AJLP & GS
African Journal on Land Policy and Geospatial Sciences

*e-ISSN : 2657-2664, Vol. 8, Issue.5, May 2025*

*https://revues.imist.ma/index.php/AJLP-GS/index*

*https://doi.org/10.48346/IMIST.PRSM/ajlp-gs.v8i5.51326* *Category of the manuscript : Articles*

***Received in***: 08 October 2024 **Revised in:** 10 May 2025 ***Accepted in***: *10 May 2025*

# HEC-RAS modeling for the determination of highest water mark as the reference surface for delineation of riparian reserve

## Case Study of Nairobi River-Kenya

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***ABSTRACT***

**Context and background:**

Highest Water Marks (HWM) has often been used as the points of reference for measurement of the width of the riparian reserve. Its determination is usually a challenge and, in most cases, its often approximated manually by physically going to the river banks during heavy rainfall seasons. This has often caused a huge challenge when delineating riparian reserves for purposes of protecting and conserving it. Hydrological Engineering Centreline River Analysis System (HEC-RAS) has proven to provide accurate simulation of the highest water mark over a long period of time using both geomorphological features and climatic data.

**Goal and objectives:**

The main aim of this study was to apply HEC-RAS model to determine the highest water mark (HWM) for Nairobi River for a flood return period of 30 years.

**Methodology:**

HEC-RAS version 6.3 was used to simulate the HWM with inputs of the Digital Terran Model (DTM), River Discharge and rainfall gauge station data. The model was found to very suitable for determining the HWM after conducting validations during the high rain fall periods of April/May 2024 which caused a heavy flood in Nairobi City. The HWM was then used to offset the different set back distances of 2m, 6m and 30m as per the legal framework and laws governing riparian delineation. Levels of encroachment was then established within those delineated riparian reserves.

**Results:**

The upper river segment, the highest water mark was found to range between 2-3m above the river bed on a well V-shaped river slope hence not susceptible for flooding while the middle river segment the highest water level was above 5m on a U-shaped river slope rendering it a flood plain where as the lower river segment the highest water mark was found be 1.5m above the river bed on a widened U-shaped river slope making it very prone to huge floods.

Keywords:

HWM, GIS, HEC-RAS, DTM, Riparian Reserve

## 1. Introduction

HEC-RAS is a powerful, yet easy-to-use software package for determining water surface profiles in a wide variety of streams(Wara et al., 2019). Cross sectional profile of the river is specified at different intervals preferably 5m. Using a two-dimensional model, HEC-RAS computes single water surface elevations for each cross section and their corresponding spread. In other words, the water surface elevation presented in the HEC-RAS results will not vary along the length of a cross section; the overbanks and the main channel will have the same water surface elevation. In reality, the overbanks typically have a higher water surface elevation than the main channel. As a result, flow will come out of bank earlier than in reality and the water surface elevation in the overbanks will be slightly lower than in reality(By & Julius, 2013). Riparian reserve delineation is determined by the landscape and the geology of the area (Ilhardt, et al, 2000) commonly referred to us river geometry. Geomorphology forms the basis of riparian reserve delineation. Riparian reserves are delineated in various methods; fixed width, variable-width methods, and multi-zone models (Ilhardt et al., 2000). The width of riparian reserve is dependent on its function and natural factors such as soil type and topography (LVPC, 2011) and are based on the HWM as the reference surface.

An effective riparian reserve is influenced by its width and vegetation within the zone LVPC, 2011). Riparian reserve width for streams and wetland habitats can be established using fixed-width and variable-width methods (Johnson et al, 1992). The fixed-width method aims to protect specific functions, while variable-width focuses on site specific conditions (Ilhardt et al., 2000). A fixed width buffer has a specific distance that applies to the whole catchment area.

The variable-width method is flexible in nature, thus encouraging sustainable land management practices for land users (Salo et al, 2016). This method focuses on site-specific conditions and ecological functions of a particular section along the river course (Johnson et al, 1992). However, this method is time consuming in decision-making and implementation (Salo et al, 2016).

The definition and demarcation of riparian reserves in Kenya depend on the objectives and the field of interest(Commission, 2017). Different laws stipulate different measures for the same riparian lands resulting to confusion in the definition and delineation of riparian lands (Lelo et al, 2005). Consequently, in most cases, the management of the riparian lands is left to the interpretation of individuals owning land adjacent to water bodies.

Therefore, there is no universally agreed definition and standard riparian width among sectors and institutions involved in management of riparian lands however the reference surface is pegged on the highest water mark(HWM)(Kwena, 1999).

The following are set back distances as specified by different legislation in Kenya.

| Statute/ Institution | Legal Definition for recommended riparian width (in metres) |
|---|---|
| Survey Act, Cap. 299 | Section 111.Reservation on all tidal rivers to at least 30 metres in width above the highest water mark. No mention of other smaller rivers. |
| EMCA(Conservation and Management of Wetlands) Draft Amendment Regulations, 2007 | 9(1) Shores of lakes protected zone of 50m from the highest water mark, shore of the ocean 60m, rivers 30m. |
| EMCA (Water Quality Regulations, 2006) | Minimum of 6m and Maximum of 30m from the edge of the river. |

| | |
|---|---|
| Agriculture Act, Cap 318 (Basic Land usage Regulations), 1965 | Minimum of 2m and Maximum of 30m. Reference point not indicated. |
| Land Act, 2012 | Land adjacent to ocean, sea, lake, river, dam and water courses as provided in Survey Act or any other written law. |
| Water Act, 2016 | Land lying within a distance equal to width of the water course with a minimum of 2m and a maximum of 30m from the HWM. |
| Water Resource Management Rules, 2007. | Minimum of 6m and a maximum of 30m from the HWM. |
| Physical Planning Act, Cap 286/ Physical Planning Handbook, 2008 | Land on each side of a water course defined as having a minimum of 2m, or equal to full width of the river as measured between the banks of the water course up to a maximum of 30m (seasonal and perennial rivers) |

## 2. Delineation of Riparian Reserves contextualized in Kenya

The Kenyan definitions of riparian lands use the centerline of river, river banks and highest water marks as different points of reference of measurement of the width of the riparian area without much consideration of the land use and biophysical factors(Commission, 2017). A Technical Advisory Committee (TAC) formed in 2011 to spearhead the development of harmonized riparian reserves for various water bodies/ wetlands in Kenya with members drawn from the then Ministry of Agriculture (MoA), Ministry of Lands (MoL), City Council of Nairobi (CCN), Water Resources Management Authority (WRMA) and National Environment Management Authority (NEMA) proposed the following for riparian reserves(Commission, 2017).

Rivers: A minimum riparian reserve of 6m or equal to the average full width of the river measured from the highest water mark, whichever is higher, up to a maximum of 30m shall be maintained. However, for rivers with an average full width of up to 2m, measured from the highest water mark, a riparian reserve equal to double the average full width of the river shall be maintained. This shall apply to both seasonal and perennial rivers.

For rivers, a minimum of 6m and maximum of 30m measured from the highest water mark (HWM) was proposed(*Final Riparian Reserve Report 2011-Final*, n.d.).

### 2.1 Study Area

Nairobi County is surrounded to the North West by Kiambu County, to the South is Kajiado and to the East is Machakos (Figure 1). The County has a total area of 696.1 Km$^2$ and is located between longitudes 36˚ 45' East and latitudes 1˚ 18' South. A prominent landscape characteristic of the County is a number of streams with steep-sided valleys covered with vegetation (Nairobi CIDP, 2018-2022). The heights range between 1 600 - 1 850 m above sea level, it enjoys moderate temperatures throughout the year (CBS 2001, Mitullah 2003). The western side of the city is the higher, with a rugged topography, while the eastern side is the lower and consist of a plain. Numerous informal settlements are crossed by the three tributaries of Nairobi River. Some portions of northern Nairobi still have access to the native Karura forest. To the west is Ngong, to the north is Mt Kenya, and to the south east on the Tanzania plains is Mt Kilimanjaro. Given that the city is situated near to the Rift Valley, along the Faultline and plates separate, small earthquakes and tremors periodically affect the city.

