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Design Of Hydraulic Structures For Sustainable Runoff Control In Kinamba Sub-Catchment, Rwanda

Twizeyimana Tharcisse[1*], Prof. Dr. Muthiah Sankaranarayanan[2]

[1]Department of Agricultural Engineering, RP-IPRC Musanze, Rwanda

[2]Department of Agricultural Engineering, University of Rwanda, Rwanda

[*]Corresponding Author. Email: cisset45@gmail.com

Abstract – The process of urbanization is among the causes of the continuous increase of flood hazard events and the associated losses worldwide; mainly due to the increasing impervious surfaces and the exposure of people and their wealth. (Muis et al., 2015) In Rwanda, mainly in Kigali City, heavy rainfall events cause rapid surges in the flow of rivers and drainage systems leading to floods in the downstream. It has been identified that inadequate drainage system in Kinamba sub-catchment located in Nyabugogo catchment is the major cause of flooding in the downstream of that area.The aim of this study was to design hydraulic structures for sustainable runoff control in Kinamba Sub-catchment. Daily rainfall data for 30 years have been collected from Gitega meteorological station. The peak runoff water discharge has been calculated by using the rational method and its prediction in 30 years by using the linear model. In this research ArcGis played a key role while analyzing spatial data.The results showed that the two existing culverts are capable of carrying water discharges at 91.168 m^3/ sec while the estimated current peak runoff discharge is 108.73 m^3/sec while considering daily maximum rainfall of 98mm. The population growth rate increase compelled to estimate the future area to be covered for facilitating human settlement. It was found that in next 30 years, all easily usable area will be covered by population leaving around 6.5% area. The remaining catchment area would be covered by houses and roads with a predicted discharge rate of 118.41m^3/sec during next 30 years.Based on the needs, a trapezoidal channel of designed 14.27 m^2 cross section has been recommended along with a rectangular box culvert with 6 boxes of 2.8m depth and 2m width with a discharge carrying capacity of 118.41 m^3/sec. It is also recommended to have household level water harvesting and management of catchment area by keeping balance in housing and open area while respecting Rwanda housing policy.

Keywords – Sustainable runoff control, Sub-catchment, Hydraulic structures

I. INTRODUCTION

The process of urbanization is among the causes of the continuous increase of flood hazard events and the associated losses worldwide; mainly due to the increasing impervious surfaces and the exposure of people and their wealth (Muis et al., 2015)

Urban impervious surfaces, houses, roads, and many more reduce the infiltration capacity of the rural catchment (Hollis, 1975).

This results into the upsurge in the amount of water available for runoff and leading to flash floods. In addition to the increase of the impervious surfaces, there is the soil compaction. According to the research done by Olson et al. (2013) , the infiltration capacity of the soils can reduce up to 70 to 99% due to the compaction induced by construction activities. Besides, some other unintended activities like moving trucks and humans also increase compaction (Randrup and Dralle, 1997).

On the other hand, the urbanization process influences the positive trends in total losses associated with flood hazard. As reported by Bouwer (2010), the flood plains being the preferred places for urbanization, continuous increase of the population and their properties in those flood prone areas significantly increase the impacts of flood regardless of the change in the intensification of the frequency of hazardous flood events. In Rwanda, mainly in Kigali City, heavy rainfall events cause rapid surges in the flow of rivers and drainage systems leading to floods in the downstream. Two types of floods are common. They are river and flash floods. The flash floods are observed mainly in urbanized areas, where the rapid urbanization of hill slopes has dramatically increased the runoff water (REMA, 2011).

