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River Flood Modelling with Mike 11: Case of Nzoia River (Budalangi) in Kenya

Lawrence Omai Muku[1*] Gilbert Nyandwaro[1,2]

1. School of Engineering, Department of Civil and Structural Engineering, Moi University
P.O Box 3900-30100, Eldoret, Kenya.
2. Laboratory of Hydraulics, Faculty of Engineering, Katholieke Universiteit Leuven,
Kasteelpark Arenberg 40, Leuven, Belgium.
*Email of the corresponding author: lawrenceomai@gmail.com

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Abstract

This paper presents a one-dimensional unsteady flow hydraulic model used for the simulation of flow in rivers: the MIKE 11 model from the Danish Hydraulic Institute (DHI). The approach used for this model leads to unsteady flow simulations along river channel reach. The study case applied to the model is the lower Nzoia River, about 25 km in length. The study's focus was the development of a MIKE 11 river model based on surveyed river cross-section data. The flooding problem in the lower Nzoia (Budalangi floodplains) in Kenya has been perennial each time causing a reversal of gains on economic and social development. The main objective of this study is to implement a one dimensional hydrodynamic model for the lower part of Nzoia river using the MIKE 11 modelling software. This was done with an aim of investigating the nature of the 2008 Budalangi floods. Two scenarios were considered, namely; reference case (intact dyke) and the breached dyke case. Longitudinal river stretch profiles were produced for the two cases and it was conclusive that the 2008 flooding was mainly necessitated by dyke breach. Further, the optimal computational spatial step (Δx) and time step (Δt) for the model were found to be 500m and 1 minute respectively. For this condition no instability of the model simulation was observed.

Key words: Nzoia River**,** MIKE 11 hydrodynamic model, Budalangi, floodplains, river hydraulics, unsteady flow

1. Introduction

The study area chosen in this research is lower Nzoia river basin, specifically in Budalangi floodplains in Kenya. The basin is a typical of a flood disaster prone basin experiencing increasing flood related disaster.

According to Federal Emergency Management Agency (FEMA), flooding is the most common natural disasters; it causes more in damages in terms of loss of life, property and economic activity than any other natural disaster (2008).

This study restricts itself to the simulation of hydraulic conditions (water level and discharge) along the lower reach of Nzoia River using the one dimensional (1D) hydrodynamic river software, MIKE 11. MIKE 11 computes one-dimensional unsteady flow by solving the Saint-Venant equations for shallow water waves in open channels using a finite-difference scheme. It requires the setup of a network file using topographical map, a cross-section file (river geometry), stream bed resistance (Manning coefficient) and boundary conditions (discharge or water level or downstream rating curve). After setting up of the model, the simulation has to be carried out for a selected time period specifying the optimal time step and improving the stability of the model. Then results can be visualized as time series of discharges and water levels at specific calculation nodes along the river branch, and as longitudinal profiles of water levels along each branch of the river network.

1.1 Objectives of the Study

The overall objective of this study is to implement a one dimensional hydrodynamic model for the lower part of Nzoia river (Budalangi), using the MIKE 11 modelling software.

1.1.1 Specific objectives

a) Implement the following elements in the 1D hydrodynamic MIKE 11 river model and ensure its stability:

(i) The river network

(ii) The cross-sections along the river course
(iii) The boundary conditions imposed to the model
(iv) The hydrodynamic parameters of the model

b) To investigate the nature of the 2008 Budalangi flood by use of the developed MIKE 11 model.

1.2 Study Area

The study area is the Budalangi floodplains located in the Bunyala District of Busia County in Kenya. The floodplain is situated at the lower reaches of Nzoia River just before it enters into Lake Victoria. The flood zone extends about 25 kilometers from the lake and covers approximately an area of 128,000 hectares (NWCPC 2008). Figure 1 shows the study area with locations of upstream and downstream boundary conditions depicted.

