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Enhancing Sustainable Road Infrastructure through GIS-Based Hydrological Modelling: A Solution for Equitable Development and Climate Resilience of Cross Culverts on The Sakpeigu-Chereponi Road (7+100 - 7+750) (N14) At the Yendi Municipality in Ghana

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Abstract:** Road drainage is vital for the safety and longevity of transportation infrastructure. Designing effective drainage facilities, including culverts, requires a precise understanding of discharge-frequency relationships. Culverts, which allow water to flow beneath roads, must consider various engineering and environmental factors. In Ghana, the Ghana Highway Authority expects culvert designs to meet peak flow specifications, but evaluating the design flood of each culvert is time-consuming. Typically, drainage culvert designs rely on estimations, which can lead to inappropriate sizes. This study aimed to assess the adequacy of existing cross culverts and propose suitable sizes for inefficient ones on the Sakpeigu-Chereponi road (7+700-7+750) in the Yendi municipality. The study employed integrated GIS and hydrological models to delineate and estimate peak flow using the modified rational method. The catchment for the scheduled culverts was delineated, with a peak flow of 44.552 m^3/s for a 25-year design period. However, the combined capacity (32.066 m^3/s) of the scheduled culvert sizes was insufficient, resulting in an excess discharge of 12.486 m^3/s. A new culvert schedule was proposed, featuring a 3m X 3m box culvert with a capacity of 70.148 m^3/s for the entire section (7+100 - 7+750) to address the inadequacy.

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Keywords: Sustainable Infrastructure, GIS-Based Hydrological Modelling, Culvert sizing, Climate Resilience, Drainage Design.

1. INTRODUCTION

Efficient road drainage, integral to infrastructure safety and longevity, demands a thorough grasp of discharge-frequency relationships. Culvert design, essential for channelling water under roads, involves nuanced engineering considerations. Geographic Information Systems (GIS) have emerged as indispensable tools for this process, aiding in its complexity (Pedrozo-Acuña et al., 2017; Huang, 2020; Kang et al., 2009).

Culverts, vital for stream crossings, wildlife access, and drainage, are numerous in extensive road networks (Bouska & Paukert, 2010). Their maintenance is often overshadowed by other infrastructure components, and aging culverts require competent design and analysis. Conventional software like the Federal Highway Administration (FHWA) Culvert Hydraulic Analysis Program (HY-8) and Bentley Culvert Master is commonly used, but designing culverts involves considering parameters like peak flow rate, slope, elevations, and barrel diameter (Hotchkiss et al., 2008). Accurately determining peak flow often requires separate hydrological analysis, which can be time-consuming and prone to data errors, necessitating the use of hydrological modelling software and GIS (CONTECH, 2023).

In Ghana, drainage culverts must meet design standards and guidelines to effectively manage peak flows. However, due to the large number of culverts, individually analysing their unique design floods is impractical and time-consuming. This leads to design estimates that may not accurately represent the specific needs of each location (WaterWorld, 2023). Outdated methods involving manual hydrological calculations and historical flow data are still prevalent, resulting in potential errors in culvert sizing. A more efficient and accurate approach to drainage culvert design, utilizing GIS and systematic design flood analysis, is needed.

Studies in Korea have explored culvert hydraulics and design flood estimation methods. Jeong and Mun (2001) compared traditional rational techniques with synthetic unit hydrograph methods and found the KICT method superior due to its incorporation of topographical and hydrological data.

Lee et al. (2004) examined Probable Maximum Flood (PMF) and critical duration for hydraulic design using culvert hydraulics and catchment peak flow estimation. They emphasized the importance of integrated GIS and hydraulic analysis in enhancing our understanding of culvert hydraulics.

Ku and Jun (2009) developed a computational model for road surface drainage design. It involves selecting a design storm with the highest peak discharge for a return period and determining outlet spacing. While their method offered a rational design solution,

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assumptions about rainfall and channel characteristics introduced inaccuracies. Their method is computationally demanding and relies on the precision of initial assumptions.

Based on the prior studies, this study seeks to evaluate the effectiveness of the existing cross culverts along the Sakpeigu-Chereponi road (7+100-7+750) in the Yendi municipality using GIS-based hydrological modelling to propose appropriate sizing solutions for those identified as inefficient. The objectives include estimating the design flood (peak flow) for these cross culverts, conducting an assessment of their adequacy, and subsequently providing recommendations for suitable culvert sizes to address any deficiencies within the infrastructure.

2. MATERIALS AND METHODS

Study Area

The national road N14 in Ghana runs from Sakpeigu through Cheperoni to Yawgu and is 120 km long (Duah, 2013). This significant road network is located in the Yendi Municipal area in Ghana's northern region. As a vital transportation artery, the N14 road connects numerous regions, facilitates economic operations, and allows for the smooth movement of people and commodities throughout the northern region. The distinctive geographic and environmental characteristics of the Yendi Municipal region create unique obstacles for road infrastructure, including drainage, topography, and weather patterns (Duah, 2013). It is critical to ensure the correct maintenance and resilience of the N14 road in the Sakpeigu, Cheperoni, and Yawgu portions to support safe and efficient transport within the region as shown in Fig. 1. To successfully address the drainage and general performance issues of this road, research and development efforts are centred on the use of advanced computational models and geographic information systems (GIS). The goal is to improve the cross-drainage system of this road, reduce flooding hazards, and increase the overall reliability and longevity of the road by leveraging these tools and personalised solutions.