In addition, inadequate drainage systems and constructions in floodprone zones have made many neighbourhoods of Kigali City highly susceptible to flooding. The flood impacts are accelerated by the physical structure of the area (mainly hilly topography) coupled with demographic pressure on scarce land resources (Bizimana and Schilling, 2010). Although flooding has been experienced since 1960s in Kigali City, but its frequency has significantly increased since 2000, and its impacts have been great on human development, properties, infrastructures as well as environment (Nsengiyumva, 2012). In 2006, 27% of buildings in Kigali City were in flood-prone zones within the Nyabugogoriver floodplain where vulnerable populations, infrastructures, and various economic activities were exposed to flash floods. That was why in the past few years, numerous flood events resulted into the destruction of houses, shops, roads, carrying away cars and even causing loss of lives (REMA, 2013). This happened mainly in the rainy season from April to June and September to December where rainfall events may extend from several hours to days although the most hazardous rainfall events were mostly of short duration, around two hours, with very high intensities. Hence, there is a need to plan and study different flood prone areas in Kigali city to prevent the damages. This caused the research with interest to study the design of appropriate hydraulic structures for sustainable flood control in Nyabugogo catchment, with focus on Kinamba sub-catchment.

II. METHODOLOGY

2.1. Study area description

The Nyabugogo catchment is located in the central eastern part of Rwanda. The catchment drains a total area of about 1647 km^2 spreaded in 8 Districts: Rulindo, Gicumbi, Gatsibo, Kayonza, Rwamagana, Gasabo, Nyarugenge and Kicukiro.The climate of the catchment is mostly of temperate and equatorial type with average temperature ranging between 16°C and 23°C, depending on the altitude of the area. The annual rainfall in Rwanda varies from about 800 mm to 1,600 mm. There are normally four seasons in Rwanda. The first is a long dry season that spans from June to September, followed by a short rainy season spanning from October to December. This season receives 30% to 40% of the annual rainfall with the highest rains falling in November. The third is a short dry season starting in December and ending in January. The fourth is a long rainy season spanning from February to end of May. This season receives around 60% of annual rainfall.The Nyabugogo river traverses the City of Kigali and has many tributaries such as the Mwange river, Rusine river and Marenge river on its upstream portion. It is later fed by other rivers from the urbanised part of Kigali such as the Rwanzekuma river, the Ruganwa river, the Mpazi river and the Yanze river (Nhapi et al., 2011). The researcher has taken up the Kinamba sub-catchment of Nyabugogo catchment for the redesign of runoff control structures.

