Flood Risk Assessment for Mpazi Basin Focusing on Land Use/Land Cover Alteration for the Kigali Master Plan 2050

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Abstract- The progression of anthropogenic encroachments on nature reflects negatively on the community inhabitants. Unequivocally, rainfall and drought patterns have changed globally due to climatic change. As a result, the Mpazi basin has been experiencing more frequent and intense flash floods in recent decades, resulting in casualties and devastation of properties. The unplanned urbanization of the Mpazi catchment plays a significant role in altering the hydrologic components, particularly an increase in the excess rainfall due to the sealing of lands. This study focuses on assessing the flood risk in accordance with the proposed alteration of land use/land cover (LULC) in the Kigali master plan 2050. Therefore, a comparison mode with the existing LULC was carried out to determine the sensitivity of different land uses, which quantitatively influence the flash flood aspects, including flood peak discharge, flood wave lag-time, flood volume, and flood inundation. The study was carried out numerically by implementing a two-dimensional unsteady Rain-On-Grid model using HEC-RAS 6.2 to simulate the spatial and temporal variation of the direct precipitation and infiltration. The study findings show that 2050's master plan would be able to attenuate the flood wave by reducing both the peak flow and cumulative flood volume by 50%, as well as delaying the draining time. Nevertheless, the flood inundation map showed relatively slight differences compared to the existing case of the basin, which was less than 20%. The findings implied that the Mpazi basin is still susceptible to flooding during heavy storm events despite the significant reduction of the flood flow and momentum.

Index Terms- land use; land cover; hydrologic modeling; flood risk assessment; direct rainfall method (DRM); rain-on-grid; HEC-RAS

I. Introduction

Human encroachments on nature and other human-induced activities pose a significant challenge to the environment and negatively influence the ecosystem service that serves as a buffer to a natural hazard [1]. The changing climate pattern is also projected to increase the intensity of extreme rainfall, which translates to an increase in the frequency and magnitude of pluvial floods [2]. This problem has been exacerbated in many developing countries, such as Sub-Saharan Africa and some parts of Asia, where the unplanned urban expansions are putting hydro morphological pressures on the water bodies and flood plains and resulting in extensive land use changes [3,4]. Both alterations have been expected to have a tremendous effect on catchment hydrological processes, including reducing infiltration, lag periods, base flow and increasing peak discharge, storm flow volumes, surface runoff, and flood frequency, which increase the risks associated with flooding and reflect aggressively on the community inhabitants [5,6].

In the last decade, Kigali city, the capital of Rwanda, has experienced rapid urbanization and economic expansion. The rapid urban expansion leads to poorly planned land use/ land cover (LULC) alterations and generates a number of adverse environmental impacts, such as floods, landslides, soil erosion, and sediment transport [7]. Floods have severely impacted Kigali city, particularly the Nyabugogo commercial district. It has intensified and affected larger areas resulting in human casualties and considerable damage to valuable infrastructure [8]. These catastrophic disasters were primarily caused by the very low retention capacity of the Mpazi catchment. The dense unplanned urbanization of the catchment significantly alters the hydrologic cycle components within the closed basin system, substantially increasing the excess rainfall and reducing the potential of subsurface infiltration induced by the semi-connected tin roofs that seal the surface [9].

In general, the Mpazi drainage channel is a trapezoidal channel made of stone masonry that drains rainwater very fast, leading to uncontrollable discharges and regular flash floods in the lower part near the Nyabugogo commercial district [10]. The high-water pressure during heavy rains, coupled with a degraded steep upstream slope, causes a wash away of the corner channel walls. The collapsing channel walls then clogged downstream culverts and bridges, reducing the river's hydraulic capacity and impeding water flow. Further, Kigali city lacks adequate drainage and household rainwater collection systems [8,9]. The combination of these factors

accelerates the water transport to the main course of the channel and may aggravate local flash flooding. Therefore, it is essential to have explicit knowledge of how development and management activities, especially land use, impact flood risks.
Kigali city released an updated plan in 2020 to redevelop Kigali into a more sustainable city, which was envisioned in the Kigali master plan 2050.

The master plan shows the vision of the urban extension and rehabilitation of the existing urban districts by 2050 [11]. The vision pursues sufficient capacity of the city to meet the community-changing demands while wisely easing the centralized urban stresses. The range of alterations in the land use of area that will be implemented implies the changes in flood hazards (different flash flood aspects such as flood peak discharge, flood wave lag-time, flood volume, and flood inundation) of the Mpazi catchment. Consequently, it is critical to direct the focus of the study toward assessing the flood risk according to the proposed alteration of LULC in the master plan 2050. Therefore, this study aims to compare the LULC of the existing with the Kigali master plan 2050 and to determine the sensitivity of physical parameters (e.g., watershed topography and shuffling of land uses) using hydrologic and hydraulic modeling nested within HEC-RAS. The analysis can help formulate appropriate recommendations to reduce the magnitude of the effect of floods in the area.

II. Materials and Methods

The flood risk assessment methodology described in this paper is divided into three stages: data acquisition, data processing, and hydrodynamic numerical investigations using Rain-on-Grid HEC-RAS Model. The different stages of the flood risk assessment consist of many dependent steps, which are presented in Figure 1.

