APPLICABILITY OF THE 3DI HYDRODYNAMIC SIMULATION SOFTWARE FOR EDUCATION PURPOSES AT THE FACULTY ITC: A CASE STUDY OF FLOOD EXPOSURE IN KAMPALA, UGANDA

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PREFACE

This internship assignment was an initial connection between Nelen & Schuurmans and the Faculty of Geo-Information Science and Earth Observation of the University of Twente. During these almost three months, I could study and implement the 3Di hydrodynamic model for a case study in Kampala, the capital city of Uganda. It was very interesting for me to explore, at the final stage of my master's program, this incredible tool that introduced me to a new concept of flood modeling. But more than a technical perspective, my internship period at Nelen & Schuurmans was a great opportunity to be part of the work environment in a Dutch consultancy company. I am glad that, in between so many restrictions, I could be present at the company and get to know colleagues that were genuinely welcoming and supportive. Despite the short period, I can certainly affirm that my experience at the company was very positive. I would like to thank my supervisor at Nelen & Schuurmans, Maud van Delden, and my supervisor at ITC, Dr. Dinand Alkema. Thanks for all your support and the constructive discussions we had throughout this assignment. They were very important to me. I would also like to thank my thesis supervisor, Prof. Dr. Victor Jetten, and my thesis advisor, Dr. Nanette Kingma, for all advice before and during my internship. Finally, I am sincerely grateful to our internship coordinator, Belinda Jaarsma. I already mentioned how much I admire your work and your incredible sense of attention and empathy. Thanks again for your support.

Cassiano Bastos Moroz

CONTENTS

1. INTRODUCTION

1.1. Background

Natural disasters have caused several human and economic losses in the last decades (IPCC, 2012). It is estimated that only in the period 2005-2015, more than 1.5 billion people were affected by disasters worldwide (UNDRR, 2015). This scenario has been intensified by rapid urbanization and population growth, especially in the context of low- and middle-income countries (LMICs) (Thomson et al., 2020; Wolff, 2020). Alongside demographic changes, climate change is likely to increase the occurrence of extreme rainfall events, resulting in more frequent and intense hydrometeorological hazards such as floods and landslides (IPCC, 2012). In this scenario, disaster risk mitigation and adaptation strategies have been receiving increased attention in the major international frameworks from the United Nations (UN). In the urban context, this includes the Sustainable Development Goal 11 of the 2030 Agenda (UN, 2015), which aims to build more resilient cities and communities.

To be able to develop environments that are resilient to extreme weather events, it is essential to understand the concept of risk. In literature, the risk is often described as a combination of hazard, exposure, and vulnerability (Klonner, Marx, Usón, de Albuquerque, & Höfle, 2016; Pitidis, Tapete, Coaffee, Kapetas, & de Albuquerque, 2018; C. J. van Westen, Damen, & Feringa, 2013), which are dynamic in time and space (IPCC, 2012). The investigation of these components is therefore essential to develop effective mitigation and adaptation measures that can minimize risk damages. In this context, most of the disaster research at the Faculty of Geo-Information Sciences and Earth Observation (ITC) of the University of Twente is based on the analysis of these components.

A significant part of this research involves the investigation of riverine and flash floods in urban areas in LMICs. This investigation often starts with the quantification of flood hazards. According to van Westen, Damen, & Feringa (2013), hazard refers to a potentially damaging event associated with a probability of occurrence within a specific time and spatial extent. In the context of flood research, hazard quantification is commonly performed with distributed hydrological and hydraulic models, which can represent catchment processes through physically-based solutions (C. J. van Westen et al., 2013). These distributed models enable the simulation of scenarios, which is essential for future predictions of risk. These scenarios often refer to changes in the catchment properties such as the implementation of structural measures (e.g. dams, dykes), land-use alterations, and urban expansion into hazardous areas.

1.2. Problem statement

A widely adopted flood modeling tool at ITC is the OpenLISEM hydrological model, an open-source software currently developed at the faculty's Department of Earth System Analysis. The model can simulate the land surface processes of runoff, flooding, and erosion in catchments of any size (Jetten & De Roo, 2018), thus being applied to investigate hydrometeorological hazards. However, ITC has a strong interest in adopting new modeling tools to support educational activities and research projects in the scope of disaster risk. In this context, a robust solution for water management practices is the 3Di hydrodynamic simulation software, a model developed by Nelen & Schuurmans in cooperation with Deltares, TUDeflt, and Stelling Hydraulics. The software has an interactive interface for novice users to model fluvial, pluvial, and coastal floods in urban and rural environments, while also allows more advanced model settings through an interface in QGIS and a Python API. In addition, Nelen & Schuurmans supports innovative research applications, thus a free license of the model is available for scientific purposes. In this context, there is a

need to further understand how the 3Di model could fulfill this interest of ITC. On one hand, there is a demand from students and researchers who are experts or want to increase their expertise in modeling. On the other hand, there are also the students and researchers who are not interested in exploring the modeling process but want to apply 3Di as a tool to produce relevant results for disaster risk studies.

1.3. Objectives

Given the problem statement, the main objective of the internship assignment was to evaluate the applicability of the 3Di hydrodynamic model for research and educational purposes at ITC. To have a more in-depth experience with the modeling process, a case study was conducted to investigate flood exposure in an industrial area in the City of Kampala, in Uganda. In addition to the main research objective, the following sub-objectives and research questions were identified:

Sub-objective 1: To explore the 3Di software by setting a model for the City of Kampala.

- What are the model input requirements and output results?
- Which hydrological processes and water systems can be simulated?
- What is the experience of a novice user when setting and running a new model?
- What are the opportunities and limitations of 3Di in research and educational activities at ITC?

Sub-objective 2: To quantify flood hazard and exposure in an industrial area in the Nakivubo catchment, in Kampala.

- What is the intensity of flood hazard and which critical factors are associated with flash floods in the case study area?
- What is the flood exposure in the case study area based on current scenarios of probable rainfall events?

This report is organized according to the following structure. Chapter 2 introduces the case study area and presents the methodology associated with the model setting and running. Chapter 3 presents the results of the case study on flood exposure in an industrial area in Kampala. Chapter 4 discusses the results of the case study and presents an overall analysis of the 3Di model, with a focus on the opportunities and limitations of the model for research and educational purposes at ITC. Finally, Chapter 5 concludes the study and provides recommendations for future research.