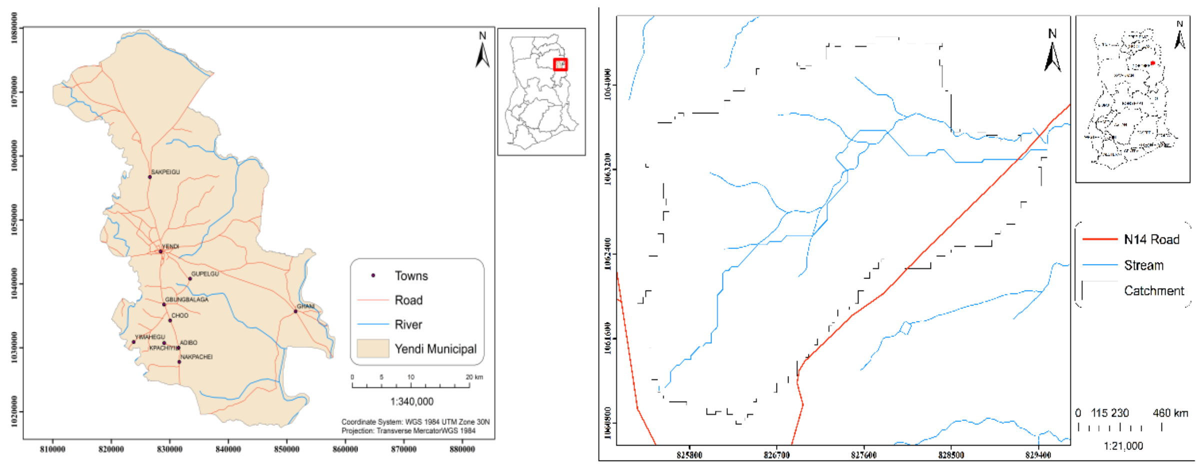

Fig. 1 Study area (N14 road within Chainage 7+100 – 7+750)

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Materials Used

Table 2 lists various data sources used in the study, including elevation data from the SRTM DEM, land use data from Copernicus, and culvert GPS locations from field surveys. It also includes rainfall information from the Ghana Meteorological Agency and road network shapefiles from UC Davis. These diverse sources contributed to the study's comprehensive analysis of the 7+100-7+750 road section.

Table 1: Materials Used with their sources

Data	Source
SRTM Digital Elevation Model (DEM)	https://earthexplorer.usgs.gov/
ArcGIS software	Geomatics GIS lab-KNUST
Land use/ Land cover data	https://land.copernicus.eu/global/products/lc
SWAT plugin	Soil and water assessment tools for ArcGIS 10.3
AutoCAD Civil 3D	Autodesk
GPS Location of Culverts	Field survey with RTK
Rainfall IDF (Intensity Duration Frequency) Curve	Ghana Metrological Agency
Average annual rainfall data	Ghana Metrological Agency
Shapefile of road networks	http://biogeo.ucdavis.edu/data/diva/adm/
Existing Culverts at 7+100-7+750 are Shown in Table 2	Ghana highways

Table 2: Existing culverts scheduled within Chainage 7+100 - 7+750 on the N14 Road

Chainage	Easting	Northing	Culvert Type	Length	Remarks
7+100	383808.908	545869.900	Box culvert (BC)	12m	3No. 2m X 2m
7+300	383955.773	546005.600	Pipe Culvert (PC)	12m	1No. 0.9m
7+550	384127.935	546186.900	PC	4m	3No. 0.9m
7+625	384180.069	546239.600	PC	4m	1No. 0.9m
7+650	384198.507	546257.600	PC	4m	2No. 0.9m
7+700	384234.391	546292.500	PC	4m	1No. 0.9m
7+750	384270.622	546327.000	PC	4m	2No. 0.9m

3. METHODS

Culvert Design and Sizing

A culvert is a hydraulic framework that is built to divert the runoff water from a highway and the buildings in its vicinity (Lyn et al., 2019). Culverts are available in a variety of forms, the most popular of which are circular, rectangular, elliptical, and arch. Reinforced concrete, steel, and aluminium represent the most commonly used materials. The materials and shapes are determined by the judgment of a drainage engineer; however, the sizes are determined by the hydrology of the region only if appropriate efficiency is necessary. The residual design serviceability, or time between servicing, of a culvert is directly tied to how well it performs.

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The following are the key variables that influence the performance or serviceability of a culvert:

1. Factors of durability (Erosion, Abrasion, and Corrosion)
2. Integrity Loss of structures (Joint Separation, Longitudinal cracks, Seam Defects, Misalignment Seam cracking, Transverse cracks)
3. Environmental Aspects (Spalling, Delamination, Scaling, Efflorescence, Honeycombs, Pop-outs)
4. Hydraulic (inadequate volume and operational flooding aspects, debris obstruction, roots, and procedures for maintenance) (Iqbal et al., 2022).

Culvert Hydraulic Setback

When the functioning of a culvert is limited as a result of hydraulic influences, the well-being of commuters, the financial position of the Agency, and the environment could suffer (CONTECH, 2023). These impacts could arise from the inundation of adjoining structures or areas downriver triggered by unforeseen floods. Hydrodynamic elements that may lead to deficiencies include:

1. Inadequate volume
2. Operational
3. Piping
4. Debris blockage,
5. Maintenance procedures

Inadequate volume at the inlet or outlet may be caused by poor design or debris obstruction.

Culvert Policy of the Ghana Ministry of Roads and Highways

The Ministry of Roads and Highways established a drainage pattern guide (Table 3 – Table 4), which is used by several Ministries and Organizations, including the Department of Urban Roads, the Ghana Highway Authority, and the Department of Feeder Roads.

Table 3: The rainfall hydrologic rate of occurrence (DUR, 2006)

Drainage system	Frequency of Occurrence (years)
Major/Long span bridges	100
Minor/medium-span bridges	50
Cross culvert	25
Side Culvert	10
Closed System Drainage	10

Portions of culverts

Circular culverts / Closed System Drains

Minimum diameter for all culverts: 900mm
Maximum diameter for cross culvert: 1, 800 mm

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Rectangular Culverts
Minimum internal height: 1000mm

Cover over Culvert
All pipes must have a minimum cover of 0.3m. The last cover for pipes under railways is 1.2 meters.

