Diagnostic assessment on urban floods using satellite data and hydrologic models in Kigali, Rwanda.

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***Abstract*—The Nyabugogo commercial center of Kigali city is geographically located between the Mont Kigali and Jali forming a bottleneck. Frequent flooding, of which no records are available, have characterized the area for the past few years. Additionally, the area hydrological behavior knowledge was lacking. This study provides an assessment of the frequent flooding in the area using hydrologic models and satellite data. CMORPH 8Km 30min, time variably bias corrected, is used to assess the rainfall events likely to cause flooding with their patterns. The HEC-HMS Curve Number (CN), Muskingum routing and base flow recession sub models are used to estimate the upstream area runoff later serving as upstream boundary conditions to the 1D2D flood model of the area set up with the national 10X10 m DTM and measured river cross sections developed in SOBEK 1D2D. Local regionalization of optimum parameters from gauged sub catchments rainfall-runoff models, using area and main channel length conversion with their proximity factors, is applied to model the runoff from ungauged systems. The Peak weighted root mean square error (PWRMSE), relative volumetric error (RVE) and Nash-Sutcliff (NS) are used as objective functions for the rainfall-runoff model calibration. A PWRMSE of 3.4, RVE of -4.9 and NS of 0.6 were obtained after calibration. 4 extreme rainfall events were detected with a spatial-temporal pattern exhibiting a horizontal movement from east to west with higher amounts observed during March-April-May and October-November-December. Results indicated flash floods in the area with 7 sub catchments found to contribute much runoff in the Nyabugogo River during flooding. Also, the flood extent, depth and velocity were affected by the DEM resolution, building representation and significantly by the surface roughness. Strong backwater effects at the confluence points of the Nyabugogo River and its tributaries Yanze and Mpazi act as triggers to flooding during heavy rainfall.**

***Keywords*—1D2D flood model, CMORPH, Extreme rainfall events, Rainfall-runoff model, Local regionalization.**

I. INTRODUCTION

Floods belong to the most common and damaging hazards (Sanders, 2007) usually experienced in forms of death, displacement, evacuation, homelessness, injury, etc.

In Rwanda, frequent flooding have become among the major problems, in Kigali city as well due to population densification and rapid urbanization (REMA, 2009). An analysis of the flood exposure and vulnerability of Kigali city using a flood risk analysis model adapted to the city's situation is provided by Bizimana and Schilling (2010). The study influenced new urban policies like restriction of building in floodplains and relocation of the former Kiruhura market. Recently, the RNRA/IWRMD[1] conducted a special investigation on the flooding issue of the Nyabugogo commercial center which indicated rapid hydrologic responses of highly urbanized sub catchments like Mpazi as main flooding triggers. Also, poor management and upgrade of existing urban structures leading to the reduction of water conveyance capacity was highlighted (SHERIngénieurs-Conseils, 2013). The investigation also indicated a lack of knowledge and practice in the country towards flood prediction and management which was reflected in the data scarcity for flood studies and management during the course of this study.

The study objective is to develop a flash flood model for the data scarce Nyabugogo commercial center. The understanding of the frequent flooding causes in the area is the main driver to this research. Remote sensing data, rainfall-runoff and 1D2D hydrodynamic modelling in HEC-HMS and SOBEK 1D2D respectively, are used to diagnose the flood behavior of the Nyabugogo catchment and effectively parameterize the system for flood modelling. Data model integration is inherent and a scientific challenge in this study.

II. MATERIALS AND METHODS

Study area

The Nyabugogo catchment, on figure *1,* have around 1,540 square kilometers (sq. km) including the Lake Muhazi draining the upstream area of 878.7 sq. km.

The conceptualization of the study area was based on the two developed hydrologic models approaches as shown on figure 1. The flood model domain covered the frequently flooded area of the Nyabugogo commercial center and the river floodplain up to the Nyabugogo River gauging station.

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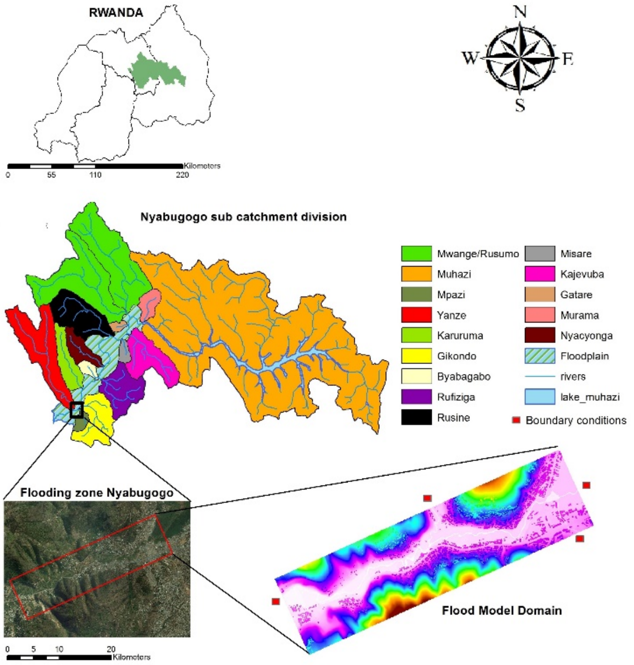
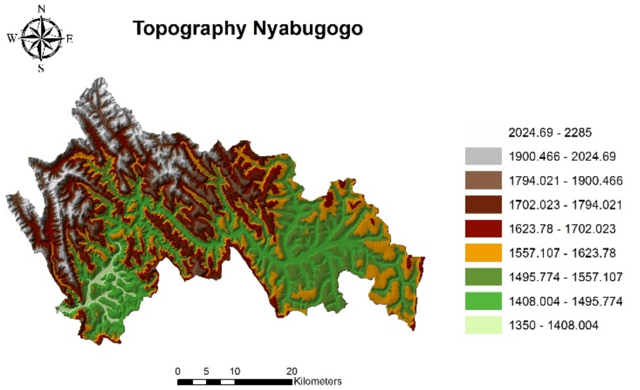
[1] Rwanda Natural Resources Authority/Integrated Water Resources Management Department.

