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SHORT COMMUNICATION

Evaluating the hydraulic performance and sustainability of the Simike–Nzovwe roadside drainage system in Mbeya City, Tanzania, using the hydrologic engineering centre's river analysis system modeling

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Abstract: This study addresses the hydraulic inefficiencies and maintenance challenges associated with the roadside drainage system along a 1.85 km stretch of the TANZAM Highway between Simike and the Nzovwe River, which includes five circular culverts. The objective was to evaluate the system's hydraulic performance under rainfall events using the Hydrologic Engineering Centre's River Analysis System (HEC-RAS) one-dimensional hydraulic model. Specifically, the study focused on analyzing flow regimes, specific energy transitions, and sediment transport dynamics to identify critical points of inefficiency. The methodology involved simulating steady flow conditions, assessing the influence of channel and culvert geometry, and performing a sensitivity analysis on key hydraulic parameters, including Manning's roughness coefficient, channel slope, and culvert dimensions. The model results revealed that subcritical flow conditions (Froude number, $Fr < 1$) upstream of culverts lead to sediment accumulation, while steeper channel sections with supercritical flow ($Fr > 1$) pose erosion risks. Pronounced hydraulic jumps were observed near culvert outlets, resulting in significant turbulence, abrupt energy dissipation, and localized erosion. Flow velocities decreased sharply from over 7 m/s to below 1 m/s across these transition zones. This study provides an integrated evaluation of hydraulic and sediment transport interactions in a real-world drainage system using HEC-RAS, supported by targeted design optimization strategies. Key recommendations include modifying side slope geometry, increasing longitudinal gradients, and enlarging culvert dimensions to enhance flow capacity and reduce sediment deposition. In addition, the application of riprap in high-velocity zones, vegetative lining in low-velocity areas, and the inclusion of sediment traps are proposed to control erosion and minimize maintenance.

Keywords: HEC-RAS modeling; Side drainage design; Supercritical to subcritical flow; Sediment accumulation; Hydraulic performance evaluation

1. Introduction

An efficient highway system requires an integrated design approach encompassing geometry, pavement, drainage, and traffic control elements to ensure safety and functionality.[1] Geometric design defines the physical layout of the highway, including cross-sections, curves, sight distances, and alignment standards.[2] In contrast, pavement design – whether rigid, flexible, permeable, or impermeable – follows mechanistic-empirical or standard methodologies.[3] Recent studies emphasize reliability-based design to enhance highway safety,[4] and the strategic use of traffic control devices has been widely documented.[5,6] Equally important is drainage design, which plays a critical role in maintaining road safety and infrastructure integrity during adverse weather events. Side drainage systems, comprising side drains, culverts, and other hydraulic structures, are essential for managing surface runoff, sediment, and debris. Typically configured as trapezoidal channels for cost-effectiveness and stability, these systems must be designed to meet hydrologic and hydraulic demands. However, inadequate design and maintenance can lead to inefficiencies, such as siltation and localized flooding. Poorly performing systems exacerbate flood risks, particularly in rapidly urbanizing areas. Wakjira and Negasa,[7] for example, used ArcGIS to assess drainage issues in Bale Robe Town, Ethiopia, and attributed failures to structural design flaws. Similarly, Mkhandi and Mbwete[8] evaluated drainage structures in Dar es Salaam and linked their inadequacy to urban expansion and poor hydraulic planning.

Extreme precipitation events and increased surface runoff, driven by urbanization and climate change, have amplified drainage challenges. Effective mitigation requires integrating nature-based solutions,[9] intelligent flow control systems,[10] and engineered interventions, such as forced retention basins.[11,12] The relevance of hydrodynamic modeling in addressing these challenges is well-established, particularly for assessing flood risks, optimizing drainage performance, and guiding sustainable design strategies.[13-15] Hydrodynamic and sediment transport models are increasingly utilized to support the design of drainage systems. These models simulate runoff, flow transitions, and sediment movement under various hydraulic conditions. Among the widely used tools are the Hydrologic Engineering Centre's River Analysis System (HEC-RAS), Modular Integrated Kinematic Emulator 11 (MIKE 11), and Storm Water Management Model (SWMM). HEC-RAS, developed by the U.S. Army Corps of Engineers, is particularly well-suited for analyzing one-dimensional open channel flows and culvert hydraulics.[16] Its strengths include a user-friendly interface, extensive documentation, and the ability to model sediment transport and variations in specific energy.[17-19] In contrast, MIKE 11 offers more sophisticated capabilities, including two-dimensional modeling and advanced sediment modules, but it requires licensing and technical expertise.[20-22] SWMM excels in urban stormwater analysis but is limited in modeling sediment dynamics in open channels.[23-25]

