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Combined 1D Modelling with HEC-RAS for Delineation Floodplain Area: A Case Study of Hennops River in the Centurion Area

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Abstract: Flooding is among the most extreme weather events, endangering lives and causing significant property damage each year. Flood events in the Centurion area occur every year during the rainy season. This causes considerable damage to road infrastructure in both residential and commercial areas. The objective of this study is to incorporate hydraulic/hydrological (i.e., HEC-RAS/HEC-GeoRAS) models with geo-spatial techniques to predict flood extent and depth along Hennops River in Centurion area, Tshwane Metropolitan Municipality, Gauteng Province. In this study, floodplain inundation areas with different return periods were predicted in a 3.1 km distance of the Hennops River that passes through the Centurion area. Flood hazard analysis indicated that areas at close proximity to the Hennops River were submerged by a minimum and maximum flood depth of 0.4 m to more than 1.1 m for both 50 and 100 year flood recurrence interval. The study's findings show that integrating GIS with HEC-RAS/HEC-GeoRAS techniques is a useful tool for floodplain mapping and analysis. Hence, the findings of this study are expected to be used as a foundation for the identification of causative factors of flash floods and the prediction of flash floods within the study area in future. The floodplain delineation maps developed in this study will be useful to policy-makers and the relevant authorities, as well as to local residents, in finding suitable measures for residential development along the floodplain while reducing flood risk in the study area.

Keywords: GIS, HEC-RAS/HEC-GeoRAS, Flood Depth

1. Introduction

Globally, floods are frequent natural disasters causing a wide variety of disruption to both environment and the society [25, 27]. Studies worldwide suggest that the number of disasters associated with extreme weather and climate, such as floods, increased during the 20th century [6, 2, 14, 19]. Ruji [30] claimed that floods can arise in several ways depending on the factors leading to flooding. There are millions of people who have been impacted every year by natural catastrophe, causing serious damage to private property and loss lives. This is also the case in Centurion, where flooding occurred due to heavy rainfall and the characteristics of the river at Centurion area, causing tremendous damage to both valuable and infrastructural properties, thereby affecting transportation and other services. As a result, exact demarcation of the floodplain's geographical extent is critical for flood control, residential and administrative development and urban planning, insurance, and other regulated operations on land and property that may be impacted by floods [24].

Flood mapping is a technique that explains the predicted level of flooding in drylands triggered by heavy rainfall or an increase of river water levels due to by natural or man-made modification [22]. The results of the process were noted by [35] not only as a better delineated floodplain with higher efficiency than conventional approaches, but also as a result of extracting a flow depth grid that shows inundation extent in the floodplain. Recently, the integration of GIS techniques with hydrological/hydraulic models have been demonstrated as a very efficient and useful technique to forecast floodplains' delineation [13, 31, 21]. The key benefit of using GIS for flood control is that it offers an inundation visualization that may be highly helpful for managing flood mitigation [31]. It is clear that GIS has an important role to play in the mapping of floodplains and other related-disasters management, because the aspect of natural disasters are multi-dimensional [8].

The integration of GIS and remote sensing with HEC-RAS/HEC-GeoRAS for predicting floodplain inundation has been conducted by various researchers. [23] researched the environmental impact of the Maroon River flood zones via HEC-RAS and GIS techniques. The findings suggest that the disparity in the expansion of flood areas primarily represents the topographic characteristics of the valley path. The Basher River hydraulic behavior with HEC-RAS and GIS was simulated by [29]. The aim of this analysis was to use the HEC-RAS and ArcView GIS simulation software with the HEC-GeoRAS interface to simulate the hydraulic parameters of the Basher River in the Kohgiloyeh and Boyerahmad provinces. The findings of this study demonstrate that the HEC-RAS model can offer the reasonable numerical values for the hydraulic properties of river flow to be studied and can be implemented with greater precision and at low cost to flood risk-mapping. The Karun river flood zoning from Bandeghir to Ahwaz was simulated by [28] using the HEC-RAS model. Flood risk zonings for a period of 50 years and 100 years using the software capability of HEC-RAS were calculated using DEM of the surrounding river and overall water level at all defined sections.

