back between the spurs will be able to slow down and deposit its silt, which will ultimately strengthen the riverbanks [46]. The following is the order in which these spurs and dikes were built: from 1931 to 1937, seven spurs were built, some of which were entirely clogged with silt; seven more spurs were built between 1976 and 1984, some of which were silted; and the years 1984–1998 saw the construction of seventeen spurs. A total of 31 spurs were thus in place, but Kassala town was seriously affected by the 2003 flood. The advocacy of institutional administrations, such as the Gash Training Unit and Meteorological Station, has been focused on non-structural measures. This includes increased communication with other related institutions to improve policies regarding the flow of the Gash River.

2.2. The Importance of the Gash River on Land Use Domain

The Gash River is the main source of water for drinking, recreation, and environmental purposes in Kassala [47]. It serves as the only supply of water for the Kassala groundwater aquifer [48]. Gash is also the source of the water that formed the delta (150,000 Hectare) and the Kalahooat Agricultural Scheme (KAS) located in western Kassala, which contains the most agriculturally productive area for food security [49] and is the basis for the land use (LU) and socioeconomic activities in the Kassala area. The people who live along both
sides of the River Gash’s banks frequently believe it to be a source of horror. The location of the Gash River’s catchment region necessitates cooperation and corporate relations with the surrounding nations.

3. Materials and Methods

3.1. Data Collection Processing Method

This research paper utilizes remote sensing and geographic information system (GIS) technologies to evaluate the effectiveness of both structural and non-structural measures in mitigating flood risks within the river basin [50]. The proposed quantitative approach (Figure 4) would identify the most effective measures in terms of reducing flood risks and improving the overall resilience of the river basin.

![Figure 4. Quantitative model for flood hazards in the process of flood risk evaluation.](image)

This study utilized digital elevation model (DEMs) values that are periodically separated and are horizontally positioned about a geographic coordinate system or the universal transverse Mercator (UTM) projection [51,52]. The ground surface was represented using the 12.5 m image resolution of DEM data from the shuttle radar topography mission by logging in to [https://search.asf.alaska.edu/#/](https://search.asf.alaska.edu/#/) (accessed on 1 January 2020), selecting and highlighting the area of interest and searching the available data within the interested area. According to the tiles data information, we have selected similar tiles for download through
the hi-res terrain-corrected option, and the downloaded file is extracted and opened in the GIS interface of the Global Mapper for data analysis. Cross-sections along the Gash River riverbed are measured using the 3D path profile method for the selected area for DEM data in the Global Mapper GIS interface. Each cross-section includes the riverbed as well as the neighboring natural ground levels. Starting at AL Gira, these cross-sections will extend to the north of Kassala Bridge. Fieldwork consists of measurements of the height of the river cross-section under Kassala Bridge and sedimentation depth measurements in the river channel near Kassala Bridge. This study uses the previous steps to develop flood control and risk mitigation. These controlling measures include structural and non-structural measures.

3.2. Elevation Points Measurement of the Gash River

The study employed flood risk mapping, which is crucial for warning of impending disasters and managing and preventing them [53]. To undertake decision-making regarding flood vulnerability variables, which may assist in urban structural and non-structural impact, in design, and in minimizing the primary effects of catastrophic disasters, the prediction of flooding scenarios in urbanized areas and their understanding are of utmost importance [54]. It is feasible to develop strategies that lessen vulnerability to flooding.

This study uses a digital elevation model (DEM) to identify the elevation points on the Gash River riverbed and balance them with the elevation points on the eastern and western banks of the river adjacent to Kassala town. These points were used to identify the impact of structural and non-structural measures on flood risk mitigation in the Gash River and disclose the influence of these measures on changing riverbed levels [55]. The critical flooding area near Kassala was divided into sections with a distance of 500 m, limited by constructed spurs for flood measures along the river course. In each section, the average elevation points were generated by using the Global Mapper interface, as were the sections around the river banks.

The study uses the option of a 3D path profile from the DEM image in the Global Mapper 11 by selecting random points inside the section and generating the average value of the total cross-section elevations [56]. Through the path profile image, we first select the CSV file (W/XYZ, distance, and slope value), which contains attribute data for the cross-section points. These attribute data were generated in an Excel file to calculate the average of the points elevation for each section as

\[ AV = \frac{T_c}{Ps}, \]

where \( AV \) is the average of the points in each section, \( T_c \) is the total of elevation points value, and \( Ps \) is the number of points samples taken in the section. Secondly, we generate a bitmap (BMP) file to identify the cross-section diagram of the pass points in each section.