The Budalangi Floodplain area extends between longitudes 33º56'30" to 34º10'30"E and latitudes 0º30"S to 0º11'30"N. According to Food and Agriculture Organization (FAO) soils bulletin, the floodplain lies in between agro-ecological zones LM3 and LM4 which can be described as Livestock-Millet zone (1996). The mean annual rainfall varies from a minimum of about 1070 mm to a maximum of 2200 mm (Githui F et al (2007).

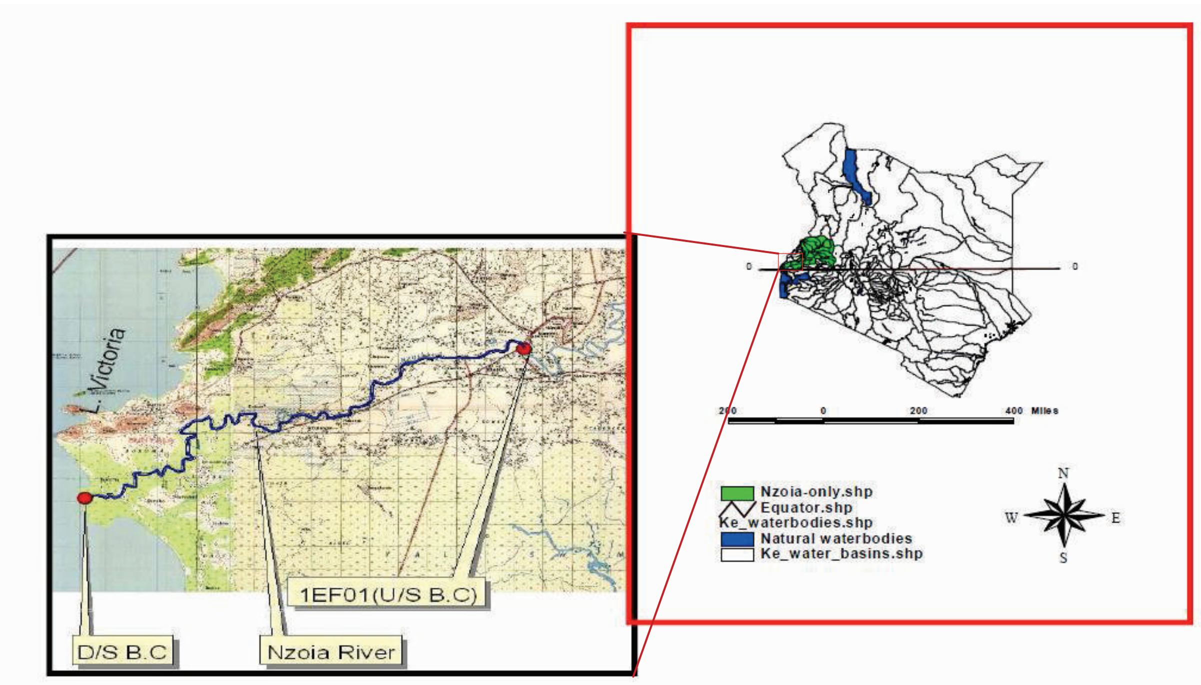

Figure 1. Study Area

The major physical features within the study area and its neighbourhood are the undulating plain landscape, which is interrupted in a few places by low hills for instance the Masoso hill. Most of the terrain has gentle slopes. The land generally slopes southwestwards as is depicted by the general direction of the Nzoia River. The river meanders greatly between river gauging station, 1EF01 and the lake forming a meandering plan. This creates an extensive floodplain characterized by wetlands (NWCPC 2008).

The prevailing soil types are vertisols (the black cotton). The moisture content when wet is as high as 40% on volume basis. The vertisols crack when dry and have low infiltration and hydraulic conductivity rate when wet. This contributes significantly to the problem in that stagnating water from the floods takes long to disappear. River bank erosion is the most significant form of soil erosion within the floodplain. The vertisols are highly susceptible to all form of erosion even on slopes of less than 5%. These develop deep gullies in a very short period (NWCPC 2008).