Figure 1: Study area conceptualization.



A complex topography varying between 1,350 and 2,300 m a.s.l. characterizes the Nyabugogo catchment. The climate of the Nyabugogo catchment is a tropical temperate climate with an average precipitation per annum of 1,200 mm and a temperature varying between 19 and 21 degree Celsius (Musoni, 2009).

Figure 2: Study area topographical map.



The major land use and land cover are rain fed agriculture, irrigated wetland and small forest plots in the center and eastern part as well as small natural open lands. A significant built up area is observed in the catchment because of the city of Kigali.

▪ Materials

For rainfall-runoff modelling, preprocessed collected rainfall and discharge data of the years 2011, 2012 and 2013 with a LULC, soil and topographic data were used. Additionally, for flood modelling bias corrected satellite rainfall data were used.

Among all the available daily rainfall stations only 10 were used, refer to figure 3. Few stations were found with missing data and erroneous data, refer to table 1.

Data collected for discharge estimation were the available water stages and field measurements of discharge at the Rusumo, Yanze and Nemba gauging stations. Also, a gauge at Lake Muhazi with no records on a fixed outlet weir was used.

Figure 3: Thiessen polygons.

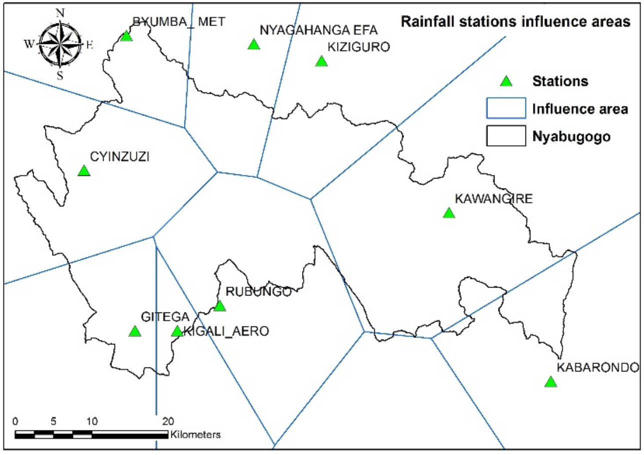


Table 1: Missing and Erroneous data per rainfall station.

#	Station name	Missing dates	Erroneous dates
1	Byumba met	20	0
2	Cyinzuzi	242	29
3	Gitega	0	1
4	Kabarondo	23	0
5	Kawangire	26	0
6	Kigali_aero	0	0
7	Kiziguro	300	0
8	Nyagahanga efa	95	0
9	Rubungo	31	0
10	Zaza	19	0

The topographical data used were the SRTM DEM[2] for the Nyabugogo catchment hydro-geomorphological parameterization and the 10 m resolution DTM[3] available locally for the 2D grid development at different resolutions.

For adequate river geometry representation, a topographic survey, refer to figure 4, was done using a total station.

Flood depth observations on site, illustrated on figure 5, were collected on the basis of local's interviews and identification of flood marks.

High spatial-temporal resolution of rainfall observations were required for flash flooding analysis. This was obtained using the time variably daily based bias corrected CMORPH 8km at 30 minutes (Habib et al., 2014) for the detection of extreme rainfall events and their patterns.

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[2] Shuttle Radar Topography Mission Digital Elevation Model

[3] Digital Terrain Model

Figure 4: Topographical points on the Nyabugogo River.

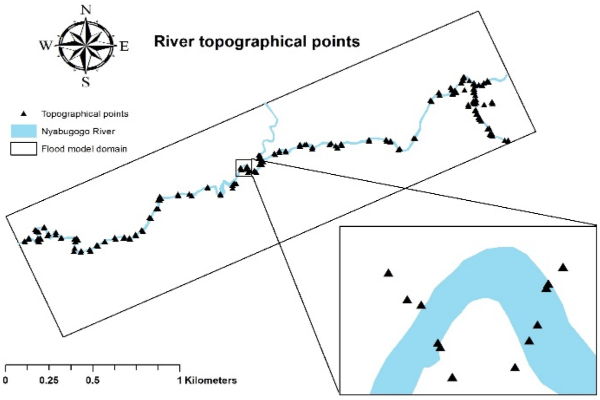
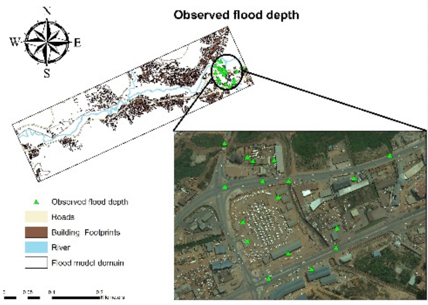


Figure 5: Flood depth observation points.



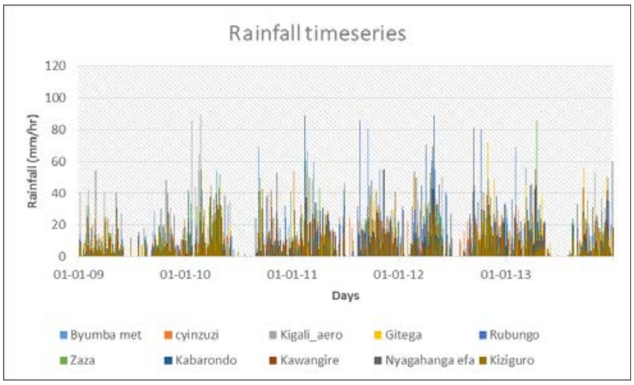
#	X	Y	Depth m
1	504964.20	4785307.41	0.60
2	505107.27	4785412.58	0.20
3	504910.67	4785424.90	0.40
4	504951.89	4785510.64	0.30
5	505217.65	4785563.70	0.30
6	504872.77	4785498.80	0.50
7	504975.57	4785554.23	0.50
8	504895.04	4785663.18	0.30
9	504871.83	4785588.34	1.20
10	505005.89	4785511.12	0.50
11	504919.67	4785560.38	0.60
12	504940.52	4785640.03	0.70
13	505054.21	4785325.89	0.60
14	505105.38	4785371.37	0.50
15	505005.42	4785359.05	0.70
16	505143.75	4785515.86	0.40
17	504919.67	4785385.11	0.60
18	504984.10	4785477.00	0.50
19	504931.52	4785551.86	0.70

Data preprocessing

The rainfall data consistency check using the daily cumulative double mass curve analysis (Searcy and Hardison, 1950), indicated high correlation between stations.

