Connecting Geospatial Research and Community Safety: Assessing Culvert Capacity with GIS-Based Hydrological Modelling

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Abstract

Culverts play a critical role in stormwater conveyance, roadway safety, and flood mitigation, particularly within low-lying urban communities vulnerable to extreme rainfall events. In Louisiana, increased rainfall intensity associated with climate variability has placed significant pressure on aging drainage infrastructure. This study assesses the hydraulic adequacy of an existing culvert located along Rafe Mayer Road in the Alsen / St. Irma Lee community of Baton Rouge, Louisiana. An integrated GIS-based hydrological modelling framework was implemented using satellite remote sensing, digital elevation models (DEM), land use/land cover (LULC) data, and rainfall intensity duration frequency (IDF) curves. Catchment delineation was performed using ASTER DEM within a SWAT-based environment. Peak discharge for a 25-year return period was estimated using the Modified Rational Method, while culvert hydraulic performance was evaluated using Manning's equation and hydraulic principles outlined in the Louisiana Department of Transportation and Development (LADOTD) Hydraulic Design Manual. Results indicate that the existing twin 1200-mm pipe culvert is hydraulically inadequate, discharging only 4.49 m³/s against a computed peak flow of 5.03 m³/s, resulting in overtopping and observed flood depths of 1–2 m. A proposed rehabilitation design involving three 1200mm circular corrugated metal pipes eliminated overtopping and safely conveyed the design discharge. The findings provide evidence-based guidance for infrastructure rehabilitation and demonstrate a replicable methodology for community-scale flood mitigation planning.

1. Introduction

1.1 Background and Problem Context

Urban flooding has become an increasingly persistent challenge in many regions of the southern United States due to a combination of aging drainage infrastructure, rapid land-use change, and intensifying rainfall patterns linked to climate change (Pyke et al., 2011; Koutroulis & Tsanis, 2010). Culverts represent one of the most critical yet often overlooked components of stormwater systems, serving as primary conduits that allow water to pass beneath transportation corridors. When undersized or hydraulically compromised, culverts can cause roadway overtopping, structural failure, and prolonged inundation in adjacent communities (Hotchkiss et al., 2008).

In Louisiana, recurrent extreme rainfall events frequently exceed historical design standards, exposing limitations in existing drainage systems designed under outdated hydrological assumptions (Kang et al., 2009). Communities such as Alsen and St. Irma Lee, located within low-relief flood-prone landscapes, are particularly vulnerable due to limited drainage gradients, clay-dominated soils, and high runoff generation.

Recent advancements in satellite remote sensing and Geographic Information Systems (GIS) provide powerful tools for evaluating hydrological behaviour at localized scales. Integration of digital elevation models, land cover data, and rainfall statistics enables accurate catchment delineation, runoff estimation, and hydraulic performance assessment of drainage structures (Kang et al., 2009; Osei et al., 2023; Issah et al., 2023). Such approaches support evidence-based infrastructure rehabilitation and climate-resilient planning.

1.2 Role of GIS and Remote Sensing in Culvert Assessment

Recent advances in Geographic Information Systems (GIS) and satellite remote sensing have significantly improved the ability to evaluate hydrological processes at multiple spatial scales. Digital Elevation Models (DEMs) derived from satellite missions such as ASTER and SRTM enable accurate representation of terrain, allowing for watershed delineation, flow direction analysis, and slope estimation. These terrain parameters are critical inputs for hydrological modelling and runoff estimation (Koutroulis & Tsanis, 2010).

In addition, land use/land cover (LULC) datasets obtained from satellite observations provide essential information for estimating runoff coefficients and surface response characteristics. Changes in vegetation cover, impervious surfaces, and urban development strongly influence runoff generation and peak discharge behaviour (Pyke et al., 2011). Integrating DEMs, LULC data, and rainfall statistics within a GIS environment allows for spatially explicit hydrological analysis that better reflects real-world watershed conditions.

GIS-based hydrological modelling tools, including SWAT and related watershed analysis frameworks, have been widely applied in infrastructure design and flood risk studies. These tools support the delineation of contributing catchments, computation

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of hydrological parameters, and estimation of peak discharges required for drainage structure evaluation (Osei et al., 2023; Issah et al., 2023). Compared to traditional manual approaches, GIS-based methods improve accuracy, reproducibility, and transparency in drainage system assessment.