2.1 Data Acquisition

Three different datasets are used for this stage: spatial data, precipitation data, and recorded overland flow data. Spatial and precipitation data are coupled to build the model, whereas recorded overland flow data is used to calibrate this event-based model.
The projected land use map of the Kigali master plan 2050 was converted into a hydrologic definition of LULC (Figure 3) using QGIS. While reprocessed precipitation data were collected at the Kigali Airport Meteorological station in the form of the Intensity-Duration-Frequency (IDF) Relationship [12]. According to [12], the daily rainfall data recorded at this station for 43 years period was subjected to different preliminary data inspections for validity check, then used to construct the IDF Relationship as shown in Equation 1, as well as identifying the station parameters as listed in Table A1.

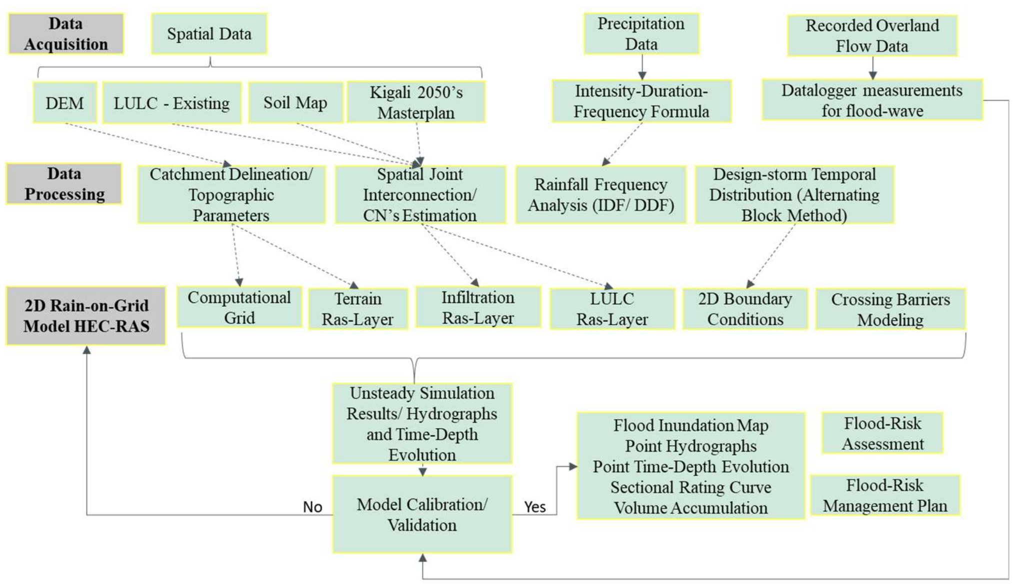

Figure 1. Diagram of flood risk assessment methodology stages.

The obtained rainfall intensities for several return periods jointed with storm durations are plotted in Figure A1. A full overland flow record for a rainfall-storm flood on February 23rd, 2013, was obtained from the data logger installed in the Mpazi basin's main channel (Figure A2) [9].

$$I = \frac{\alpha}{(t+\gamma)^{c}} \qquad (1)$$

Where I = maximum intensity (mm/hr); t = rainfall duration (min); α = regression coefficient (mm/hr); γ = time constant (min); and c = exponent with values less than unity.

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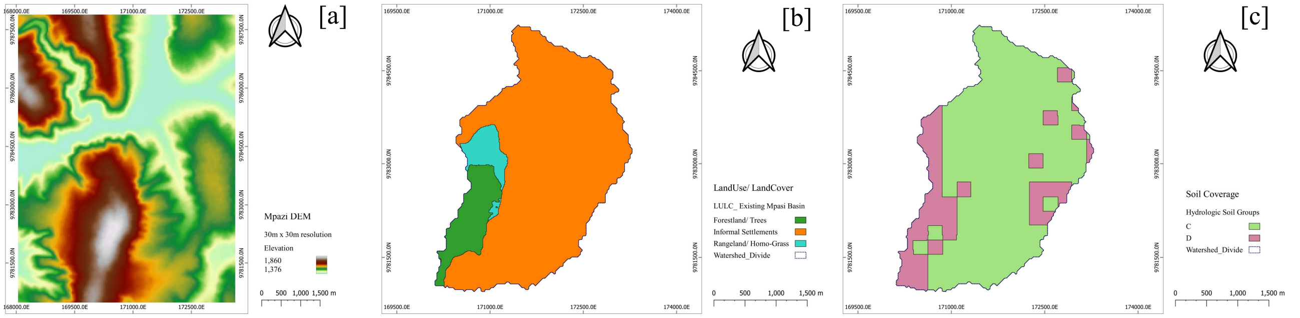

Figure 2. Spatial data a) SRTM 30 m resolution [13]; b) land use/ land cover 10 m resolution [14]; c) soil map 250 m resolution according to the hydro-soil grouping [15].

2.2 Data Processing

Evaluation of the hydrologic landscape aspect of the Mpazi basin, watershed divide, and stream delineation were accomplished with QGIS Hydrologic tools. The GIS interpretations revealed that the entire area of the catchment with approximately 8.5 km^2 inclines in relatively rough steep slopes from the southern and western uphill downward to the valley, unlike a small portion of the delineated area at the eastern end of the basin with quite mild slopes (Figure 4a). The joint spatial feature of GIS was used to examine the spatial correlation between the land use/land cover layers and the hydrologic soil-groups map according to TR-55 procedures [16], and to assign each subarea a reasonable curve number (CNs). The CNs values for the Mpazi basin are shown in (Figures 4b and 4c) for both the existing land use and the projected master plan, respectively.