Filling in, illustrated on figure 6, was done with a combination of 2 methods. Simple linear regression (Helsel and Hirsch, 1992) for gaps less than a week and the modified normal ratio method (Tang et al., 1996). The resulting time series per station was quality checked as described by Debru (2010).

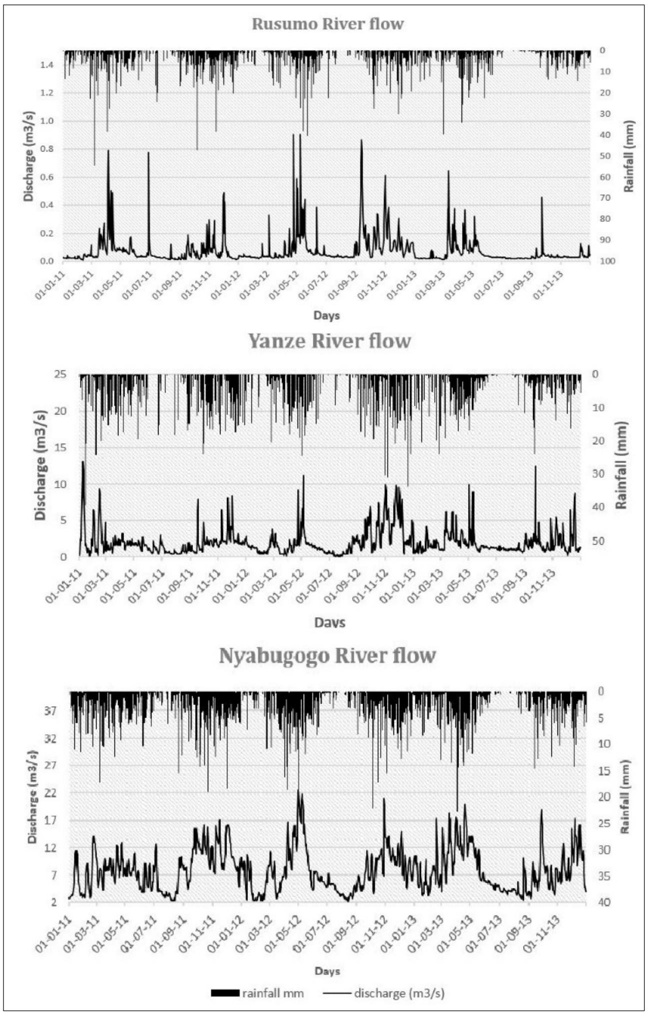
Figure 6: Filled in and corrected rainfall time series.



The effects of altitude among the rainfall stations were assessed by analyzing the relationship between the altitude and annual rainfall. These effects were negligible in the study area since the regression coefficient of the relationship was found less than 0.55. The Thiessen polygon method (Searcy and Hardison, 1950, Wanielista et al., 1997) was used to estimate the aerial rainfall.

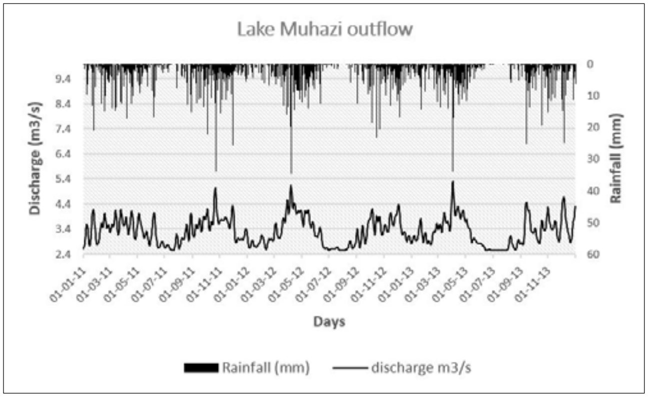
Discharge estimations for gauged systems, provided on figure 7, with available field discharge measurements and water stages were done using the simple rating curve fitting method (Braca and Futura, 2008). The filling in and correction methods used were the linear interpolation and interpolation between the logarithmically transformed values of the beginning and end of the gap (Hydraulics, 1999). For the consistency check and outliers removal, the rates of change were compared to the corresponding rainfall change rates (Debru, 2010) and detected outliers were removed (Hoyos Goez, 2011).

Figure 7: Corrected Hydrographs of Rusumo, Yanze and Nyabugogo Rivers respectively.



To estimate the discharge of the lake Muhazi, refer to figure 8, based on the water marks on the gauge (considered minimum and maximum water levels) and the lake outflow fixed concrete weir were used. Effective rainfall obtained using the curve number method (Feldman, 2000) over the lake Muhazi catchment was normalized to the water level limits and transform to discharges using the manning's equation (Bray, 1979).

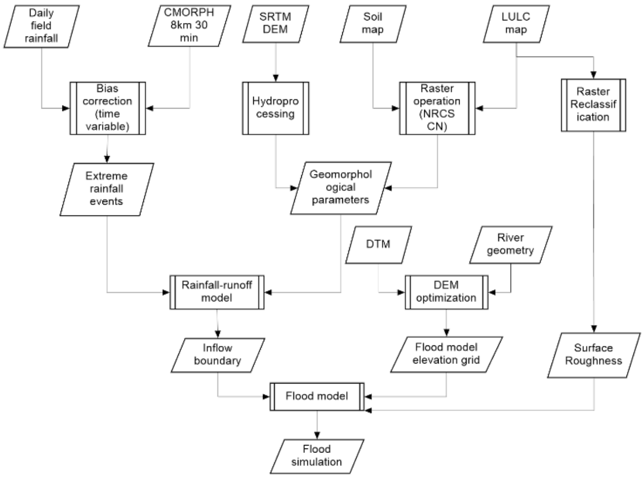
Figure 8: Estimated hydrograph of the Lake Muhazi.