This study aims to evaluate the hydraulic performance of side drains along a 1.85 km stretch of the TANZAM Highway between Simike and the Nzovwe River. It addresses a gap in existing research by incorporating specific energy variations into the design assessment, thereby capturing transitions between subcritical and supercritical flows and their implications for sediment transport. By applying the HEC-RAS model, the study provides practical recommendations for optimizing side drain design to reduce sedimentation, enhance flow efficiency, and ensure system sustainability under extreme hydrologic conditions.

2. Methods

2.1. Study area

The study was conducted along the TANZAM Highway, specifically within the 1.85 km Simike–Nzovwe section, which features a trapezoidal-lined drainage channel (Figure 1). This section includes five circular culverts that connect feeder roads to the main highway. The slope along the side drain varies from steep to gentle, impacting the flow dynamics throughout the channel (Figure 2). Over time, this section has been prone to issues, such as sedimentation (silting) and surface runoff, which frequently spills onto the road carriageway. Figure 3 illustrates the physical condition of the culverts at both the inlet and outlet following a rainfall event, highlighting the accumulation of debris and sediment that exacerbates drainage inefficiency.

2.2. HEC-RAS software

HEC-RAS is a widely utilized tool for the design and analysis of roadside drainage systems due to its advanced capabilities in simulating complex hydraulic conditions. One of its key strengths lies in its ability to model varied water surface profiles under different flow regimes – subcritical, supercritical, and critical – making it particularly effective in understanding transitional flow dynamics that influence channel performance, water velocity, and depth.[26,27] In roadside drainage applications, flow often transitions from subcritical (slow and deep) to supercritical (fast and shallow) due to channel slope, directly affecting the system's runoff management capacity. Accurate representation of these transitions is crucial for ensuring the resilience of drainage infrastructure, particularly during extreme weather events, when sediment deposition can significantly reduce flow capacity. HEC-RAS provides tools to simulate such sediment buildup and long-term debris accumulation, enabling proactive