Table 4: Manning's roughness (n)

Condition	n
Concrete lined channel	0.013 – 0.015
Sand Crete block	0.015 – 0.020
Masonry	0.017 – 0.030
Earth (new)	0.018 – 0.030
Earth (existing)	0.022 – 0.060

Flow Velocities in Road-size drains
Maximum Flow Velocities:
Concrete 2.5 – 6.0 m/s
Minimum Flow Velocities: For all Concrete, 0.80 m/s is the lowest flow velocity (DUR, 2006)

Hydraulic structure design and analysis
There are two stages to hydraulic structure planning and analysis
1. Hydraulic Design
2. Hydrologic Design

Hydrology
Hydrology, as studied methodically, explores water's presence, movement, and interactions on Earth and beyond, particularly within the hydrologic cycle. Understanding discharge patterns and frequency is crucial for drainage facility design. Different infrastructures require either peak flow rates or hydrographs, with culverts and bridges typically designed based on momentary peak flows (Osei et al., 2019).

Estimation of Peak Flow and Methods of Estimation
The widely used Rational Method for runoff calculation is complemented by non-computer techniques like the Transport and Road Research Laboratory (TRRL), unit hydrograph, and Soil Conservation Service methods. For ungauged sites, the Ministry of Roads and Highways recommends approved approaches (Wang & Wang, 2018). These are:

1. Modified Rational Method
2. NRCS WinTr 20 Model

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Modified Rational Method

A framework based on data is used to estimate peak discharges in drainage basins up to an area of 25 km^2 using the rational equation that has been updated (Koutroulis & Tsanis, 2010). Unlike the core concepts technique which can be applied to drainage basins as limited to a maximum area of $0.8km^2$. This model is shown in Equation (1) to Equation (9).

$$Q = 0.278 \; F C I A \tag{1}$$

Where:
Q = Design discharge (m^3/s)
C = Run-off coefficient (dimensionless)
I = Rainfall intensity (mm/hr)
F = Areal reduction factor (dimensionless)
A = Catchment area (km^2)

The Rational Method and Modified Rational technique both incorporate the following theories:

1. The intensity of the rainfall is equal to or more than the time of concentration, and the runoff rate generated by any intensity of rainfall is greatest.
2. The probability of reaching the calculated peak runoff rate is equivalent to the probability of exceeding the method's average rainfall intensity.
3. There is a linear relationship between high runoff capacity and rainfall durations that are equal to or longer than the time of concentration; for instance, rainfall at a rate of 2 inches per hour (5 millimetres per hour) will result in a peak discharge that is twice as large as rainfall at a rate of 1 inch per hour (2.5 millimetres per hour) average intensity.
4. For storms with all possible incidence likelihoods, the runoff coefficient is the same.
5. In a given watershed, the runoff coefficient is constant for all storms (Wang and Wang, 2018).

Areal Reduction factor (F)

Rainfall studies frequently concentrate on decentralized (point) rainfall, which may not correctly reflect geographic extent. For each drainage basin, the point rainfall distribution is transformed into a spatial distribution by the areal reduction factor (Gericke & Pietersen, 2020). Despite the lack of this factor or equation for Ghana, the areal reduction equation that Rodier devised for West Africa in 1975 as shown in Equation (2) is frequently used.

$$F = 1 - 0.001 \; (\log A) \; * \; (9 \; * \; \log N \; - \; 0.042 \; * \; P \; + \; 152) \tag{2}$$

Where:
F = areal reduction factor
N = return period of rainfall (years)
P = average annual rainfall (mm)
A = catchment area (km^2)

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Time of Concentration (T_c)

At the basin under consideration, the time of concentration is comparable to the length of the intended rainfall intensity for peak flow rates. In Ghana, the drainage manual frequently uses Bransby William's model to calculate the time of concentration (DUR, 2006). The following is the formula:

$$T_c = 0.975L / (A^{0.1} * S^{0.2}) \quad (3)$$

Where:
L = Mainstream length (km)
A = Catchment area (km²)
S = Mainstream slope (m/km)
T_c = Time of concentration (hrs) (DUR, 2006)

Coefficient of Runoff

Surface morphology, soil conditions in the watershed, vegetation cover, and future land use patterns are used to calculate the rainfall run-off coefficients (Chow, 2010). The percentage of rainfall that is turned into stormwater runoff is the physiological inference of a watershed's runoff coefficient (Chow, 2010). Since any type of land used and a known percentage of impervious surface can be used to predict the "C" value, the runoff coefficient should be between 0 and 1 as shown in Table 5.

Table 5: Runoff coefficient table (Chow, 2010)

	Return period (years)						
Character of surface	2	5	10	25	50	100	500
Developed							
Asphaltic	0.73	0.77	0.81	0.86	0.90	0.95	1.00
Concrete/roof	0.75	0.80	0.83	0.88	0.92	0.97	1.00
Grass areas (lawns, parks, etc.)							
Poor condition (grass cover less than 50% of the area)							
Flat, 0–2%	0.32	0.34	0.37	0.40	0.44	0.47	0.58
Average, 2–7%	0.37	0.40	0.43	0.46	0.49	0.53	0.61
Steep, over 7%	0.40	0.43	0.45	0.49	0.52	0.55	0.62
Fair condition (grass cover 50% to 75% of the area)							
Flat, 0–2%	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2–7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.37	0.40	0.42	0.46	0.49	0.53	0.60
Good condition (grass cover larger than 75% of the area)							
Flat, 0–2%	0.21	0.23	0.25	0.29	0.32	0.36	0.49
Average, 2–7%	0.29	0.32	0.35	0.39	0.42	0.46	0.56
Steep, over 7%	0.34	0.37	0.40	0.44	0.47	0.51	0.58
Undeveloped							
Cultivated land							
Flat, 0–2%	0.31	0.34	0.36	0.40	0.43	0.47	0.57
Average, 2–7%	0.35	0.38	0.41	0.44	0.48	0.51	0.60
Steep, over 7%	0.39	0.42	0.44	0.48	0.51	0.54	0.61
Pasture/range							
Flat, 0–2%	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2–7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.37	0.40	0.42	0.46	0.49	0.53	0.60
Forest/woodlands							
Flat, 0–2%	0.20	0.25	0.28	0.31	0.35	0.39	0.48
Average, 2–7%	0.31	0.34	0.36	0.40	0.43	0.47	0.56
Steep, over 7%	0.35	0.39	0.41	0.45	0.48	0.52	0.58