▪ Methodology

Figure 9 illustrates the conceptual framework of the study approach.

Figure 9: Conceptual framework of the study.

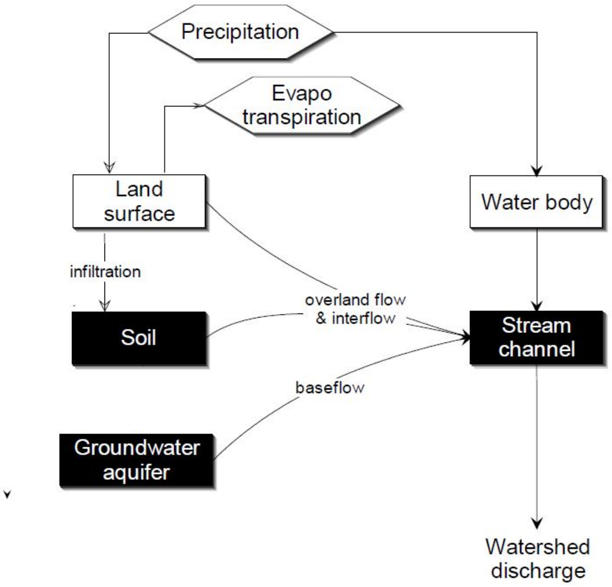


Extreme rainfall events identification was done based on the Nyabugogo catchment hydrograph peaks and the corresponding rainfall. 2 weeks windows were taken in order to ensure that all the spatial-temporal aspects of rainfall variability were accounted for. The maximum daily rainfall per window was selected. To obtained high spatial-temporal resolution, from the maximum daily rainfall selected, the CMORPH 8km 30 min product time variably corrected was used.

To estimate the geomorphological parameters of the study area, the DEM hydro processing (Maathuis and Wang, 2006) and the NRCS CN[4] model (Feldman, 2000) were used.

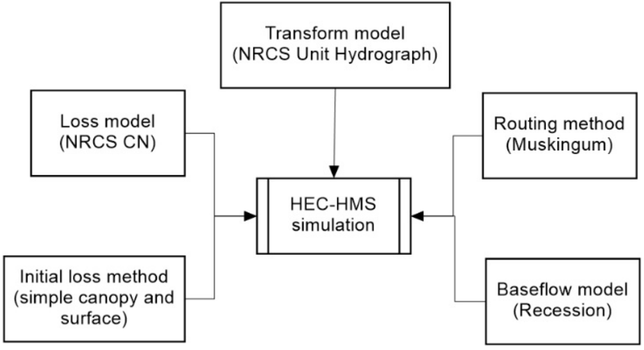
HEC-HMS (Feldman, 2000) was used for rainfall runoff modeling. A simpler approach, illustrated on figure 10, was adopted as suitable for flood studies. Separate sub models available in HEC-HMS were used, as illustrated in figure 11, based on their suitability for event modeling as well as data availability and limitations. The purpose of the sub models combination was to enable estimation of all required parameters values from the available data. Unknown values of ungauged sub catchments were estimated from the local regionalization of the optimum parameters obtained from the calibration of the gauged sub catchment models.

Figure 10: Watershed Representation adopted.



Source: Arlen D. Feldman, HEC-HMS User manual.

Figure 11: Adopted HEC-HMS sub models.



The objective functions used for calibration of the rainfall-runoff model were the Peak Root Mean Square Error (PRMSE) (Feldman, 2000), the Nash-Sutcliff coefficient of efficiency (NS) (Nash and Sutcliffe, 1970) and the Relative Volumetric Error (RVE) (Rientjes et al., 2011).

Local regionalization of the obtained optimum parameters was done based on the principles of rationing of the river length and area conversion and the proximity factor with respect to gauged sub catchments.

A representation of the study area for flood modeling was done using the available DTM used to interpolate the terrain while the measured topographic points were used to represent features like main channels, roads, etc. The kriging and inverse distance weighting methods were compared to assess their interpolated result differences. These were found negligible.

Sobek 1D2D (Delft/Hydraulics, 2014) was used for flood modeling. A combination of 1D and 2D approaches to simulate water flow in river reaches, riverbank overflow and flow in floodplains (Haile, 2005). The water flow computation was done by solving the complete Saint-Venant equation using the Delft-scheme numerical solver.

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[4] Natural Resources Conservation Services Curve Number

For 1D flow, the 2 equations solved are:

- The continuity equation (1D):

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \qquad (1)$$

- The momentum equation (1D):

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + gA_f\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2RA_f} - W_f\frac{\tau_{wind}}{\rho_w} = 0 \qquad (2)$$

The terms in equation (2) describes the inertia, the convection, the water level gradient, the bed friction and the wind friction respectively.

For 2D flow, the 3 equations solved are:

- The continuity equation (2D)

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \qquad (3)$$

- The momentum equation (2D) in the x- and y-direction

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{u|\vec{u}|}{C^2h} + au|u| = 0 \qquad (4)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{v|\vec{u}|}{C^2h} + av|v| = 0 \qquad (5)$$

The terms in the equations (4) and (5) are respectively the acceleration, horizontal pressure gradient, convective, bottom friction and wall friction terms. The descriptions of symbols in the equations are provided in table 2.

Table 2: Symbols, Quantity and Units used in equations (1), (2), (3), (4) and (5).