2. METHODOLOGY

2.1. Case study area

The Nakivubo catchment was selected as a case study area to explore the applicability of the 3Di hydrodynamic model in flood risk research. The catchment is entirely located in the City of Kampala, the capital of Uganda, with its limits between the latitudes 00°17'13"N to 00°21'00"S and the longitudes 32°33'28"E to 32°38'50"E. The catchment drains a total area of around 38 km², with its main watercourse, the Nakivubo channel, flowing into Lake Victoria to the east. The climate in the region is classified as Köppen Am or tropical monsoon, with clearly defined wet and dry seasons. The elevation in the basin ranges from 1,222 to 1,306 meters, with slopes of up to 55 degrees. The land cover is predominantly built-up, encompassing a highly urbanized central business district of Kampala (Mugume & Butler, 2017). During the last years, Kampala has experienced rapid urbanization, mostly as informal settlements (Pérez-Molina, Sliuzas, Flacke, & Jetten, 2017). This increasing population growth and urban expansion, combined with

heavy rainfall during the wet season, is associated with a significant risk to flash flooding (Umer, Jetten, & Ettema, 2019). To further explore the applicability of the model, this research focused on the quantification of flood exposure in a specific industrial area in the catchment. An overview of the Nakivubo catchment and the analyzed industrial area is presented in Figure 1.
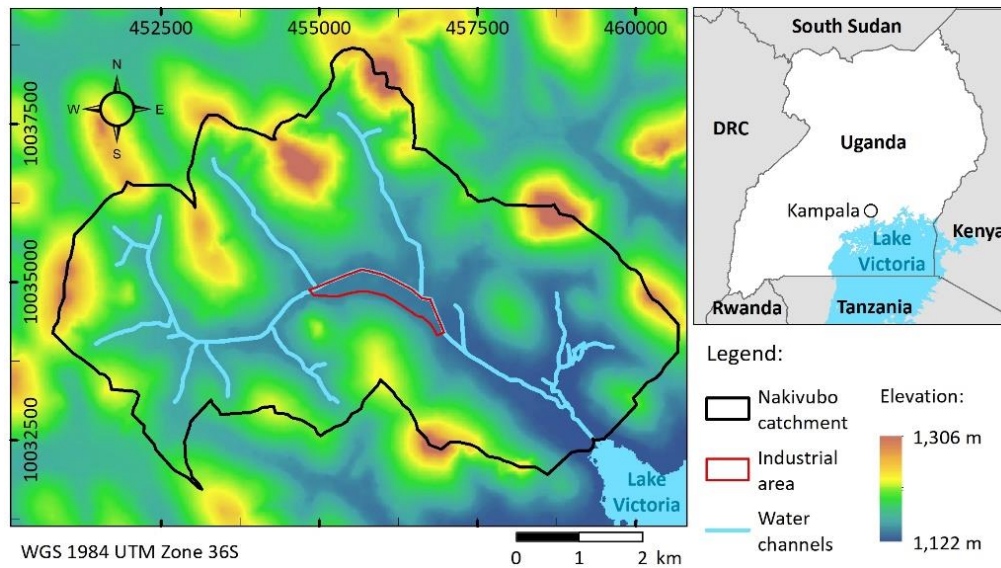
Figure 1. Location of the Nakivubo catchment and the analyzed industrial area in Kampala, Uganda.

2.2. Setting the model

This chapter describes the process of setting a 3Di model from scratch for the Nakivubo catchment. In 3Di, this process constitutes the following steps: (1) organizing the folder with the required raster files, which contains spatial information for distributed modeling, (2) configuring the SpatiaLite database, which contains all geometric information and settings of the model, and (3) defining the input rainfall events to be simulated.

2.2.1. Input raster files

A group of raster files was adopted to represent the topography and other spatially distributed parameters. All the required input data of Kampala was provided by ITC in a spatial resolution of 20 meters. This database was developed based on the OpenLISEM input data requirements, which include layers of rainfall, topography, land use, soil types, and infrastructure (Jetten & De Roo, 2018). Considering that the data requirements of 3Di are different from OpenLISEM, an initial screening was performed to select only the relevant datasets.

Initially, the DEM was pre-processed to be included in the model. The DEM is an essential input in hydrodynamic models such as 3Di, as topography plays an important role in the pathways of the runoff movement (Wu, Li, & Huang, 2008). In this research, a 2D representation of the water channels was preferred because of the unavailability of precise information about the channel cross-sections and dimensions. Therefore, the 2D representation was a good alternative, given that the available dataset, as provided by ITC, assumed rectangular cross-sections for the channels, which can be easily represented in a 2D schematization. Therefore, to include the channels in the analysis, the DEM was excavated at the location of the channels according to the dimensions of the rectangular cross-sections. Because most channels presented a width of around 5 meters, the DEM was first resampled to 5 meters through the nearest neighbor technique. Later, the channel depth was adopted as a reference to excavate the DEM, thus assuming rectangular cross-sections. In the case of channels wider than 10 meters, the corresponding

number of pixels was adopted to represent the width. As an example, channels with a width between 15 and 20 meters were represented as three pixels wide. This was performed through the Buffer tool in ArcGIS, with the buffer polygons converted to a raster file and adopted as a reference for the excavation.

During the excavation process, it was observed that the location of the water channels presented a few spatial mismatches when compared with the flow accumulation map derived from the DEM. This is possibly a consequence of the coarse spatial resolution of the available database. As a result of these mismatches, the elevation of the channel bottoms was sometimes inconsistent, presenting higher values downstream. To create a hydrologically correct channel network, these elevation peaks in downstream locations were eliminated by replacing the pixel value with the elevation at the nearest neighbor upstream. This process was performed through the Fill tool in ArcGIS. To cut the downstream peaks instead of filling the upstream depressions, the DEM was first inverted by multiplying all pixel values by -1, later returning to the positive values after correction. Figure 2 illustrates a channel profile before and after correction.
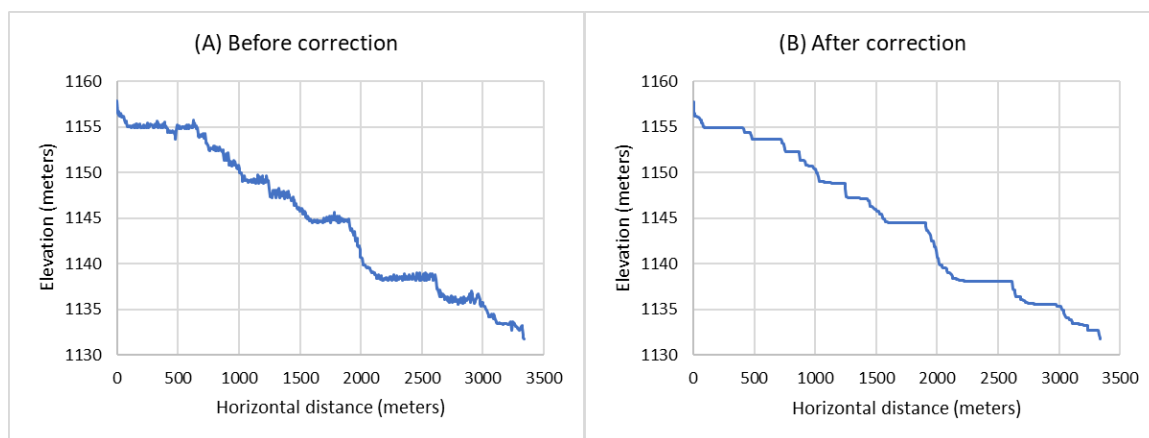