2. Model Description and Concepts

The MIKE 11 is an implicit finite difference model for one dimensional unsteady flow computation and can be applied to looped networks and quasi-two dimensional flow simulation on floodplains. The model has been designed to perform detailed modelling of rivers, including special treatment of floodplains, road overtopping, culverts, gate openings and weirs.

MIKE 11 is capable of using kinematic, diffusive or fully dynamic, vertically integrated mass and momentum equations (the "Saint Venant" equations). The solution of the continuity and momentum equations is based on an implicit finite difference scheme. This scheme is structured so as to be independent of the wave description specified (i.e. Kinematic, Diffusive or dynamic). Boundary types include water level (h), Discharge (Q), Q/h relation, wind field, dambreak, and resistance factor. The water level boundary must be applied to either the upstream or downstream boundary condition in the model. The discharge boundary can be applied to either the upstream or downstream boundary condition, and can also be applied to the side tributary flow (lateral inflow). The lateral inflow is used to depict runoff. The Q/h relation boundary can only be applied to the downstream boundary. MIKE 11 is a modelling package for the simulation of surface runoff, flow, sediment transport, and water quality in rivers, channels, estuaries, and floodplains. The most commonly applied hydrodynamic (HD) model is a flood management tool simulating the unsteady flows in branched and looped river networks and quasi two-dimensional flows in floodplains. When using a fully dynamic wave description, MIKE 11 HD solves the equations of conservation of continuity and momentum (the 'Saint Venant' equations). The solutions to the equations are based on the following assumptions (DHI 2008a).

(i) The water is incompressible and homogeneous (i.e. negligible variation in density)
(ii) The bottom slope is small, thus the cosine of the angle it makes with the horizontal may be taken as 1.0.
(iii) The wave lengths are large compared to the water depth, assuming that the flow everywhere can be assumed to flow parallel to the bottom (i.e. vertical accelerations can be ignored, and a hydrostatic pressure variation in the vertical direction can be assumed)
(iv) The flow is sub-critical (a super-critical flow is modelled in MIKE 11; however, more restrictive conditions are applied)

2.1 Governing equations

MIKE 11 is based on the 1D Saint-Venant equations:

- Continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad [1]$$

- Momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \qquad [2]$$

Where:

Q – discharge, (m^3/s)

A – flow area, (m^2)

q – lateral inflow, (m^2/s)

h – stage above datum, (m)

C – Chezy resistance coefficient, ($m^{1/2}/s$)

R – hydraulic or resistance radius, (m)

α – momentum distribution coefficient

The four terms in the momentum equation are local acceleration, convective acceleration, pressure, and friction. In MIKE 11, a network configuration depicts the rivers and floodplains as a system of interconnected branches. Water levels and discharges (h and Q) are calculated at alternating points along the river branches as a function of time (Figure 2). It operates on basic information from the river and floodplain topography to include man-made features and boundary conditions.

The Discretization of the MIKE 11 equations is based on an implicit, finite difference 6-point Abbott numerical scheme (DHI 2008b).

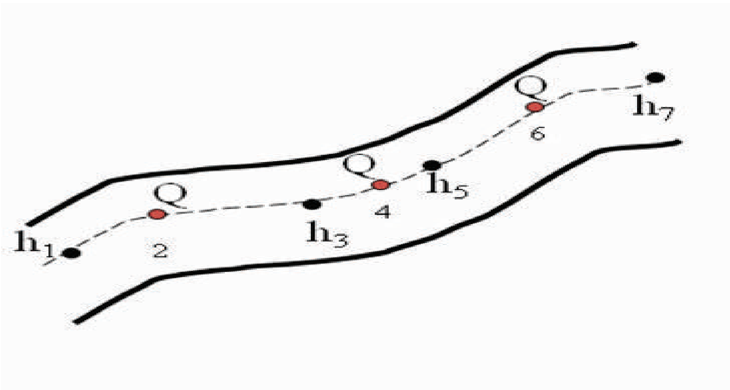

Figure 2. Channel section with computational grid

2.2 Solution Scheme in MIKE 11

The solution of the equations of continuity and momentum is based on an implicit finite difference scheme developed by Abbott and Ionescu (1967). The finite difference scheme used in MIKE11 (6-point Abbott scheme), allows Courant numbers up to 10-20 if the flow is clearly sub-critical (Froude number less than 1). A graphical view of this method showed as below [Figure 3]:

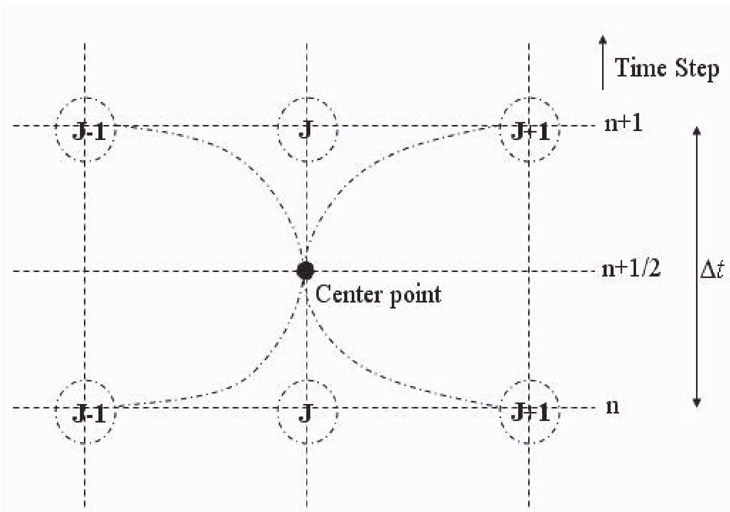

Figure 3. Centered 6-point Abbott Scheme

As we can see at n+1/2 step the model bring data from steps n and n+1, so unknowns will obtain simultaneously for each time step. MIKE11 model is fully implicit method to solve the problems and usually there is no limitation about computational steps.

3. Methodology for Model Set up

MIKE 11 includes multiple editors each operating on different types of data. Where Data from these editors must be saved in separate editors, the integration and exchange of information between each of the individual data editors is achieved by use of the MIKE 11 Simulation editor. The Simulation Editor contains simulation and computation control parameters and is used to start the simulation as it provides a linkage between the graphical view of the network editor and the other MIKE 11 editors.

The following steps were followed in order to setup the one-dimensional, MIKE 11 model for the river network of the Lower Nzoia River.

3.1 Defining the River Network

The MIKE 11 model's River Network file is the common link to the various MIKE 11 files. It also has an XY coordinate system, allowing the model to import and export data to and from other software. The River Network file allows the modeller to 1) define the river network and reference cross-sections and control structures to the network; and 2) graphically obtains an overview of model information in the current simulation. Figure 3 shows the river network file that was digitized and defined graphically in MIKE 11 network platform.

The network file was saved as Nzoia River and thus the stretch is referred here as by the same name.