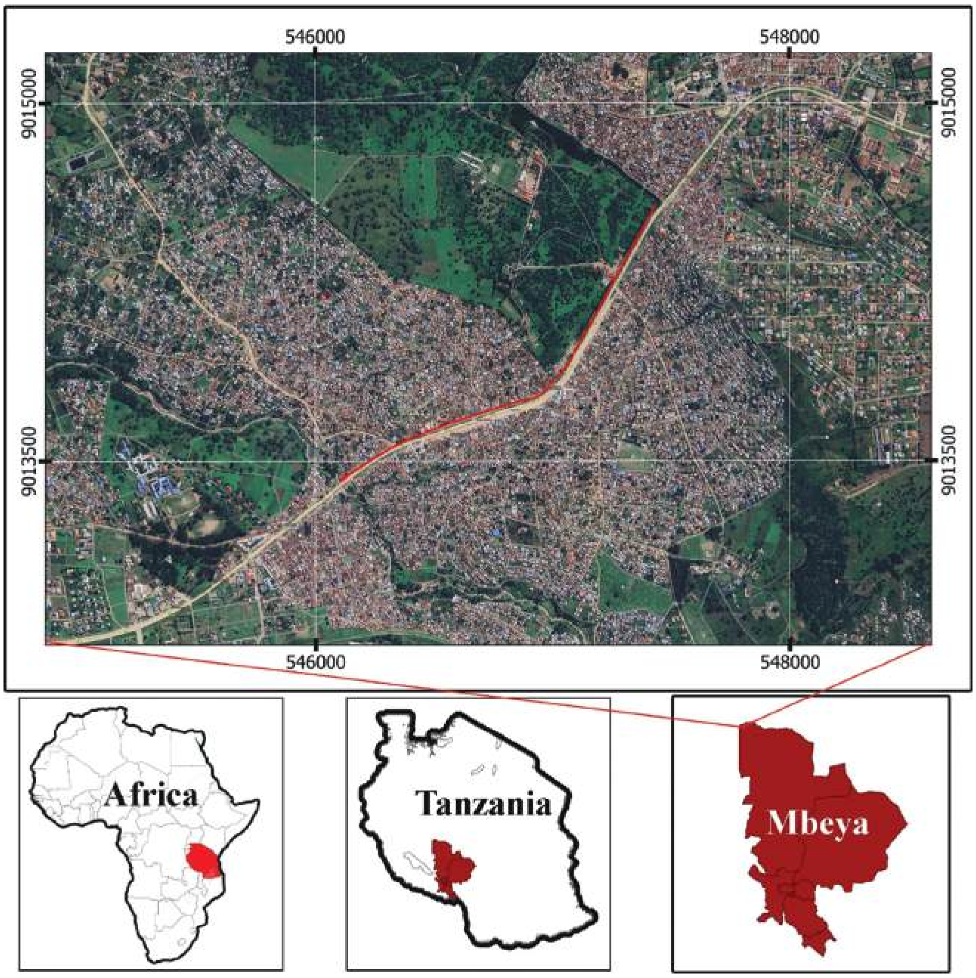

Figure 1. Location of the study area

Note: Red line on the map represents location of the study area of the side drain along the road section.

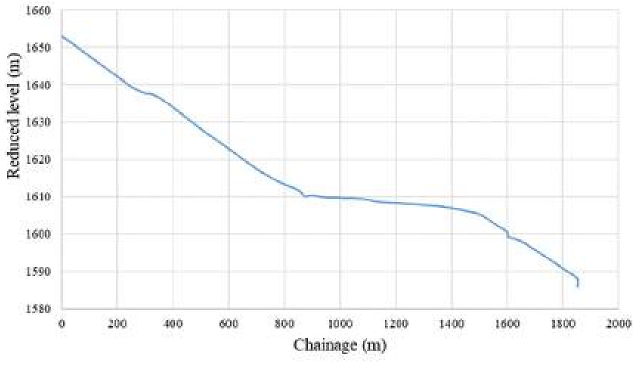

Figure 2. The channel bed profile of the side drain along the Simike–Nzovwe highway section

maintenance planning and system optimisation.[27,28] Recent advancements in HEC-RAS have enhanced its capability to model stormwater pipe networks and manage mixed flow regimes, allowing application in both urban and rural drainage contexts.[29] For example, a study demonstrated the effectiveness of HEC-RAS in simulating urban stormwater behavior,[30] while two other studies applied the model to assess riverine flooding and cross-sectional changes in Indian rivers.[31,32] Similarly, calibrated models by Samal *et al.*[33] validated HEC-RAS's accuracy in replicating real-world flow scenarios. Building on this robust foundation, the present study utilizes HEC-RAS to assess the adequacy of side drains along the TANZAM Highway, focusing on their capacity to manage runoff and sediment under dynamic hydraulic conditions.

2.2.1. Specific energy

The specific energy of flow in an open channel is a crucial factor in understanding flow behavior, especially during transitions between subcritical and supercritical regimes. It is defined as the sum of the potential and kinetic energy of the flow, and is given by Equation I. This equation helps determine critical flow conditions,

Figure 3. Photographs of the trapezoidal side drain showing (from left to right) the upstream inlet, downstream outlet, and channel approach section

where the specific energy is minimized. Critical flow occurs when the Froude number (Fr) is equal to 1, meaning the flow velocity equals the speed of shallow water waves, and is given by Equation II. A Fr <1 indicates subcritical flow (slow, deeper flow) while that of more than 1 indicates supercritical flow (fast, shallow flow).

$$E = y + \frac{v^2}{2g} \tag{I}$$

$$Fr = \frac{v}{\sqrt{gy}} \tag{II}$$

Where E is the specific energy (m); y is the flow depth (m); v is the velocity of the flow (m/s); g is the acceleration due to gravity (m/s^2); and Fr is the Froude number (unitless).