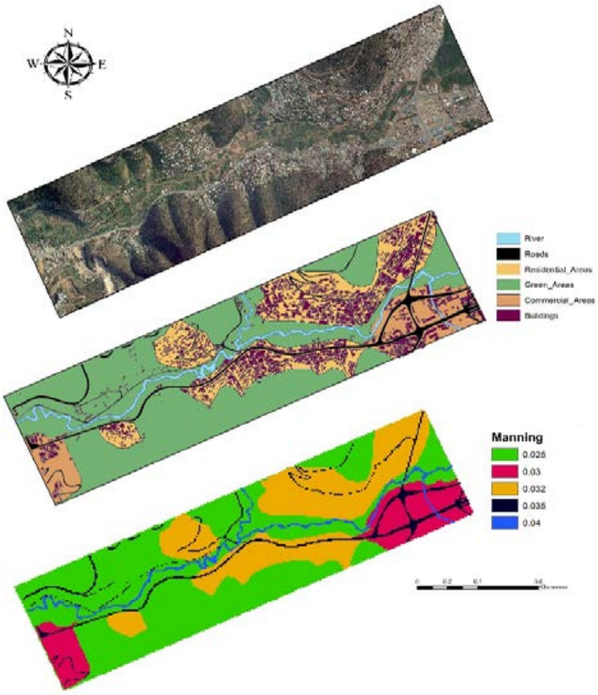
Symbol	Quantity	Units in SI [a]
A_f	Cross sectional area	L^2
Q	Discharge	L^3T^{-1}
q_{lat}	Lateral discharge per unit length	L^2T^{-1}
W_f	Cross sectional width at the water level	L
C	Chezy coefficient	$L^{1/2}T^{-1}$
R	Hydraulic radius	L
ρ_w	Water density	ML^{-3}
τ_{wind}	Wind shear stress	$LT^{-2}M^{-1}$
h	Water level	L
u	Velocity in x-direction	LT^{-1}
v	Velocity in y-direction	LT^{-1}
$\lvert\vec{u}\rvert$	Velocity magnitude	$L^{1/2}T^{-1}$
ζ	Water level above reference plane	L
d	Depth below reference plane	L
a	Wall friction coefficient	L^{-1}

[a] SI units are L= length, T= time and M= mass in kilogram.

Table 3: Manning's coefficient per LULC classes.

#	LULC Classes	Manning's coefficient
1	Green areas	0.025
2	Commercial zones	0.03
3	Residential areas	0.032
4	Roads and parking	0.035
5	River channel	0.04

Figure 12: Study area roughness map.



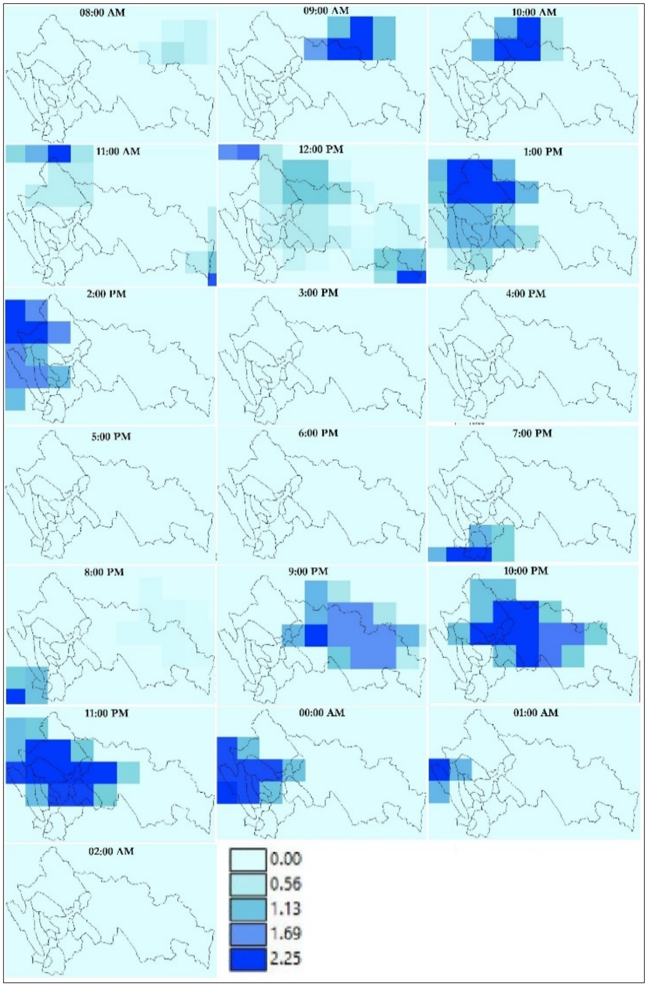
Manning's coefficients were used to define the roughness in the flood model based on five land cover land use classes of the study area. The tabulated values of manning's coefficient (Tennakoon, 2004) used per land cover land use are illustrated in table 3 and figure 12. The digitized building footprints served as basis for building representations in the flood model. These were represented as solid (requiring pixels height to be raised), partially hollow and hollow blocks; obstructing, partially obstructing and not obstructing the 2D water flow respectively.

III. RESULTS & DISCUSSIONS

- **Extreme rainfall events**

November 28th, 2011 to December 7th, 2011; May 3rd, 2012 to May 14th, 2012; October 21st, 2012 to November 1st, 2012 and March 11th, 2013 to March 20th, 2013 were selected for the detection of extreme rainfall events which were done on catchment area basis. The 4 detected extreme events were found with similar characteristics. All were extended on a 2 days period within which 2 successive events in an interval less than 24 hours were detected and the rainfall patterns were found to have a horizontal axis from East to West with a vertical inclination from North West to South East. Similar findings regionally are reported by Gamoyo et al. (2014).

Figure 13: Rainfall event pattern.



The sub catchments of Byangabo, Karuruma, Mpazi, Nyacyonga, Rugunga, Rusine and Yanze were classified as receiving much water during the 4 detected extreme events based on the heights of peaks per sub catchments with respect to the highest peak per extreme event.

- **Rainfall-runoff model**

The adopted sub models were found weak in simulating the base flow as the model was forced in a continuous mode while it is adapted to event modelling. However, the peak discharges were well captured. The results are summarized in table 4 and figure 14.

Figure 14: Simulated hydrographs of Rusumo, Yanze and Lake Muhazi respectively.