Figure 2. Example of channel profile before (A) and after (B) the correction of elevation.

Finally, the soil properties of infiltration rate and maximum infiltration capacity were obtained from the maps of soil physical properties provided by ITC. These maps were derived from SoilGrids (2020), a platform that applies machine learning techniques to provide global soil maps at a 250-meter spatial resolution based on soil profile observations and environmental covariates (de Sousa et al., 2020). The platform was adopted to extract the properties of organic carbon, bulk density, and contents of clay, sand, and silt, which were later converted to infiltration parameters through pedotransfer functions. These functions are predictive equations that estimate soil physical properties based on regression-type analyses of soil survey data (Dingman, 2015). Analogously to the DEM, the raster files of infiltration rate and maximum infiltration capacity were also resampled to 5 meters through the nearest neighbor technique.

2.2.2. Input SpatiaLite

The SpatiaLite file is the basis for all the schematization of a 3Di model. This SQLite file contains a database with all information required to build and run the model, including a group of attribute tables and vector layers. This includes the configuration of general and numerical settings (e.g. hydrological parameters), boundary conditions, laterals, 1D elements, obstacles, and grid refinements. Apart from these configurations, the SpatiaLite file is also the basis to relate the model with the input raster files as, for example, through the indication of the path for the Digital Elevation Model (DEM). To access and edit the file, it is required to install the 3Di modeler interface through a plugin for QGIS[1]. After the installation of

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[1] Information on the installation of the QGIS plugin: https://docs.3di.live/d_qgis_plugin.html

this plugin, it is possible to create a connection with the database and to start configuring the model. Figure 3 illustrates the SpatiaLite database of the Kampala model, highlighting the attribute table of general settings with information on the path to the DEM, and parameters of friction, groundwater, and initial water level.

The configuration of the model started with changes in the attribute tables. Initially, the numerical settings were modified to account for the sloped topography in the study area. This was performed based on parameters indicated in the 3Di tutorial for a 2D flow model over sloped terrain[2]. In the following step, the global settings were modified to include the required parameters and settings of the model. The settings were first altered to account for both 1D and 2D flow, and 2D rain. The grid space was defined as 60 meters to decrease the runtime of the simulations. In this context, it is important to mention that 3Di adopts the subgrid method, an advancement in hydrodynamic modeling. In this method, high-resolution data is preserved in subgrids to compute volumes, cross-section areas, friction, and advection, while a coarser resolution can be adopted in the full computation to reduce the runtime (Verstegen, 2020). Therefore, while the grid was defined as 60 meters, the spatial resolution of the raster files was preserved as 5 meters. In its turn, the Manning's surface roughness coefficient was assumed as 0.026 for the entire catchment based on expert advice at the company. Finally, the raster files of DEM, infiltration rate, and maximum infiltration capacity were associated with the model through the indication of the paths in the attribute tables of general settings and simple infiltration.
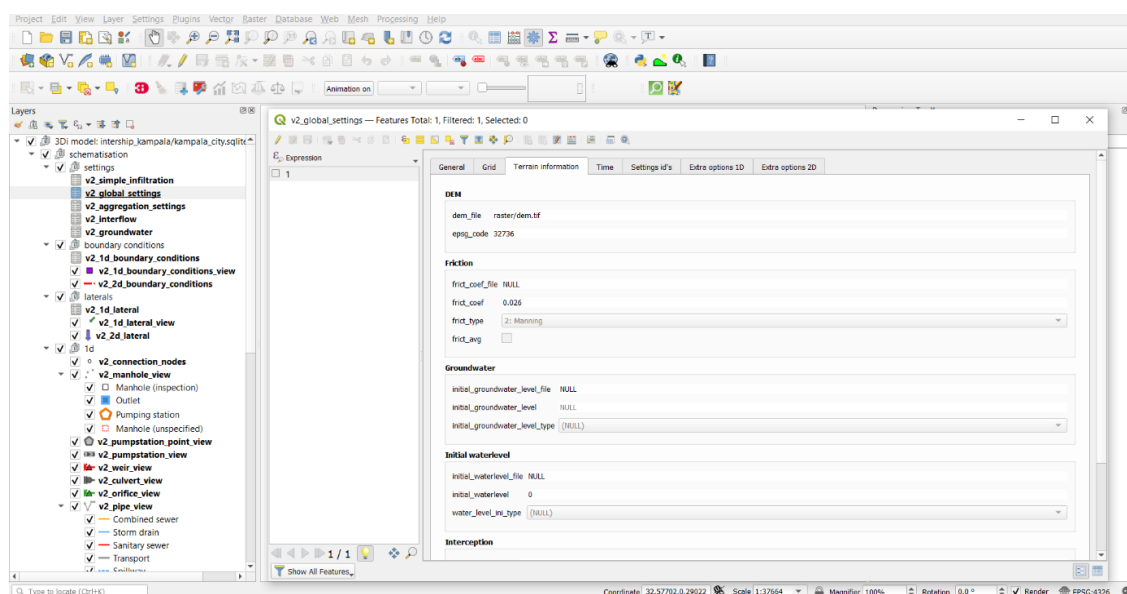

Figure 3. Representation of the SpatiaLite database with a focus on the attribute table of global settings.