2.2.2. Energy equation for flow profiles

The HEC-RAS uses the energy equation to compute water surface profiles for gradually varied flow, which is critical for understanding how water levels change in roadside drainage systems and is given by Equation III.

$$\frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + h_L \tag{III}$$

Where v_1, v_2 are the velocities at two different sections (m/s); y_1, y_2 are the depths at two different sections (m); z_1, z_2 are the channel bed elevations (m); h_L *is* the head loss due to friction and channel resistance (m).

This equation ensures energy conservation along the flow, accounting for frictional losses, which are modeled using Manning's equation.

2.2.3. Manning's equation

To compute the open channel flow velocities, Manning's equation (Equation IV) is utilized.

$$v = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}} \tag{IV}$$

Where v is the flow velocity (m/s); n is the Manning's roughness coefficient (s·m$^{-1/3}$), R is the hydraulic radius (m), which is the cross-sectional area divided by the wetted perimeter (m); and S is the slope of the energy grade line (water surface slope, m/m).

Manning's equation is crucial for calculating flow depths and velocities, particularly under subcritical conditions where frictional forces prevail.

2.2.4. Hydraulic jump and flow transition

When water transitions from supercritical to subcritical flow, a hydraulic jump occurs. The associated energy loss can be calculated using Equation V.

$$h_L = y_2 - y_1 \tag{V}$$

Where h_L is the energy loss during the hydraulic jump; y_2 is the downstream water depth after the jump (m); and y_1 is the upstream water depth before the jump (m).

The downstream depth (y_2) can be estimated from the upstream depth (y_1) using the momentum equation, typically requiring iterative methods to solve.

2.2.5. Application of the HEC-RAS model

To set up the HEC-RAS model, surveyed reduced levels and cross-sectional geometry data were pre-processed and imported into the model environment. All culvert locations along the 1.85 km drainage section were identified and accurately represented within the model by inputting their respective dimensions and placements. The elevation data showed a difference of 66.969 m between the upstream and downstream reaches. A longitudinal profile was generated, and cross-sections were interpolated at 50-m intervals to ensure continuity and detail (Figure 4). The simulations were conducted under steady-state flow conditions with flow discharges ranging from 3.5 m^3/s to 7.5 m^3/s, capturing both typical and extreme hydraulic scenarios. Boundary conditions were defined as a known upstream flow rate and a normal depth at the downstream end. Manning's

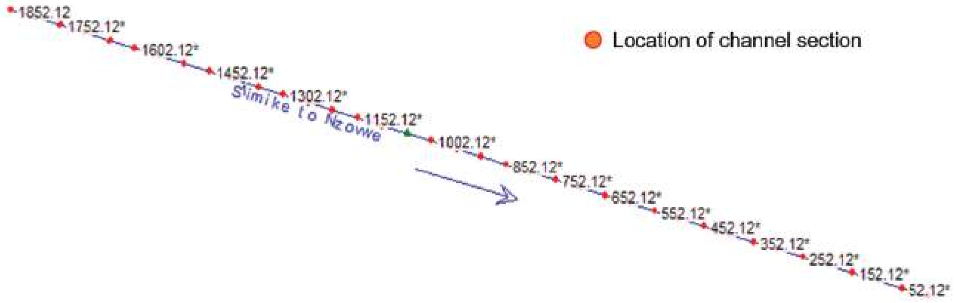

Figure 4. Longitudinal profile of the side drain channel

roughness coefficient (n) was assigned values between $0.05\ \mathrm{s{\cdot}m^{-1/3}}$ and $0.02\ \mathrm{s{\cdot}m^{-1/3}}$, based on channel conditions and supported by literature benchmarks.[34] The model assessed water surface profiles and flow velocities to determine critical points of overtopping and potential failure. Results indicated that the system's conveyance capacity is exceeded when the discharge surpasses $5.76\ \mathrm{m^3/s}$, resulting in channel overtopping.