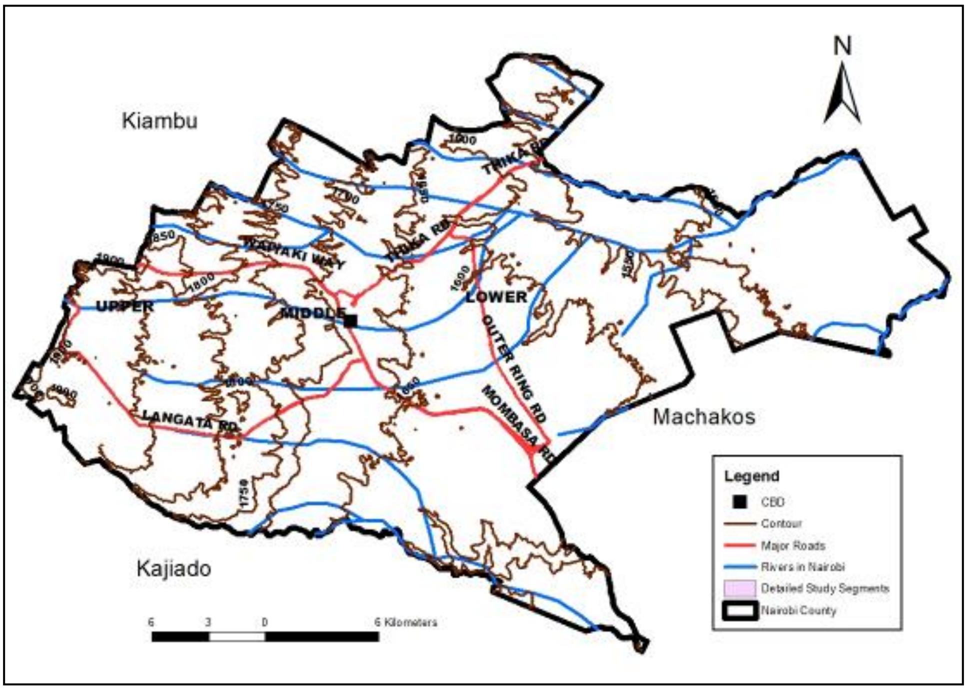



**Figure 1: Study Area (Author, 2024).**

Due to the City's rapid growth, urbanization processes have led to immense pressure to the Nairobi River riparian reserve. Nairobi river traverses the county from the upper side in the west, through the middle all the way to the lower side at on the eastern direction. These shall form the selected segments under the study. This is due to diversity and uniqueness of the land uses prevalent in those sections, differences on the terrain and water volumes. The sections shall be divided into blocks for ease of data collection and detailed assessment of their riparian corridors(Tibaijuka. A, 2007).

Nairobi has two rainy seasons, short and long rains which occur in October-December and March-May, respectively. The mean annual rainfall is about 900mm and decrease from Kikuyu escarpment to the Athi Plains. Temperature conditions are characterized by a small annual range and a large diurnal range due to high temperatures during the day and low temperatures during the night. The mean annual temperature is 17c and the mean daily maximum and minimum are 23°C and 12°C, respectively(Kwena, 1999).

Nairobi's population is estimated at 4.397 million with annual growth rate of 4% (KNBS, 2019). The average density of Nairobi is 2,600 persons per square kilometre. However, densities vary widely within the city. High income areas have average densities of as low as 2,100 persons per square kilometre while low income areas have average densities as high as 55,000 persons per square kilometre (Lamba, 1994). The observed land use activities along these rivers include: farming, residential, commercial, industrial and recreational. All these land use activities are randomly spread with no clear pattern.

Nairobi city is divided into two physiographic units or land forms. The western and the northern parts are generally high rising to 1905 and 1975m above sea level forming part of Kikuyu plateau. Eastern and southern parts are generally lower and flat about 1600m above sea level forming Athi Plains (Kwena, 1999). The rivers originate from Kikuyu highlands and Ngong' hills and flow north-west to south-east direction. These rivers traverse the city passing through areas of different socioeconomic activities and population densities. Nairobi River originates from Kikuyu escarpment. It then flows through Central Business District (CBD), Eastland residential estates to join Athi River. (Kwena, 1999).