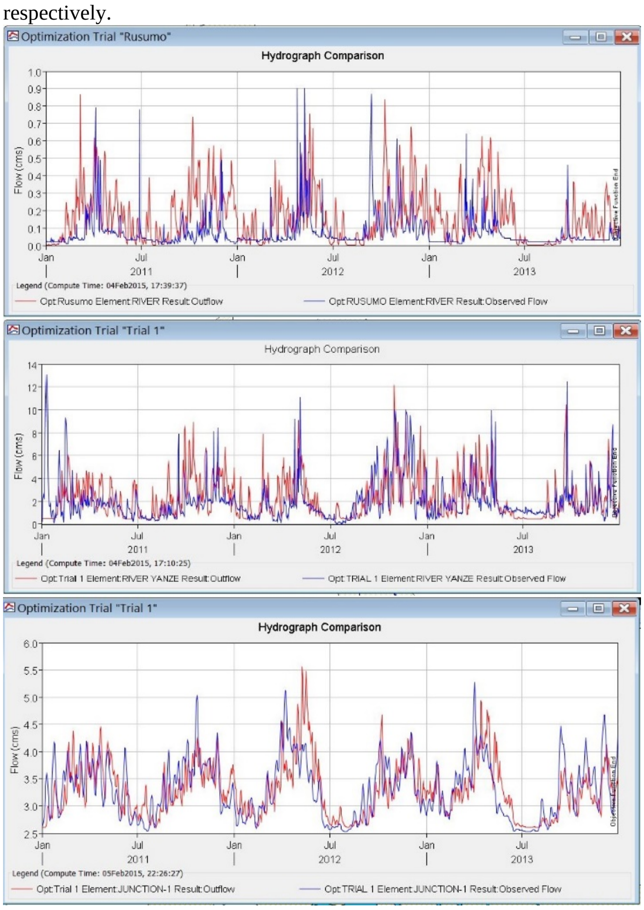


Table 4: Calibration outcomes and optimum parameters.

#	Parameters	Sub catchments		
		Rusumo	Yanze	Lake Muhazi
1	X	0.0010052	0.00078471	N/A
2	K (hr.)	29.311	25	N/A
3	Recession constant	0.95411	0.995	N/A
4	Initial base flow (m3/s)	0.031849	1.0276	N/A
5	Threshold base flow (m3/s)	0.0752987	1	N/A
	Objective functions	Values		
1	PWRMSE	0.2	0.6	0.4
2	NS	0.55	0.6	0.5
3	RVE	32.5	18.4	-0.51

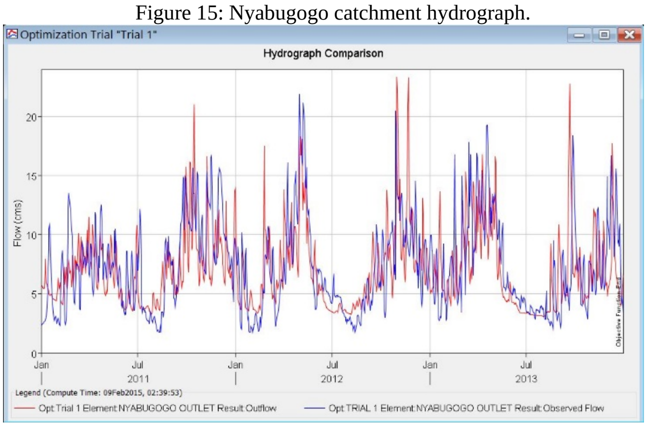
The ratios applied for local regionalization of optimum parameters for ungauged sub catchments are presented in table 5.

The Nyabugogo catchment hydrograph is illustrated in figure 15. The obtained calibration results of the model were a PRMSE of 3.4, a NS of 0.6 and a RVE of -4.9.

Table 5: Local Regionalization ratios.

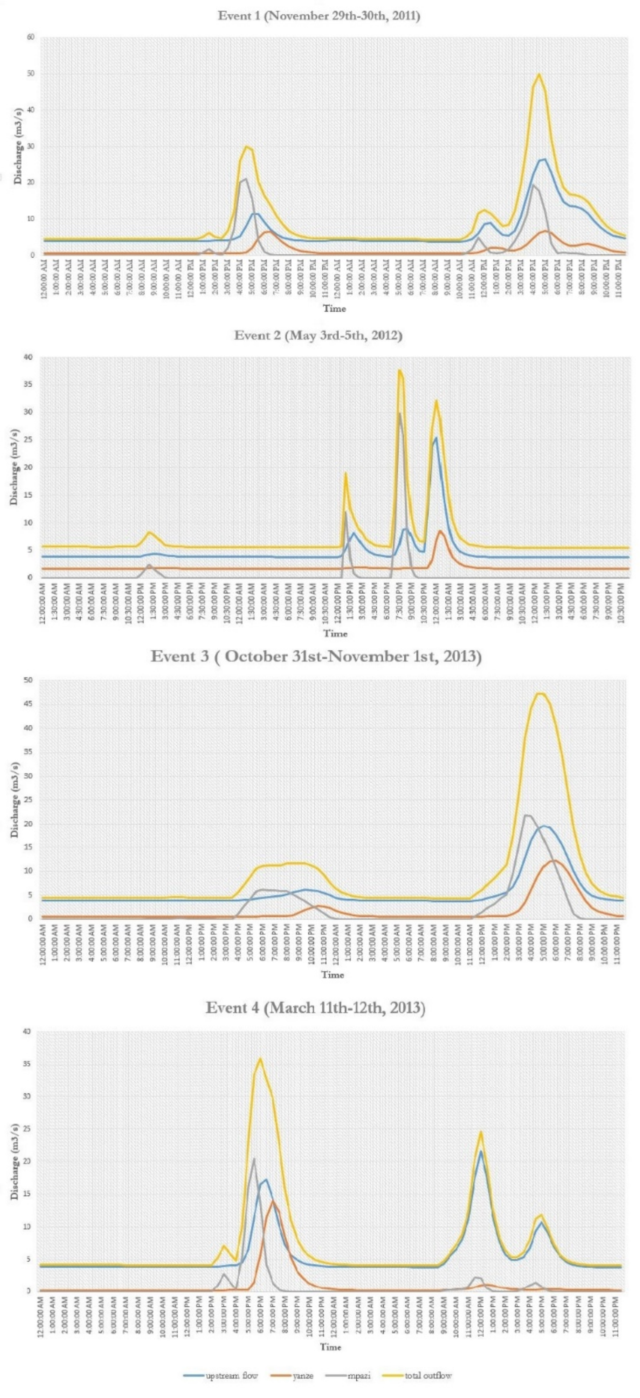
Optimum parameters	Rusumo sub catchment	Yanze sub catchment	Applied ratios	
K (hr/km)	1.331	1.555	length conversion	proximity factor applied
X (/km)	0.00004565	0.0000488		
Recession coefficient	0.95411	0.995	Average	0.9745
Initial base flow (m3/s/km2)	0.0002469	0.0106	Surface conversion	0.0054
Threshold base flow (m3/s/km2)	0.0005837	0.01035		0.0054
Sub catchments within proximity	Mwange, Rusine, Murama, Kajevuba, Gatare, Misare and Nyabugogo reach 1	Rugunga, Nyacyonga, Karuruma, Rufigiza, Byangabo, Nyabugogo reach 2 and Nyabugogo reach 3		