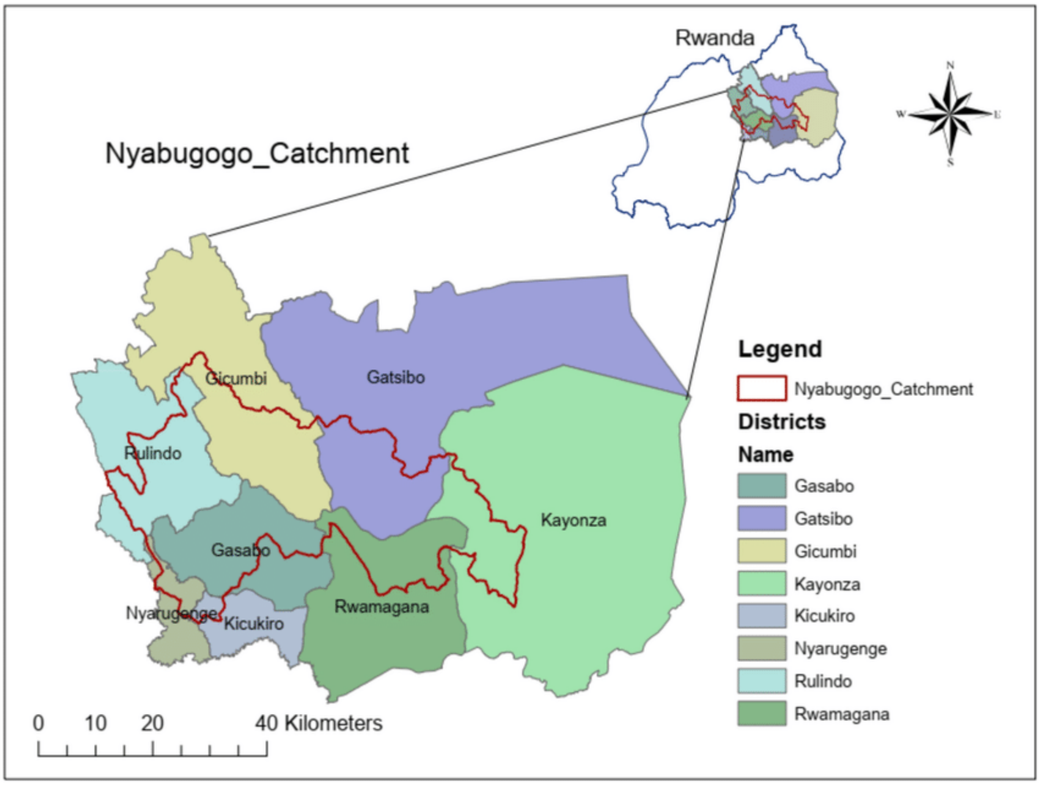


Figure 1: Overall Nyabugogo catchment for flood control (Niyonkuru, 2019)

2.2. Kinamba sub-catchment delineation

From the figure 1, the sub-catchment of Kinamba was delineated for the present study. It is shown in figure 2. Kinamba sub-catchment is an overlapping area of Gasabo District, Kicukiro District and Nyarugenge District. The catchment delineation has been done by use of ArcGIS software and Global positioning system (GPS) for marking outlet point.

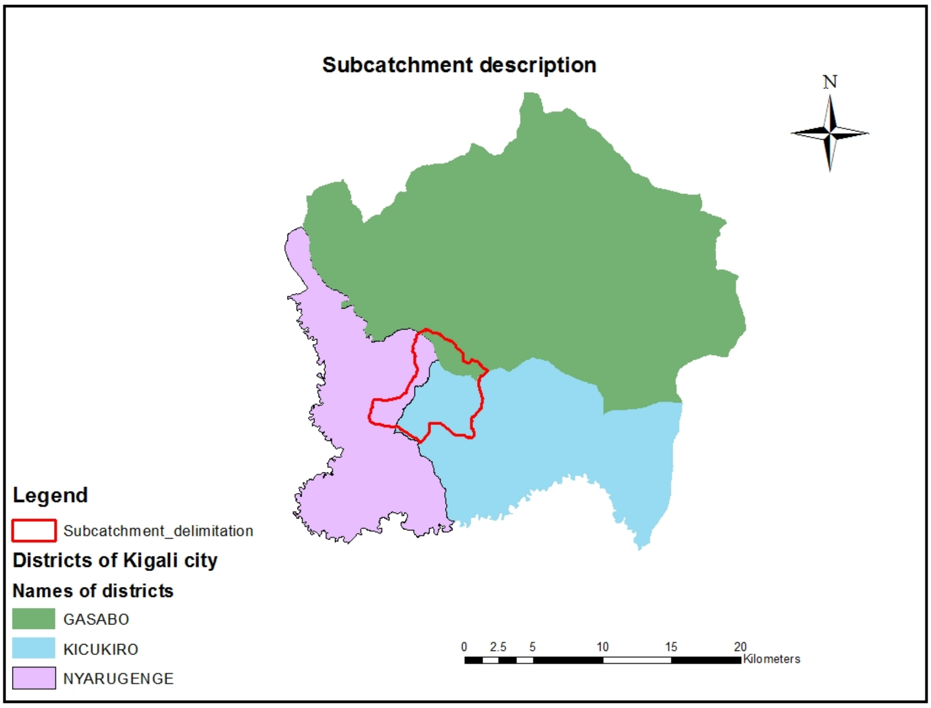


Figure 2: Boundary of Kinamba sub-catchment

After delineating, the Kinamba sub-catchment area was computed in ArcMap, it was found to be equal to 9.12 square kilometres as it is shown on the figure 3.