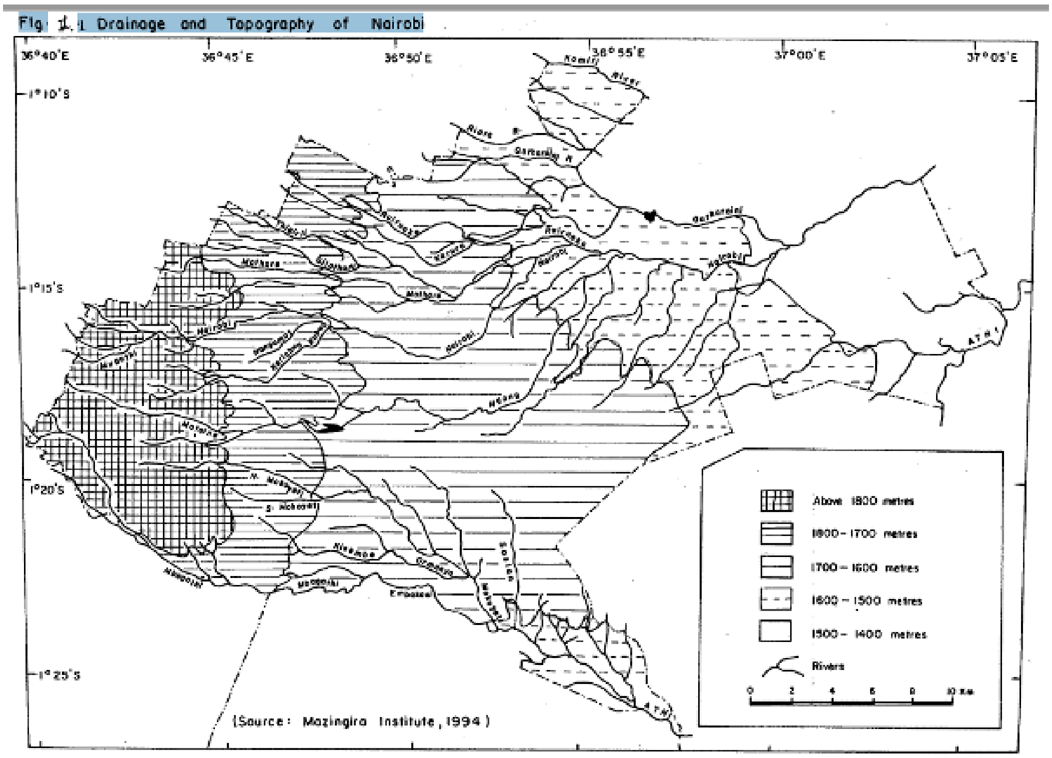



Figure 2: Height Elevations of Nairobi City by Mazingira Institute,1994

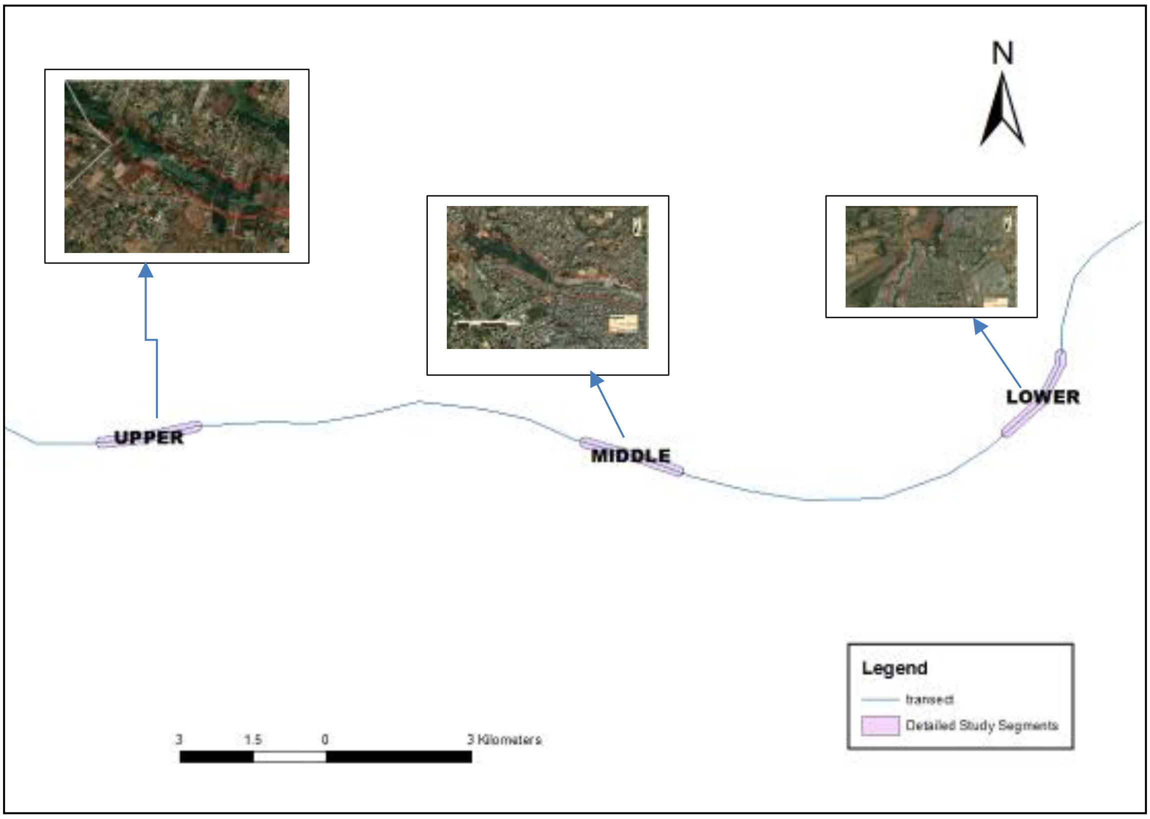



Figure 3: Study Segments

## 3. Methods

Hydraulic modeling of the three segments of Nairobi River was conducted using the Hydrological Engineering Centre-River Analysis System (HEC-RAS) version 6.3 software. The data inputs were collected from the river gauge stations 3BA32, 3BA40, 3BA29 and Rainfall stations within that catchment for a period of 30 years. Digital Terrain Models (DTM) were sourced from Ramani Geosystems with a resolution of 5m.

Determination of the highest water mark was conducted using the Hydrological Engineering Centre, River Analysis System (HEC-RAS). The input data sets were derived from DTM, rainfall data from the gauge stations and the river discharge data from the river gauge stations.

With the such data, high peaks of water levels were established using flood undulation mapping process under the HEC-RAS 6.3 model for the three different segments of the river. Riparian set back distances of 2m, 6m and 30m were set out using spatial analysis tool in QGIS version 3.32 and land uses were depicted by overlaying the riparian buffers with high resolution orthoimagery.

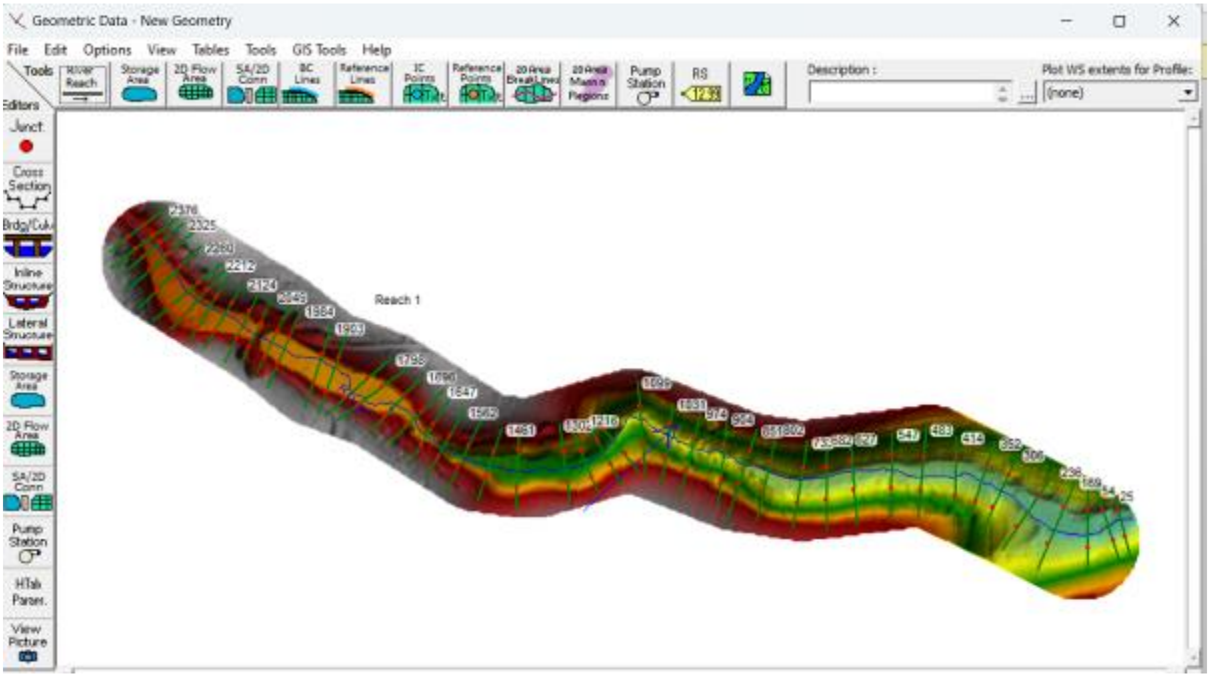



**Figure 4: Upper segment profile**

The cross sections were developed at averagely 5m intervals, bank lines specified and parameters input into the model so that undulation maps are developed.

### 3.2.1 Highest Water Mark in the Upper Segment

From the 2km stretch of the upper river segment, the highest water mark was modeled as in figure 6. It depicts wider spread where the river valley is U-shaped and less spread where it is V-shaped as indicated in the vertical profile. The highest water mark is also not uniform based on the interpolation of the parameters of the river geometry, discharge and the morphology.