3.3. Gash River Flood Analysis

The study analyzes the data for flooding simulation in the Gash River at Kassala. The simulation was performed through the Global Mapper software 11 interface by digitizing new line features on the selected area on the river course line. We modified the line to shapefile format through the modified feature info function, the river is converted to shape through the advanced feature option, and a buffer is created for this line [57]. Consequently, we add the elevations to the river shape, select the analysis measurement, and apply elevation to a selected feature of the river shape; then, the shape receives all the elevations. Following this, we select the highest level of water to simulate flooding, and for the accuracy assessment, we upload a point showing the level of rainfall water out of the river reached during the rainy season by the geographical positioning system (GPS) device. We use the analysis function to simulate water level rise, choose a water level of 2 m for river water rise, and combine all the shapes on the shapefile layer.

Additionally, the study utilizes high-resolution images of Google Earth by digitizing the features of structural measures, e.g., dikes, embankments, bridges, and drainage
canals [58]. These structures have been constructed to control high levels of flash flood, decrease flow velocity, and retain the flood water inside the river course. The high sediment load of the Gash River has been precipitated and has risen the riverbed.

The study used analysis and simulation methods utilizing DEM and GIS to provide valuable information on potential flash flood risks and help in decision-making for flood early warning systems, flood mapping, the development of infrastructure, and the emergency and evacuation response [59]. The integration of reliable elevation data and hydrologic and hydraulic modeling techniques leads to a more informed understanding of flash flood dynamics and their effects on the surrounding landscape [60]. DEM is a digital representation of the Earth’s surface with regard to the terrain condition and the elevations of different terrain features, such as highlands, valleys, and rivers. It provides a successive grid of elevation values, allowing for the formation of topographic maps [61].

3.4. The Study Outline

The study overview consists of utilizing RS data (digital elevation model, DEM) and GIS for flash flood risk mitigation and the impact of structural and non-structural measures (Figure 5). We assess terrain processing data and their relevance to flash flood risk mitigation assessment; the integration of DEM data with GIS for leveling, spatial analysis, and mapping; and the utilization of satellite imagery data for the monitoring and detection of flood-prone areas.

The structural measures are examined through DEM analysis for flood control structures. The method focuses on changes and the effectiveness of dikes, spurs, and embankment structures through GIS modeling, flood simulation, and incorporating drainage system structure. The non-structural measures based on creating land use plans and institutional regulations rely on flash flood hazard mapping from DEM data and GIS analysis.

Figure 5. The study outline shows the impact of structural and non-structural flood risk mitigation measures.

The structural measures are examined through DEM analysis for flood control structures. The method focuses on changes and the effectiveness of dikes, spurs, and embankment structures through GIS modeling, flood simulation, and incorporating drainage system structure. The non-structural measures based on creating land use plans and institutional regulations rely on flash flood hazard mapping from DEM data and GIS analysis.
We utilize early warning systems and emergency response approaches using RS data and GIS platforms and implement public awareness campaigns concerning flood risks and resilience strategies. Eventually, the impact and comparative analysis will comply with the evaluation of the effectiveness of structural measures and the assessment of non-structural measures’ impact on flash flood risk mitigation with remote sensing and GIS tools.

4. Results and Discussion

The study results show the extraction of the layers of the riverbed on the western and eastern banks and their correlation to flood occurrence. The eastern bank was most affected by flood. The variation attributed to the Gash River morphology changed according to sediment precipitation in the riverbed and sediment loading by flood water in the catchment area. The construction of embankments, dikes, and spurs affected the sediment conveyed by floodwater; however, the river is perennial in Eritrea before turning ephemeral as it approaches Sudan [62]. The plateau is between 2000 and 2500 m above mean sea level (MSL), but as the river enters the Sudan Plains, its elevation falls to around 600 m then dips much more to 500 m at Kassala town and at a 35 km distance from Al Gira Point at the Eritrean border. As a result, the current’s velocity decreases, and the river’s silt load starts to precipitate [63]. The construction of the 22 dikes and spurs exacerbates the sediment precipitation and leads to a rising riverbed.

This river flows through the center of Kassala city from south to north and divides the town into eastern and western parts. We measured the elevation at 10 locations downstream and 16 locations upstream of Kassala bridge with a 0.5 km length for each location. The study results show a rising of the riverbed adjacent to Kassala town both upstream and downstream of Kassala bridge, and according to the resulting data analysis, the riverbed shows an increase and is higher than in the eastern part (Figure 6; Table 1), where the structural measures of 22 dikes and spurs were constructed perpendicular to the flow direction during the 1970s for flash risk resilience [64].