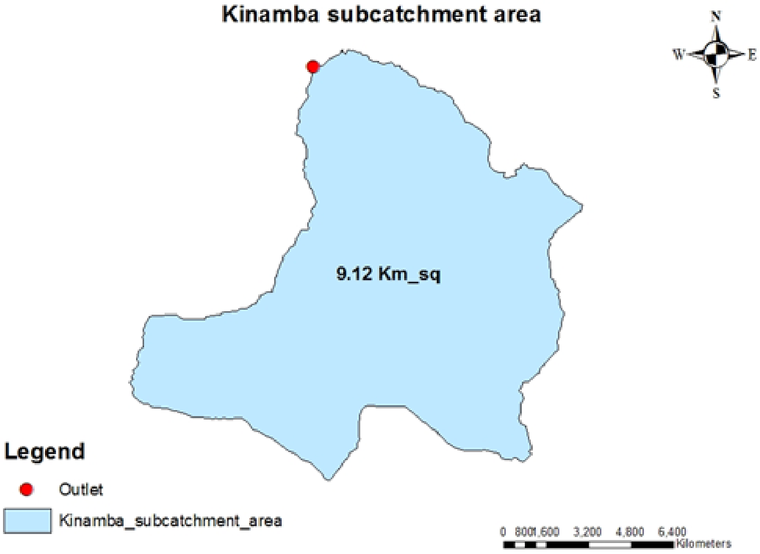


Figure 3: Area of the Kinamba sub-catchmen

The length of the main channel in Kinamba sub-catchment has been calculated by using the ArcMap by digitalizing the main channel on orthophoto with respect to the boundary of the sub-catchment. It is the distance between the pour point (outlet) and the farthest point along the channel within the sub-catchment, the length was found as 7.6 Km. It is shown in figure 4.

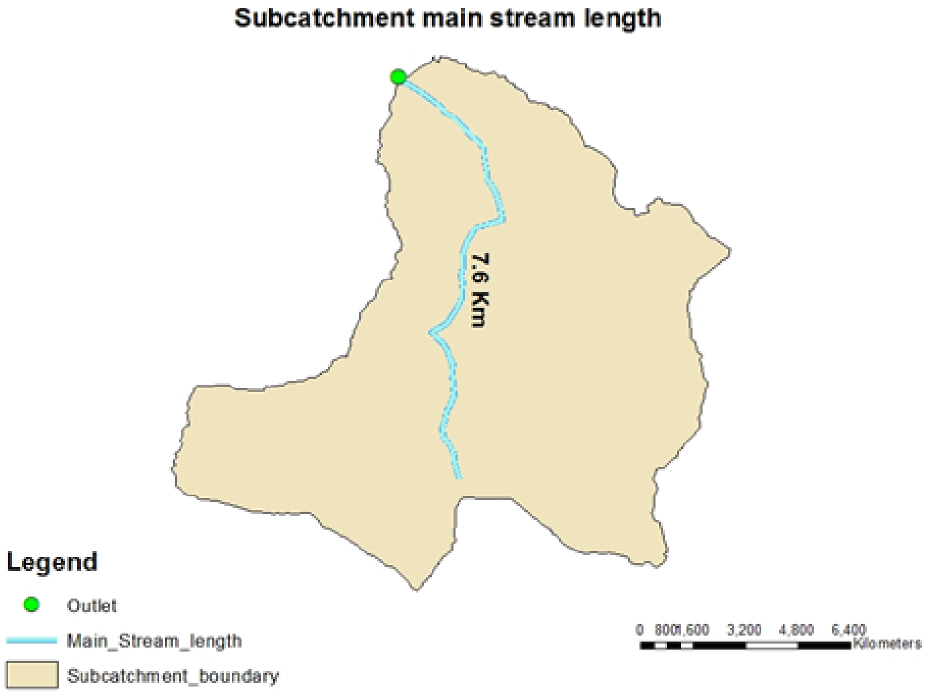


Figure 4: Length of the main channel in Kinamba sub-catchment

The variation in altitudes of Kinamba sub catchment has been determined by use of digital elevation model along with spatial analyst tools in ArcGIS software with contours interval of 20m, the highest elevation within the sub catchment has been found to be 1800m; the lowest one is 1380m. In between highest and lowest elevation, the relief presents the variation of altitudes forming ridges and vallys. Hence the sub-catchment is composed of different hills of various elevations. The closer contours presents steep slopes while wider spacing shows flatter areas. The slope ranges from 2% to 24%. The average slope of the main stream 4.21%. The map of different contours of elevation is shown in figure 5.