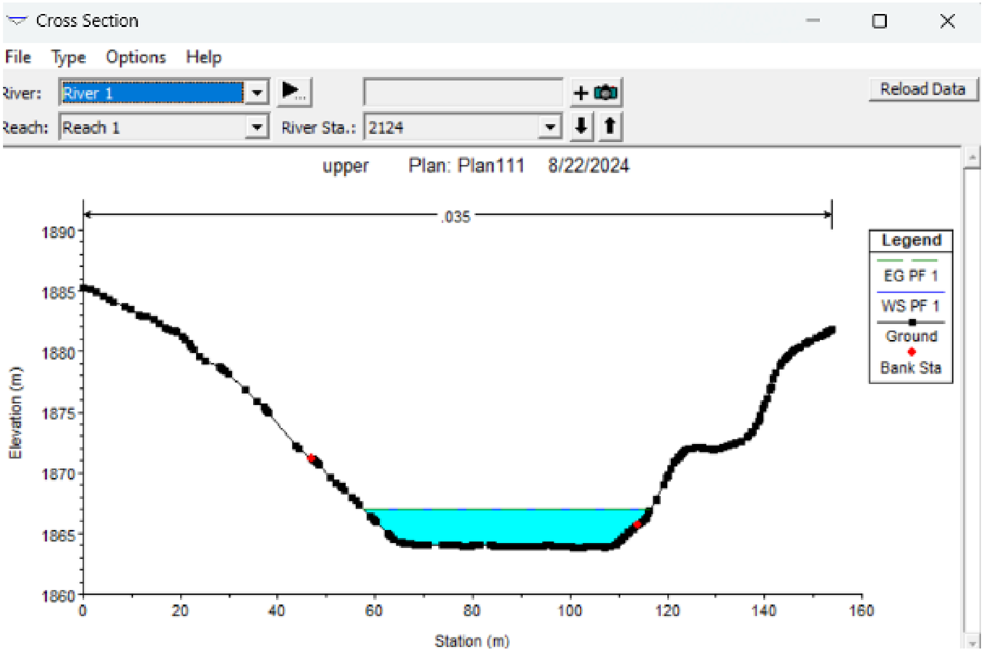



Figure 5: River Sample Cross-Section

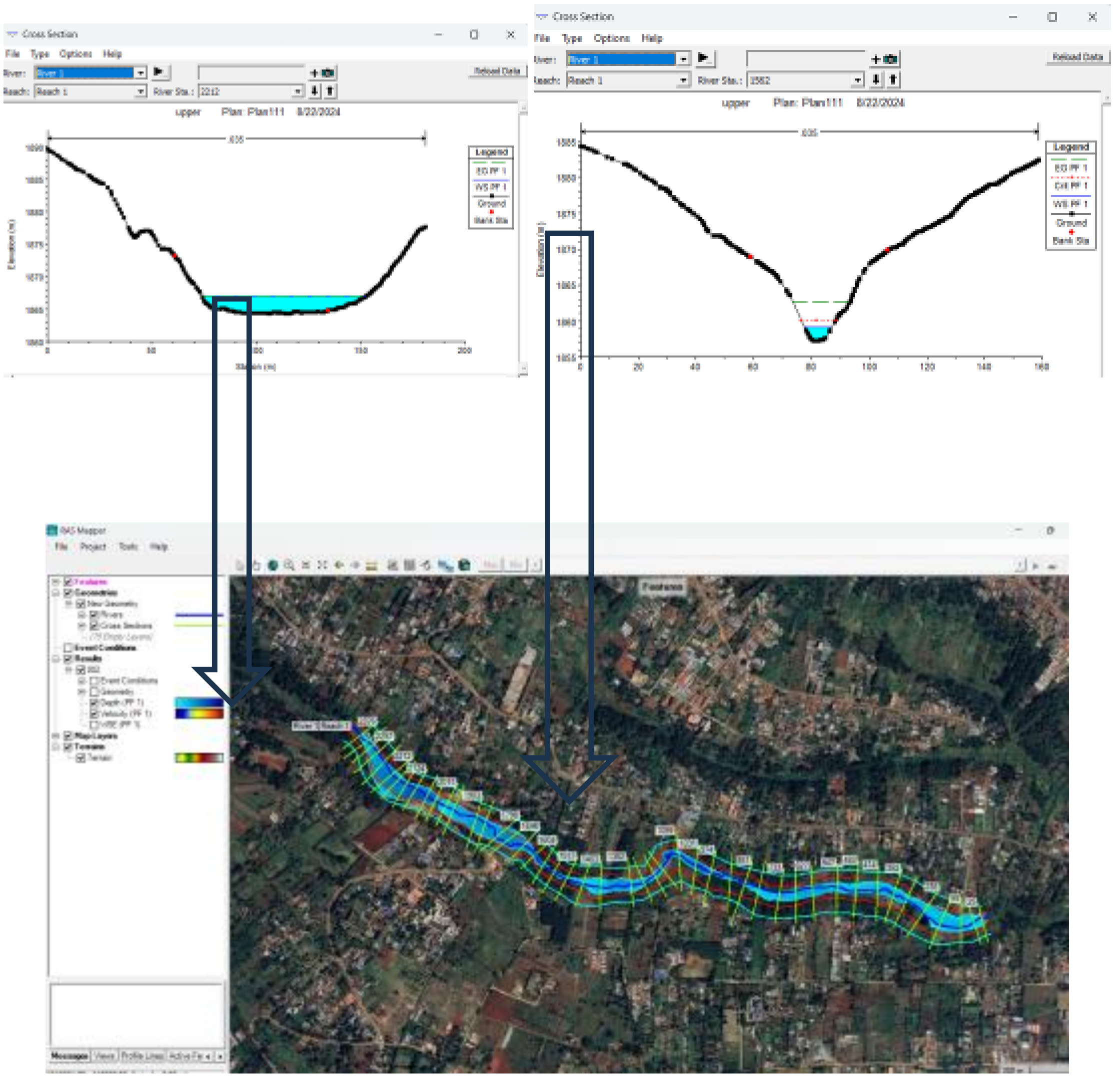



Figure 6: Highest water mark in the upper river segment

### 3.2.2 Highest water mark at the Middle segment

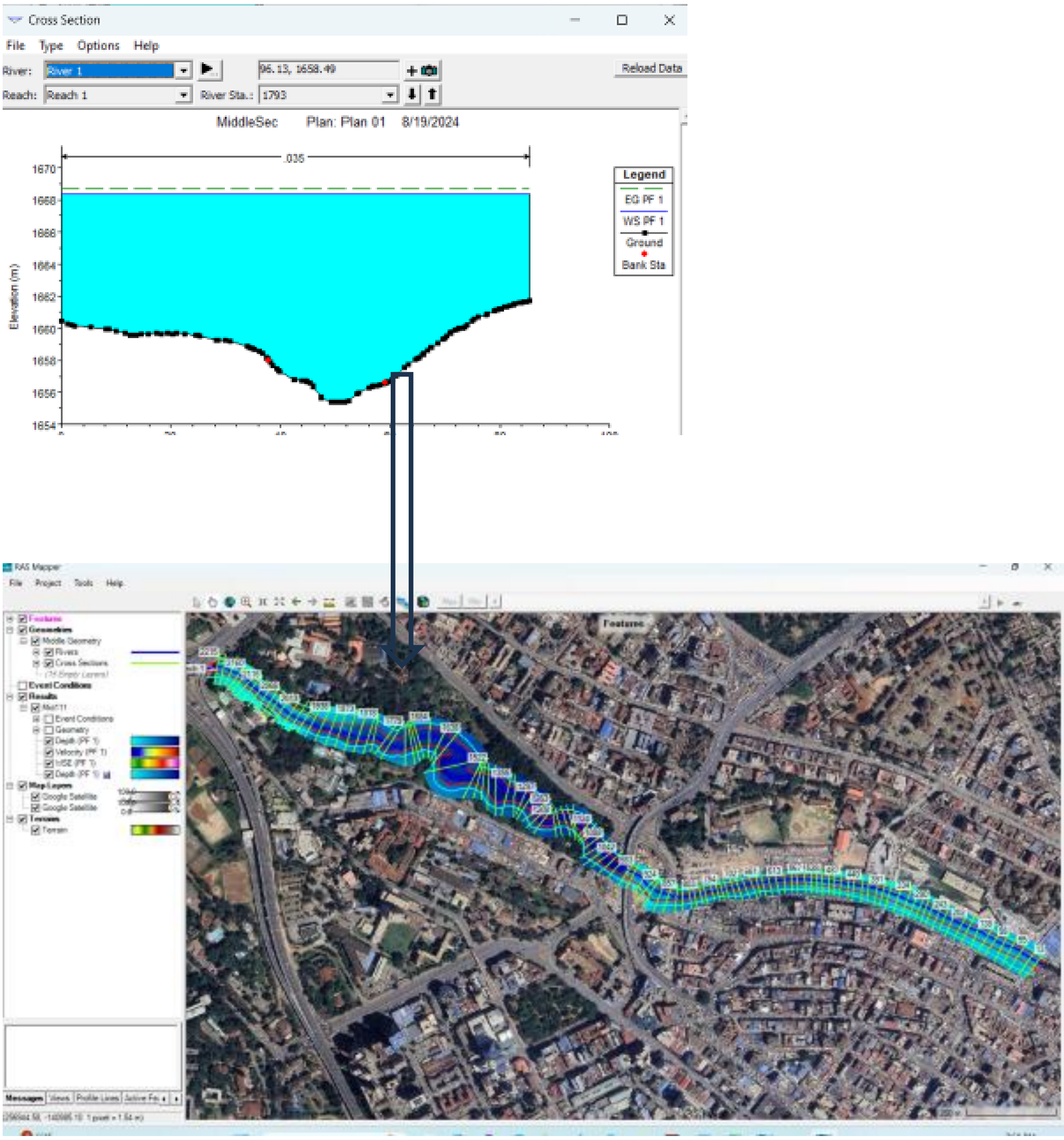



**Figure 7: Highest water mark in the middle section**

At the middle section on a stretch of 2km, the water flows over the bank as depicted hence makes the middle section more of a flood plain. This means the highest water mark within this section is relatively constant with minor fluctuations.