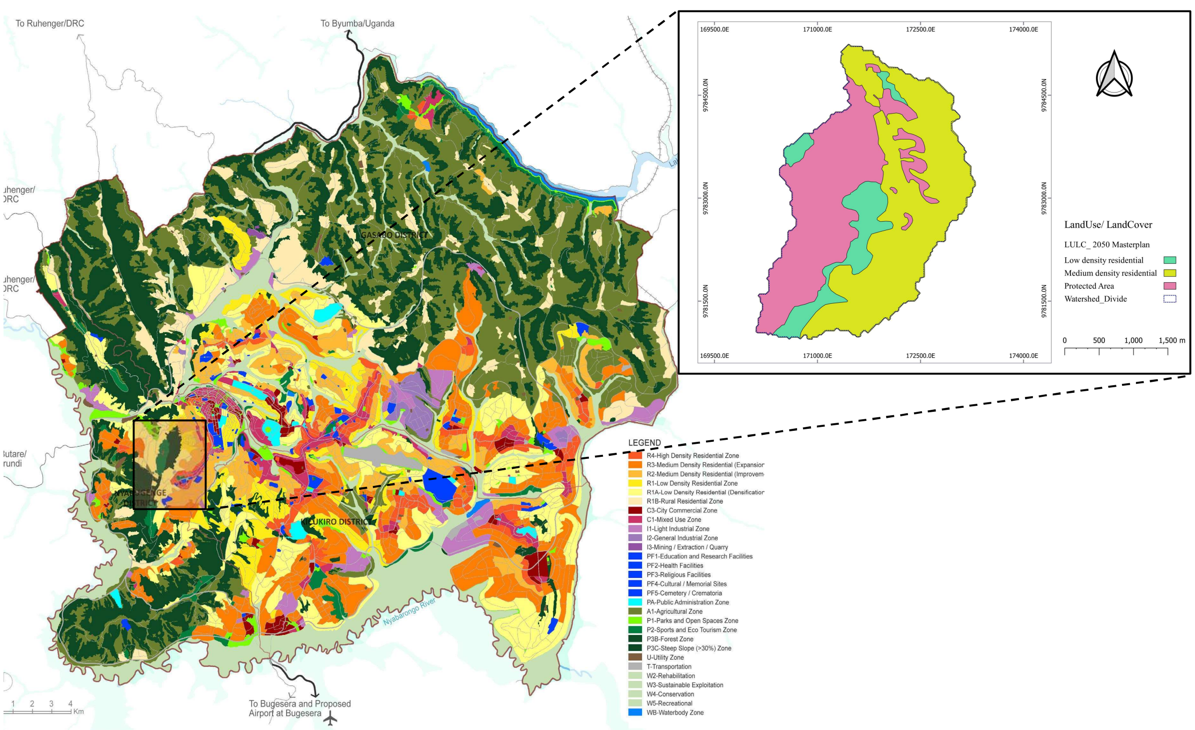

Figure 3. Kigali master plan 2050 [11], with converted hydrologic LULC map covering the study area (upper-right corner).

The fifty-years return period rainfall storm was investigated and 2-hours design storm duration was selected [17]. The IDF curves were then converted into DDF curves, and a design rainfall storm of *66.26 mm* was calculated (Figure A3a). Once the total design-storm depth is identified as a set of design criteria for the selected return period and storm duration, the storm was then temporally disaggregated over the rainfall duration which was used in the rainfall-runoff analysis [18].

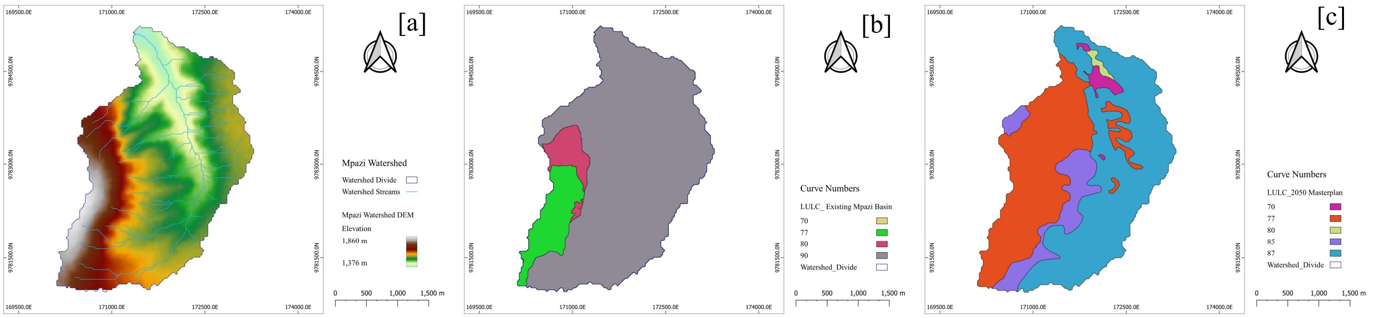

Figure 4. a) Delineated watershed divide and streams; b) CN's estimated map for the existing case in Mpazi; c) CN's map for the 2050's master plan in Mpazi.