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Land Use

The level of absorption of the land is determined by its use. Runoff coefficients are close to one on comparatively impervious surfaces such as streets and parking lots. Surfaces with vegetation that catches surface runoff and allows rainfall infiltration have reduced runoff coefficients (Chow, 2010).

Topography

The runoff coefficient will be larger in a watershed with an elevated slope than one with a lower slope, all else being equal. This is because a raised slope will experience more stormwater runoff (Chow, 2010).

Soil Type

High sand content soils allow for better infiltration and as a result have low runoff coefficients, in contrast to soils with high clay content, which allow for less infiltration and have very high runoff coefficients. When drainage areas are separated into sections with various types of runoff, a weighted run-off coefficient for the entire drainage area is computed by dividing the area and its coefficients by the drainage area as a whole (Chow, 2010).

$$C_w = (C_1A_1 + C_2A_2 + \ldots\ldots + C_NA_N) / A_{total} \quad (4)$$

NRCS WinTR20 Model

A hydrograph technique is preferred for catchment areas larger than 25 km^2. This is because the rational method considers that rainfall intensity is homogeneous across the whole catchment, which is inaccurate, particularly for bigger areas. The NRCS WinTR-20 method is among the most commonly used and incorporated hydrograph methods in Ghana. The following basic information is required by the method:

1. Catchment area (km^2)
2. Runoff curve number (RCN) (dimensionless)
3. Time of concentration (hr)
4. 24hr - Rainfall depth (mm)

Run-off curve number (RCN)

The RCN is based on the hydrologic soil, type of land use, and vegetation characteristics of the contributing region. A zone with less infiltration is indicated by a high RCN, while a previous surface is indicated by a low RCN. The Ministry of Roads and Transport (Ghana) Highway drainage manual has compiled the hydrologic soil types of various sites (DUR, 2006).

Hydraulic

1. Hydraulic Design Considerations

- Design Flood Discharge
- Watershed characteristics
- Design flood frequency or return interval

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- Every design needs to be assessed for flood flows that are higher than the design flood.

2. Headwater Elevation -check upstream water surface elevation
3. Tailwater -check that the outlet will not be submerged
4. Outlet Velocity -usually controlled by barrel slope and roughness.

Types of Flow Control

a. Inlet Control: The depth of headwater and entry point geometry, such as the barrel shape, cross-sectional area, and inlet edge, the control flow rate at the opening as shown in Equation (5) and Equation (6).
b. Outlet Control hydraulic performance is influenced by all of the same variables as Inlet Control, as well as culvert length, roughness, and tailwater depth as shown in Equation (7).

Culvert Hydraulics-Inlet Control

Two possible conditions:

i. UNSUBMERGED - steep culvert invert and headwater not sufficient to submerge inlet. The Culvert inlet acts effectively like a weir.

$$Q = Cw\ B\,(HW)\frac{2}{3} \qquad (5)$$

B = width of the weir crest
A weir coefficient Cw = 3.0 may be assumed for initial calculations.
SUBMERGED -headwater submerges the top of the culvert inlet but the barrel does not necessarily flow fully. A culvert inlet acts like an orifice or sluice gate.

$$CdA\sqrt{2g(HW-\frac{b}{2})} \qquad (6)$$

Where, b = culvert height
HW – b/2 = head on culvert measured from barrel centreline Orifice discharge coefficient,
Cd varies with the head on the culvert, culvert type, and entrance geometry.

Culvert Hydraulics - Outlet Control

If the headwater is deep enough, the culvert slope is adequately plain, and the culvert is lengthy enough, outlet control will regulate. There are three potential flow situations:

1. Both inlet and outlet submerged, with the culvert flowing full.
2. The inlet is submerged but the tailwater does not submerge the outlet. In this case, the barrel is full over only part of its length.
3. Submersion is not possible at either the headwater or tailwater depths. Calculating culvert capacity using the energy equation

$$HW + SoL = TW + H_e + H_f + H_v \qquad (7)$$

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Where:
HW - TW = headwater -tailwater
SoL = total energy head loss (feet)
H_e = entrance head loss (feet)
H_f = friction losses (feet)
H_v = velocity head (feet)
Entrance Head Loss, He

$$He = Ke(\frac{v^2}{2g}) \quad (8)$$

Friction Losses, Hf
Manning's Equation

$$Hf = \left(\frac{1.49}{n}\right) Rh^{\frac{2}{3}} S^{\frac{1}{2}} \quad (9)$$

Design equation:

$$HW = TW + [Ke + \frac{29n^2L}{R^{1.33}} + 1](\frac{v^2}{2g}) - SoL \quad (10)$$

Where So = slope of the culvert
L = length of the culvert

Catchment Delineation
In this study, catchment delineation involved ArcGIS 10.3 and the Soil and Water Assessment Tool (SWAT) plugin. Using the Digital Elevation Model (DEM), the process calculated flow accumulation and direction, extracting drainage channels and referencing culvert locations for outlet points. It delineated catchment areas for culverts and identified sub-basins for the entire study area. SWAT computed essential basin parameters, including slope, reach length, elevation range, and total catchment area, to determine the time of concentration.