Specific energy analysis was applied to evaluate flow regimes along the drainage path, distinguishing between subcritical and supercritical flow conditions. These insights allowed for a more nuanced understanding of flow transitions, hydraulic jumps, and associated sediment transport risks – aligning with findings that energy dissipation rates significantly influence sediment dynamics under both steady and unsteady flow regimes.[35,36] Although this preliminary simulation was not calibrated with observed flow data due to limited field measurements, sensitivity analyses of roughness coefficients and flow rates were conducted to approximate realistic conditions. This approach follows established methodologies demonstrating that sensitivity analysis can effectively identify critical parameters affecting sediment flux and model behavior under varying flow regimes.[37,38] The absence of calibration data is a limitation of the present study. Future efforts will focus on acquiring flow monitoring data to support robust model calibration and validation, as recommended for reliable modeling in sediment transport scenarios.[39,40]

3. Results and discussion

The HEC-RAS hydraulic simulation of the Simike–Nzovwe road section reveals significant inadequacies in culvert performance under dynamic flow conditions. As observed in the water surface profile (Figure 5), the simulated flow overtops the ground elevation at multiple locations where culverts are installed. This indicates that the design flow threshold of $5.76\ \mathrm{m^3/s}$ exceeds the capacity of the existing culverts. This is likely attributed to land use changes that have promoted surface runoff.[41] The overtopping not only highlights the risk of roadway flooding but also underscores the urgent need for culvert redesign. These findings are consistent with flood modeling literature, which emphasizes that under-designed culverts are a significant contributor to urban roadway inundation and associated public safety risks.[42]

The simulation further shows that the energy grade line closely follows the water surface profile at culvert entrances, a typical characteristic of inlet-controlled subcritical flow regimes. This interpretation is reinforced by the position of the critical depth being consistently lower than the water surface, indicating smooth transitions without hydraulic jumps. While subcritical flow conditions are generally stable, they are susceptible to sediment deposition when flow velocities drop. This phenomenon is evident in the velocity profile (Figure 6), which shows abrupt reductions in flow velocity at culvert locations – dropping to approximately 1.0 m/s. This significant velocity loss translates into a reduction in sediment transport capacity, resulting in the likely accumulation of debris and silt within the culverts. This issue is a known limitation in low-slope or flat urban drainage systems.[43]

Supporting this model-based analysis, field photographs (Figure 3) provide crucial ground-level validation. The left image shows a culvert inlet completely clogged with organic debris and plastic waste. The center image displays ponded water at another culvert, likely due to flow resistance or backwater effects. The right image depicts sediment buildup and trash in an open roadside channel, suggesting that even under dry conditions, poor solid waste management and hydraulic inefficiencies persist. These visual observations align with the simulation findings and confirm that the existing infrastructure not only struggles to convey

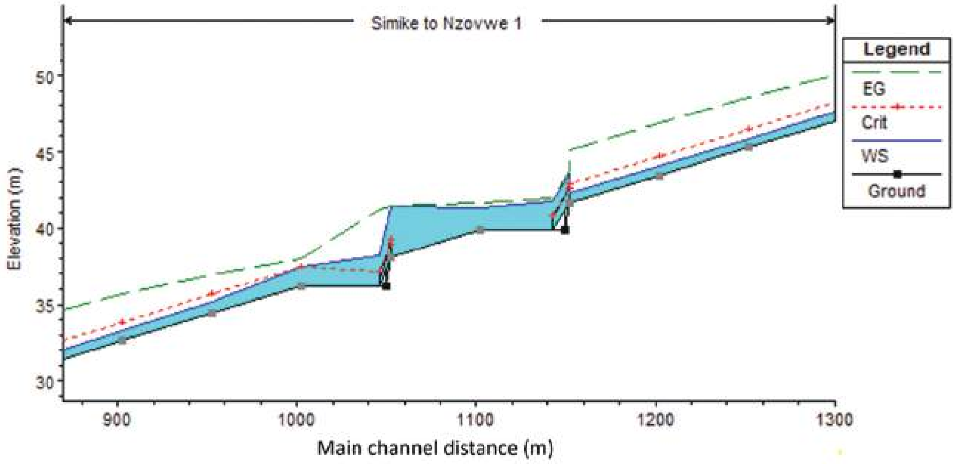

Figure 5. Specific energy distribution along the side drain channel at a selected culvert location
Abbreviations: Crit: Critical depth; EG: Energy grade; WS: Water surface.