The final stage in the configuration of the SpatiaLite database was the definition of the 1D elements to represent bridges and tunnels along the water channels. The identification of the bridges and tunnels was done through a visual interpretation of satellite images in ArcGIS. These elements were added to the model as culverts located in between two connection nodes, integrated with the 2D model via manholes. Because of the unavailability of information about the existing structures (e.g. material, dimensions), the culverts were represented with the same cross-section and friction as the channel section where they were implemented. In addition, infinitely high obstacles were added to block the 2D surface runoff at the location of the culverts, thus forcing the water to flow only through the 1D elements.

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[2] Access to the tutorial: https://docs.3di.live/d_2d_slope_tutorial.html#

2.2.3. Input rainfall

The exposure to flash floods in the case study area was quantified through the definition of design storms representing the input rainfall. Design storms are hypothetical hyetographs that are associated with a specific return period, or probability of occurrence (Krvavica & Rubinić, 2020). Therefore, it is assumed that the simulated flood hazard map represents the same return period as the rainfall input. In this research, the design storms were obtained from the studies of Mugume & Butler (2017). The authors generated design storms for the Nakivubo catchment through the rainfall block method, which assumes a constant rainfall intensity over a specific duration, often equals to the time of concentration of the basin. In the Nakivubo catchment, the authors estimated a time of concentration of 70 minutes, which was adopted as the duration of the design storms. In total, five events were generated to represent the return periods of 5, 10, 25, 50, and 100 years. Table 1 presents the design storms of Mugume & Butler (2017).

Table 1. Design storms at the Nakivubo catchment for the return periods of 5, 10, 25, 50, and 100 years. Source: Mugume & Butler (2017).

Return period (years)	Rainfall intensity (mm/h)	Rainfall duration (min)
5	56	70
10	65	70
25	73	70
50	88	70
100	96	70

2.3. Running the model

This chapter describes the process of running a 3Di model. There are three ways of starting a new simulation: (1) through an interactive interface in the Live site, (2) through a modeler interface in the QGIS plugin, and (3) through a Python API. In this research, the two first options were tested. The following sub-chapters briefly describe how each interface works.

2.3.1. 3Di Live site

The Live site is the interactive interface of 3Di. Through this platform, the user can start a new session for an existing model that was previously configured in QGIS. In the Live site, the user can interactively start a simulation with the implementation of discharges (inflow and outflow), pumps, rainfall, and wind. It is also possible to edit the raster files to make some small alterations as changes in elevation, which can be adopted to represent structures such as dykes and dams. The rainfall events can be added as constant intensity, radar, or design storms. However, the options of radar and design storms are only available for study areas in the Netherlands. Figure 4 illustrates the platform.
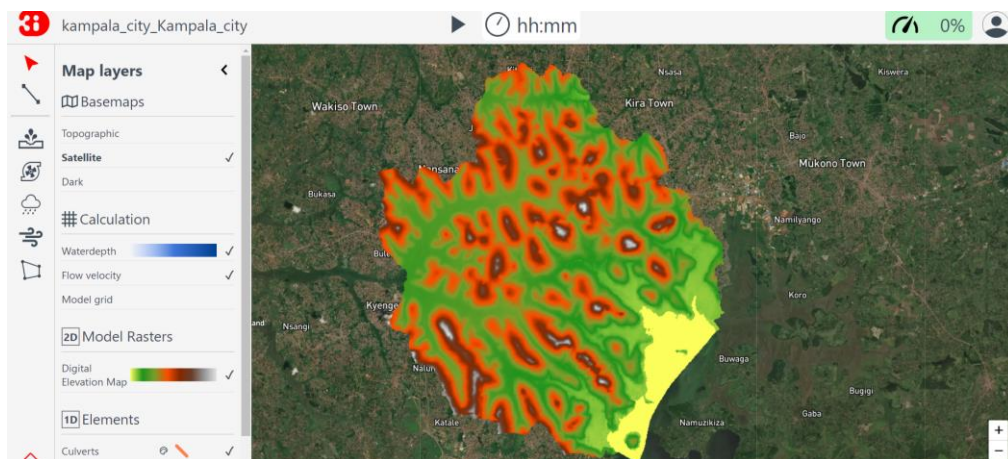

Figure 4. Representation of the 3Di Live site.

2.3.2. QGIS modeler interface

Apart from the configuration of the SpatiaLite database and the visualization of the simulation results, the modeler interface in QGIS also enables the user to start a new simulation. The advantage of the modeler interface when compared with the Live site is the higher flexibility to include information such as initial conditions, laterals, breaches, precipitation, and wind. An overview of these settings is presented in In contrast with the Live site, these parameters can be configured as input time series as, for example, in the case of hyetographs with changing rainfall intensities over time. The simulation in the modeler interface also enables the user to save the results to be post-processed in Lizard, a data warehouse and analytics platform developed by the company to be integrated with 3Di. In this platform, the user can visualize and download maps of flood depth, level, velocity, and arrival time for different timesteps. Therefore, taking into consideration the larger amount of settings to start a simulation, the QGIS modeler interface was adopted in this research to model the flood hazard scenarios for the analyzed return periods.
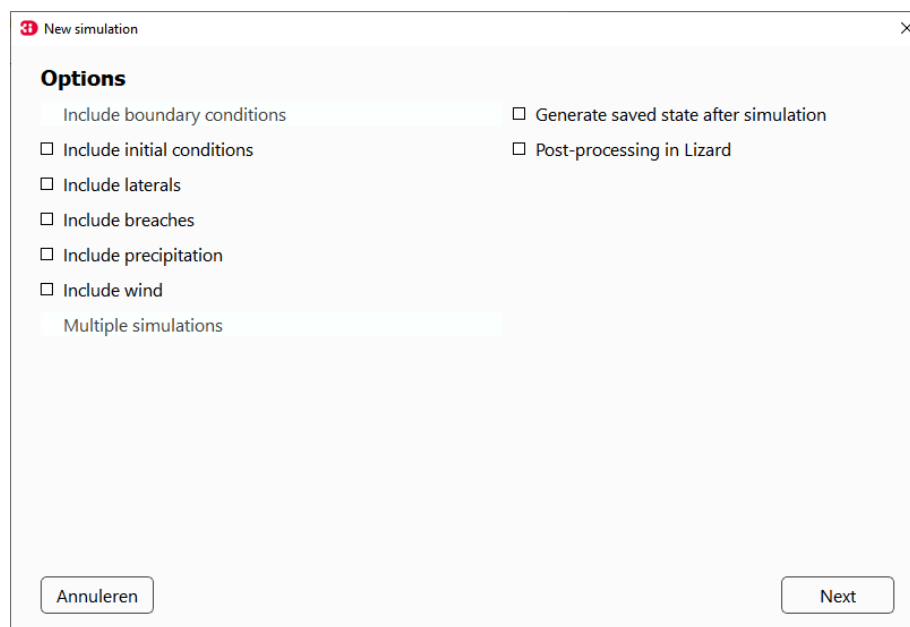

Figure 5. Representation of the QGIS modeler interface. Source: 3Di documentation.