Determination of Time of Concentration and Rainfall Intensity
Time of concentration (in hours) was determined using Bransby-William's equation (Eq. (3)) with delineated data from ArcGIS 10.3. Key parameters like catchment area, slope, and flow length were derived from the DEM. This time of concentration was essential for extracting rainfall intensity from the IDF curve for a 25-year design period, crucial for the study.

Determination of the Runoff Coefficient (C)
Google Earth images were employed to assess the percentage of vegetation and built-up areas in the catchment. Using ArcGIS 10.3 and SRTM DEM, the slope was classified into Flat, Average, and Steep based on Table 5. The runoff coefficient was then calculated using slope, grass cover percentage, and a 25-year return period.

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Determination of Areal Reduction Factor for the Catchment

The average annual rainfall for the Yendi municipal was obtained from the Ghana Meteorological Agency. This was used to compute the areal reduction factor by using Equation (2). A return period of 25 years was used according to the design standard (Table 3) for cross culverts in Ghana (DUR, 2006)

Estimation of Peak Flow

The modified rational method, expressed in Eq. (1), was utilized to determine the peak flow in the catchment for a 25-year return period. Microsoft Excel 2019 was employed for computation, using parameters obtained from GIS-based catchment delineation, including flow length, elevation range, and catchment area as shown in Table 6.

Checking the Adequacy of Existing Culverts within Chainage 7+100 – 7+750

The computed peak flow for the catchment was employed to assess the adequacy of all scheduled culverts within the 7+100 – 7+750 section of the road. Discharges for each culvert were calculated, and their total was compared to the computed peak flow. New culvert sizes were proposed to manage the peak discharge effectively, aiming to reduce costs and prevent future flooding, as illustrated in Fig. 2.

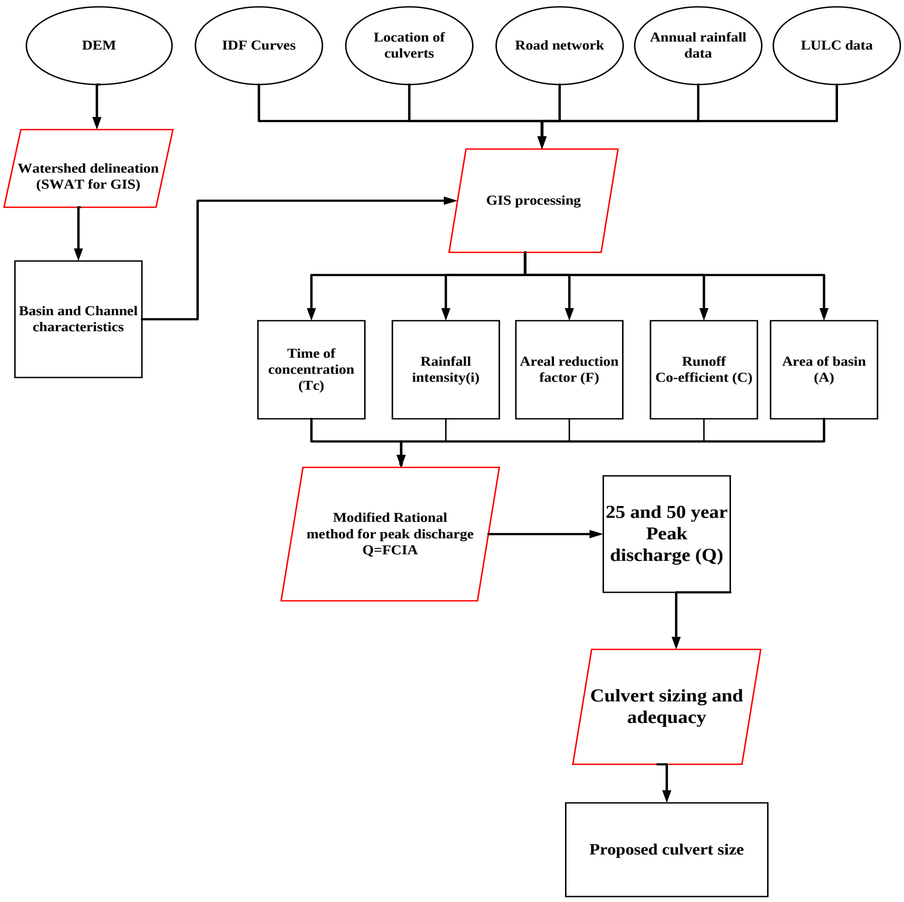

Fig. 2 Conceptual Framework of the study

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4. RESULTS

The Catchment of the Channel Crossing the Road within 7+100 – 7+750

For the culvert location at chainage 7+100 to 7+750, the catchment delineation revealed a 6.11 km^2 area with a rainfall intensity of 45mm/h and a time of concentration (Tc) of 2.78 hours, detailed in Table 6. Notably, runoff from the southwestern part of the catchment is directed toward the culvert location, as depicted in Fig. 3.