2.3 Rain-on-Grid HEC-RAS Model Setup

Quasi-2D hydrodynamic rainfall-runoff models (HDRRM) employing the direct rainfall method (DRM) by applying 2D precipitation input over the whole catchment were developed using HEC-RAS tools. A computational mesh with 256,341 cells covering the Mpazi catchment was constructed by reasonable resolutions with local differences. The cell sizes vary from the finest accuracy of 3m at streams to the coarsest of 10 m in the watershed; the model was configured with adjustable computational timestep to keep the courant-friedrichs-lewy number within the practiced acceptable limits. Furthermore, the diffusion wave approximation was used as the governing equations set. Manning's roughness coefficients (n values) for each relevant land cover category were interpreted according to shallow overland flow roughness definitions from [19] summarized and jointed with imperviousness estimates in Table A2.

HEC RAS 6.2 was used to run DRM simulations with the SCS-CN method, which estimates excess rainfall as a function of the cumulative precipitation, hydrologic soil grouping, land use, and antecedent moisture status [20]. According to Mishra & Singh (2003), The SCS-CN model is derived from the water balance conception (Equation 2) and two major hypotheses. The first hypothesis relates the fraction of the actual amount of direct runoff (Q) from the total effective rainfall (P) to the proportion of the amount of actual infiltration (F) to the amount of the probable maximum soil-retention (S) (Equation 3), which is known as proportionality concept as illustrated in (Figure A4). The second hypothesis corresponds to the initial abstraction (I_a) to the probable maximum soil-retention (S) (Equation 4). The incorporation of the water balance concept with the two fundamental hypotheses results in the popular SCS-CN formula (Equation 5), whereas it is valid at $P \geq Ia$; otherwise, $Q = 0$.

$$P = I_a + F + Q \tag{2}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{3}$$

$$I_a = \gamma S \tag{4}$$

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{5}$$

where P = cumulative precipitation; I_a = initial abstraction; F = cumulative infiltration excluding initial abstraction (I_a); Q = direct runoff; S = potential maximum retention; and γ is the user-defined initial abstraction ratio (between 0.05 and 0.2).

The SCS-CN infiltration mode in the study is parametrized by a 0.2 initial abstraction ratio based on soil retention in Equation 6. The soil retention values are calculated for each cell with respect to the specified CNs for the cell. The CNs for the various LULC subareas, in both existing and master plan scenarios, are tabulated in (Table A3).

$$S = \frac{25400}{CN} - 254 \tag{6}$$

Furthermore, the existing hydraulic barriers within the study area were modeled to obtain a reliable perception of hydraulic behavior. The bridge at the outlet point of the basin, which acts like a bottleneck with two box vents of dimensions 3 m x 1.5 m was geometrically modeled.

2.4 Model Calibration

Model calibration was performed by determining unique values for the model tuning parameters, roughness and CNs's parameters, that accurately capture the behavior of the system. Calibrated model setup was achieved by comparing model predictions of the outlet hydrograph to real in situ measurements recorded [9] during a relatively high-level rainfall event. The model was able to mimic the basin routine during the storm with reference to the drain timing, flood peak value, and lag-time, even though it was difficult to perfectly fit the actual measurements due to the hypothetical temporal distribution of the storm event (Figure 5).

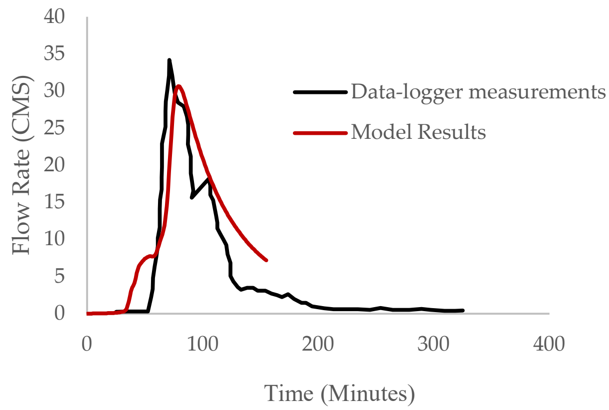

Figure 5. Calibration results show a comparison between simulated and measured overland flow at the mainstream of the Mpazi's watershed on February 23rd, 2013.

III. Results and Discussion

The existing impermeable landscapes with steep slopes and apparent of the watershed small size are causing a significant increase in flood flow rates and accelerate flood wave incursion. Delineated Mpazi's watershed map illustrates the gross flow outpouring point on the mainstream and its two major tributaries, Kove & Ruhurura (Figure 6). The extracted hydrographs at these points for both the existing case and the master plan reveal the significant contribution in flood discharges comes from the over-urbanized zones where the flood water is gathered in Ruhurura; in contrast to Kove, which transports the majority of the overland flows generated from the woods and grass-cover zones (Figures 7a). In like manner, the flood routing behavior of the prementioned tributaries for the master plan 2050 shows a more flat hydrograph at Kove with much less contribution as a result of demolishing the entire urban communities on the western side of the catchment and replacing it with protected areas with higher infiltration potential (Figure 7b).