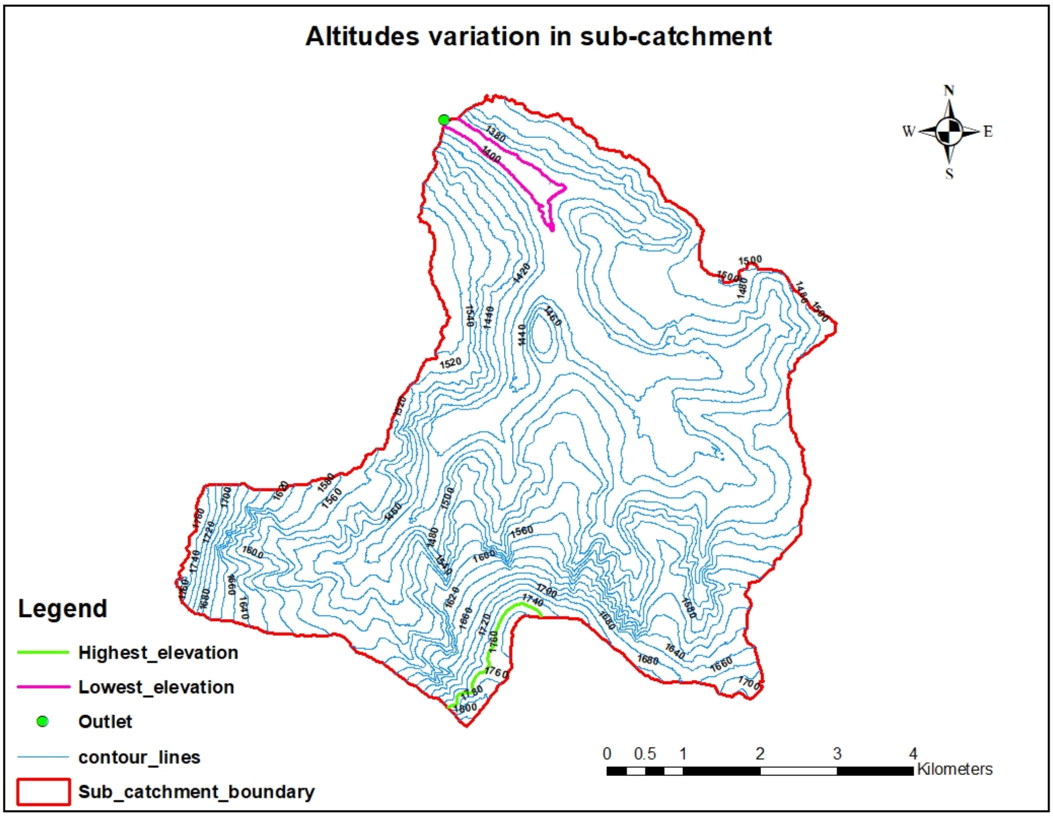


Figure 5: Altitudes variation within Kinamba sub-catchment

This analysis was done by the use of orthopho and ArcGIS has shown that the Kinamba sub-catchment is occupied by two types of land uses such as built up area comprising of houses, schools, factories and roads etc. This covers 6.41 Km^2 (70.29% of the sub-catchment total area) and grassland which occupies the remaining 2.71 Km^2 (20.71% of the total area). This clearly indicates that due to high proportion of built up area which allows very low water infiltration causes more runoff. Hence, the coefficient of runoff remains high and produces high runoff flows in the event of intense rainfall during rainy season.