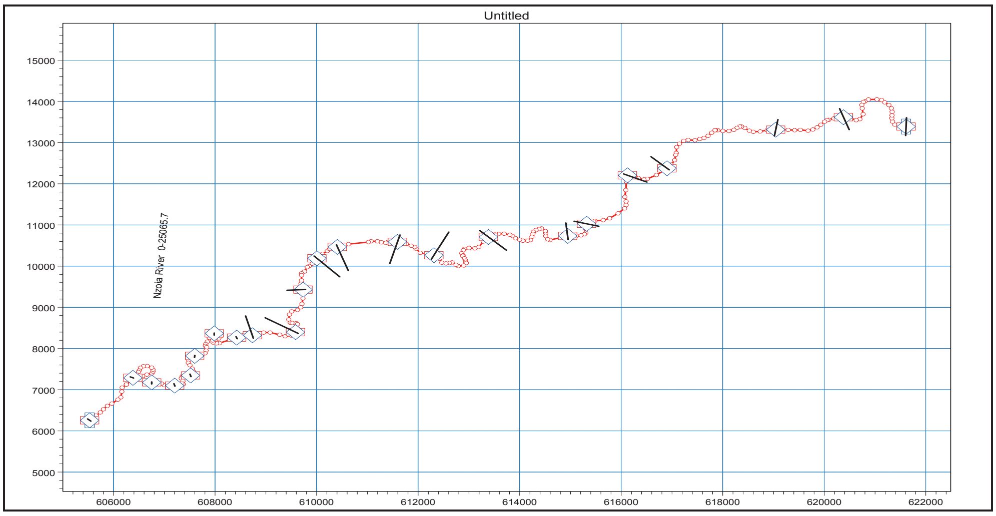

Figure 3. River network defined by XY coordinate data point*s*

3.2 Inserting River Cross-sections

The geometry of cross-sections was obtained from field-surveyed data. The raw data was entered into a MIKE 11 cross-section file and the graphical display of the cross-section could be visualized. See Figure 4.

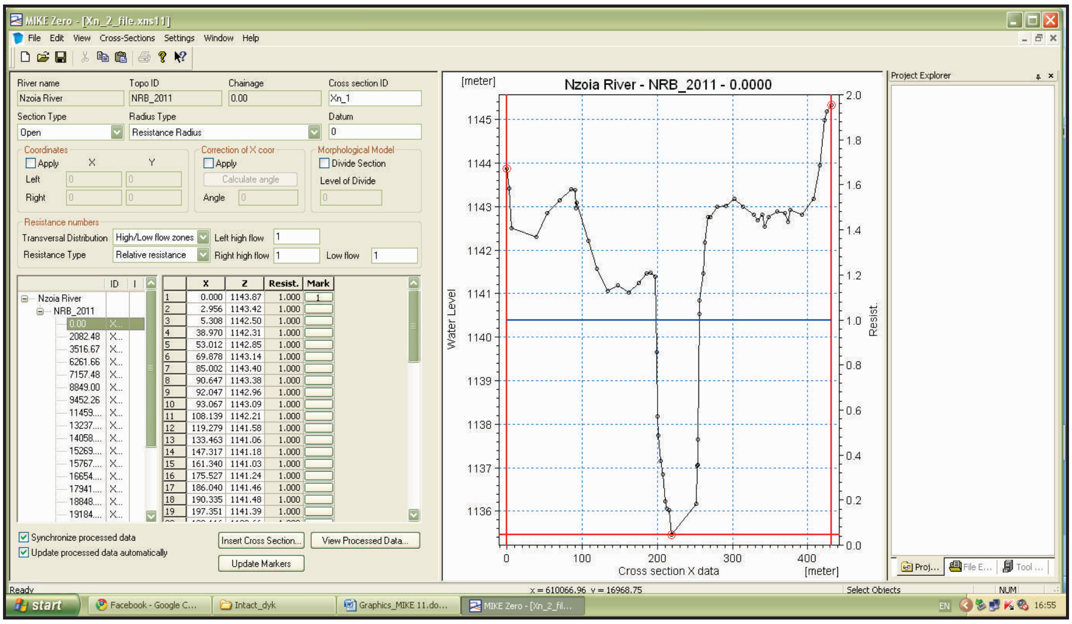

Figure 4. Raw data view of the cross sections in MIKE 11

3.3 Boundary Conditions

Two boundary conditions were defined for the river reach in question. For the upstream boundary conditions, it consisted time-series of daily river flows at river gauging station code, 1EF01. This was obtained for a period of 1 year i.e. January – December 2008.

The downstream boundary condition consisted of a time-series of lake levels for the Lake Victoria for the corresponding period as for the river flow.

3.4 Hydrodynamic (HD) Parameters

The final data required to run a simulation is the HD parameters. In this study, the river bed resistance value and the initial conditions of discharge and water level/depth are specified. The global values of discharge of 80 m3/s and water depth of 0 m were specified.