In this study, part of Hennops River bounded by the N1 highway and N14 highway covering a distance of 3.1 km passing through the Centurion area was chosen. The main goal of this research was to integrate GIS techniques with HEC-RAS/HEC-GeoRAS for predicting floodplain inundation in the Hennops River, Centurion area. Floodplain inundation (i.e. flood depth) maps for different recurrence interval were developed. The proposed maps can be used effectively by the municipality and private institutions in order to minimize flooding and to manage disasters.

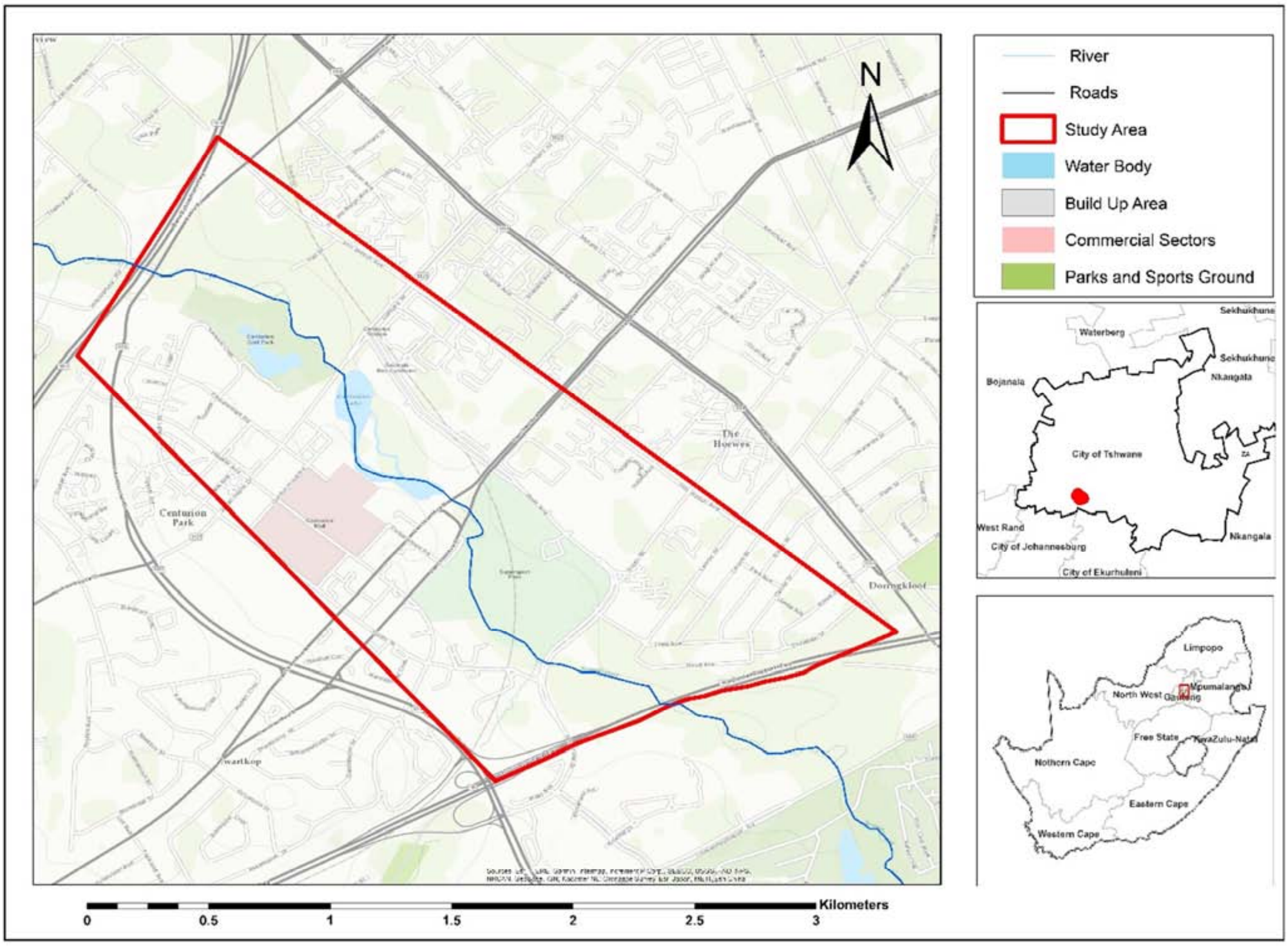

Figure 1. Locational map of an area of interest.