Figure 15: Nyabugogo catchment hydrograph.



The estimation of the upstream area inflows used as boundary flows of the flood model, were obtained by forcing the detected extreme rainfall events into the rainfall-runoff model. Figure 16 illustrates the upstream area, Mpazi and Yanze sub catchments flows and the total outflow as aggregated from all the upstream inputs. The analysis of the inflow contribution per sub catchments per extreme rainfall events revealed that Yanze, Mpazi, Karuruma, Nyacyonga, Rufigiza and Rugunga contributed much runoff. The Lake Muhazi was also observed as a heavy contributor to runoff during extreme rainfall event with a dumping effect on the water release due to its area.

Figure 16: Flood model upstream boundary conditions.



- **Flood model**

A step wise based approach, due to data scarcity, was applied to ensure efficient flood model set up.

Figure 17 illustrates the river longitudinal profile obtained from the topographic survey. Negligible differences are observed for the different spatial resolutions used.

The effects of the DEM resolution were assessed and are summarized in table 6. It was observed that coarser DEM resolution led to higher flood depth, extent and velocity as well as lower computational time. It was therefore observed that the topographic representation and spatial discretization affects the flood model outputs as reported by many authors like Md Ali et al. (2015), Zhang et al. (2014), Haile (2005), Tennakoon (2004), etc.

The sensitivity of the flood model with regard to the roughness was assessed. The sensitivity analysis illustrated on figure 18 indicates that the flood model is very sensitive to the main channel roughness, as similarly reported by DeChant (2014).

The assessment of the building representation effects in the flood model, illustrated in figure 19, indicated that higher values of flood depth and velocity were observed for buildings as solid blocks due to the flow obstructions while larger flood extents were observed for building as partially hollow blocks due to the delay in releasing flood water. Similar observations were highlighted by Haile (2005).

The simulation results, on figure 20 and 21, revealed that the Nyabugogo River was filled with the upstream areas runoff before receiving any from the Mpazi and Yanze tributaries. Significant backwater effects and high velocities at the confluence points occur due to high water levels in the river inducing overflowing of water which dissipate quickly.

Figure 17: Nyabugogo river longitudinal profiles.

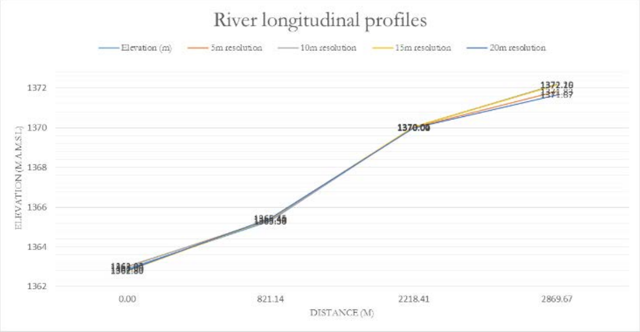


Table 6: Effects of DEM resolutions.

#	DEM	Depth (m)		Velocity (m/s)		Extent area (m2)	Computation time (hrs)
		Max	Mean	Max	Mean		
1	5m	5.267	1.565	3.23	0.442	201700	97
2	10m	5.524	1.315	3.579	0.465	280100	25
3	15m	4.266	1.034	3.301	0.415	430650	10
4	20m	5.398	1.511	4.4	0.579	444800	4

Figure 18: Surface roughness sensitivity analysis plot.

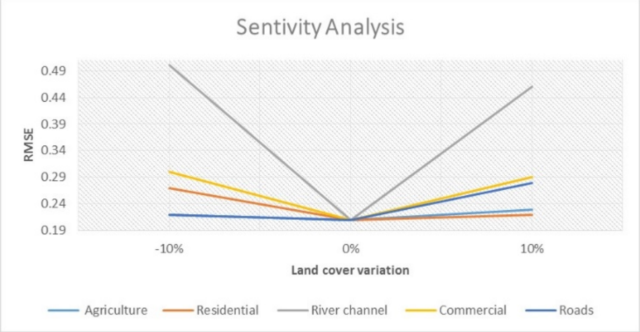


Figure 19: Building representation effects.

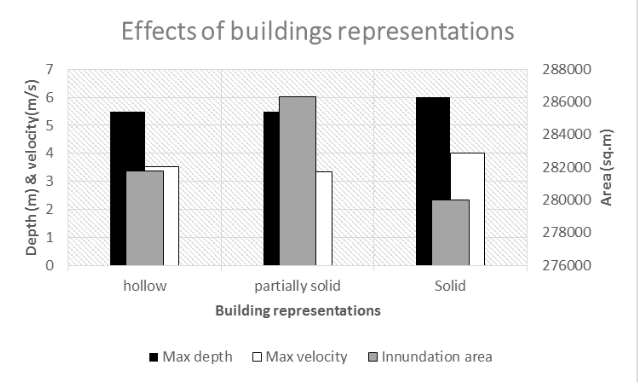


Figure 20: Simulated flood depths.