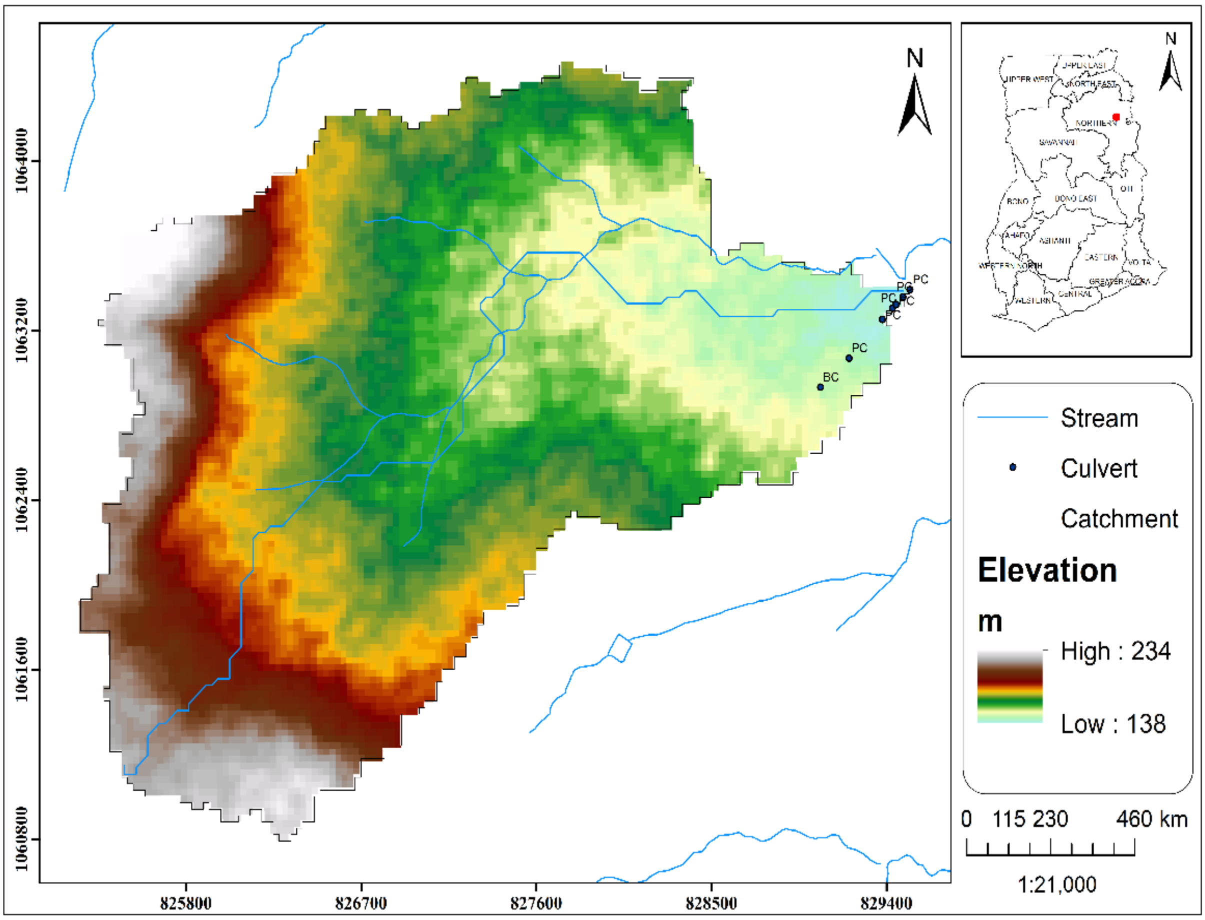

Fig. 3 Catchment contributing flow to the stream crossing the road within 7+100 - 7+750

The Peak Flow for the Catchment of the Channel Crossing the Road within 7+100 – 7+750

Analysis of the topography of the catchment revealed 38% vegetation cover and 62% built-up areas, indicating poor conditions for the catchment given an average slope (2-7%) (Table 5). The computed runoff coefficient (C) for a 25-year return period was 0.46, a critical parameter for calculating the peak flow of the catchment, detailed in Table 6.

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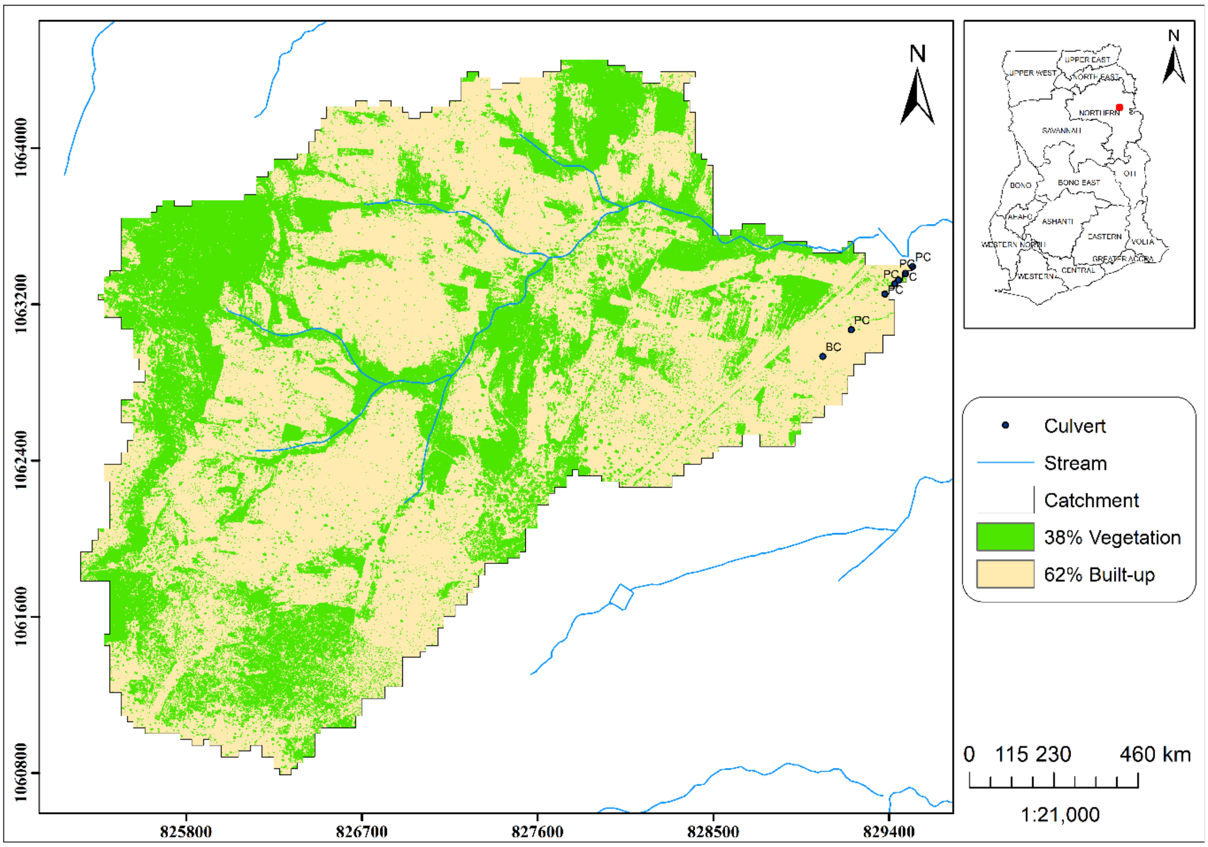