1.3 Hydrological and Hydraulic Design Considerations

Peak discharge estimation represents a central component of culvert design and evaluation. For small to medium-sized catchments, the Modified Rational Method remains one of the most widely used approaches due to its simplicity and effectiveness when reliable intensity duration frequency (IDF) rainfall data are available (Chow, 2010). The method incorporates catchment area, rainfall intensity, and runoff coefficient, allowing rapid estimation of design discharges for selected return periods.

However, hydrological estimation alone is insufficient for determining culvert adequacy. Hydraulic analysis is required to assess whether the structure can safely convey the computed discharge without excessive headwater buildup or overtopping. Manning’s equation remains the foundation of open-channel and conduit flow analysis and is incorporated into transportation hydraulic design manuals worldwide (Hotchkiss et al., 2008). Performance indicators such as headwater-to-diameter ratio (Hw/D), inlet control conditions, and overtopping discharge provide critical measures of structural safety and flood risk potential.

Several studies have shown that undersized culverts are a primary contributor to localized flooding, roadway failure, and maintenance costs, particularly in rapidly urbanizing environments (Kang et al., 2009; Iqbal et al., 2022). As climate extremes intensify, the importance of reassessing existing drainage infrastructure using updated hydrological inputs becomes increasingly evident.

1.4 Research Gap and Need for the Study

Despite the availability of advanced geospatial and hydrological tools, many local drainage systems continue to be evaluated using limited field-based methods that do not fully account for spatial variability in terrain, land use, and rainfall response. In underserved communities, infrastructure assessments are often reactive rather than proactive, conducted only after repeated flood events have occurred.

There remains a need for integrated, community-scale studies that combine satellite remote sensing, GIS-based hydrological modelling, and hydraulic simulation to support evidence-based culvert rehabilitation. Such studies are particularly important in flood-prone neighbourhoods where small drainage failures can produce disproportionate social and economic impacts.

The objective of this study is therefore to assess the hydraulic adequacy of the Rafe Mayer Road culvert using an integrated GIS-based hydrological modelling framework and to propose an optimized rehabilitation design capable of safely conveying design flood discharges.

2. Materials and Methods

2.1 Study Area

The study area is located along Rafe Mayer Road (606 & 594) within the Alsen / St. Irma Lee community in Baton Rouge, Louisiana. The site is characterized by low-lying terrain and recurrent flooding during heavy rainfall events. The existing drainage structure consists of (2) circular pipe culverts, each 1200 mm in diameter. Field observations and community reports indicate flood depths ranging between 1 and 2 m during intense storm events, leading to roadway overtopping and impaired accessibility.

Figure 1. The study area is located along Rafe Mayer Road (606 & 594) within the Alsen / St. Irma Lee community in Baton Rouge, LA, USA

2.2 Materials and Data Sources

This study utilized a combination of satellite remote sensing datasets, geospatial data products, engineering design references, and hydrological modelling tools (Table 1) to assess the hydraulic performance of the Rafe Mayer Road culvert in the Alsen / St. Irma Lee community of Baton Rouge, Louisiana. Terrain analysis and catchment delineation were conducted using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model with a spatial resolution of 30 m, which enabled the extraction of watershed area, slope, flow direction, and flow length. Rainfall characteristics were obtained from two sources: long-term precipitation data from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database and design storm information derived from Intensity Duration Frequency (IDF) curves developed by the Louisiana Department of Transportation and Development (LADOTD), with the study area located within Region I.

Land use and land cover conditions were characterized using the Copernicus Global Land Cover dataset to determine surface characteristics and select appropriate runoff coefficients for hydrological modelling. Hydraulic assessment was guided by criteria outlined in the LADOTD Hydraulic Design Manual, including headwater-to-diameter limits and overtopping thresholds. Spatial data processing and watershed analysis were performed using ArcGIS and the Arc SWAT extension, while culvert hydraulic simulations for existing and proposed designs were carried out using AutoCAD Civil 3D with the Hydra flow Express module. The integration of these datasets and tools provided a consistent and reliable framework for evaluating peak discharge, culvert capacity, and flood risk under a 25-year return period storm scenario.