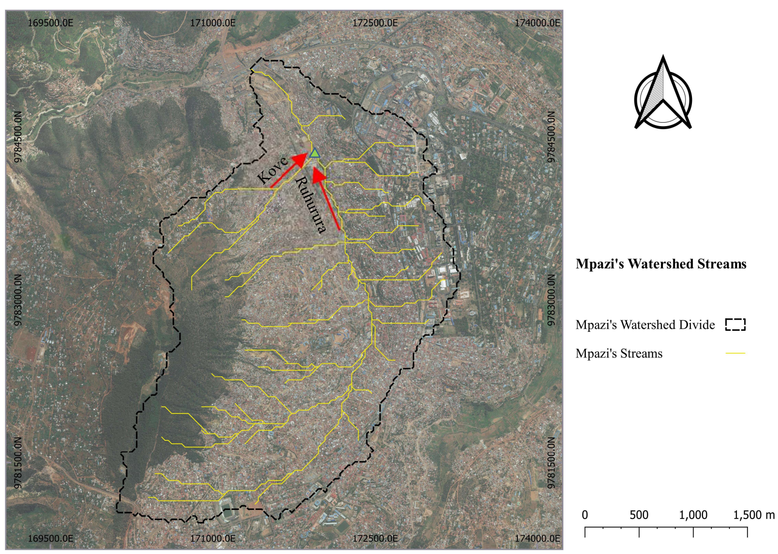

Figure 6. Mpazi's watershed streams map.

The Kigali master plan 2050 indicates a significant attenuation in flood-peak parameters (flow and lag-time) through the latest LULC hydrologic layer definition. As a result, comparing the existing and the master plan scenarios reveal a peak flow rate modulation of about 50% owing to the master plan LULC alteration (Figure 8a). Subsequently, a significant reduction of approximately 50% of the cumulative flood volume in the master plan scenario is also observed, as illustrated in Figure 8b. The alteration of LULC in the master plan 2050 proved the feasibility of suppressing the key quantitative elements of extreme flood events (flood flow rates and volumes) to a certain extent. In contrast, the flood inundation map revealed slight differences in the comparative ratio of the flooded areas between the two scenarios, the existing case and the master plan 2050. In comparison to the existing case, the modeled flood plain for the master plan results in less than 20% reduction of inundated areas and less than 15% in the average stream widths (Figure 9).

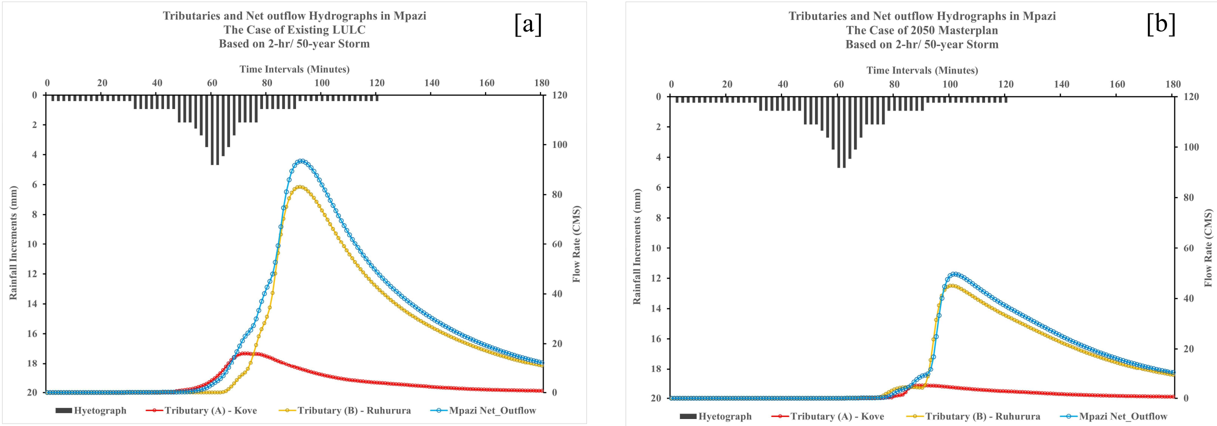

Figure 7. Flow hydrographs represent the two major tributaries and the gross flow in the mainstream at a) the existing case; b) the master plan 2050.

The master plan 2050 shows a significant influence on flood wave attenuation. Nonetheless, the floodplain map shows that properties and lands beside the stream overbanks will still drown. For this reason, some hydraulic investigations are done on the results in order to understand the basin dynamics. The extraction of time-evolution of water depth, at the same spot of junction point at the mainstream, shows rapid water-depth development over the draining time, in both of existing case and the master plan 2050, with a slight comparative reduction by 17% in the peak water-depth of the master plan (Figure 10a). In fact, that implies the topography of the stream might be the point of concern triggering the flood inundation. The extraction of ratting curves at the same spot expresses the behaviour of water levels with respect to flow rates. The rating curves show rapid evolution of the flow stages in the early flow rates. Quantitatively, the cross-section can reach almost 75% of the flood-peak depth while it carries only 20% of the flood-peak discharge (Figure 10b).