### 3.2.3 Highest water mark at the Lower Segment

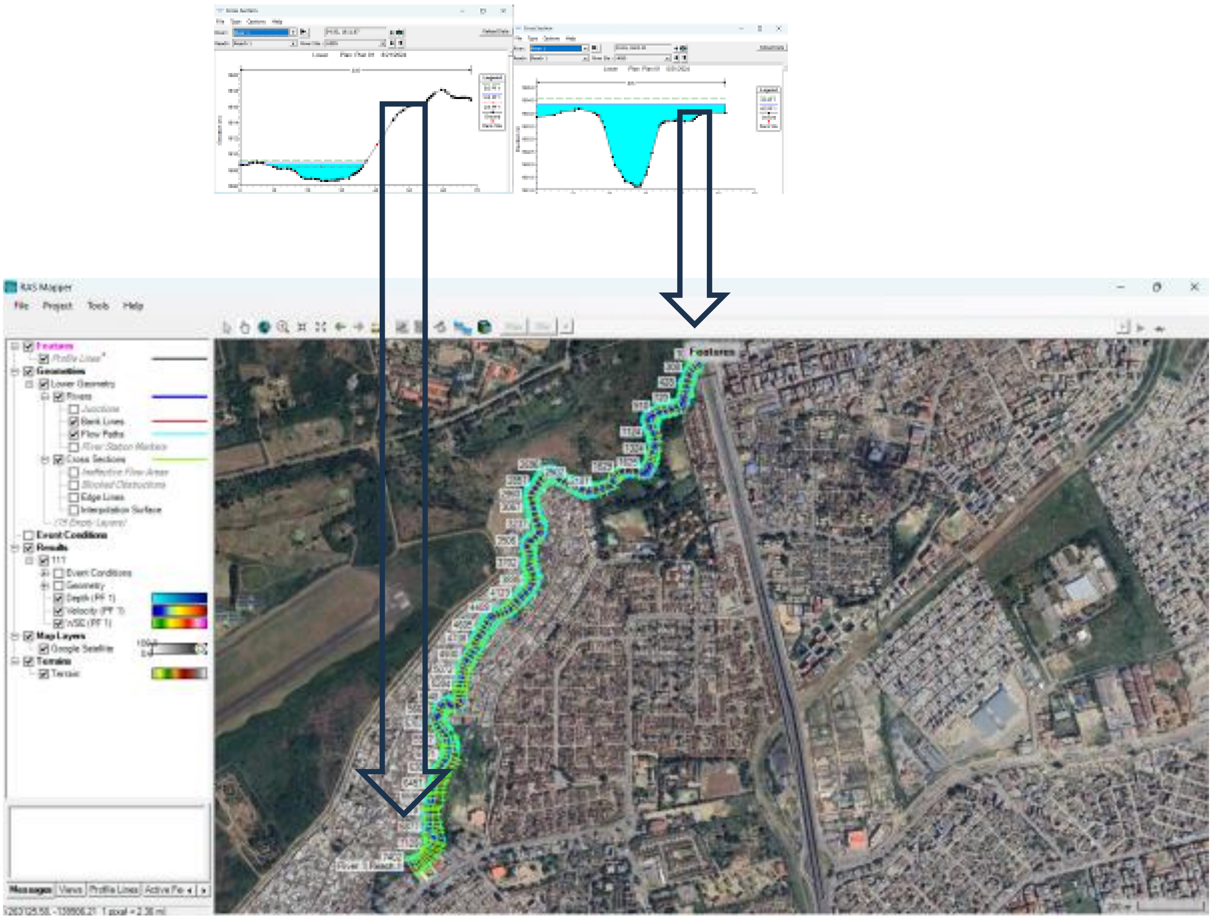


**Figure 8: Highest water mark in the Lower segment**

At the lower segment, the left bank of the river, the water spreads out while on the right bank side, there is less spread while on the extreme lower side, the water spreads on both sides of the bank as shown in figure 8.

## 4. Results and Discussion of Results

### Highest water mark and riparian widths

The 2D HEC-RAS model generated the Highest Water Mark (HWM) for each of the segments of the river morphology upon which different set bank distances of 2m, 6m and 30m from the Agriculture Act, Water Act and Environmental Management and Coordination Act respectively. The model was validated during the heavy rainfall period of April/May 2024 and found to be in compliant with the flood levels hence it formed a reliable and scientific reference surface for the delineation of the riparian reserve.