2.4.   Quantifying flood hazard

To understand the intensity and the factors associated with the flood hazard in the study area, the results of the 3Di model were loaded in the modeler interface in QGIS. The interface provides a set of tools to explore the space-time structure of the hydrological measurements in any element or sub-domain of the model. The tool *Show 3Di results in Graph* plots the discharge and height measurements in a specific flowline or node of the model schematization. Therefore, the user can define any location, including 1D and 2D elements, and interactively visualize measurements such as wet cross-section area, discharge, velocity, water depth, rainfall, and others. In its turn, the *Water Balance Tool* enables the user to define an interest area by drawing a polygon over a specific sub-domain of the model. As a result, the tool calculates and plots the water flows in all elements that are part of the model: 2D, 1D, rainfall, interception, groundwater, infiltration, boundaries, laterals, and others. These flows can be visualized as a time series of intensities or cumulative values. The user can also calculate the total water balance, which provides a bar chart of the water volumes in each element. All the information on the graphs can be exported as an image or table file. In addition, the *Statistical Tool* and the *Show sideview of 3Di model with results* are powerful tools to explore 1D water systems. The first generates statistics for different hydrological measurements in elements including pipes, manholes, pumps,

and weirs. In its turn, the latter provides a schematical view of a pre-defined trajectory in a 1D system, illustrating the dimensions, surface levels, and water levels along the analyzed trajectory. Finally, there are also tools to create an animation of the hydrological measurements over time and to export maps of water depth and level. These tools enable better visualization of the space-time structure of the flows and the flood hazard.

In this research, the *Water Balance Tool* was selected to obtain information about the hydrological measurements and to better understand the critical factors associated with the flood hazard in the region. First, the intensity of the events was investigated through the extraction of the hydrograph at the outlet of the Nakivubo catchment in Lake Victoria for each return period. This enabled the estimation of the peak flow intensity and the total runoff volume. Later, the *Show 3Di results in Graph* tool was adopted to verify at which time the maximum water levels were registered in the industrial area, which is the focus of this case study. Finally, the *Animation* tool was applied to visually explore the space-time structure of the water flows, as it enables an interactive animation of multiple hydrological measurements.

2.5.   Quantifying flood exposure

After investigating the flood hazard, a simplified exposure assessment was conducted in the case study area to further explore the functionalities of the 3Di hydrodynamic model. First, the maps of maximum flood depth for each return period were downloaded via Lizard. Then, a building database of the study area was obtained from OpenStreetMap (OSM), which presents relatively complete databases at the location of the city of Kampala. To facilitate the interpretation of the results, the flood exposure was conducted based on the calculation of the number of buildings instead of the building area. In this process, the average value among all buildings in the study area was used as a representative of the area of a single building. Finally, the flood hazard maps were intersected with the building database to estimate the total number of buildings exposed to flash floods in the study area, per return period and water depth.

3.   RESULTS

3.1.   Flood hazard

The first step in the flood hazard quantification was the extraction of the hydrograph and the calculation of water volumes at the outlet of the Nakivubo catchment. Figures 6 and 7 illustrate the obtained hydrographs for the return periods of 5 and 100 years, respectively, which refer to the lowest and highest probabilities being analyzed. The graphs were exported directly from the modeler interface through the *Water Balance Tool.* Another option is to obtain the time series as a table file to be further analyzed in other software. The purple polygon represents the inflow and outflow at the outlet of the catchment, while the orange dashed line represents the volume change between inflow and outflow. For a 5-year rainfall event, the peak discharge at the outlet was estimated as 224 m³/s at the time 11 ks (around 3 hours), where a time of 0 ks refers to the start of the rainfall event. The total discharge volume was estimated as 2.46 million m³. In its turn, for a 100-year rainfall event, the peak discharge at the outlet was estimated as 465 m³/s at the time 9.5 ks (around 2 hours and 38 minutes), and the total discharge volume as 4.72 million m³. The changes in the shape of the hydrographs when increasing the return period demonstrate the influence of the rainfall intensity on the space-time structure of the flood hazard.
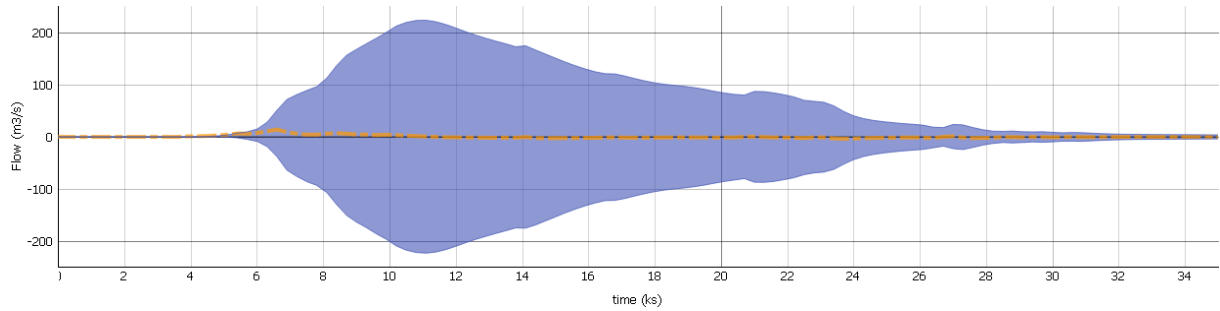
Figure 6. Hydrograph at the outlet of the Nakivubo catchment for a 5-year rainfall event.
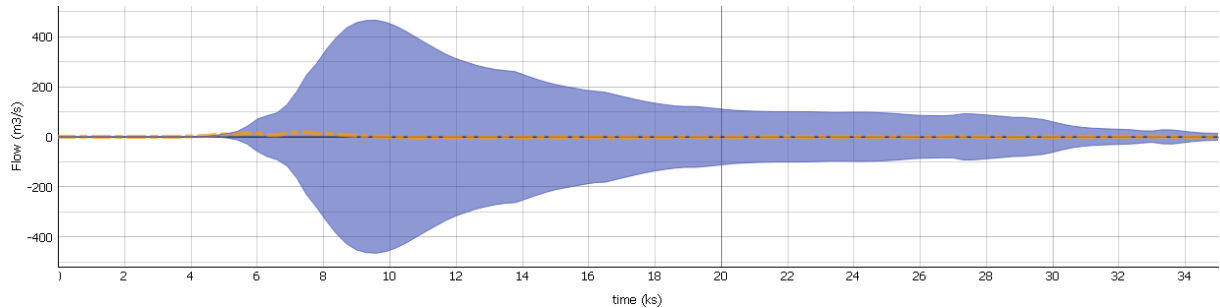

Figure 7. Hydrograph at the outlet of the Nakivubo catchment for a 100-year rainfall event.