<table>
<thead>
<tr>
<th>Location</th>
<th>Western R. R. Bed</th>
<th>Eastern R</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.5 km 7.5 km 12.5 km 20 km</td>
<td>2.5 km 5.0 km 7.5 km 10.0 km 15.0 km</td>
</tr>
<tr>
<td>3</td>
<td>2.5 km 5.0 km 7.5 km 12.5 km</td>
<td>2.5 km 5.0 km 7.5 km 10.0 km 15.0 km</td>
</tr>
<tr>
<td>2</td>
<td>2.5 km 5.0 km 7.5 km 12.5 km</td>
<td>2.5 km 5.0 km 7.5 km 10.0 km 15.0 km</td>
</tr>
<tr>
<td>1</td>
<td>2.0 km 4.0 km 6.0 km 8.0 km</td>
<td>1.0 km 2.0 km 3.0 km 4.0 km 5.0 km</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0 km 2.0 km 3.0 km 4.0 km 5.0 km</td>
<td>0.5 km 1.0 km 1.5 km 2.0 km 2.5 km</td>
</tr>
</tbody>
</table>

Figure 6. Cont.
1.5

2.5

3.5

4.5

5.5

Figure 6. Three-dimensional elevation path of the river channel: eastern and western side banks measured.

4.1. The Effect of Gash River Morphology, Climate Change, and the Catchment Area on Sediment Transport

Despite being seasonal, the Gash River has a significant impact on its valley. The Gash River appears to have an excessively high sediment load [65]. Recent sediment load measurements show huge fluctuations, with the maximum amount exceeding 75,000 ppm. During the 1950s, the highest sediment concentration ever observed was 9722 ppm [66]. The increased loading of sediment (eight times) demonstrates the significant impact of climate change and the recent drought years (during the 1980s) on the catchment basin of the Gash River. In addition, it has a detrimental impact on the flash flood’s size and destructive consequences. According to the sediment analysis in the Gash River course, there has been a huge quantity of silt deposition along the riverbed with variations in thickness (1 to 3 m), particularly close to and under the spurs, dikes, and Kassala bridge, which operates as a bottleneck, blocking the flow. Some commentators insist that this bridge’s restriction of the river’s flow at high discharge was to blame for the recent flood’s effects on Kassala town. One of the factors contributing to the 2003 flood and the situation becoming worse was the bridge’s presence and its low deck.

The Gash River’s discharge measurements, which date back to 1970, exhibit significant variability. The minimum yearly total discharge was 140 million m$^3$, and the maximum annual discharge was 1430 million m$^3$, both of which were recorded in 1983. It should be remembered that 1983 was the year before the 1984 drought, which hit all of Africa’s nations during the 1980s, especially Ethiopia and Sudan, where it reached its height. The fact that the maximum yearly flow is almost ten times greater than the smallest flow clearly shows how variable the flows in the Gash River are [67,68]. The lowest instantaneous discharge, however, was 170 m$^3$/s in 1921, and the highest, 870 m$^3$/s, was in 1983 [69]. Accordingly, this river is characterized as a flash-flood river with steep slope; the Gash River’s flow can rapidly increase from a very little trickle to more than 850 m$^3$/s. The flow is $1 \times 10^5$ m$^3$ on average per year.
Table 1. The average of the 3D level path shows the differences between the riverbed average value and the eastern and western sites for each dike zone.