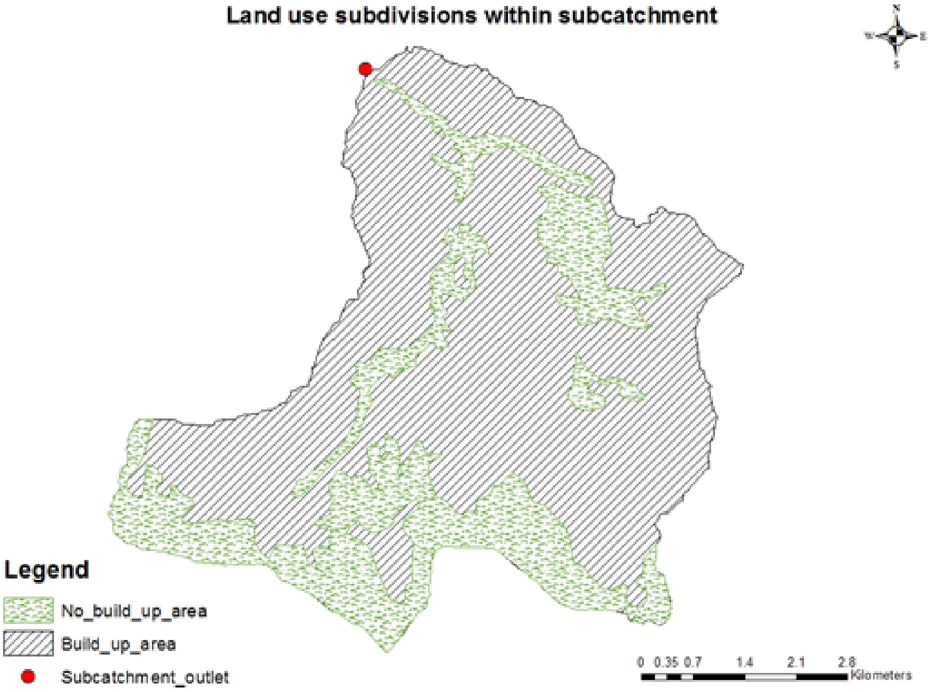


Figure 6: Different land use patterns within sub-catchment

2.3. Quantification of peak runoff discharge for Kinamba sub-catchment and its prediction for next 30 years

The rational method has been used in order to estimate the peak runoff discharge (Qp) within kinamba sub-catchment.

$$Q = \frac{CIA}{Z}$$

Where:

Q = Maximum rate of runoff (m^3/sec.)

C= Runoff coefficient

I = Average rainfall intensity (mm/hr.)

A = Drainage area (in ha)

Z = Conversion factor is 36 if I is in cm/hr and 360 if I is in mm/hr.

As the land use keeps changing, the runoff coefficient which is the major factor in the determination of peak runoff discharge, also changes due to the fact that the build up area which covers 6.41 Km^2(70.29% of the sub-catchment total area) will increase within 30 years while non build up area which occupies the remaining 2.71 Km^2(20.71% of the total area) will reduce. Knowing the annual urbanisation growth rate for Kigali city is 9% (MININFRA, 2008), the land use can be predicted in the next 30 years by using linear prediction formula as follows:

$$Li + n = Li(1 + n\frac{a}{100})$$

Where:

L_{i+n}: Build up area in (i+n) years

Li: current build up area

i: the current year (2019)

n: prediction period = 30 years

III. RESULTS AND DISCUSSIONS

It was found that 108.2 m^3/sec is the maximum runoff discharge that is likely to be produced currently by Kinamba sub-catchment.The maximum runoff discharge that is likely to be produced by Kinamba sub-catchment at least once within 30 years in the next 30 years is 118.41 m^3/sec and it is the one that was used for designing new hydraulic structures namely most economical trapezoidal open channel and rectangular culvert.

Figure 1: Existing culverts under the road Nyabugogo-Muhima-Kacyiru

The figure 8 shows that the dialy rainfall which is equal to 76 mm can result in a flooding event since its corresponding runoff discharge (92.25 m^3/sec) exceeds the discharge (91.168 m^3) that can be carried by the existing culverts. The figure also shows that different values of daily rainfall ranging from 76 mm to 98 mm produce runoff discharges that exceed the capacity of existing culverts.