In the following step, the *Show 3Di results in Graph* tool was adopted to visualize the time series of water levels at the analyzed industrial area. A central node was select among the 156 nodes that intersect the area to identify the exact time when the maximum water levels were registered. Figure 8 presents the time series at the location of the reference node for all analyzed return periods. In this context, each graph represents a different return period, ranging from 5 years (lowest peak) to 100 years (highest peak). This graph was exported directly from the modeler interface. As observed, the maximum water level was registered slightly earlier than the peak discharge at the outlet of the catchment (see Figures 6 and 7), or at the time 10 ks (around 2 hours and 45 minutes) for a 5-year event and 9 ks (around 2 hours and 30 minutes) for a 100-year event. This might be explained by the location of the study area, around 3 km upstream from the outlet of the Nakivubo catchment.
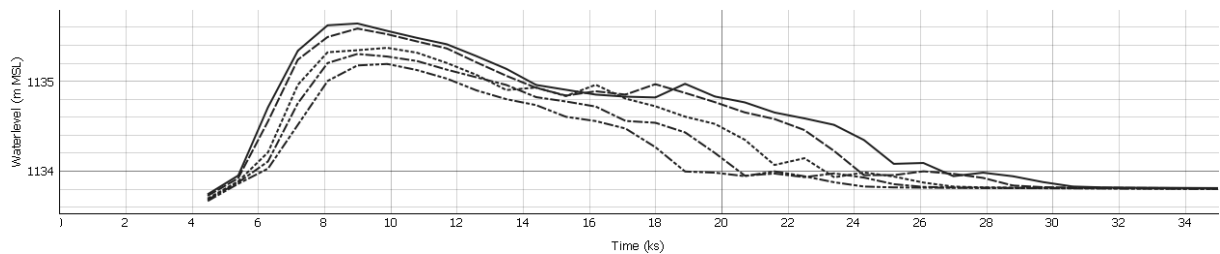

Figure 8. Time series of water levels at the nodes that intersect the industrial area.

Finally, the space-time structure of the water flows was visually inspected through the *Animation* tool. Figure 9 illustrates the interface of the tool through a demonstration of discharge measurements over the Nakivubo catchment for a return period of 100 years at the time 2 hours and 30 minutes. The boundaries of the catchment and the water channels are indicated with black and blue lines, respectively. The time was selected because it refers to the maximum water level at the study area, at a moment when the rainfall event stopped, and the surface flow already reached the floodplains.
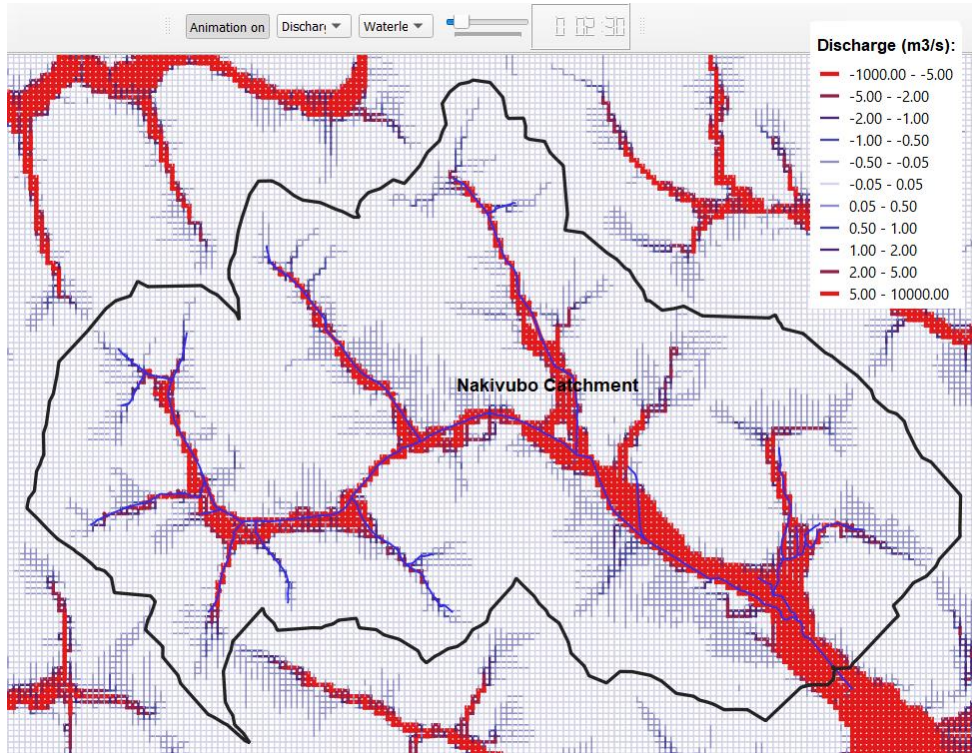
Figure 9. Representation of the *Animation* tool for a 100-year event at the time 2 hours and 30 minutes.