Fig. 4 Characteristic of Surface and Land use/Land cover within the catchment

Table 6: Survey of buildings within the study area

Catchment Area			**Flow Length**		**H_{UP}**	**H_{down}**	**ΔH**	**Slope (S)**	**Tc**	**Tc**	**i_o (mm/hr)**
(m^2)	**ha**	**(Km^2)**	**(m)**	**(Km)**	**(m)**	**(m)**	**(m)**	**(m/km)**	**(min)**	**(hr)**	**25 years**
8,730,000.00	8730.0	8.73	6112.57	6.11	233	138	95	15.542	166.333	2.772	45

Tc	**Tc**	**i_o (mm/hr)**		**RUN-OFF COEFF (25YRS)**	**Areal Reduction Factor**	**DISCHARGES**
(min)	**(hr)**	**25 years**	**50years**	**C_{R25}**	**F_C**	**Q(m^3/s),25 yrs.**
166.333	2.772	45	48	0.46	0.89	44.55

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The Adequacy of Existing Culverts within 7+100 - 7+750

The assessment of existing culverts for the 7+100-7+750 road section indicates a total capacity of 32.066 m^3/s, falling short of the catchment's peak flow of 44.552 m^3/s for a 25-year design period. This results in a significant excess discharge of 12.486 m^3/s, leading to potential overflow issues on the Sakpeigu-Chereponi road at 7+100 – 7+750 as shown in Table 7.

Table 7: Discharge for existing Culverts within chainage 7+100 - 7+750

Chainage	Culvert Type	Length	Total Discharge (m^3/s)	Remarks
7+100	BC	12m	25.456	3/2m*2m
7+300	PC	12m	0.661	1/0.9m
7+550	PC	4m	1.983	3/0.9m
7+625	PC	4m	0.661	1/0.9m
7+650	PC	4m	1.322	2/0.9m
7+700	PC	4m	0.661	1/0.9m
7+750	PC	4m	1.322	2/0.9m
Total			32.066	

Proposed culvert schedule for Sakpeigu-Chereponi road within chainage 7+100 – 7+750

In addressing inadequate culverts scheduled at 7+100 – 7+750, it was observed that replacing the 2m x 2m Box Culvert (BC) at 7+100 with a 3m x 3m BC with a capacity of 70.148 m^3/s could efficiently handle the entire flow at the section. This modification eliminates the need for the originally planned 10 number 0.9m Pipe Culverts (PC) and streamlines the culvert schedule, as presented in Table 8.

Table 8: Proposed culvert schedule within 7+100 - 7+750 on the Sakpeigu-Chereponi road

No.	Chainage	Type	No. of Barrels	Size (m)	Design Length (m)	Proposed Length (m)	Remarks	
							Status	Instruction
1	7+100	BOX	3	3	12	12	New	Install 3No. 3m x 3m BC
2	7+300	PIPE	1	0.9	12	-	New	Exclude from design
3	7+550	PIPE	3	0.9	4	-	New	Exclude from design
4	7+625	PIPE	1	0.9	4	-	New	Exclude from design
5	7+650	PIPE	2	0.9	4	-	New	Exclude from design
6	7+700	PIPE	1	0.9	4	-	New	Exclude from design
7	7+750	PIPE	2	0.9	4	-	New	Exclude from design

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5. DISCUSSION

The catchment analysis for the Sakpeigu-Chereponi road (7+100 – 7+750) revealed a 6.11 sq. km area with a rainfall intensity of 45 mm/h and a 2.78-hour time of concentration. Notably, runoff primarily originates from the southwestern catchment area, emphasizing the importance of understanding topography and flow patterns for culvert design. The peak flow estimation for the catchment was determined based on various factors, including the slope, land cover, and a 25-year return period. It was observed that 38% of the catchment is covered with vegetation, while 62% is designated as built-up areas. This land cover distribution indicates a poor condition for the catchment within an average slope range. The calculated runoff coefficient (C) for the catchment was 0.46 for a 25-year return period. This coefficient played a pivotal role in computing the peak flow for the catchment, a critical parameter for culvert design.

The evaluation of existing culverts on Chainage 7+100 – 7+750 of the road networks revealed 10 number 0.9m Pipe culverts and three number 2m x 2m Box culverts. Their combined capacity of 32.066 m^3/s for a 25-year design period falls short of the catchment's peak flow of 44.552 m^3/s. This results in a concerning excess discharge of 12.486 m^3/s, raising the risk of overflow and flooding during significant storms in the Sakpeigu-Chereponi road section.

To enhance drainage capacity on the Sakpeigu-Chereponi road section (7+100 – 7+750), this study proposed culvert schedule recommends replacing the 2m x 2m Box culvert at 7+100 with a larger 3m x 3m Box culvert, offering a capacity of 70.148 m^3/s. This eliminates the need for 10 number 0.9m Pipe culverts, streamlining infrastructure and reducing costs. The thorough analysis of the catchment, peak flow, and culvert adequacy provided vital insights into addressing drainage challenges, emphasizing the importance of tailored engineering solutions for road safety in the Yendi Municipality.