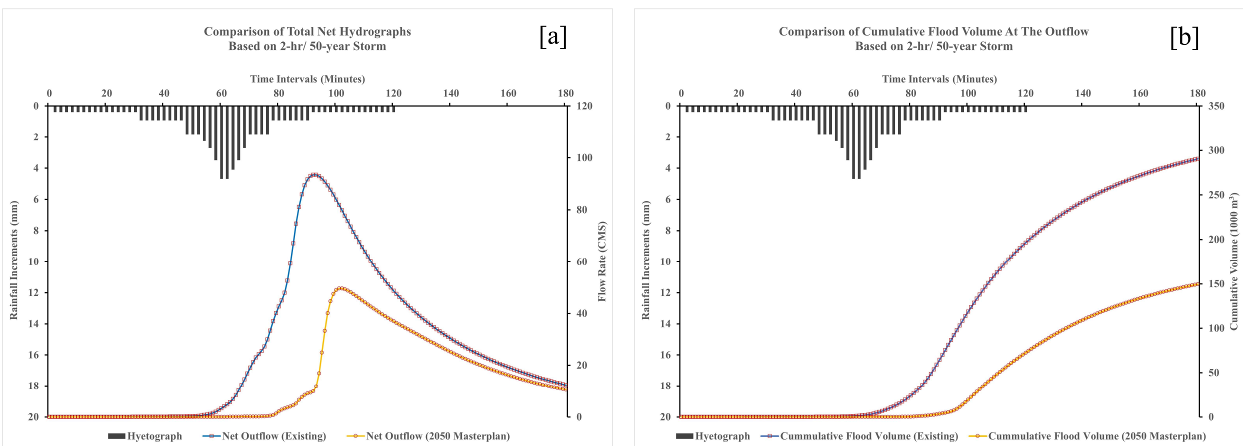

Figure 8. Comparative graphs of the master plan 2050 relative to the existing case in two main aspects: a) flow rates; b) cumulative volume.

Mpazi's watershed streams are encroached by residential settlements at its margins, occupying the natural plain of the valley, resulted in channelizing the valley streams. The developed steepness in the early segments of the rating curve, that drives the small discharges to reach relatively high-water levels, is due to the narrowness of the channelized stream course. As a consequence of the insufficient hydraulic capacity of the bridge vents [9], the bridge works as a bottleneck in the high discharges by retaining the water, subsequently creating a backwater curve which gives rise to taking up all the upstream waters to high levels due to damming effect. The damming effect can be evidenced by comparing the mild segments in the two rating curves for both scenarios (Figure 10b). However, a rating curve is a graph that describes the flow-head behavior of a particular cross-section, and it corresponds to the same flow stage at the same flow rate, but 2050's tends to form milder rating curves due to the less damming than the existing case (Figure 10b). Altogether, a serious damming-induced flow occurs throughout both scenarios, characterized by high water depths in the downstream reaches of the catchment and relatively low water depths at the uphill reaches (Figure 11).

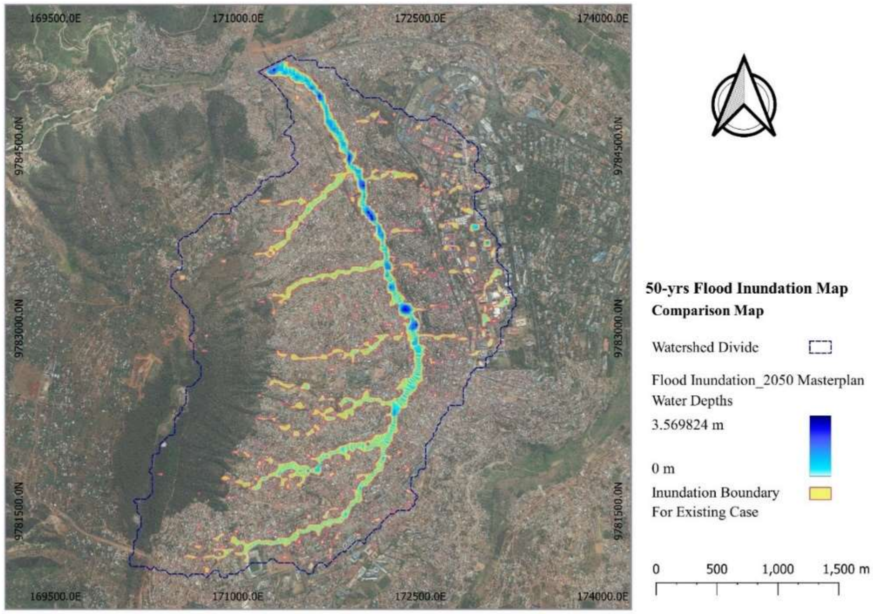

Figure 9. The inundation map depicts the flood plain coverage and depths in both the existing case and the master plan 2050 with different color schemes.