<table>
<thead>
<tr>
<th>Dike No</th>
<th>Contrast of Western Side with Riverbed Level</th>
<th>Contrast of Eastern Side with Riverbed Level</th>
<th>Flood Control Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rb</td>
<td>W. Level</td>
<td>Δ(Rb-W)</td>
</tr>
<tr>
<td>1</td>
<td>0.11</td>
<td>−1.19</td>
<td>−1.08</td>
</tr>
<tr>
<td>2</td>
<td>1.45</td>
<td>2.37</td>
<td>−0.92</td>
</tr>
<tr>
<td>3</td>
<td>3.57</td>
<td>3.4</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>3.08</td>
<td>4.59</td>
<td>−1.51</td>
</tr>
<tr>
<td>5</td>
<td>3.94</td>
<td>4.96</td>
<td>−1.02</td>
</tr>
<tr>
<td>6</td>
<td>4.46</td>
<td>5.56</td>
<td>−1.1</td>
</tr>
<tr>
<td>7</td>
<td>4.84</td>
<td>5.64</td>
<td>−0.8</td>
</tr>
<tr>
<td>8</td>
<td>5.22</td>
<td>6.28</td>
<td>−1.06</td>
</tr>
<tr>
<td>9</td>
<td>8.66</td>
<td>7.42</td>
<td>1.24</td>
</tr>
<tr>
<td>10</td>
<td>7.34</td>
<td>6.63</td>
<td>0.71</td>
</tr>
<tr>
<td>11</td>
<td>8.45</td>
<td>7.9</td>
<td>0.55</td>
</tr>
<tr>
<td>12</td>
<td>8.63</td>
<td>8.03</td>
<td>0.6</td>
</tr>
<tr>
<td>13</td>
<td>9.84</td>
<td>9.02</td>
<td>0.82</td>
</tr>
<tr>
<td>14</td>
<td>9.36</td>
<td>10.22</td>
<td>−0.86</td>
</tr>
<tr>
<td>15</td>
<td>10.48</td>
<td>11.23</td>
<td>−0.75</td>
</tr>
<tr>
<td>16</td>
<td>11.07</td>
<td>12.3</td>
<td>−1.23</td>
</tr>
<tr>
<td>17</td>
<td>10.4</td>
<td>12.21</td>
<td>−1.81</td>
</tr>
<tr>
<td>18</td>
<td>11.55</td>
<td>13.33</td>
<td>−1.78</td>
</tr>
<tr>
<td>19</td>
<td>12.57</td>
<td>14.98</td>
<td>−2.41</td>
</tr>
<tr>
<td>20</td>
<td>15.72</td>
<td>16.27</td>
<td>−0.55</td>
</tr>
<tr>
<td>21</td>
<td>18.72</td>
<td>20.11</td>
<td>−1.39</td>
</tr>
<tr>
<td>22</td>
<td>24.09</td>
<td>24.88</td>
<td>−0.79</td>
</tr>
<tr>
<td>23</td>
<td>29.6</td>
<td>32.43</td>
<td>−2.83</td>
</tr>
<tr>
<td>24</td>
<td>39.98</td>
<td>41.44</td>
<td>−1.46</td>
</tr>
</tbody>
</table>

4.2. Structural Measures Outcomes and Effectiveness Analysis

Embarkments, dikes, bridges, spurs, and diversion channels were frequently constructed between the 1960s and the 1980s. Notably, it is thought that the structural activity will immediately reduce the flash flood hazard and regulate it effectively [70]. However, with some of these measures, their effectiveness decreased with time due to a variety of reasons, including changes in land use/cover, construction without a plan, and increasing population in flood-protected locations; hence, in any of these occurrences, disastrous flood consequences are possible [71].

Figure depicts 12 cross-sections that are routinely measured between the upstream and downstream sides of Kassala’s bridge, adjacent to Kassala town, and the flood control structural measures. The cross-section of the river shows how the surface of the riverbed is higher than the terrain of the surrounding area and a portion of Kassala city. In this segment and cross-section number, the height difference between the riverbed and the eastern site area of the river is greater than 2 m. The overall trend of these 3D profiles shows that the Gash River’s bankside surface topography is lower on the east side than on the west. This pattern can be taken to mean that Kassala’s east side is more vulnerable to flooding than its west side. Additionally, it may be said that the protective system of the Gash River is very much dependent upon the physical safety of Kassala city.

Structural measures include building physical structures like embankments, groins, stop banks, rock linings, gabions, revetments, and vegetation buffers that are intended to stop floods and reduce river erosion [72,73]. This was put into reality in the Gash River’s protection works. Decades ago, due to the annual variability of the river discharge, a structural earth embankment had been constructed around the river on both sides [74]. With time, sedimentation increased, and the embankment efficiency decreased due to the
increase in riverbed level. Additional work was then conducted to heighten it. Another structural measure was conducted for river flood control, which included the construction of 12 spurs perpendicular to the river course adjacent to Kassala city.

Embankment and dike structures for flood control measures have an effect on the sediment precipitation in the riverbed during the water flow period; they cause sediment deposition with slower discharge and changing flow patterns, conserving soils from erosion and increasing sedimentation within the river channel [75]. Understanding these effects is important for effective river environment management and sustainable sediment translocation planning. Embankments and dikes act as fences that prevent sediments from spreading over adjacent floodplains. Consequently, sediment retention within the riverbed will lead to increased silt accumulation in the riverbed during the water flow period [76]. Over time, this might result in an exacerbated change in the riverbed, affecting the overall river dynamics and altering its morphology [77]. Embankments and dikes, used as water control structures, change the flow direction within the river channel. This control structure over the water flow will affect the transport of sediment. When the water flow encounters the flood control structures, it loses energy and begins to precipitate sediment. The sedimentation occurred in the slower-moving zones behind the structures, leading to sedimentation in the riverbed [78].