Data / Material	Description	Source
ASTER DEM	30 m resolution elevation data for catchment delineation	NASA Earth Data
IDF Curves	Rainfall intensity data (Region I)	Louisiana DOTD
Annual Rainfall	Long-term precipitation records	NASA POWER
LULC Data	Land cover classification	Copernicus Global LULC
Hydraulic Design Manual	Culvert design criteria	LADOTD
Arc SWAT	Watershed analysis	ESRI
AutoCAD Civil 3D Hydra flow	Culvert hydraulic modeling	Autodesk

Table 1. Materials and data used with their sources

2.3 Catchment Delineation and Morphometric Analysis

This study adopted an integrated GIS-based hydrological and hydraulic modelling framework to evaluate the adequacy of the existing culvert along Rafe Mayer Road and to develop an appropriate rehabilitation design. The methodology combines watershed delineation, rainfall–runoff analysis, peak discharge estimation, and culvert hydraulic performance assessment. The workflow followed established engineering practices recommended in transportation hydraulic manuals while incorporating spatial analysis techniques enabled by satellite remote sensing and GIS technologies (Chow, 2010; Hotchkiss et al., 2008; Osei et al., 2023; Issah et al., 2023).

Catchment delineation was performed using the ASTER Digital Elevation Model (DEM) within a GIS environment using the Arc SWAT hydrological tool. DEM preprocessing involved sink filling to remove artificial depressions and ensure hydrological continuity. Flow direction and flow accumulation algorithms were subsequently applied to determine drainage pathways and identify the contributing watershed draining toward the culvert inlet.

From the delineated catchment, key morphometric parameters were extracted, including drainage area (A), average slope (S), and maximum flow length (L). These parameters are fundamental in rainfall–runoff modeling because they control runoff velocity, travel time, and peak discharge generation (Koutroulis & Tsanis, 2010). For small urban watersheds, accurate delineation of the contributing area is particularly important, as minor errors in area estimation can significantly influence discharge calculations.

2.4 Estimation of Time of Concentration

The time of concentration (Tc) represents the time required for runoff from the hydraulically most distant point in the watershed to reach the outlet. It is a critical variable in determining rainfall intensity from IDF curves and therefore directly influences peak discharge estimation.
The time of concentration was computed using Equation (1), a standard empirical relationship suitable for small catchments.

$$T_c = \frac{0.0195 L^{0.77}}{S^{0.385}} \qquad (1)$$

where:
T_c = time of concentration (minutes),
L = flow length (m),
S = watershed slope (m/m).

This formulation has been widely applied in urban drainage studies and is recommended for rational-based runoff estimation where catchment size is limited (Chow, 2010). The derived time of concentration was subsequently used to obtain rainfall intensity values from regional IDF curves.

2.5 Rainfall Intensity Determination

Rainfall intensity corresponding to the computed time of concentration and a 25-year return period was extracted from the Louisiana Department of Transportation and Development (LADOTD) Intensity Duration Frequency (IDF) curves. IDF curves describe the statistical relationship between rainfall intensity, storm duration, and recurrence interval and are essential for infrastructure design (Kang et al., 2009).

The 25-year return period was selected because it represents the standard design criterion for roadway drainage structures in Louisiana and many U.S. transportation agencies. The extracted rainfall intensity (I) was expressed in millimeters per hour (mm/hr) and used as a direct input in peak discharge estimation.

2.6 Runoff Coefficient Determination

The runoff coefficient (C) represents the fraction of rainfall that becomes direct surface runoff and is influenced by land use, soil condition, slope, and vegetation cover. Land use and land cover information derived from the Copernicus Global Land Cover dataset was used to characterize surface conditions within the catchment.

Based on hydrological runoff coefficient tables and observed land cover conditions (50–75% grass cover with moderate development), the catchment was classified as being in fair condition. For steep slopes greater than 7%, a runoff coefficient of 0.46 was adopted for the 25-year return period. This value is consistent with standard hydrological design references and previous studies in similar environments (Chow, 2010; Osei et al., 2023; Issah et al., 2023).