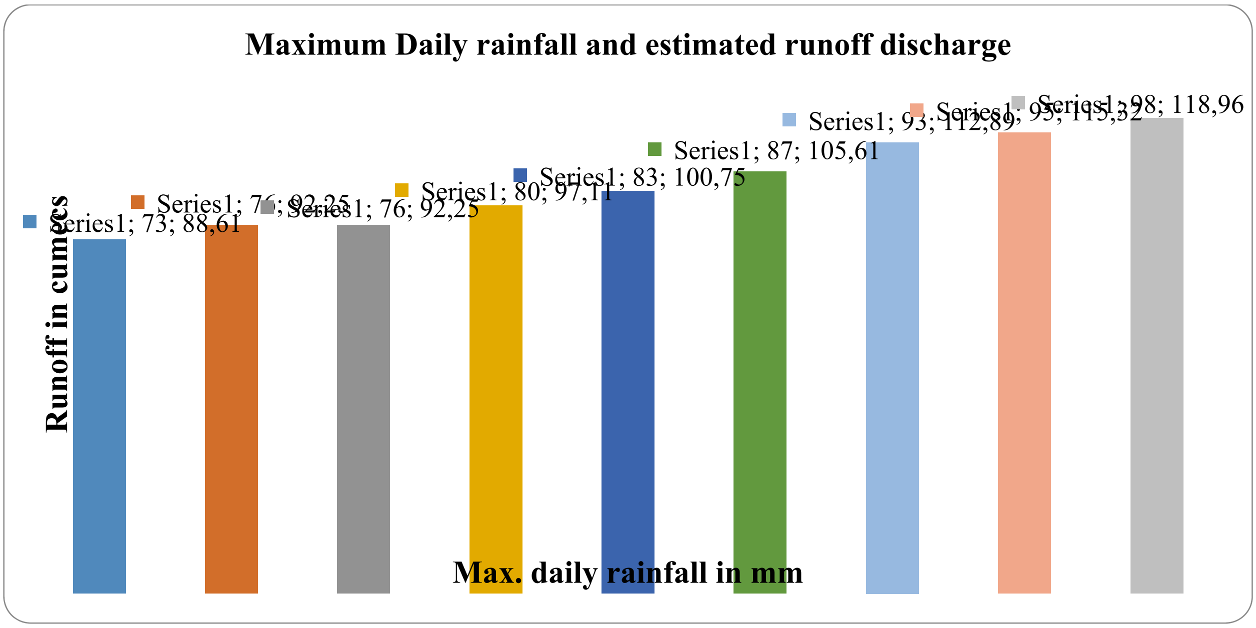


Figure 2: Daily rainfall and runoff disharge relationship

The newly designed most economical trapezoidal open channel cross section is shown in Figure 9. It has the top width of 7900 mm and bottom width of 2300 mm; The sloping side has a length of 3950 mm and the depth of the channel is 2800 mm. The side slope is in the ratio of 1:1.