4.3. Analysis of Flood Hazard within the Prone Area

Flood simulations in Kassala show large areas submerging when the river flows over 2 m high. The simulation outcomes are visualized through flood maps. The maps show areas at risk of flooding and flood extents. It shows flood hazard boundaries and is employed for land-use planning, emergency response, and risk assessment purposes (Figure 7). The map shows that the eastern site of Kassala City is more vulnerable to flood hazards caused by the Gash River. Flooding in the eastern part is more likely to result in a catastrophic outcome at a high cost. The western part shows low flood hazards; this means that the western part of Kassala town is more highly elevated than the eastern part. Consequently, with the riverbed rising systematically every year, the structural measures should be redesigned and maintained to avoid flood consequences.

Figure 7. (a) The likelihood of the area being submerged as the flood rises by 2 m is depicted on the flood simulation map. (b) The embankments, dikes, and bridges are now being used as flood protection in the Kassala section of the Gash River.
As assessed in this study, flood risk management encompasses three interrelated components: risk analysis, risk evaluation, and risk reduction [79]. These three factors heavily rely on the analysis of geospatial data in various modalities and at various degrees of both temporal and spatial resolution to produce the necessary data and knowledge for managing flood hazards [80]. Since elevation data, land use data, and hydrological data analysis and modeling interact and are integrated in this study, a significant portion of the work can be viewed as such. The opinions of professionals and local populations demonstrate good knowledge and understanding of the area’s floods and their relationships.

Risk reduction includes various factors such as the effectiveness of the embankment, the dimensions required to prevent torrential floods, and the distance between the eastern and western embankments. However, it should be noted that due to sedimentation, the dimensions of the embankment may change, and its height could be reduced. This, in turn, results in the riverbed rising and leads to a decrease in the cross-sectional area under the bridge, thereby increasing the risk of flooding. To address this issue, measures can be taken in the upstream area, including the catchment, to reduce the risk of floods. One approach is to construct a drainage canal before the border of Kassala city to help reduce high discharge. Additionally, artificial recharge of groundwater can be implemented, and land use activities in the watershed area can be modified to minimize sediment erosion [81,82]. This can be achieved by increasing vegetation cover in the uplands and constructing small dams in the small streams of the catchment area. The structural and non-structural measures for remediation will take this mixed approach into account. In practice, the validity and dependability of risk reduction methods under various hydrological loads determine their overall performance and effectiveness [83,84].

4.4. The Elevation Layer Variance of the Riverbed: Western and Eastern Bank

According to a 1976 survey, the ground level in Kassala town is typically 10 cm higher than the Gash riverbed level on the downstream side of the bridge [85]. This shows that training and protection work in this zone, which primarily involves dry pitching, has implemented defined design and construction systems. The river’s channel carrying capacity being trained as a result of flow-blocking infrastructure in the form of bridges, spurs, and dikes is another major factor contributing to the rising water level. Moreover, morphological changes like the increase in the riverbed and the change in slope contribute to the rise in river levels (Figure 8).

The driver factor of the riverbed rising is attributed to the catchment area characteristic of the Gash River. The Gash River catchment was affected by the drought as part of the Horn of Africa drought period during the 1980s. The upper third and, partially, the middle third of the basin’s dissected topography, the hilly topography, the inadequate vegetation cover, the unfavorable geological formations that are linked to poor soil formation, and the low infiltration rates are the main causes of flash floods. The steep slope of the Gash River basin (2 m/km) increases water flow energy, flow velocity, and the soil erosion rate. Accordingly, the area is impacted by land degradation, desertification, and deforestation, which increase soil erosion [86,87]. Climate change exacerbates land degradation and soil erosion by torrential rains during the rainy season, hitting the bare and lost top soil layer and washing a million tons of sediment in the form of silt, clay, and loam particles into the water flowing downstream [88,89]. Most of the unconsolidated layers of gravel, sand, silt, and clay make up the alluvial deposits [90]. The flood control activity of the Gash River during the flood season resulted in the formation of alluvial deposits in the river channel. The finer materials (clay) are dumped downstream, and the coarser materials (sand and gravel) are dumped upstream. Consequently, the river channel bed rose and became higher than the eastern and western side of Kassala town, which will increase the risk of floodings.
Figure 8. Layer extraction of the riverbed: western and eastern bank. (a) The Gash River’s western, channel bed, and eastern locations exhibit topographic variations. (b) Flood-prone area likelihood for the eastern site at Kassala city. (c) The leveling of the bed channel is entirely higher than at the eastern location. (d) The leveling of the bed channel is somewhat higher than at the eastern site.