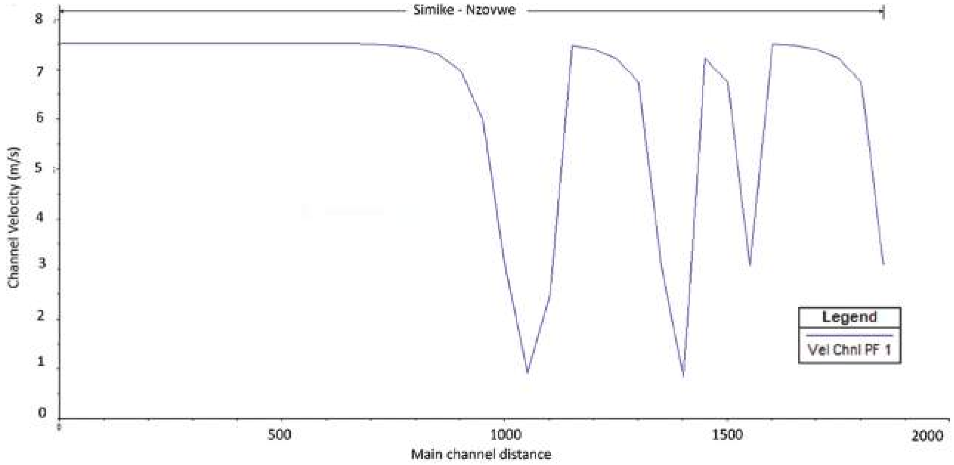

Figure 6. Velocity profile along the side drain channel

peak flows but also promotes localized clogging and sedimentation. This outcome is well documented in the literature, where poor velocity conditions at culvert throats are linked to recurring maintenance needs and long-term drainage inefficiencies.[44]

4. Conclusion and recommendations

This study employed the HEC-RAS model to evaluate the hydraulic behavior of a 1.85 km roadside drainage system along the Simike–Nzovwe section of the TANZAM Highway. The analysis identified critical performance limitations associated with both sediment deposition and erosional processes. Subcritical flows (Fr <1) upstream of culverts were linked to sediment accumulation and frequent blockages, while supercritical flows (Fr >1) on steeper slopes resulted in high shear stresses and localized erosion. Flow transitions at culvert locations – marked by hydraulic jumps and velocity drops from approximately 7 m/s to <1 m/s – contributed to turbulence, sedimentation, and energy loss. These findings suggest that the present drainage design is ineffective in managing flow transitions and sediment transport, ultimately compromising system efficiency, increasing maintenance requirements, and reducing infrastructure resilience.

To enhance the hydraulic performance and long-term sustainability of the Simike–Nzovwe roadside drainage system, an integrated approach combining engineering upgrades, ecological design, and advanced modeling is recommended. Optimizing channel geometry by reducing side slopes from 1:2 to 1:1.5 and increasing longitudinal gradients to 1.5 – 2% can help maintain supercritical flow in targeted sections, minimizing sediment deposition and hydraulic jumps. Enhancing culvert capacity from 1.2 m to 1.5 m and incorporating bell-shaped or flared inlets will improve flow continuity and reduce upstream turbulence and blockage risks. In high-velocity zones (>7 m/s), reinforced concrete or riprap linings are necessary to resist shear-induced erosion. In contrast, vegetative linings or geotextiles can stabilize banks and offer ecological benefits in subcritical regions. Installing sediment traps or forebays upstream, combined with regular inspection schedules, will help manage debris and maintain system integrity. Incorporating sustainable design elements – such as biomimicry-based channel shaping, vegetated benches, and natural flow paths – can further enhance hydraulic efficiency and environmental resilience. To ensure effectiveness, these interventions should be calibrated with field-based measurements, including flow velocities, water depths, and sediment loads, to validate HEC-RAS outputs. However, reliance on steady-state modeling presents limitations in capturing transient flow dynamics. Future work should integrate unsteady or 2D/3D hydrodynamic models for more accurate simulations. Furthermore, the use of high-resolution Light Detection and Ranging data, real-time flow and sediment sensors, and machine learning techniques for parameter calibration is strongly recommended to enhance model accuracy and inform adaptive, climate-resilient infrastructure development.

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Conflict of interest

The authors declare no competing interests.

Author contributions

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Methodology: Zacharia Katambara
Writing – original draft: Zacharia Katambara
Writing – review & editing: Zacharia Katambara

Availability of data

Data are available from the corresponding author upon reasonable request.

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