2.7 Peak Discharge Estimation Using the Modified Rational Method

Peak discharge was estimated using the Modified Rational Method, which is commonly applied for small urban and peri-urban catchments due to its simplicity and effectiveness when reliable IDF data are available (Chow, 2010).
The governing equation is expressed as Equation (2):

$$Q = 0.278\, C\, I\, A \qquad (2)$$

where:
Q = peak discharge (m³/s),
C = runoff coefficient (dimensionless),
I = rainfall intensity (mm/hr),
A = catchment area (km²).
The coefficient 0.278 converts rainfall intensity and area into metric discharge units. The Modified Rational Method assumes uniform rainfall intensity over the watershed for a duration equal to or greater than the time of concentration, which is appropriate for design storm analysis in small watersheds (Kang et al., 2009).

This method has been widely validated and remains a standard approach in transportation drainage design, particularly when combined with GIS-derived catchment parameters (Osei et al., 2023; Issah et al., 2023).

2.8 Hydraulic Analysis of Existing Culvert

The hydraulic performance of the existing culvert was evaluated using Manning's equation, which governs steady uniform flow in open channels and closed conduits flowing full or partially full (Chow, 2010).

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad (3)$$

where:
Q= discharge (m³/s),
n= Manning roughness coefficient,
A= cross-sectional flow area (m²),
R= hydraulic radius (m),
S= energy slope (m/m).
Hydraulic simulations were conducted using Hydra Flow Express within AutoCAD Civil 3D to compute flow capacity, upstream headwater elevation, and inlet control conditions.
A key performance metric used in culvert evaluation is the headwater-to-diameter ratio (Hw/D):

$$\frac{H_w}{D} \leq 1.5 \qquad (4)$$

where:
H_w = headwater depth (m),
D = culvert diameter (m).
Transportation hydraulic guidelines recommend maintaining Hw/D values below 1.5 to prevent roadway overtopping, inlet submergence, and structural instability (Hotchkiss et al., 2008).

2.9 Proposed Culvert Design and Performance Evaluation

Following assessment of the existing structure, alternative culvert configurations were evaluated to identify a design capable of safely conveying the computed peak discharge. The proposed design involved increasing the total hydraulic capacity by introducing an additional 1200-mm circular corrugated metal pipe.

The proposed culvert configuration was analysed under identical hydrological conditions to ensure comparability. Hydraulic performance indicators evaluated included discharge capacity, headwater elevation, overtopping potential, and compliance with LADOTD design criteria.

Comparison between existing and proposed designs enabled quantitative assessment of flood mitigation effectiveness and informed selection of the optimal rehabilitation option.

2.10 Methodological Reliability and Validation

The adopted methodology consists of widely accepted engineering and hydrological practices applied in roadway drainage design. Integration of GIS-derived spatial parameters with established hydrological equations improves accuracy and reduces subjectivity in parameter estimation. Similar integrated frameworks have been successfully applied in culvert sizing and flood mitigation studies across different geographic settings (Koutroulis & Tsanis, 2010; Osei et al., 2023; Hotchkiss et al., 2008; Issah et al., 2023).

The approach provides a replicable and transferable framework suitable for community-scale drainage assessment under changing climatic conditions. The Conceptual Framework used to Assess Culvert Capacity with GIS-Based Hydrological Modelling in this study is shown in Figure 2.