3.2. Flood exposure

Finally, the flood exposure was assessed by integrating information on the flood hazard and elements-at-risk. The simulation of the rainfall scenarios resulted in a total of five flood hazard maps associated with the return periods of 5, 10, 25, 50, and 100 years. Figure 10 illustrates the maximum flood extent for each return period and the location of the existing buildings in the case study area.
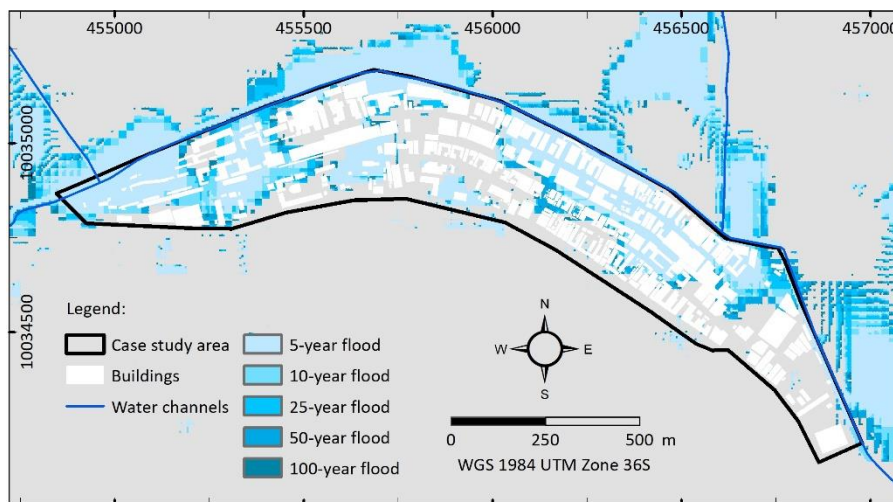

Figure 10. Simulated flood extent in the case study area per return period, and location of the existing buildings.

In addition to the analysis of flood extent, the maps of maximum flood depth were downloaded from Lizard. These maps were then integrated with the OSM building database to quantify flood exposure in the study area according to the return period. Table 2 presents the total estimation of exposure to flash floods in the study area per return period. The exposure was expressed as the number of buildings instead of the area. The reference area of a building was estimated as 545 m².

Table 2. Total number of exposed buildings per return period.

Return period (years)	Annual probability	Number of exposed buildings*
5	0.2	148
10	0.1	169
25	0.04	191
50	0.02	222
100	0.01	231

*The area of each building was assumed as 545 m².

Finally, the level of exposure was also evaluated in terms of the intensity of the hazard event, expressed as the water depth. This information is expressed in Figure 11, which represents the total number of buildings (y-axis) exposed to a flood depth equal to or deeper than a certain reference value (x-axis).
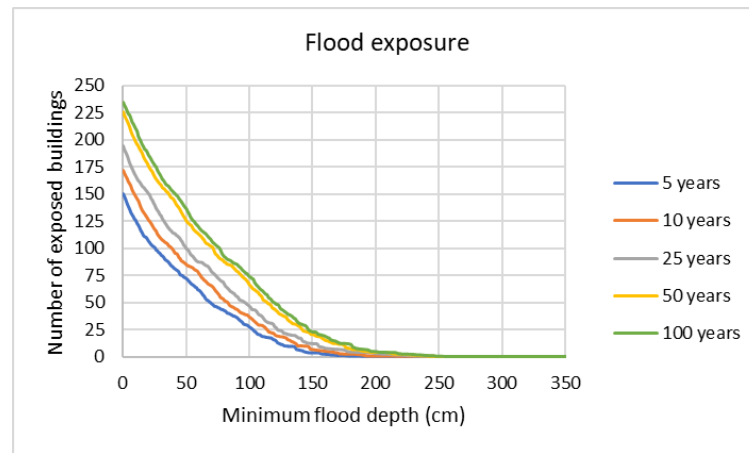

Figure 11. Total number of exposed buildings per return period and water depth.

4. DISCUSSION

4.1. Flood hazard and exposure

This study presented a quantification of flood hazard in the Nakivubo catchment, in Uganda, for multiple return periods from 5 to 100 years. As initial analysis of the hydrographs at the main outlet of the catchment indicated discharges ranging from 224 m³/s to 465 m³/s for a 5- and 100-year event, respectively. These peak discharges were registered between the times 2.5 and 3 hours, which highlights the low time of concentration in the catchment. The analysis of these hydrographs and the water levels was conducted through specific tools in the modeler interface in QGIS. Overall, these tools provided an interactive way of exploring the entire study area, and flexibility to extract time series of hydrologic measurements in all flowlines and nodes of the model. Adding to the interpretation of hydrographs, a visual analysis of the space-time structure of the water flows was conducted through the *Animation* tool in the modeler interface of 3Di. Although it was not possible to illustrate the entire animation in the report, the tool demonstrated to be a straightforward way of visualizing the results in space, thus helping to understand the dynamics of the water flows in the study area. In addition to the adopted tools, other functionalities are also available to further explore the results in 1D elements, which can be highly useful for the study of urban systems.

The analysis of flood exposure in the case study area demonstrated a high exposure of the industrial buildings to flash floods in Kampala. When considering a return period of only 5 years, which refers to an annual probability of occurrence of 20%, it was estimated that approximately 148 buildings would be

exposed to the hazard. This number is based on the assumption of an area of 545 m² for each building, calculated as the average value among all buildings in the study area. As expected, the exposure increases with higher return periods, reaching a total value of around 231 buildings for a 100-year event. Another important aspect is the analysis of flood exposure according to the flood depth, as illustrated in Figure 11. It was observed that an increase in the return period did not only increase the total number of exposed buildings, but also the intensity of the flood event. For example, while a flood depth equal to or lower than 50 cm represented around 48.8% of all exposed buildings for a 5-year event, this percentage increased to 58.9% for a 100-year event. This information is extremely important in disaster risk research given that the flood intensity, often expressed as the flood depth and velocity, is directly associated with the estimation of the physical vulnerability, which is part of the risk equation (van Westen, Alkema, Damen, Kerle, & Kingma, 2011).

It is essential to highlight the limitations presented in this case study, particularly regarding data scarcity. First, the 3Di model was implemented taking into consideration DEM and infiltration raster files with an original spatial resolution of 20 meters. Despite being more accurate than open-source datasets such as the DEM of the Shuttle Mission Topography Mission (STRM), a resolution of 20 meters is still not suitable to represent urban flooding, as it does not represent finer details such as buildings and other built-up elements. In addition, the implementation of culverts to represent bridges and tunnels assumed cross-sections with the same dimensions as the water channels. This is a great source of uncertainty, given that changes in the dimensions – and thus discharge capacities – of culverts and other 1D elements significantly affect the simulated flood patterns. Finally, the nonexistence of flood inventories or stream gauges in the Nakivubo catchment impaired the calibration and validation of the model. Therefore, the initially adopted parameters such as friction, infiltration rate, and maximum infiltration capacity remain uncertain and may not represent the real conditions in the catchment.

4.2.   Functionalities and applicability of the 3Di model

This chapter critically analyses the main aspects of the 3Di model, including the input data requirements, output results, and the processes and systems that can be simulated in the scope of disaster risk. All these findings are complemented with a critical discussion on the experience of a novice user when setting and running a model from scratch.