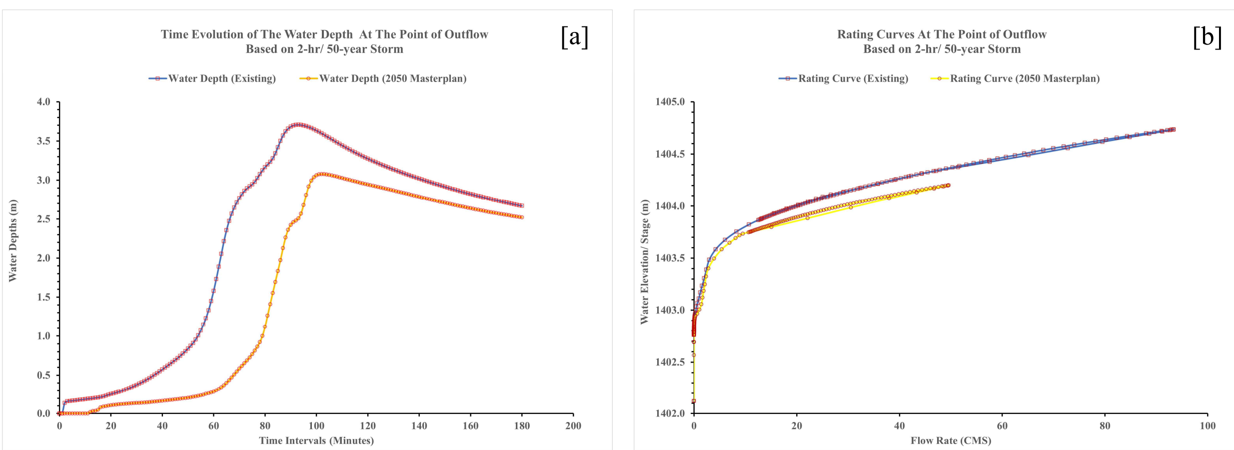

Figure 10. a) Time evolution water-depth graphs at point of outflow for the existing case and the master plan 2050; b) Rating curve graphs at point of outflow for the existing case and the master plan 2050.

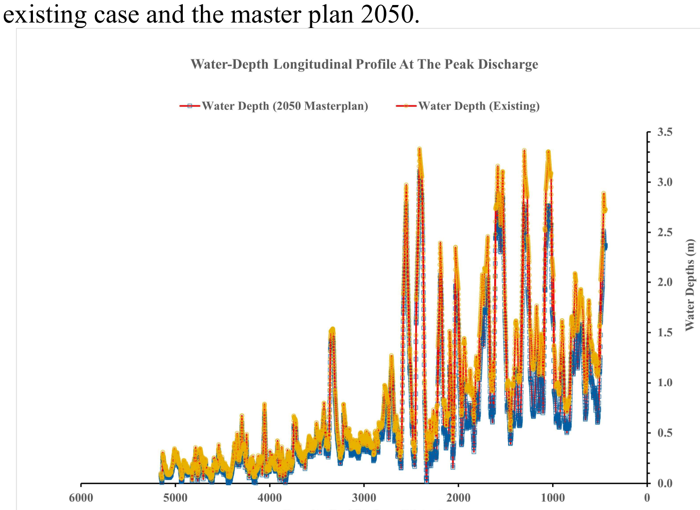

Figure 11. The longitudinal profile shows the development of water depths along the mainstream, from the watershed's furthest divide to the outlet spot (i.e., station 0.0).

4. Conclusions

The hydrologic models results of the current and projected LULC alterations in the Mpazi basin show that the LULC alterations envisioned in the master plan 2050 would significantly attenuate the flood wave by lowering peak flow, delaying drain time, and reducing cumulative flood volume by almost 50%. Despite the significant reduction in flood flow and momentum, the Mpazi settlement is still susceptible to flooding during heavy storms and high discharges. This prompts the investigation of the flood hydraulics of the basin. From the 2D Rain-on-Grid hydraulic model and analysis, we can conclude that the two culverts in the basin are not adequately designed, as they cannot allow the effective flow of water during high discharge, causing water to be retained upstream of the bridge, resulting in a destructive flash flood in the area. Thence, we recommend the removal or rehabilitation of the two culverts along the main streams of the basin to ensure a standard-safe hydraulic behavior and the restoration of the river channel to a more natural state to minimize flood wave superimposition. Also, the remodification of house roofs to green roofs and the implementation of drainage systems, medium-sized retention ponds, and rainwater harvesting systems in all new houses to minimize runoff and increase infiltration. Conclusively, as a safety measure, a buffer of about 100 m on both sides of the major river should be maintained before any residential area is constructed.

Appendix A

Table A1. Kigali's rainfall station IDF parameters [12].

	2-years	*5-years*	*10-years*	*25-years*	*50-years*	*100-years*
α	1040.31	1592.58	2130.82	3047.59	4010.53	5792.7
γ	7.79	10.7	14.94	21.54	27.79	37.88
C	0.86	0.91	0.93	0.95	0.96	0.99

Table A2. Manning's roughness coefficients applied for the different land use categories.

	Land use Category	**Manning's n value**	**Imperviousness %**
LULC Existing Case	Existing dense settlements	0.1	60
	Grassland (good condition cover > 75%)	0.035	0
	Woods	0.15	0
LULC 2050's Master Plan	Low-density residential area	0.1	25
	Protected area	0.07	0
	Medium density residential area	0.1	38

Table A3. Calibrated Estimates of CN's values according to the correlation between the different land uses and hydro-soil grouping.

	Land use Category	**Hydrologic Soil Group**	**Curve Number**
LULC Existing Case	Existing dense settlements	D	90
	Existing dense settlements	C	90
	Grassland (good condition cover > 75%)	D	80
	Grassland (good condition cover > 75%)	C	74
	Woods	D	77
	Woods	C	70
LULC 2050's Master plan	Low density residential	D	85
	Low density residential	C	80
	Protected Area	D	77
	Protected Area	C	70
	Medium density residential area	D	87
	Medium density residential area	C	83

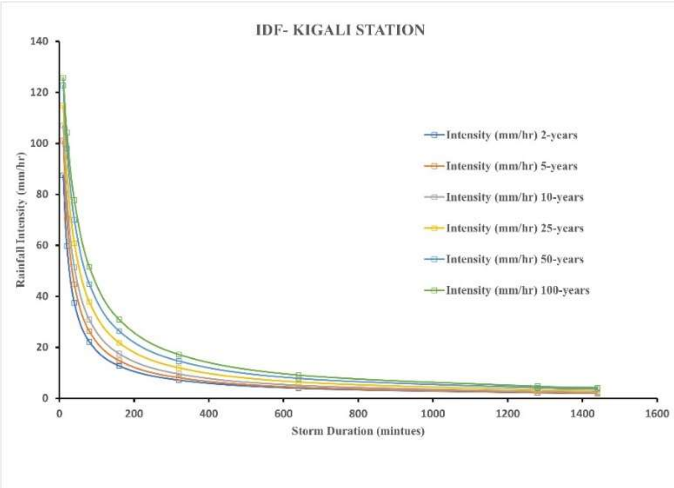

Figure A1. IDF curves for Kigali rainfall station.