The Gash River reaches the Sudan border at the Al Gira area, which is 40 km away to the south of Kassala town. In this area, the river’s morphology changed to a wider, braided, and milled slope until it reached Kassala bridge (Figure 9). The Gash basin region of Kassala is distinguished by broad flood plains on both sides of the river bank. In the Gash delta, the topography is flat to lightly rolling, with a gentle inclination toward the northwest. There is not much elevational separation between the southeast and northwest [91,92]. Kassala city historically experienced flood devastation; for example, in 1974, 1969, and 1944, flash floods occurred due to torrential rain in the catchment area, and the city was hit by flood probability every 5 years. Accordingly, in the 19th century, structural measures such as earth and dry pitch embankments were constructed along the river’s two sides to retain flooded water inside the river course [93]. Additional flood control measures were implemented by constructing 11 spurs and a dike perpendicular to the river flow direction with a length of 500 m and a width of 10 m on both sides of the river, starting from the embankment body and with a distance of 500 m between each spur (Table 2). These structures slow water flow and lead to increased sedimentation with the rising of the riverbed channel.
warning system in place to allow residents to prepare for the flood. The Ministry of Agriculture and Irrigation in Kassala is leading the Gash River Training
pressure between its two sides [96]. In addition to the poor drainage, there is no early
Table 2. The impact of the river cross-section at Kassala bridge on the likelihood of flooding in the
area surrounding Kassala City.

<table>
<thead>
<tr>
<th>Spur</th>
<th>River Width</th>
<th>Spur</th>
<th>River Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1181</td>
<td>5</td>
<td>458</td>
</tr>
<tr>
<td>2</td>
<td>620</td>
<td>6</td>
<td>813</td>
</tr>
<tr>
<td>3</td>
<td>541</td>
<td>7</td>
<td>891</td>
</tr>
<tr>
<td>4</td>
<td>586</td>
<td>8</td>
<td>731</td>
</tr>
<tr>
<td>5</td>
<td>458</td>
<td>9</td>
<td>375</td>
</tr>
<tr>
<td>6</td>
<td>813</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>891</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>731</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>375</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kassala bridge</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1280</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>1160</td>
</tr>
</tbody>
</table>

Accordingly, sediment precipitation increased due to the slowing of the flow by these
spurs, and the riverbed rise was exacerbated and became 2 m higher than the city level. In
addition to that, the river channel under Kassala bridge narrowed due to the bed rise with
a constant bridge body height and a constant river width of 140 m at the same location,
and by the riverbed, the capacity to increase the cross-section decreased. Then, the river
body impeded water flow during torrential floods and backwater occurred, increasing the
height and increasing the flood hazard to Kassala city due to an embankment breakage
due to the rising riverbed [94, 95]. In comparison to a projected flood wave of 700 m³/s,
the estimated channel carrying capacity under the bridges is 400 m³/s. The backwater of
the bridges allowed for the embankment to be overtopped, scoured from the back, and
destroyed as a result of the lack of spurs, which allowed the water current to directly impact
the embankment. The embankment’s breakdown was largely caused by the disparity in
pressure between its two sides [96]. In addition to the poor drainage, there is no early
warning system in place to allow residents to prepare for the flood.

4.5. Non-Structural Measures and the Sustainability of the Gash River Basin

Flood risk mitigation and management in the Kassala area has been a concern for a
long time. However, though non-structural measures are essential for reducing flood risk,
some of the measures have been carried out and others have not been adopted (Table 3).
The Ministry of Agriculture and Irrigation in Kassala is leading the Gash River Training
Unit (GRTU) for Gash River Training activities and emergencies in flood control by keeping annual maintenance of the embankment. These efforts are not minimizing the flood hazard risk due to inappropriate non-structural measures. Non-structural flood measures refer to actions and strategies taken to mitigate flood risk without changing the physical structure of a river basin [97]. These measures focus on managing the flash flood water and lowering damage occurrence through various methods other than constructing structures such as embankments, dikes, and barriers or changing the river flow direction.

Table 3. The adoption and implementation of non-structural measures for flood hazard mitigation policies and strategies in the Kassala area.