2. Description of the Study Area

Centurion is an area that falls within the City of Tshwane Metropolitan Municipality and is located between Pretoria and Midrand between the latitudes of 25°51’32” S and longitudes of 28°11’08” E. The estimated elevation of the area under study is 1432 m above the average sea level and is relatively flat-lying, sloping gently towards the Hennops River. The location map of the study area is shown in Figure 1. The study area includes developed residential areas with commercial development where the Hennops River is bounded by the N1 highway in the south and N14 highway in the west. The Hennops river is among the major rivers that drain the Gauteng Province. It has its source near Kempton Park, in the eastern part of Johannesburg and flows into the Crocodile River which is the main water supply to the Hartebeespoort Dam. The tributaries are formed by the Transvaal Super-dolomite, group's quartzite, shale, and conglomerate [1]. The Hennops river passes through the middle of Centurion area and periodically triggers floods during intense rainfall. A sub-humid, moderate climate is experienced in the area. The overall mean observed daily temperature is 24.1°C, with a minimum recorded average daily temperature of 7.6°C. The summers are warm, and winters cool with moderate to severe frost. Most of the rainfall occurs as afternoon thunderstorms between November and March with annual average precipitation of 689 mm [32].

3. Description of Hydraulic Model

The Hydrologic Engineering Centre-River Analysis System (HEC-RAS) is a hydraulic model that has the capacity to perform 1D surface stream calculations using the St Venant equations in different channel networks during the approximated flow dynamics [18]. HEC-RAS is a commonly used as a GIS interface that can execute 1D or 2D-dimensional hydraulic simulation for a complete network of natural and man-made channels, overbank/floodplain areas and levee protected [16]. It is viewed as the most widely used floodplain hydraulic model in the world with constant upgrades [11]. In this research study, the Jukskei River along the modelled area in Alexandra Township is assumed to be a steady flow river. A river that flows steadily can be described as a river that will flow continuously as the energy equation does not require time dependence [31]. In the HEC-RAS model, a 1D energy equation solution is used as a simple computational method [31]. Equation 1 illustrate the energy equation:

$$Z_2 + Y_2 + a_2V_2^2 = \frac{Z_1}{2g} + Y_1 + a_2V_1^2 + \frac{h_e}{2g} \quad (1)$$

where:

Z_1, Z_2 main channel elevation inverted (m); Y_1, Y_2,=cross-sectional (m) water depth; V1, V2=average velocities (total release / total flow area); a1, a2=coefficients for velocity weighting; *g*=acceleration of gravity; and *he*=loss head of energy (m) which is determined by the Manning formula as reported by Masoud [20]:

$$h_e = L\left(\frac{Qn}{AR^{2/3}}\right)^2 \quad (2)$$

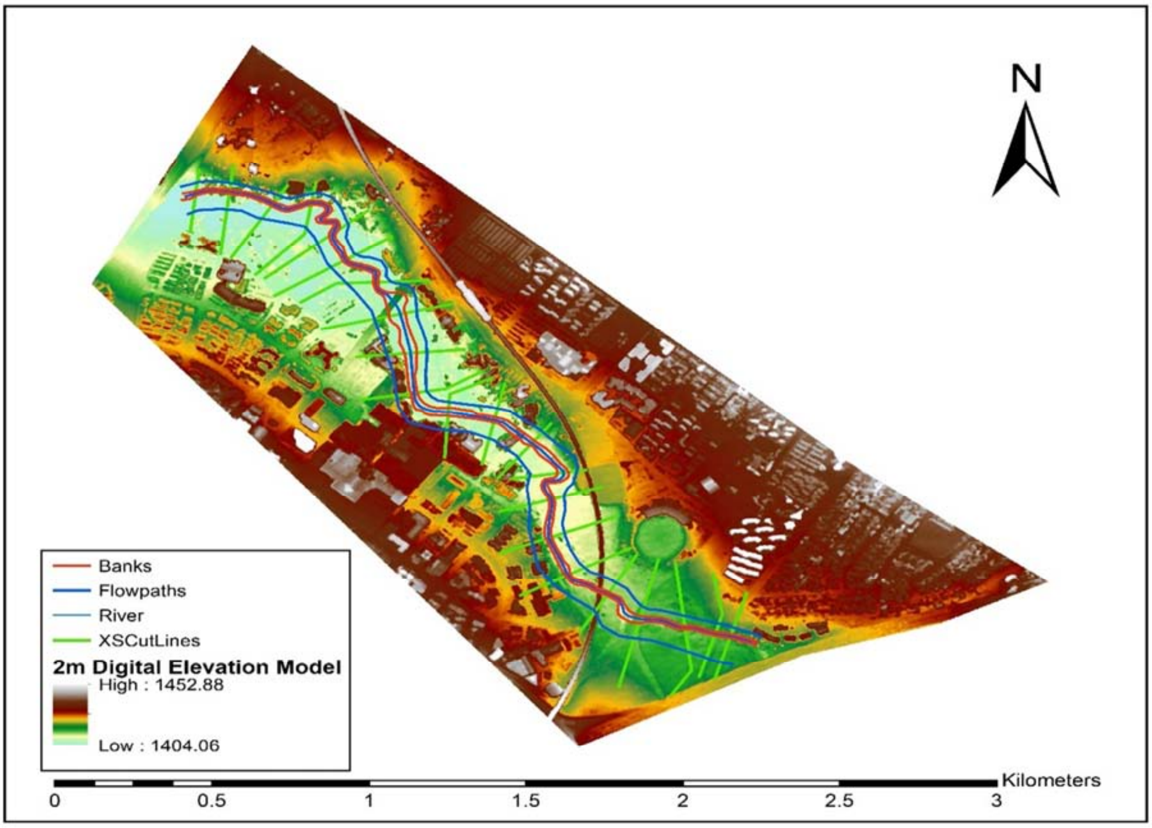

Figure 2. *Digital elevation model of the study area.*

4. Materials and Methods

For the purpose of this study, three main datasets including streamflow data, classified image and the digital elevation model (DEM) were used for predicting floodplain inundation. Streamflow data recorded at the HNP gauge station, located in the upstream of Hennops River, was used for this study. The length of the streamflow dataset covers a period of 23 years from 1987 – 2010. After verification of the dataset was done to ensure that no missing or gaps within the dataset, flood frequency analysis could be done using statistical distribution. The most commonly used probability distribution functions, including normal, log-normal II, Gumbel, Pearson type III and log-Pearson type III distributions, are currently used by researchers in frequency analysis of the hydrological data [4, 17]. Therefore, for the purpose of this study, flood frequency analysis for the Hennops River, a log-Pearson type III was applied to estimate discharge (m^3/s) for 50 year and 100 year flood return periods.

DEMs play a critical role in flood inundation mapping by providing floodplain topography as an input to hydrodynamic models, thereby enabling the mapping of the floodplain by using water surface elevations [3]. For the purpose of this study, a very high-resolution DEM (i.e. spatial resolution of 2 m and 5 m vertical interval) covering the entire study area was acquired from the Centre for Geographical Analysis (CGA) at Stellenbosch University, South Africa [34]. In developing a floodplain delineation model, for the first step in creating RAS layers, a 2 m DEM derived from LiDAR data was converted to a triangular irregular network (TIN) using the 3D Spatial Analyst Tool in ArcMap. A TIN was further used in HEC-GeoRAS to create RAS layers which characterise of line and polygon themes (i.e. feature datasets). Figure 2 shows 2m DEM and RAS geometry layers that are required for floodplain delineation. These include stream centrelines, flow paths, riverbanks and XS-Cutline (known as a cross-section in HEC-RAS) and were captured in ArcMap using TIN and a geo-referenced Google Earth image.