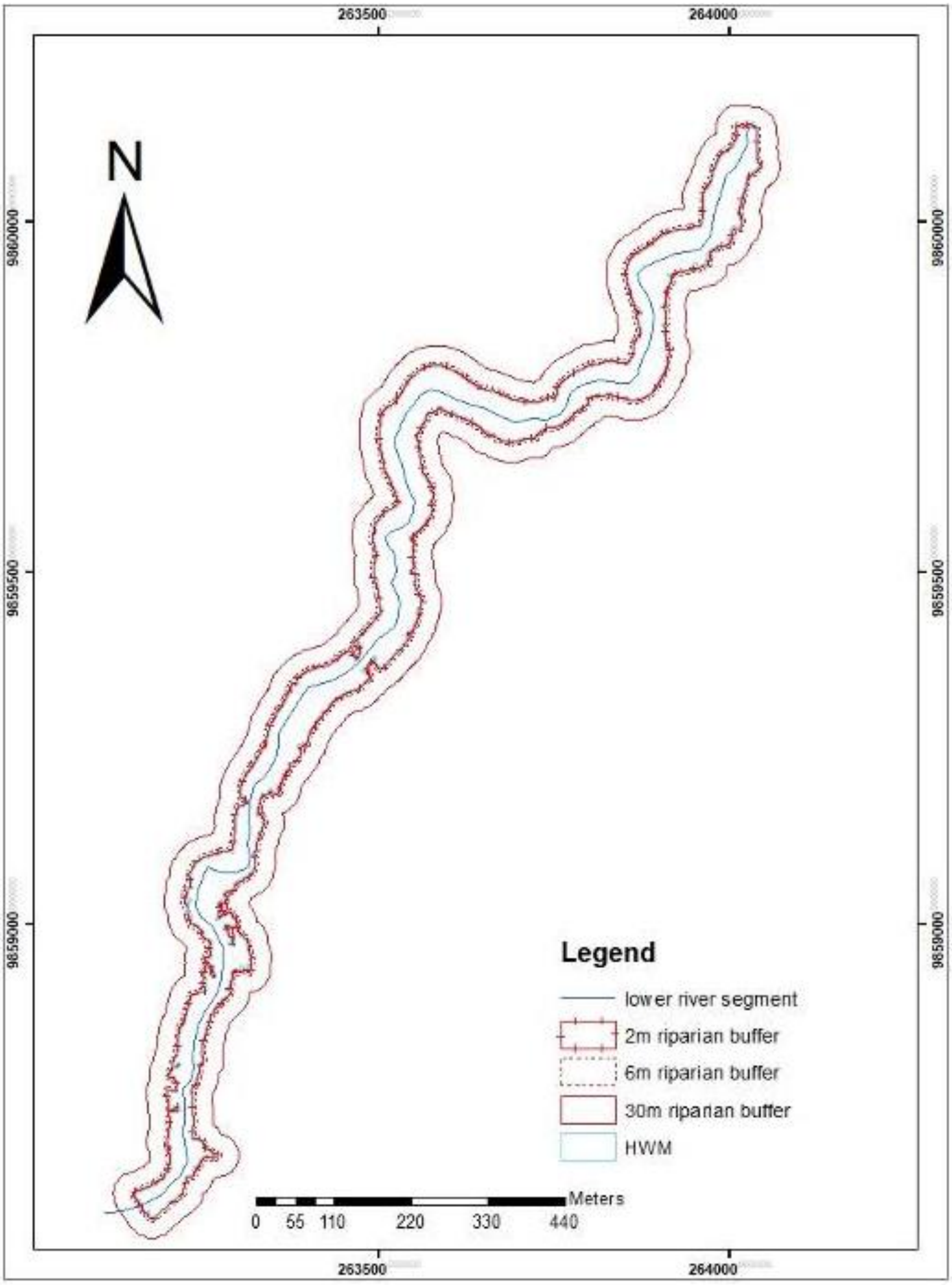



**Figure 9: Riparian delineation at the lower segment**

At the lower section of the river as depicted in figure 9, the highest water mark was found to be evenly spaced at approximately 30m from the centre-line of the river which was confirmed by carrying field measurements as in the figure 10. It was interesting to find that most of developments especially informal structures commenced from this point yet it was the zero mark for the start of the riparian reserve. Therefore, encroachments immediately were found irrespective of the set distances of 2m, 6m or 30m with the only difference on the intensity as the distances increases.


Figure 10: 30m riparian reserve

Most of the encroachments were found to be residential informal structures as shown in figure 11 except at the far end in the North West direction where formal estate was found to have encroached at Buruburu next to Outering road. This formal encroachment was only found for 30m riparian corridor.

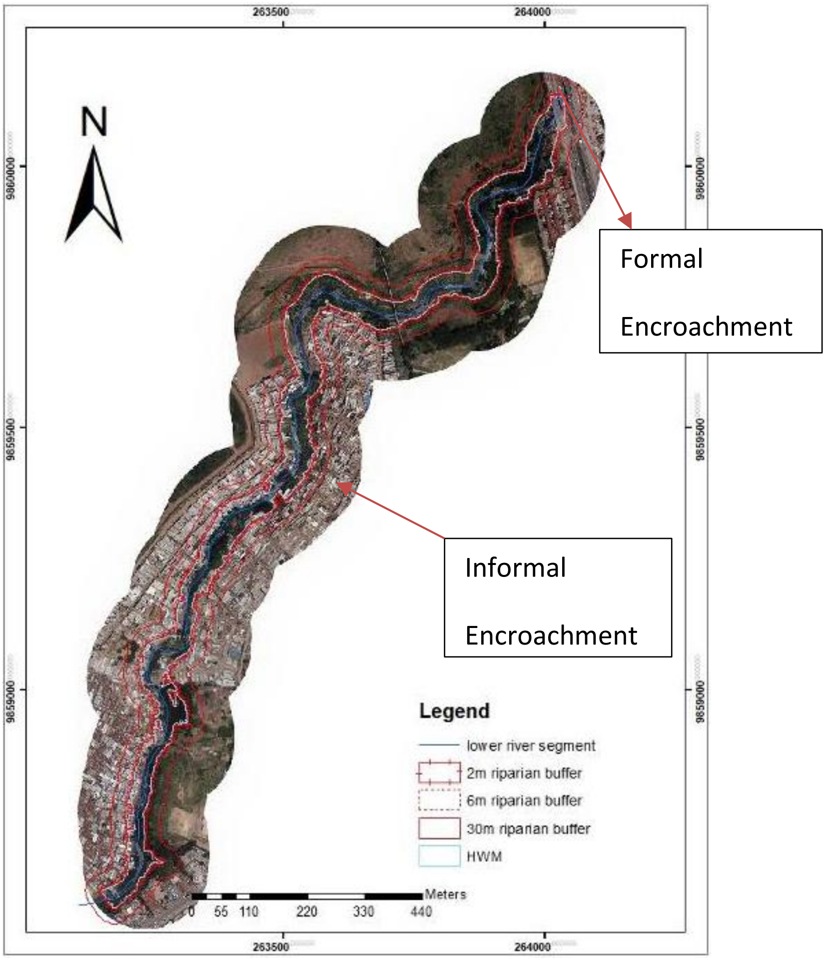
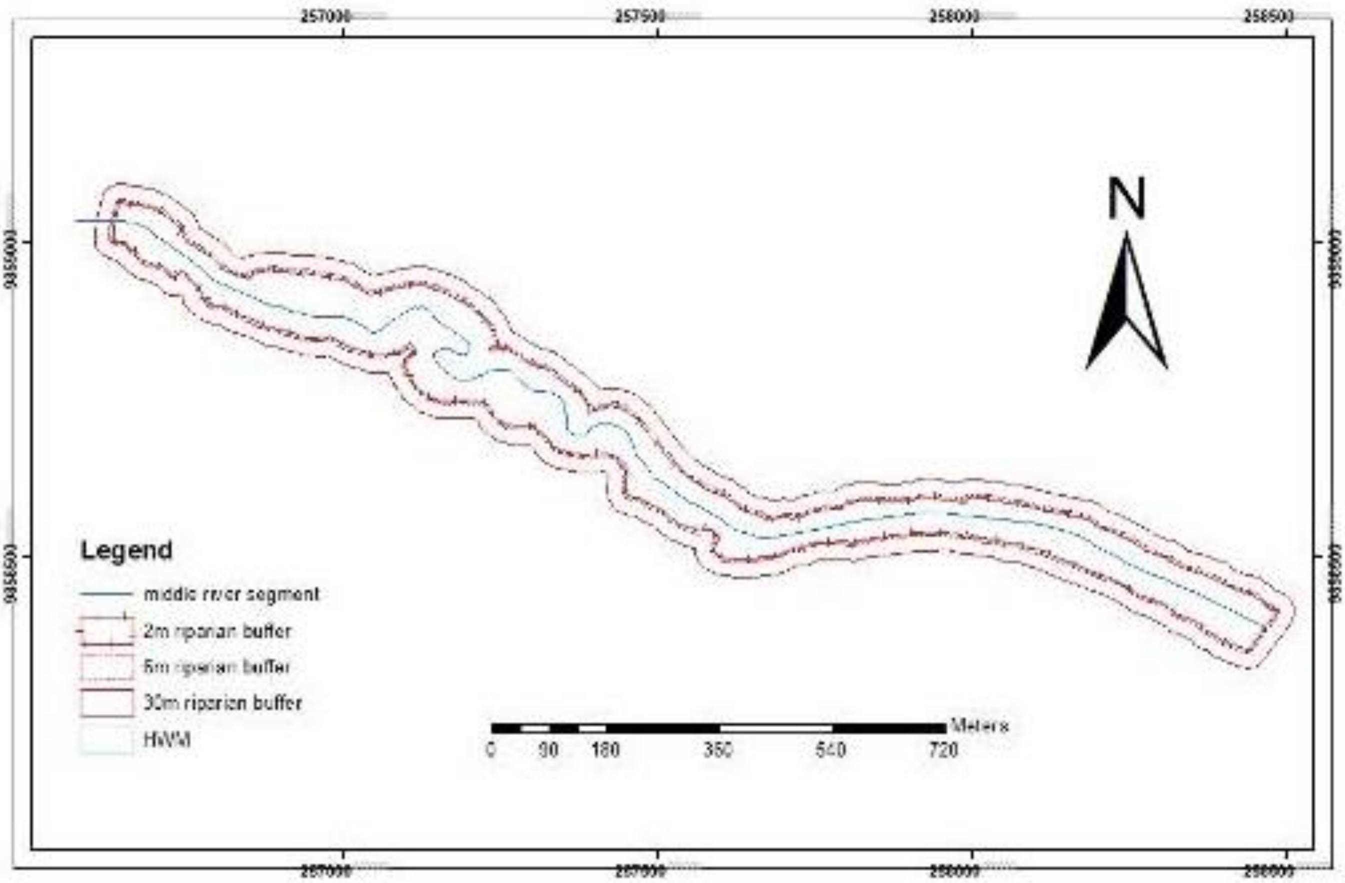