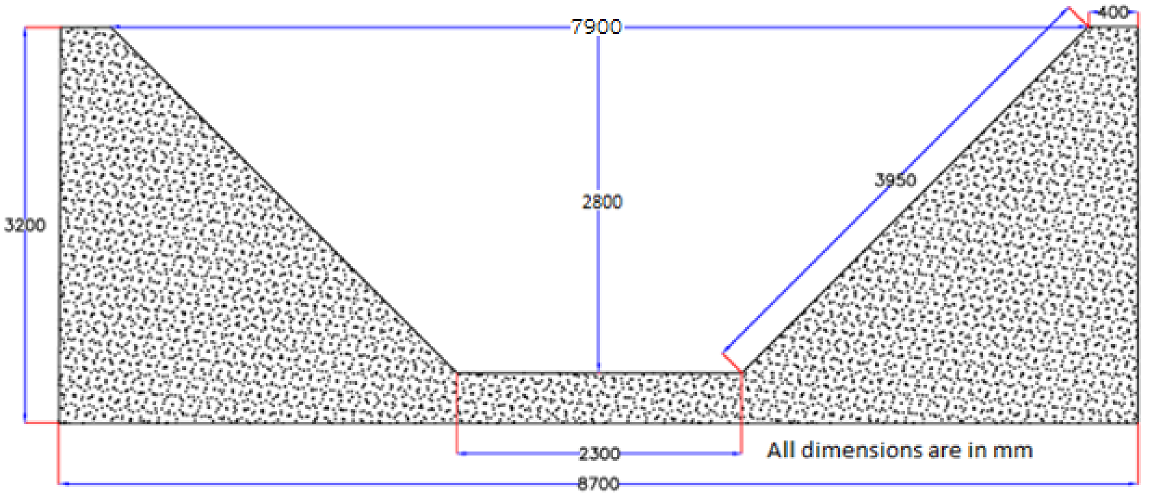
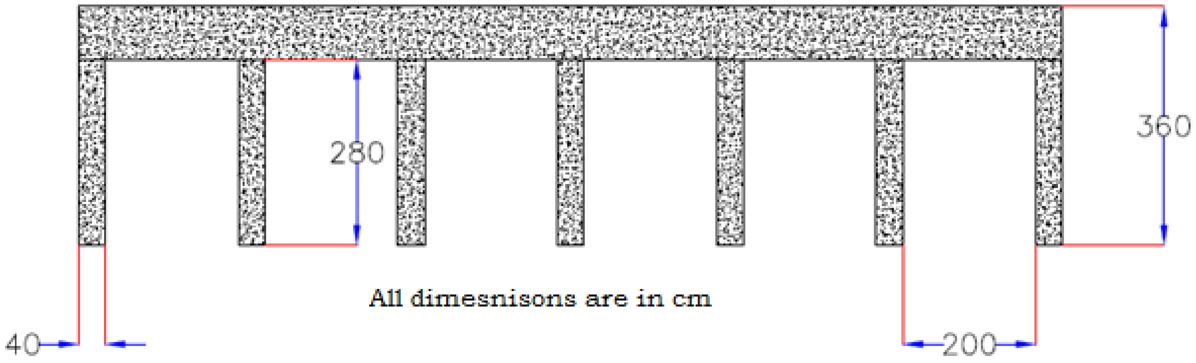


Figure 9: Most economical trapezoidal open channel cross section view

The design of new culverts maintained the vertical dimensions of the existing culverts where the inside height (D), equivalent to the diameter of existing culvert was kept 2.8 m and the upstream energy level, relative to the interval level (H_1) was maintained 3.6 m. This means that the culverts have been widened than deepened. The reason to focus on widening other than deepening is to avoid the change of the road position.Since the span of 11.8 m would be too long, to ensure its stability, it has been subdivided into six spans by considering 2m width for each: Number of spans= B/ 2m=11.8/2=5.9≅ 6. From the above results, by maintaining the vertical dimensions for the existing culverts, it is shown that the new culvert would have six openings having 2.8 m depth, 2 m width each and 3.6 m as the upstream energy level ,relative to the interval level.



IV. Conclusion

The overall objective of this research was to design an appropriate hydraulic structure for sustainable runoff control in Nyabugogo catchment, with focus on Kinamba sub-catchment. According to the results the this research, it is concluded that the existing hydraulic structures are not enough capable of carrying both current peak runoff discharge and the predicted one in the next 30 years. For that reason, new hydraulic structures have been designed to overcome the issue of flooding, the design focused on a) New most economical trapezoidal open channel having top width of 7.9 m, depth of 2.8 m, bottom width of 2.3 m, sloping side of 3.95 m and side slope of 1:1. And b) New rectangular culvert having six openings, each of 2.8 m depth, 2m width and 3.6 m as upstream head of water, relative to the top box level. The implementation of these proposed new hydraulic structures is of great important since it would sustainably solve the problem of flooding events which frequently take place generally in Nyabugogo catchment and in Kinamba sub-catchment in particular.

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