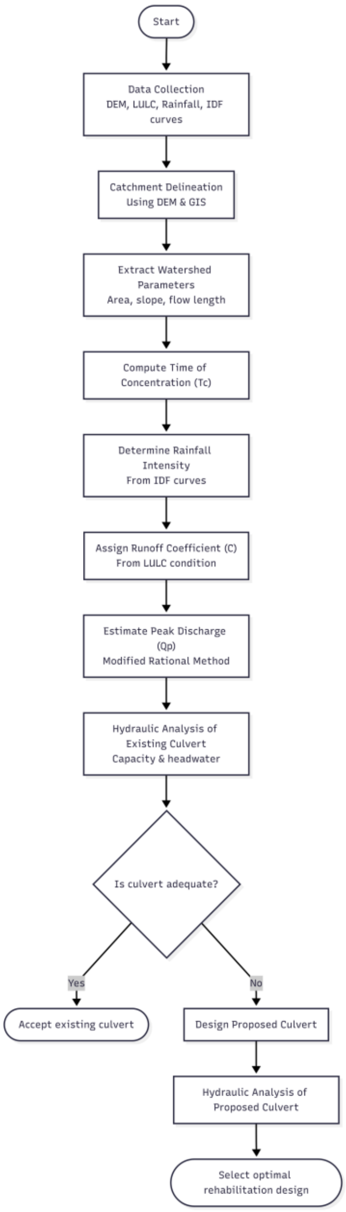

Figure 2. Conceptual Framework used to Assess Culvert Capacity with GIS-Based Hydrological Modelling

3. Results and Discussion

3.1 Catchment Characteristics and Hydrological Response

The GIS-based watershed delineation identified a contributing catchment area of approximately 0.19 km² draining toward the Rafe Mayer Road culvert (Figure 3). The extracted maximum flow length was 0.65 km, with an average watershed slope of 36.9 m/km, indicating a relatively steep local gradient for a low-lying urban environment (Figures 4 and 5). Such slopes significantly accelerate runoff travel time, reducing infiltration opportunity and increasing peak discharge magnitude during intense rainfall events.

The calculated time of concentration (Tc) of 21.8 minutes reflects a rapid hydrological response typical of small urban catchments. Previous studies have shown that watersheds with Tc values below 30 minutes tend to exhibit sharp hydrograph peaks and elevated flood risk during short-duration storms (Kang et al., 2009; Koutroulis & Tsanis, 2010). This finding suggests that the study area is highly sensitive to short, high-intensity rainfall events, which are increasingly common in southern Louisiana.

Figure 3. Delineated catchment area and drainage flow path toward the Rafe Mayer Road culvert in the Alsen / St. Irma Lee community, Baton Rouge, Louisiana.

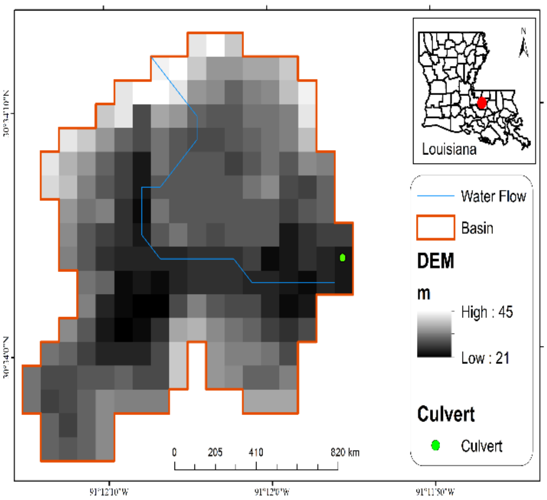

Figure 4. Digital Elevation Model (DEM) of the delineated catchment showing surface elevation variation, drainage flow path, basin boundary, and culvert location along Rafe Mayer Road, Baton Rouge, Louisiana.

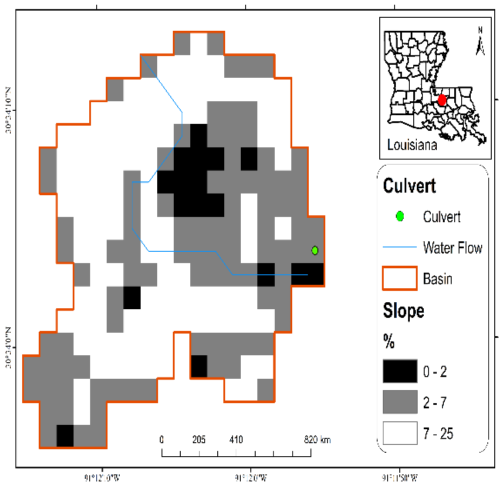

Figure 5. Spatial distribution of slope classes (0–2%, 2–7%, and 7–25%) within the contributing basin, illustrating terrain controls on runoff direction and concentration toward the Rafe Mayer Road culvert.