Figure 11: Encroachment at the lower segment of the riparian reserve

At the middle segment, the HWM was found to be larger at the Michuki Park, approximately 50-60m from the centre-line of the river while at the channeled section in Ngara, it reduced to 20m from the centre-line all the way to Grogon area. Therefore at Michuki park wider riparian reserves as the land is slightly flat hence a possible flood plain while the Ngara and Grogon areas are gently undulating resulting to smaller riparian reserves

Figure 12: Riparian delineation at the middle segment



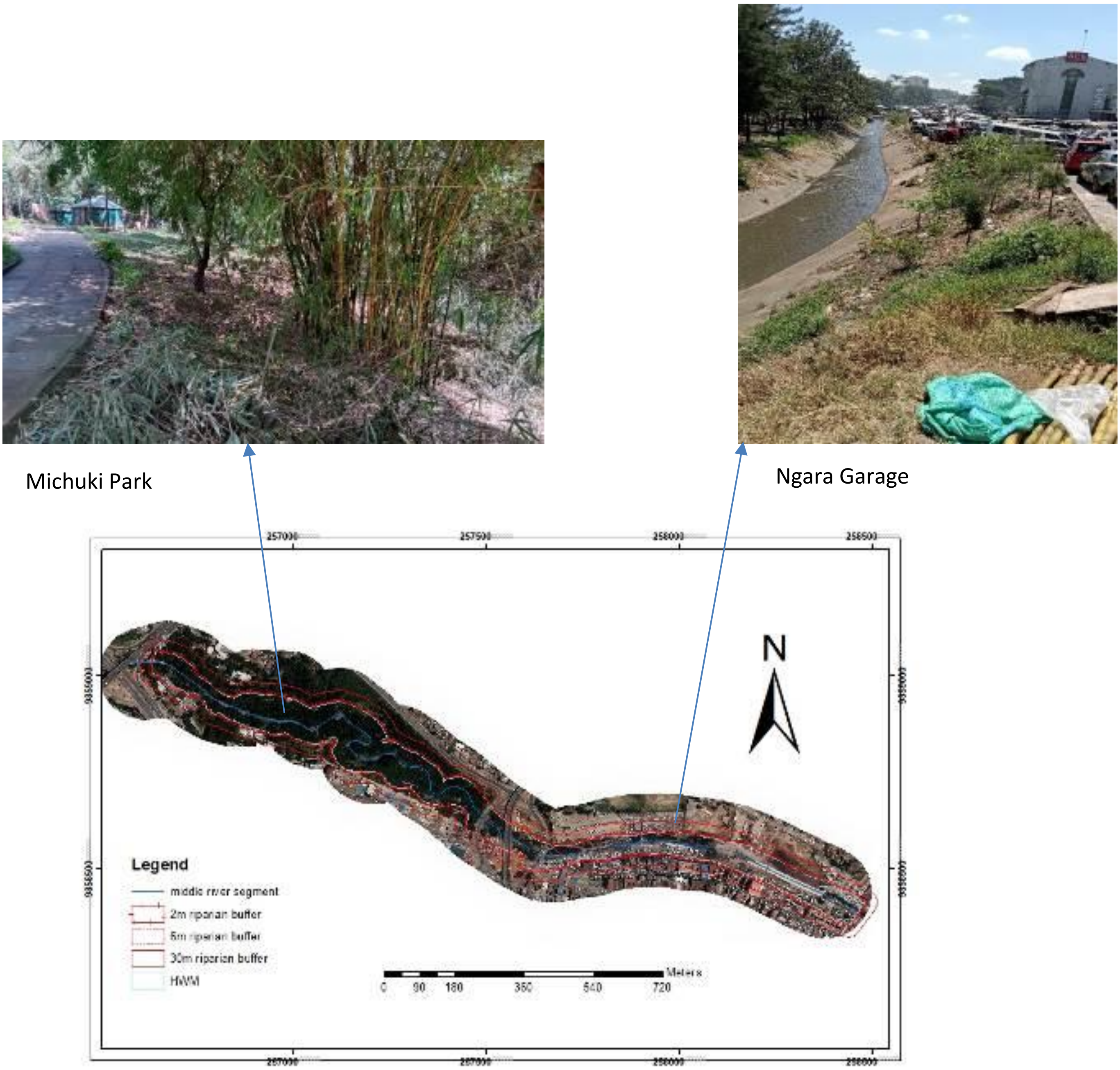



**Figure 13: Encroachment at the middle segment of the riparian reserve**

At the upper section, the HWM is generally stable at approximately 40m from the centre-line and was maintained almost throughout the section. The area has well defined steep slopes which could have restricted the water flow. This was validated through GPS measurements as depicted in figure 14.