The Manning's (n) resistance formula is adopted and a resistance number (n) of 0.033 was specified as an overall resistance for the whole stretch of the river under study.

3.5 Simulation of the MIKE 11 model

Once all information was inputted into the file editors described above, the Simulation file identifies any errors with the established conditions before running a simulation. After trying several computation time steps higher than 1 minute in conjunction with a fixed spatial step (Δx) of 500 m normally specified in the network file, it was realized the model was unstable and it kept on crushing. Finally, the model became stable at time step (Δt) equal to 1 minute and at Δx equal to 500 m. Thus the model's optimal Δx and Δt were found to be 500 m and 1 minute respectively.

4. Results and Discussions

The results of MIKE 11 simulations were visualized using the MIKE View software. MIKE View displays longitudinal profile animations of both stage height and discharge resulting from a MIKE 11 unsteady simulation. It also can display stage height at any given cross-section, as well as provide rating curves at a specified location along the river network.

MIKE View can also aid the visualization of time-series results of stage heights at cross-section locations and time-series results of discharge at midpoints between two cross-section locations. The water level profiles for the two scenarios as pointed out earlier are given in figures 5 and 6.

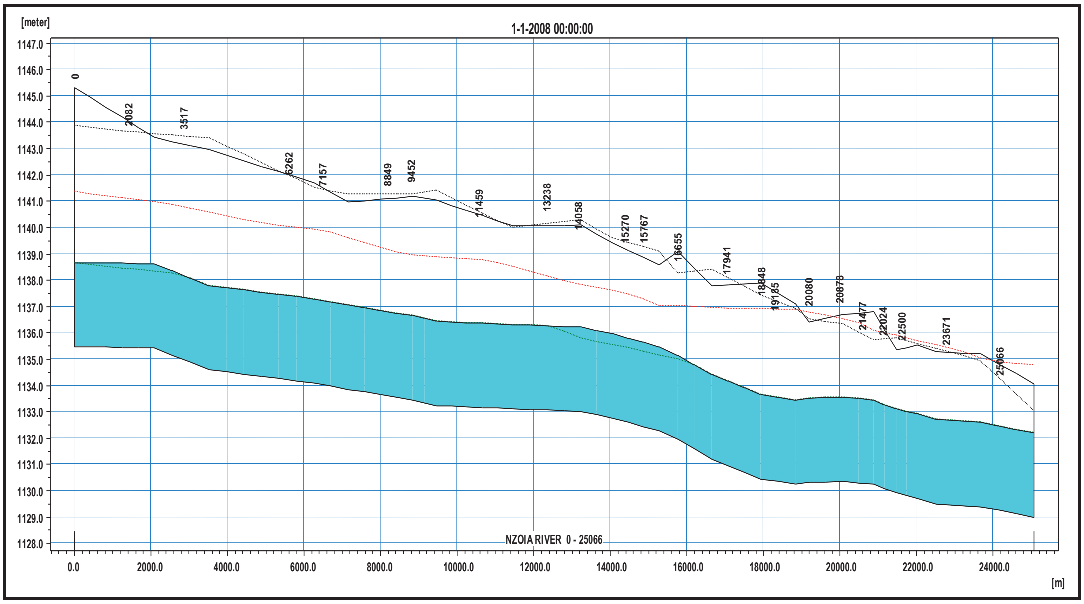

Figure 5. Water level profile for the river network (Scenario I: Intact dyke)