3.2 Rainfall Intensity and Design Storm Characteristics

Using the computed time of concentration and LADOTD Region I Intensity Duration Frequency (IDF) curves, a rainfall intensity of 190.5 mm/hr was obtained for the 25-year return period. This value is considerably high and consistent with recent observations that Gulf Coast regions experience some of the most intense short-duration rainfall rates in the United States (Pyke et al., 2011).

The magnitude of the design rainfall intensity highlights the limitations of drainage structures designed using older rainfall datasets, which often underestimate peak intensities. Studies indicate that rainfall intensities across the southeastern United States have increased by 10–30% over recent decades, significantly affecting stormwater infrastructure performance (Kang et al., 2009).

3.3 Peak Discharge Estimation

Application of the Modified Rational Method yielded a peak discharge of 5.03 m^3/s for the 25-year storm event. This discharge magnitude is notably high relative to the small catchment size, underscoring the combined effects of steep slopes, short time of concentration, and moderate runoff coefficient ($C = 0.46$) derived from land cover conditions (Figure 5). The hydraulic profile (Figure 5) demonstrates upstream water surface rise above the roadway crest, confirming structural inadequacy during the 25-year storm event.

Similar studies have demonstrated that even small urban watersheds can generate disproportionately large peak flows when rainfall intensity and surface conditions align unfavourably (Chow, 2010; Osei et al., 2023; Issah et al., 2023). The computed discharge therefore represents a realistic and conservative estimate for infrastructure design and flood risk assessment.

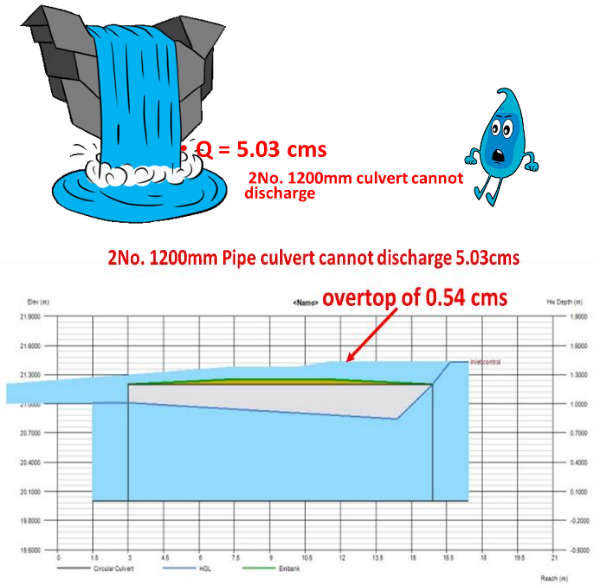

Figure 5. Hydraulic profile of the existing twin 1200-mm pipe culvert showing overtopping under the 25-year design discharge, with an excess flow of 0.54 m³/s at the roadway crossing.

3.4 Hydraulic Performance of the Existing Culvert

Hydraulic simulation of the existing 2 × 1200 mm circular pipe culvert (Figure 5) revealed a maximum discharge capacity of 4.49 m³/s, which is insufficient to convey the computed peak discharge of 5.03 m³/s. The deficit of 0.54 m³/s results in upstream water accumulation and roadway overtopping during design storm conditions.

The calculated headwater-to-diameter ratio (Hw/D) of 1.19 falls within the acceptable limit of 1.5 as recommended by the LADOTD Hydraulic Design Manual. However, despite meeting the Hw/D criterion, the culvert fails hydraulically due to inadequate total cross-sectional flow area. This finding confirms that compliance with headwater ratios alone does not guarantee flood protection, a conclusion also emphasized by Hotchkiss et al. (2008).

Field observations indicating 1-2 m flood depths within the surrounding community correspond closely with the modeled overtopping discharge, providing strong validation of the hydraulic analysis. Similar relationships between undersized culverts and localized flooding have been documented in transportation drainage studies across urban and peri-urban environments (Kang et al., 2009; Iqbal et al., 2022).

3.5 Performance of the Proposed Culvert Design

The proposed rehabilitation alternative, consisting of 3 × 1200 mm circular corrugated metal pipes (Figure 6), significantly improved hydraulic performance. Simulation results indicate that the proposed design is capable of safely conveying the full peak discharge of 5.03 m³/s with zero overtopping (Figure 6).