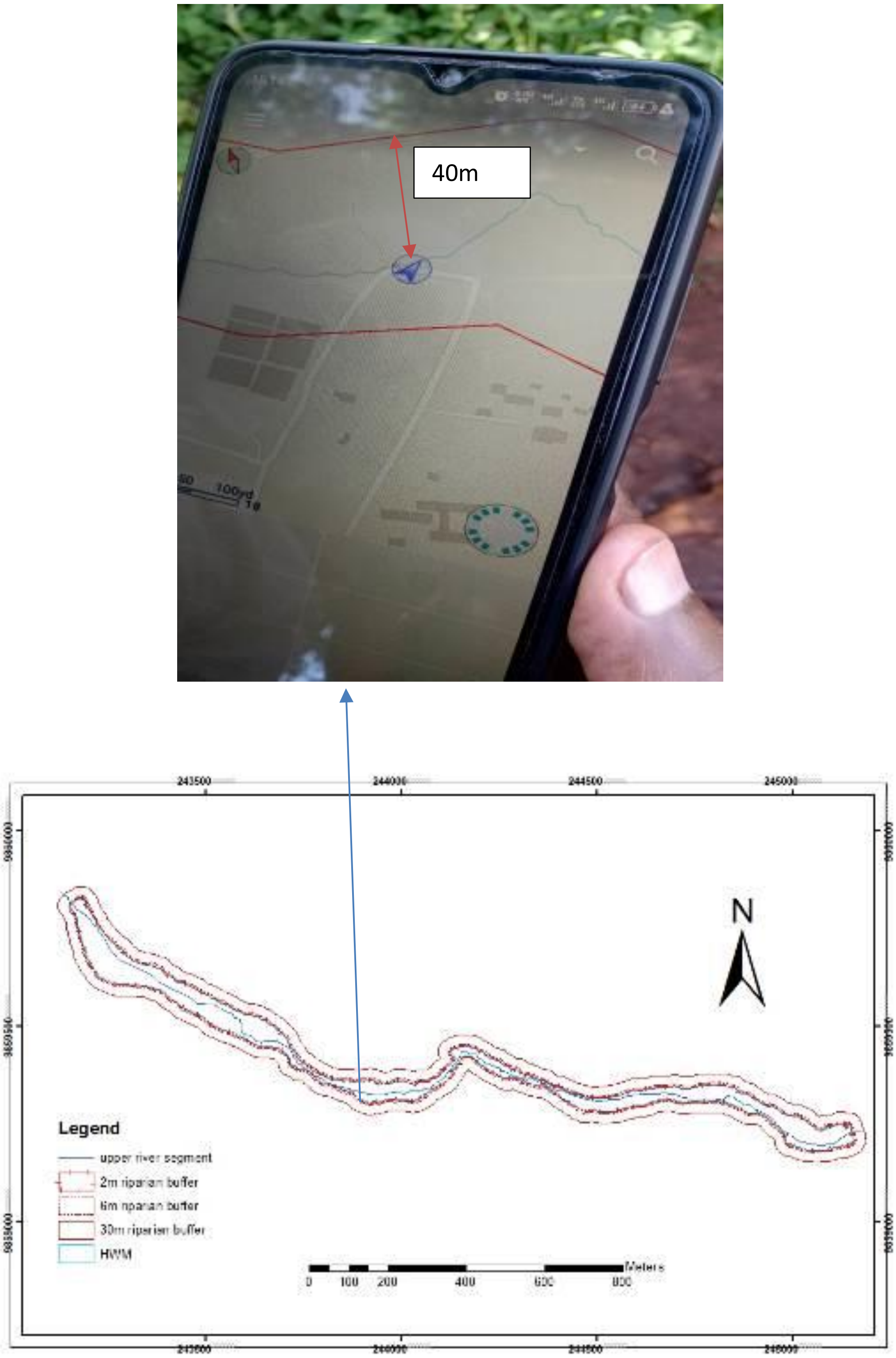



**Figure 14: riparian delineation of the upper segment**

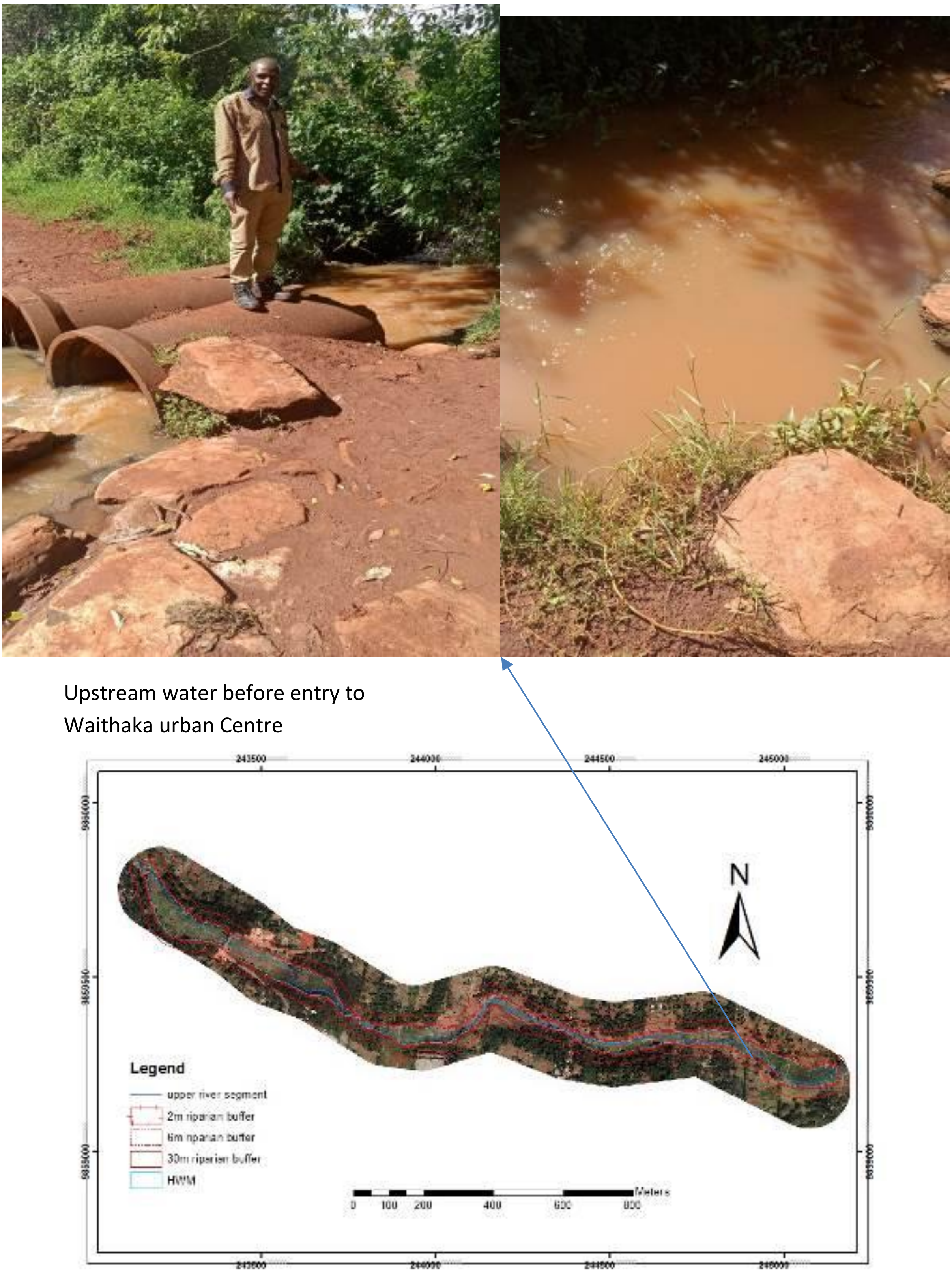



**Figure 15: Encroachment at the upper segment of the riparian reserve**

The land uses at the upper section were predominantly farm lands coupled with some forestation done at household levels. This could be the reason why the water appeared less polluted as shown in figure 15. Encroachment under this section were more of agricultural farms.

Table 1: Dominant Land uses with the riparian reserves

| *River Segment* | *Categories* | *Land Use* | *Examples* |
|---|---|---|---|
| *Lower* | 1 | Informal Residential structures | Kiambiu slums |
| | 2 | Formal Structures | BuruBuru estate |
| *Middle* | 3 | Garages and Commercial Structures | Grogon and Ngara Garages and car wash |
| | 4 | Recreational Park | Michuki Park |
| *Upper* | 5 | Agricultural farms | Urban agriculture |

In all the three segments, 2m riparian reserve is not encroached per say but consist of a lot of dumping especially at the Lower and Middle segments, at 6m riparian reserve encroachments starts and more dumping and some urban agricultural activities while 30m riparian was found to be heavily encroached by almost all the land uses in table 1 above.

## 5. Conclusions

Where as various laws in Kenya provide different set back distances for riparian reserve for rivers, the reference surface has generally been agreed as the Highest Water Mark(*Final Riparian Reserve Report 2011-Final*, n.d.) however this reference surface have not been scientifically been determined hence HEC-RAS provided an excellent framework for establishing this surface for Nairobi river(Wara et al., 2019). It emerged that indeed, its not a static measurement and with climatic data, river discharge and DTM, it has been established and validated in this research and used to delineate riparian reserves at 2m, 6m and 30m as per the riparian law specification of set back distances in Agriculture Act of 1965, Water Act 0f 2006 and EMCA Act of 2009 respectively(Commission, 2017). It can be therefore established that haphazard measurements of riparian reserves as observed by the Water Resources Authority during eviction of people encroaching on riparian reserves has been due to lack of a scientific method of determining the reference surface resulting to inadequate assessment of the level of encroachments on such reserves (NETWAS -Nairobi KE & Sanitation, 2005).

With such reference surface in place, riparian set back distances of 2m, 6m and 30m were measured and their level of encroachment established though overlaying with high resolution satellite imagery. Different land uses such as residential structures were predominantly found in the Lower segment, commercial structures found at the middle segment and agricultural practices found on the upper segment.

## 6. Acknowledgement

This paper is an extract from the PhD work by Malachi Odongo that was supervised by Prof. Caleb Mireri and Dr Patricia Mwangi of Kenyatta University. As such, the intellectual input was jointly constructed but largely written by Malachi Odongo. Drafts were jointly reviewed until a final version was agreed upon for submission.

## 7. Funding

The German Academic Exchange Services (DAAD) financed this research.

## 8. Authors' contributions

Malachi Odongo (Conceptualization, Formal analysis, Funding, Methodology, Writing—manuscript), Caleb Mireri (Supervision, Writing—review & editing), and Patricia Mwangi(Supervision, Writing—review & editing).

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## 10. Key terms and definitions

HWM: The highest recorded water level for a flood return period of 30 years

Riparian Reserve: Set back distances that are usually measured from either side of the river bank from the highest water mark

Modeling: Simulation of water levels based on input parameters such as slope, land use land cover, river discharge and digital terrain model (DTM).

River Geometry: Properties of the river channel such as channel width, river banks and water channels.

River Discharge: The volume of water flowing through the river at a specific time.

Mannings co-efficient: It's a ratio representing the ground roughness value that offers resistance to the river flow.