Once the cross-sections XS-cutlines were populated using TIN and the entire input datasets, including the stream centerline, banks, flow paths, and Manning's *N*-values were exported into HEC-RAS for further hydraulic analysis. This procedure allows the geometric data to be transferred from HEC-GeoRAS to HEC-RAS format for a flood simulation model. The portion of the Hennops River that flows through selected study area was assumed to have a steady flow. Steady flow rivers can be defined as rivers which are assumed to flow steadily along the reach as the energy equation is not time dependent [31]. Boundary conditions are necessary to establish the starting water surface at the ending of the river system. The Hennops River profile from upstream to the downstream was calculated using a TIN and was further used as the model's initial boundary condition (normal depth) for the steady flow. In this research, normal depth was selected for upstream boundary conditions and critical depth was selected for downstream boundary conditions. HEC-RAS consists of three flow regimes (namely subcritical, supercritical and mixed flow regimes) which are used in modelling a network of channels and river reaches [34]. In this study a steady flow analysis was performed using a mixed flow regime. Lastly, RAS mapping was used for floodplain delineation, whereby TIN elevations were subtracted from simulated water surface elevations to obtain a spatial extent of flood inundation and flood depth [24].

5. Results and Discussion

The development of a steady flow simulation model for the study area was based on the HEC-RAS/HEC-GeoRAS coupled with GIS techniques. The Hennops River that flow through the Centurion area has been identified as the river that contributes to the occurrence of flood. Using Log-Pearson Type III flood frequency analysis, the flood peak discharge for the recurrence interval of 50 years and 100 years were estimated. Figure 3 shows flood levels in one of the analysed cross-sections for 50 year and 100 year flood recurrence interval. The model analysis showed that in the two described recurrence intervals, there is more than a 1.0 m discrepancy between water levels. Thus, a large part of the study area would be affected by a flood depth of more than 1.0 m during intense rainfall for a 100 year recurrence interval.

Based on the incorporation of the HEC-GeoRAS extension of ArcMap, flood extent and depth in the floodplain of the Hennops River was carried-out in various flood recurrence interval. Figure 4 shows maps for flood-depth of 50 years and 100 years flood recurrence interval are represented in Figure 4. Flood depth maps provide information about the degree of impact along the stream centerline and alongside areas for a given flood return period (Goodell and Warren, 2006). The analysis of the results revealed that the depth at the stream centreline is higher compared to areas alongside the stream centerline with varying flood depths. A previous study by [26] highlighted that the presence of obstructions (i.e. buildings, embankment, and bridges) appear to raise the flood depth and thus the appropriate number of flood damage. Along the Hennops River, the spatial distribution of the flooded area is higher in the lower and upper stream compared to the central part. The analysis of the model output result revealed that some of the areas were reached by a minimum and maximum flood depth of 0.4 m and 1.1 m, for both 50 and 100 year recurrence interval (see Figure 4).

According to [12] wading by a normal adult becomes increasingly challenging and riskier when the level of water surpassed 1.2 m and light vehicles can become imbalanced when the water depth exceeds 0.3 – 0.4m. With reference to modelled 50 year and 100 year flood recurrence interval and those suggested by [12], were higher with minimum and maximum flood depths of 0.4 m to more than 1.1 m. As a result, individuals are unstable and susceptible to toppling over and drowning; cars and vehicles (i.e. small and large) will lose stability and float off-road (see Figure 5d); buildings will be at risk of being affected and damaged by high flood water (see Figures 5 b and f). Additionally, routes crossing bridges that provide access to the Centurion CBD are also covered by floods owing to the structural design of the bridge which allows high flood water to pass through a narrow passage, thereby causing routes to be flooded (see Figures 5 a, c and e). Therefore, the areas at close proximity to the Hennops riverbank will experience the impact of floods during rainfall seasons unless preventive measures are implemented to reduce runoff volume prior to flood events.