The resulting Hw/D ratio of 0.96 demonstrates improved hydraulic efficiency and reduced upstream water levels. Additionally, increasing the culvert top elevation from 21.25 m to 21.5 m further enhanced freeboard and roadway safety. These improvements collectively eliminate flood risk at the crossing under the design storm scenario.

The effectiveness of increasing the number of barrels rather than significantly enlarging pipe diameter aligns with findings from previous culvert optimization studies, which report improved flow distribution and redundancy when multi-barrel configurations are applied (Hotchkiss et al., 2008; Kang et al., 2009). Figure 6 illustrates the hydraulic profile of the proposed culvert, which safely conveys the design discharge of 5.03 m³/s without roadway overtopping. Compared with the existing structure (Figure 5), the proposed culvert configuration significantly reduces upstream headwater elevation and eliminates overtopping (Figure 5).

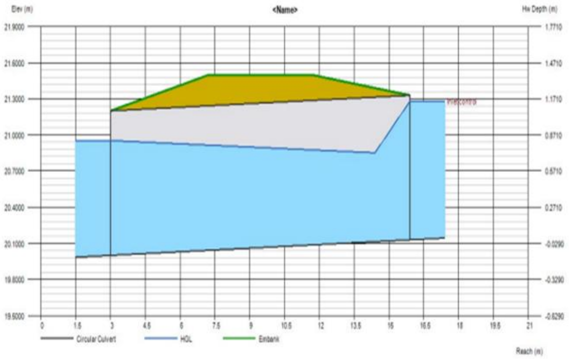

Figure 6. Hydraulic profile of the proposed culvert configuration (3 × 1200 mm pipes) showing adequate conveyance of the 25-year design discharge with no overtopping.

3.6 Implications for Flood Risk Mitigation and Community Resilience

The results highlight the critical role of hydraulic capacity in controlling localized flooding within vulnerable communities. In the Alsen / St. Irma Lee area, flooding is not driven by large-scale river overflow but rather by drainage bottlenecks at roadway crossings. Such failures can produce severe impacts despite relatively small contributing watersheds.

The study further indicates that structural upgrades alone may not fully address long-term flood risk. Increasing vegetated areas within the catchment could reduce the runoff coefficient from 0.46 to approximately 0.39, resulting in meaningful reductions in peak discharge generation. Previous studies demonstrate that green infrastructure and vegetation restoration can reduce runoff volumes by 15-30%, particularly in small urban catchments (Pyke et al., 2011; Pappalardo et al., 2017).

Therefore, integrating engineered solutions with nature-based strategies offers a more sustainable and resilient approach to flood mitigation.

4. Conclusion

This study applied an integrated GIS-based hydrological and hydraulic modeling framework to assess the adequacy of the Rafe Mayer Road culvert within the Alsen / St. Irma Lee community of Baton Rouge, Louisiana. Using satellite-derived terrain data, regional rainfall statistics, and established hydraulic design criteria, the study quantified watershed behavior, peak discharge, and structural performance under a 25-year return period storm.

Results indicate that the existing twin 1200 mm culvert is hydraulically inadequate, discharging only 4.49 m^3/s against a required peak flow of 5.03 m^3/s, resulting in an overtopping discharge of 0.54 m^3/s and observed flood depths of up to 2 m. Although the headwater-to-diameter ratio met design thresholds, insufficient total flow capacity rendered the structure ineffective under extreme rainfall conditions. The proposed rehabilitation design, consisting of three 1200 mm circular corrugated metal pipes, successfully conveyed the full design discharge with no overtopping and improved headwater conditions. This modification provides a practical and cost-effective solution for mitigating flood risk and improving roadway safety. The findings demonstrate the value of integrating GIS, remote sensing, and hydraulic modeling in community-scale infrastructure assessment. The methodology is transferable to similar flood-prone urban environments and supports evidence-based decision-making for climate-resilient transportation infrastructure. Future flood mitigation strategies should combine structural upgrades with land cover management and green infrastructure to enhance long-term watershed resilience.

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