6. CONCLUSIONS

A comprehensive assessment of the Sakpeigu-Chereponi road section (7+100 – 7+750) in the Yendi Municipality of Ghana focused on catchment delineation, peak flow estimation, and culvert adequacy. The 6.11 square kilometre catchment, with a 45 mm/h rainfall intensity, predominantly channelled runoff from the southwest. Peak flow estimation yielded 44.552 m^3/s for a 25-year design period. Existing culverts, including ten 0.9m Pipe culverts and one 2m x 2m Box culvert, had a combined capacity of 32.066 m^3/s, falling short by 12.486 m^3/s. To address this, a proposed culvert schedule recommended replacing the 2m x 2m Box culvert with a 3m x 3m Box culvert (70.148 m^3/s), improving drainage and reducing costs, enhancing road resilience and safety in the municipality.

Recommendations

1. Drainage engineers should employ the use of GIS to accurately delineate the catchment areas for channels.

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2. Engineers should use the modified rational method to estimate peak flow for efficient culvert sizing.
3. The new proposed culvert schedule should be used for the road construction at 7+100 – 7+750 on the Sakpeigu-Chereponi road.

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7. REFERENCES

1. Bouska, W. W., & Paukert, C. P. (2010). Road crossing designs and their impact on fish assemblages of great plains streams. Transactions of the American Fisheries Society, 139(1), 214–222. https://doi.org/10.1577/t09-040.1.
2. Chow, V. T. (2010). Handbook of applied hydrology. https://agris.fao.org/agris-search/search.do?recordID=US201300485114.
3. CONTECH. (2023). Culvert Hydraulics: Basic Principles. https://www.conteches.com/Knowledge-Center/PDH-Articles/Culvert-Hydraulics-Basic-Principles.
4. Department of Urban Roads. (2006). Ghana Highway Drainage Manual. https://www.research4cap.org/ral/MinRoadsandHighwaysGhana-2020-ManualforLVR-PartC-200415-compressed.pdf
5. Duah, W. O. P. (2013). Ghana Highway Authority - G.H.A. http://highways.gov.gh/
6. Gericke, O. J., & Pietersen, J. P. J. (2020). Estimation of areai reduction factors using daily rainfall data and a geographically centred approach. Journal of the South African Institution of Civil Engineering, 62(4), 20–31. https://doi.org/10.17159/2309-8775/2020/v62n4a3.
7. Hotchkiss, R. H., Thiele, E. A., Nelson, E. J., & Thompson, P. L. (2008). Culvert Hydraulics. Transportation Research Record. https://doi.org/10.3141/2060-16.
8. Iqbal, U., Barthélemy, J., & Perez, P. (2022). Prediction of hydraulic blockage at culverts from a single image using deep learning. Neural Computing and Applications, 34(23), 21101–21117. https://doi.org/10.1007/s00521-022-07593-8.
9. Jeong, S., & Mun, J. (2001). The comparison of existing synthetic unit hydrograph method in Korea. Journal of Korea Water Resources Association, 34(6), 659–672. http://www.koreascience.or.kr/article/ArticleFullRecord.jsp?cn=SJOHCI_2001_v34n6_659.
10. Kang, M., Koo, J., Chun, J., Her, Y., Park, S., & Yoo, K. (2009). Design of drainage culverts considering critical storm duration. Biosystems Engineering, 104(3), 425-434. https://doi.org/10.1016/j.biosystemseng.2009.07.004.
11. Koutroulis, A. G., & Tsanis, I. K. (2010). A method for estimating flash flood peak discharge in a poorly gauged basin: A case study for the 13–14 January 1994 flood, Giofiros basin, Crete, Greece. Journal of Hydrology, 385(1-4), 150-164. https://doi.org/10.1016/j.jhydrol.2010.02.012.

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http://journal.hmjournals.com/index.php/IJRISE
DOI: https://doi.org/10.55529/ijrise.36.43.60

12. Ku, H., & Jun, K. S. (2009). Design of road surface drainage facilities based on varied flow analysis. In Springer eBooks (pp. 240–245). https://doi.org/10.1007/978-3-540-89465-0_45.
13. Lee, S., Choi, H. I., Shin, H., & Park, S. (2004). An analysis of PMF and critical duration for the design of the hydraulic structure. Journal of Korea Water Resources Association, 37(9), 707–718. https://doi.org/10.3741/jkwra.2004.37.9.707.
14. Lyn, D. A., Dey, S., Saksena, S., & Merwade, V. (2019). Assessment of HY-8 and HEC-RAS bridge models for Large-Span Water-Encapsulating structures. https://doi.org/10.5703/1288284316781.
15. Osei, M. A., Amekudzi, L. K., Wemegah, D. D., Preko, K., Gyawu, E. S., & Obiri-Danso, K. (2019). The impact of climate and land-use changes on the hydrological processes of Owabi catchment from SWAT analysis. Journal of Hydrology: Regional Studies, 25, 100620. https://doi.org/10.1016/j.ejrh.2019.100620.
16. Pedrozo-Acuña, A., Moreno, G., Mejía-Estrada, P., Paredes-Victoria, P., Breña-Naranjo, J., & Meza, C. (2017). An integrated approach to determine highway flooding and critical points of drainage. Transportation Research Part D: Transport and Environment, 50, 182-191. https://doi.org/10.1016/j.trd.2016.11.004.
17. WaterWorld. (2023). StackPath. https://www.waterworld.com/home/article/16202127/stormwater-solutions-in-ghana.
18. Wang, S., & Wang, H. (2018). Extending the Rational Method for assessing and developing sustainable urban drainage systems. Water Research, 144, 112-125. https://doi.org/10.1016/j.watres.2018.07.022.