The input data requirements of the 3Di model are constituted by the SpatiaLite database and the raster files, which can be configured through the modeler interface in QGIS. The process of organizing the input database is intuitive, but there is an extensive amount of parameters to be defined in the SpatiaLite file, which contains all the settings and geometric properties of the model. This database is then complemented by the raster files. Different from other models such as OpenLISEM, the 3Di model uses a much lower number of raster maps. In this context, the only compulsory raster file is the DEM, which is one of the most important data inputs in distributed flood models. However, the model can also be refined through the implementation of more raster datasets, including maps of friction, infiltration, and interception. Therefore, it is the user's choice to decide the level of detail required for his/her research purposes.

The 3Di model also allows the implementation of multiple 1D elements such as channels, culverts, weirs, orifices, obstacles, pump stations, and others. These elements are implemented as part of the SpatiaLite file through operations in QGIS. The 1D flow can be integrated with or isolated from the 2D flow by adjusting the settings in the SpatiaLite file. This enables, for example, the representation of complex urban drainage and sewage systems. As a step further, boundary conditions and laterals can be added to the model. These configurations can be implemented as a time series of inflow or outflow discharges. This brings a lot of opportunities to the simulation of mitigation measures such as reservoirs and detention basins, but also

potential hazards such as the failure of pipes and other hydraulic structures. Another advantage of the boundary conditions is the possibility to narrow down the scale of the analysis to a specific area instead of the entire catchment, thus optimizing the modeling process. This is particularly interesting when design floods or time series of river discharges are available. In addition to all these elements, the user also has the option to model only the surface runoff or to enable the processes of infiltration and groundwater flow.

Overall, the process of setting a 3Di model from scratch can be, at the first moment, a bit challenging for a novice user. This complexity increases with the addition of more elements and raster maps, as when implementing the 1D flow. Another aspect that can be unfamiliar is the structure of the model, especially the SpatiaLite file. The configuration of the file differs from models such as OpenLISEM, which often require a more manual configuration of the input database through the generation of several raster files. Despite this initial unfamiliarity, the documentation of the 3Di model[3] provides a complete step-by-step with tutorials, flowcharts, and tables to guide the user. Also, after setting the model, the SpatiaLite database can be easily edited to change parameters or to enable/disable processes. This flexibility is a great advantage of 3Di when compared with other models that rely on databases of raster files. In its turn, the process of running a 3Di model is extremely intuitive and allows the simulation of rainfall events, wind, and laterals. In this context, both interfaces have their advantages. On one hand, the Live site is very interactive, allowing the user to "play" with forcing elements such as rainfall and wind and to make small alterations in the topography. On the other hand, the modeler interface in QGIS is very flexible, for example allowing the implementations of custom rainfall and laterals as input time series. Another positive aspect is the short runtime of the model, especially considering the subgrid method, which enables the adoption of coarser calculation cells while maintaining the high resolution of the results. In the case study in Kampala, the 3Di model was run in less than 10 minutes to simulate a 24-hour event with timesteps of 60 seconds. This model represented a study area of 189 square kilometers (the entire City of Kampala) with a calculation cell of 60 meters.

In the context of the outputs, the results of the 3Di model are easily visualized through the modeler interface in QGIS. The group of tools to create graphs, extract statistics and calculate the water balance provides a good picture of the situation, which is extremely important in disaster risk studies. The QGIS plugin also enables the visualization of 1D and 2D water flows throughout the entire study area. In this context, the user can select a node, element, or flow line, and obtain the required results in that specific location. This interactive visualization is more flexible than in OpenLISEM, where the location of the hydrograph outpoints must be defined before running the model. The 3Di model can also be integrated with Lizard, a data warehouse and analytics platform developed by Nelen & Schuurmans. In this platform, the user can visualize and download raster maps of water depth, level, velocity, and arrival time.

Therefore, the 3Di model demonstrated to be a promising modeling tool for disaster risk studies at ITC, both for research and educational purposes. Although the learning process can be time-consuming depending on the experience of the user, the ability of the model to represent different scales, processes, and water systems provide several opportunities. An example is the integration of 3Di with OpenLISEM to simulate riverine floods in urban environments. First, OpenLISEM could be adopted to obtain a time series of river discharges through a large-scale model of the entire catchment. These time series could then be implemented as boundary conditions in a high-resolution 3Di model to generate more accurate flood hazard maps in a specific urban area. Apart from this research application, 3Di can also be beneficial in education. In this case, a powerful tool is the Live site. This interface provides a very interactive environment for students to better visualize and understand hydrological processes and to easily test the effects of basic flood

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[3] Access the documentation: https://docs.3di.live/index.html

mitigation and adaptation strategies. The students could, for example, start with the development of 2D models with only a DEM as a raster input, which significantly simplifies the process of setting the SpatiaLite database. Then, the model could be refined, step-by-step, through the implementation of other elements such as infiltration, groundwater flow, 1D elements, according to the student's interests. In this context, a great advantage of 3Di is the possibility to develop both simple and complex models depending on the purposes and requirements of the user.

5.   CONCLUSION

This internship assignment aimed to evaluate the opportunities and limitations of applying the 3Di hydrodynamic model for research and education purposes at the Faculty ITC of the University of Twente. A case study was conducted to better understand the processes of setting and running a 3Di model from scratch. This case study involved the quantification of the exposure to flash floods in an industrial area in Kampala, the capital city of Uganda. An analysis of the simulated scenarios highlighted a high exposure of the analyzed industrial to flash floods, with an estimated number of affected buildings of 148 and 231 for a 2-year and 100-year event, respectively.

The performance of this case study was an important tool to explore the range of functionalities of the 3Di model and to critically evaluate how it can be useful in research and education activities at ITC. Overall, there is promising applicability of the model for disaster risk studies, especially considering the high flexibility to model complex water systems, and the interactive interfaces to facilitate the learning process. In addition, the subgrid method is promising to enable the simulation of the flood hazard in urban areas, which often require the adopting of high-resolution data to result in more accurate results. In this context, while the processes of setting a model from scratch can be time-consuming for a novice user, the model's documentation provides all the necessary information to understand the theory and practice when building and running a 3Di model, including a list of input requirements and output results. Finally, the availability of multiple interfaces to start a simulation can provide the student with an important tool to better understand hydrological processes and other concepts that are relevant in the study of hydrometeorological hazards.

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