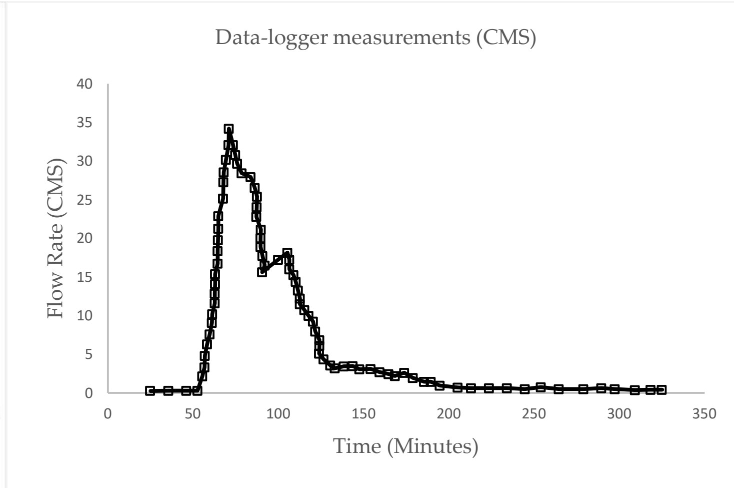

Figure A2. Overland flow records via data- logger on Mpazi's main channel during a rainstorm flood in February 2013 (SHER Ingénieurs-Conseils, 2013).

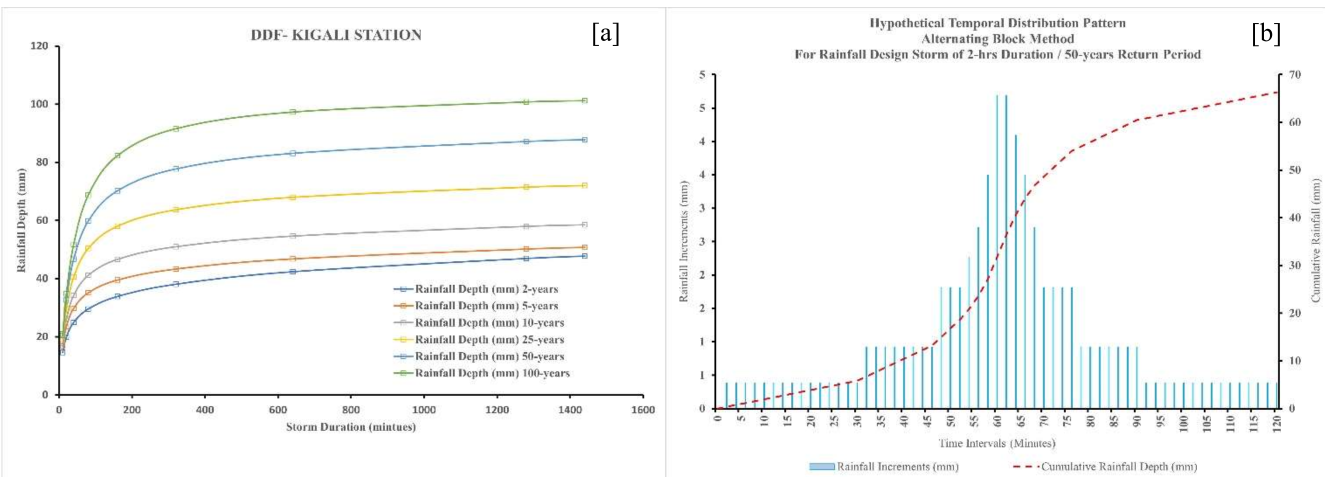

Figure A3. a) Calculated DDF-curves for different return periods at Kigali's rainfall station; b) Alternating Block hypothetical distribution for the total rainfall depth (66.26 mm for 50-years return period) over 2-hrs storm duration.

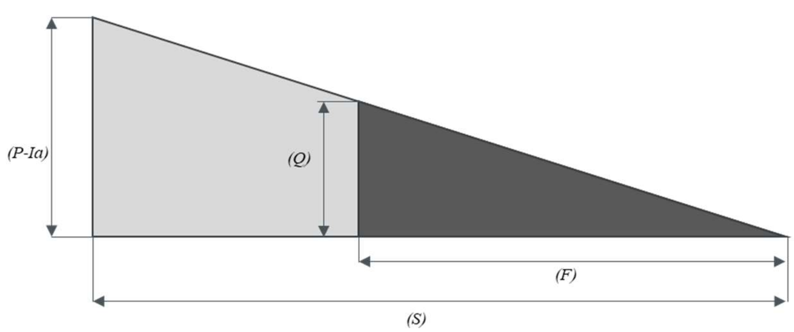

Figure A4. SCS-CN Proportionality Concept.

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