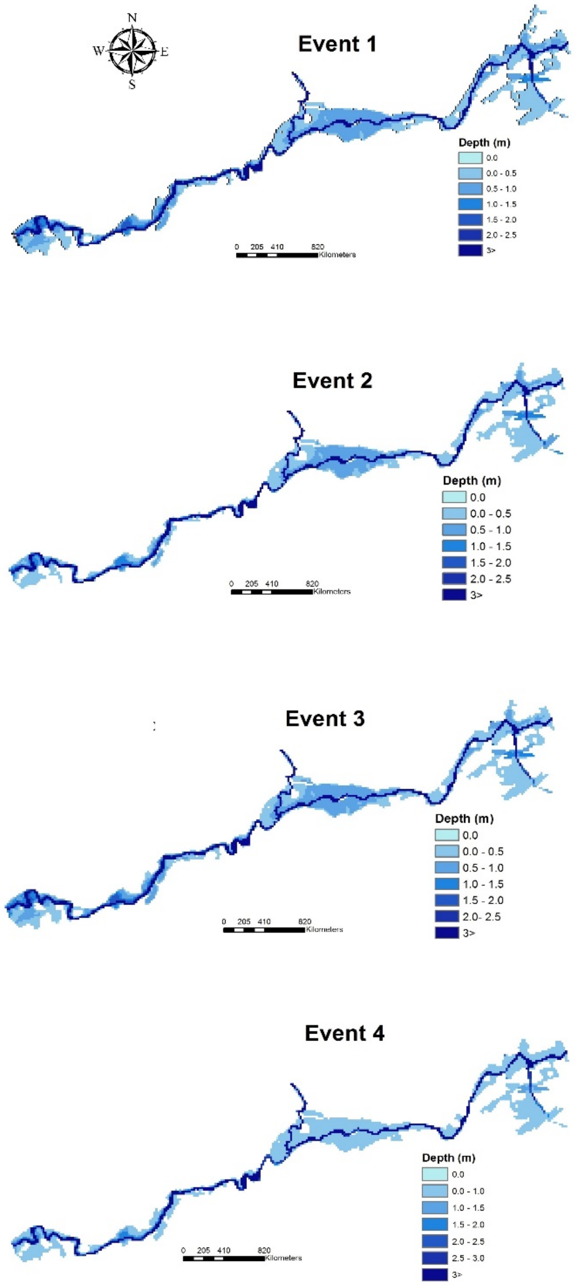
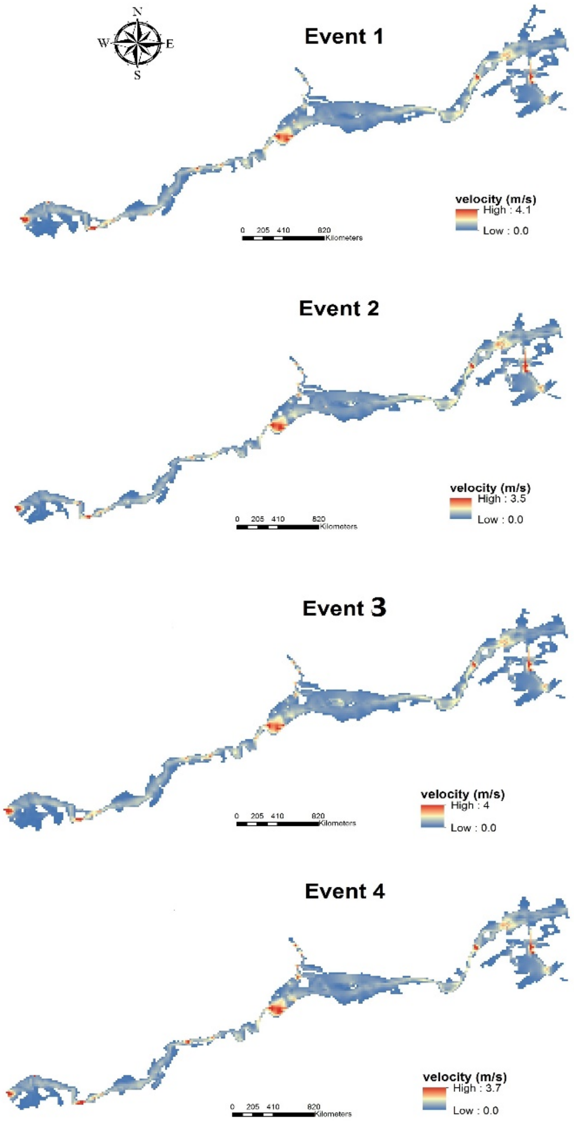


Figure 21: Simulated flood velocities.



IV. CONCLUSION & RECOMENDATIONS

Conclusion

The study developed a flash flood model of Nyabugogo commercial centre using remote sensing data, rainfall-runoff and 1D2D hydrodynamic flood modelling. The data scarcity and their integration in the hydrologic models used, was inherent and a scientific challenge.

A combination of daily rainfall measurements and satellite rainfall allowed the detection of extreme rainfall events at high spatial-temporal resolutions as well the understanding of their patterns.

Rainfall-runoff modelling was used to estimate the upstream area runoff, serving as boundary conditions to the flood model. The combination of sub models used were found weak in simulating base flows, however the target was peak simulation to enable flood assessment in the area. Local regionalization of optimum parameters was done in order to estimates the runoff of ungauged sub catchments. 3 objective functions (PRMSE, NS and RVE) were used for the calibration of the rainfall-runoff model.

Flood modelling was done stepwise based to compensate for the data scarcity. This exercise allowed assessment of the DEM resolution, building representations and surface roughness effects on the model results; and the hydrological behaviour of the Nyabugogo catchment was revealed.

The major limitation was data scarcity for extreme rainfall events and flood characterization. Even though this was a scientific challenge, a calibration and validation of the flood model could not be performed. This limitation led to the methodology that was presented.

Recommendations

The daily rainfall measurements does not fully capture extreme rainfall events. This should be improved and a denser automated network be installed.

The flow measurement practices using local observers only have proven to be weak in terms of quality and quantity. Solutions like data logger should be looked at as well as a network densification for improved measurements.

Only one satellite product was applied for the detection of extreme rainfall events based on available literatures. The application of satellite rainfall products for flood modelling was found not common and therefore assessment of more satellite products is highly recommended.

2 hydrologic models were used for this study. It is recommended to apply different hydrologic models structures for further assessments.

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