<table>
<thead>
<tr>
<th>No</th>
<th>Non-Structural Measure</th>
<th>Project</th>
<th>Output</th>
<th>Outcome</th>
<th>Specific Objective</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Early warning system</td>
<td>Rain gauge Meteorological data center</td>
<td>200</td>
<td>7</td>
<td>3%</td>
<td>Weak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>0%</td>
<td>Not implemented</td>
</tr>
<tr>
<td>2</td>
<td>Drain system</td>
<td>Drainage canals (downstream) Artificial recharges of groundwater</td>
<td>27 m³/s</td>
<td>5 m³/s</td>
<td>18.5%</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>Soil conservation activities</td>
<td>Increasing vegetation cover in the catchment area</td>
<td>1</td>
<td>0</td>
<td>0%</td>
<td>Not implemented</td>
</tr>
<tr>
<td></td>
<td>Land use and stakeholders</td>
<td>Natural resources committee</td>
<td>1</td>
<td>0</td>
<td>0%</td>
<td>Not implemented</td>
</tr>
<tr>
<td>4</td>
<td>Insurance</td>
<td>Flood insurance</td>
<td>1</td>
<td>0</td>
<td>0%</td>
<td>Not implemented</td>
</tr>
<tr>
<td>5</td>
<td>Maintenance</td>
<td>Budget</td>
<td>420,000 USD</td>
<td>54,000 USD</td>
<td>13%</td>
<td>Weak</td>
</tr>
</tbody>
</table>

The institutional engagement is represented in the annual strategic plan for non-structural measures set by relevant government and non-government institutions for flood risk mitigation in Kassala [98]. An early warning system for flood monitoring is in its initial stage in the catchment area. As many as 200 units of rain gauges are planned to be distributed for rainfall measurement within the catchment area in addition to the water gauge at the main river channel. However, the implemented plan has 3% weak activity with respect to the early warning system [99]. A drainage system is required to reduce torrential flooding. Someet canals have been constructed to reduce torrential floods and irrigate the Kalahoat Agricultural Scheme (KAS). Someet canals’ capacity for water flow has been reduced to 18.5% due to a lack of cleaning and siltation, in addition to the lack of artificial recharge of groundwater, which improves drinking water supply and reduces flood risk in Kassala. Soil conservation activity in the catchment region is planned to increase natural vegetation to prevent soil erosion, which is the primary source of silt load in flood water; however, this project has not been well executed. The natural resource committee is not established, which would coordinate activities to increase the efficiency of flood risk mitigation. The annual budget for flood risk mitigation is low, while the flooding potential increases. The Kassala area will be threatened by flooding due to the inappropriate management of non-structural measures and the changing design efficiency for structural measures.

Strengthening early warning systems to forecast and alert communities of impending flash floods will help minimize loss of life and evacuate people. Implementing land use planning elements to prevent housing construction in flood-prone areas and encouraging sustainable development activities that will increase flood resilience [100,101]. Sediment precipitation was observed due to the high load of silt, and the riverbed level increased annually, changing the capability of structural measures for flood mitigation (Figure 10). Understanding flood plain dynamics will assist in developing effective land management strategies [102]. This includes preserving the river’s natural water spate areas and promoting ecologically sensitive land use activities [103,104]. Raising community awareness of flood risk resilience, readiness to respond to flash floods, and community preparedness...
will significantly minimize vulnerability and devastation. We also recommend encouraging businesses in flood-prone sites to offer flood insurance to individuals and providing financial support for flash flood damage improvement to minimize economic loss [105].

Figure 10. Normal water flows are hampered by the river rising due to sedimentation in the river channel.

The sustainability of river basins indicates the overall health and resilience of the river ecosystem and its ability to sustainably provide essential ecological services while meeting community needs [106]. Considering flash flood mitigation measures in a river basin, it is important to ensure that they are aligned with long-term sustainability objectives. This amounts to the use of ecological restoration techniques in flash flood resilience strategies that will assist in maintaining sustainable natural habitats and strengthen biodiversity within this river basin [107], and the reinforcement of sustainable soil and water management activities—for instance, soil erosion control in the catchment area, water conservation, efficient irrigation methods for food security and production, and IWRM—which assist in maintaining the ecological balance of the river basin ecology while conserving the water needs of various users and stakeholders, for instance, F and drinking water supply, and increasing productivity [108]. Considering the potential impacts of climate change on the Gash River basins and including adaptive activities will enhance resilience and sustainability. The inclusion of all stakeholders involved in flood mitigation decision-making processes related to river basin management, including local societies, government administrations, NGOs, and private sectors, will ensure diverse perspectives, leading to further sustainable goals. By integrating non-structural flood measures with sustainability objectives, river basins will adapt to changing conditions, minimize vulnerability to floods, and conserve ecological integrity [109].

5. Conclusions and Recommendations

Risk management for flash floods is prevalent worldwide, especially in arid and semi-arid regions. This study focuses on the impact of structural and non-structural measures applied for torrential flood mitigation in the Gash River basin around Kassala town, eastern Sudan, on land use and cover and the socioeconomic domain. The study uses multiple approaches that have not previously been systematically disclosed. The study used RS and GIS techniques to analyze the study area’s flood-prone area through the utilization of DEM data.