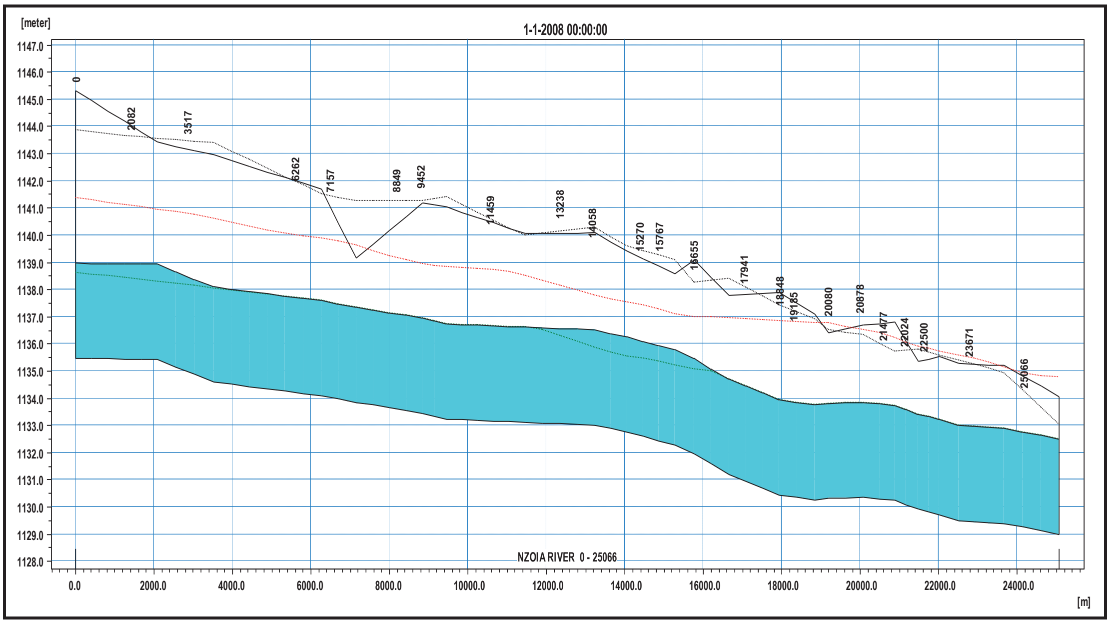

Figure 6. Water level profile for the river network (Scenario II: Breached dyke)

The blue-coloured section represents water in the river channel. The red dotted line denotes the maximum water level simulated during the period. The dark continuous line represents the right river bank, while the dark broken represents the left one.

4.1 Scenario I: Intact dykes (reference situation)

This plot, explicitly communicates that for the year 2008, no flooding event could have been experienced if all the dykes were intact. This is due to the fact that the maximum water simulated (red dotted line) does not rise above the river banks. The flooding experienced at the area near the mouth of Lake Victoria is attributed to backwater effect and the effect of the marshy conditions.

4.2 Scenario II: Breached dyke*s*

The results indicate that the water level at the breached section of the dyke was above the dyke level after the dyke failure at the shown section (figure 6). It is also explicit that the right-hand side (northern) dyke is the one that breached during the flood event. This was the main cause of the 2008 Budalangi flooding event and not overtopping.

According to the Government of Kenya (GOK), Flood Mitigation Strategy document, the total number of people affected during this flood event were 12,123 (2009). This is quite a high number of people to be affected.

5. Conclusions

From the MIKE 11 River hydrodynamic modelling and results, the following conclusions can be enumerated:

a) The 1D hydrodynamic MIKE 11 model has been implemented for the lower part of the Nzoia river, the last 25,067m. The network file, cross-section file, boundary conditions file, and model parameter file has been created for this river.
b) The components of MIKE 11 river hydrodynamic model were implemented efficiently for Nzoia River.
c) For the MIKE 11 river model to be stable, specification of optimal time step (Δt) and space step (Δx) are required. The inappropriate selection of the time step normally leads to instabilities, depicted as warning and error reports after the simulation, which compromises the computed water levels in the river channel. This was noted especially when water level was calculated at a value less than the streambed elevation, the flow simulation crashes. The optimal Δx and Δt for the model was established to be 500m and 1 minute respectively.
d) Results from the scenarios investigations indicate that dykes breaching was the major cause of the 2008 Budalangi flood event. At the breached dykes, the water level was above the river embankment.

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