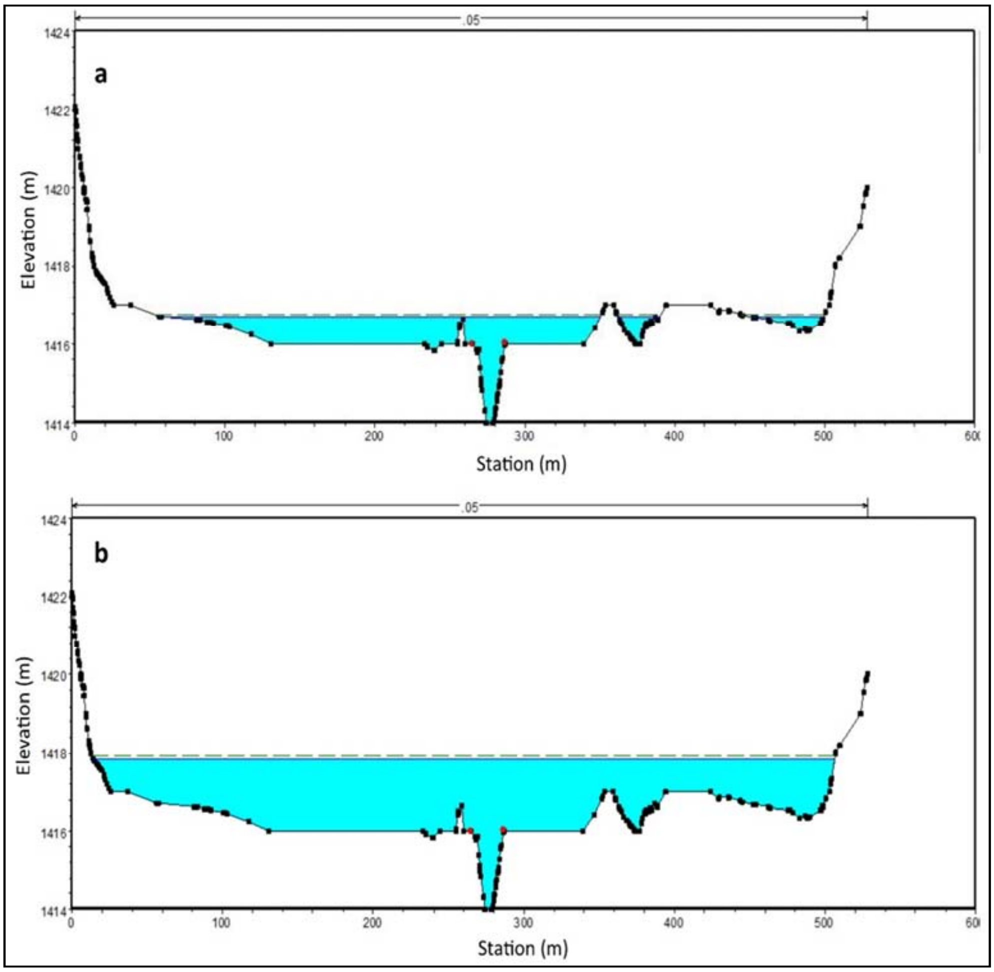

Figure 3. Flood level in one of the cross-section (a) 50 years and (b) 100 years recurrence interval.