According to the findings of the study, the elevation layers of the riverbed on both the western and eastern banks were extracted, and we have determined the variations and their relationship to flood risk occurrence. The construction of dikes and spurs near Kassala town has led to sediment precipitation, causing the riverbed to rise. To reduce the risk of flash floods in Kassala and its upstream area along the Bridge of Gash River, several
measures will be implemented. First, a dam will be constructed to minimize flood hazards during torrential flash floods. Accordingly, sedimentation could be managed and removed through maintenance activities during drought season. Kassala bridge will be extended on both sides. Consequentially, for normal water flow during the high discharge, the river width at the bridge site could be increased from 140 m to about the general average width of the river. Many artificial recharge wells would be built to conserve the Kassala aquifer. In recent years, a report has been subjected to the dropping of groundwater storage in Kassala, where the drinking water supply source in Kassala depends on it. Accordingly, flood risk mitigation will improve by directing a portion of flood water to groundwater and draining canals in the upstream area of Kassala town. The drained canal’s capacity for water flow dropped from 27 m$^3$/s to 5 m$^3$/s due to a lack of maintenance and cleaning; the growth of Mesquite trees inside the canal, which would impede the water flow and increase silt precipitation; and the lack of management at the canal intake gate.

In order to increase the river channel capacity for water discharge and avoid flow restriction by the bridge wall, the continuous removal of silt from the riverbed will help maintain a lower riverbed to recover the cross-section area of 725 m$^2$ in 1970 instead of 290 m$^2$ in 2022 under the bridge. An effective early warning system would be established in the Gash basin, particularly in the catchment areas throughout the river share countries of Sudan, Eritrea, and Ethiopia, by distribution of 200 units of rain gauges to monitor actual precipitation in the basin and improve readiness for, and monitoring of, flood. Sustainable flood control would be implemented by increasing vegetation cover along the embankment, which is involved in sediment precipitation, thus supporting the embankment construction goals for flood control. Additionally, to protect Kassala town against floods and the Gash Agricultural Scheme (GAS—which is located in northern Kassala—from lack of irrigation water, the study strongly recommends further intensive research and study on the Gash River Valley concerning integrated water resources management (IWRM), particularly in the areas of flood management and sediment management.

This study provides a compelling argument for reducing the catastrophic effects of torrential rivers and creating opportunities for resolving the water shortage problem in Kassala. This could be accomplished by adding the evaluation of structural and non-structural measures to mitigate flood risk in Kassala town. Ultimately, this study concludes by disclosing the effects of structural and non-structural measurers on the risk of flash floods in the Gash River in Kassala town, eastern Sudan. Sedimentation attributed to the dikes and embankment construction has raised the riverbed to 1.5 m higher than Kassala City; this change will increase the flood risk during the rainy season. This study suggests promoting measures like redesigning water control structures, bridge extension, artificial recharge systems for groundwater replenishment, and silt removal to mitigate flood risks. A water conservation activity and early warning system is proposed for the basin area shared by neighboring countries. Increasing vegetation cover and enhancing drainage capacity are also part of the plan. This study underscores the need for more detailed research on integrated water resources management in the Gash River.

**Author Contributions:** K.A.M.S. and K.W. conceptualized the study, proposed and designed the study plan, implemented, processed, and analyzed the data, and extensively wrote the original draft; K.W., supervision, data curation, and investigation; G.A.A. and T.X. conducted the graphics, software, and editing of the manuscript; T.X. and K.W., funding acquisition. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research is supported by the National Natural Science Foundation of China (Grant No. 41971236).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data is contained within the article.
Acknowledgments: We would like to acknowledge our indebtedness and render our warmest thanks to Wang Ke for his invaluable guidance and expert advice throughout the research process. We also thank the academic staff and Ph.D. students of the Agricultural Remote Sensing and Information Technology Institute at Zhejiang University for their collaboration and support. The authors also thank the Ministry of Agriculture, Kassala, Sudan, for their support during data collection. We also express our deepest gratitude to all our family members and friends for their constant support during the research process.

Conflicts of Interest: The authors declare no conflicts of interest. All authors have read and agreed to the published version of the manuscript.

References


22. Ren, M.; Shi, Y. Sediment Discharge of the Yellow River (China) and Its Effect on the Sedimentation of the Bohai and the Yellow Sea. *Cont. Shelf Res.* 1986, 6, 785–810. [CrossRef]


99. Sukhwani, V.; Gyamlfi, B.A.; Zhang, R.; AlHinai, A.M.; Shaw, R. Understanding the Barriers Restraining Effective Operation of Flood Early Warning Systems. *Int. J. Disaster Risk Manag.* **2019**, *1*, 1–19. [CrossRef]


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.