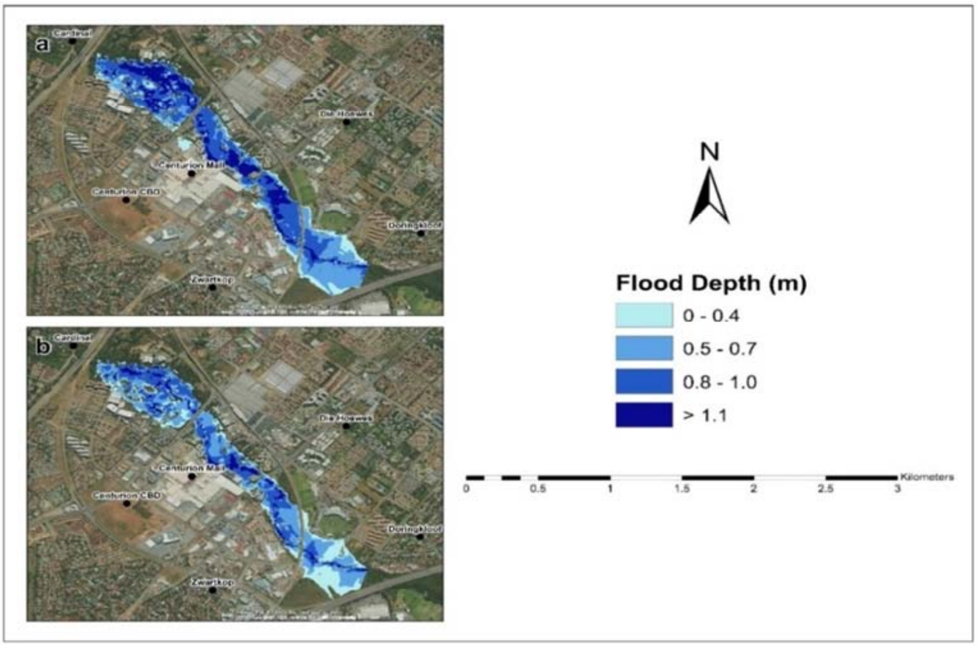

Figure 4. Flood depth maps (a) 100 and (b) 50 year flood recurrence interval.

Figure 5. *Flood event occurred in the Centurion area during the 31 December 2019.*

Figure 6. *Surveyed cross-section and bridge along Hennops River.*

In a road network, a bridge is a critical component which connects two road networks or provides a traffic diversion that can reduce traffic congestion, travel distance and time [15]. The construction of a bridges across the rivers, on the other hand, might have a detrimental impact on the hydrological response [5]. Figure 6 shows one of the analysed bridges along the Hennops River with a height of 3 m, a 26 m width and a surveyed cross-section. This bridge is located across the river where a high discharge normally occurs. However, during a heavy rainfall event the bridge is frequently at risk of being flooded, making it impossible for the Centurion CBD and other areas to be accessed. In addition, the road is closed for two to three days depending on the intensity of the rainfall. Therefore, the bridge has a design flaw in that is not high enough to allow high flow velocity of flood water to pass through without blockage. Additionally, a section of the Hennops River within the study area is not deep enough and is also too narrow to accommodate high surface runoff. With reference to Figure 5 c, the areas on the left bank of the river, including both commercial and residential properties, will continuously be affected by floods owing to landscape characteristics (i.e. the gentle slope and flat area) of the area. Therefore, when designing bridges, a good understanding of river behaviour as well as the safety of the structure is extremely important as it may have hydrological impacts, thereby increasing the risk of flooding [9].

6. Conclusions

This study focused on integrating HEC-RAS/HEC-GeoRAS models with GIS techniques in order to predict floodplain delineation area along Hennops River at Centurion area. The fundamental benefit of employing geospatial approaches to predict floods is that, is not only provides a visual representation of flooding, but it also allows for further analysis to estimate flood damage. Flooding is by far the most frequent phenomenon in the Centurion area, occurring during rainy seasons. The route bridges that allow access to the research area are built at a low elevation and are not high enough to withstand significant flood levels during heavy rainfall, resulting in flooded bridges. Therefore, to reduce the effect of route bridges on flooding, the height of the bridges must be increased to at least 3 m from the ground surface as the river is not deep or wide enough to accommodate high levels of flood water. The study's findings indicate that an integration approach that allows HEC-RAS/HEC-GeoRAS to be integrated with geospatial techniques has shown that it has the potential to accurately predict disasters due to floods and generate floodplain and flood hazard mapping. The findings of the research are intended to be valuable in flood prevention, preparedness, and management planning in the Centurion area, as well as in determining the dimensions of hydraulic infrastructure such as bridges.

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