

## Article

# Effects of River Channel Structural Modifications on High-Flow Characteristics Using 2D Rain-on-Grid HEC-RAS Modelling: A Case of Chongwe River Catchment in Zambia

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## Abstract

Rapid urbanization has led to increasing structural modification of river catchments through dam construction and concrete-lining of natural channels as flood management measures. These interventions can alter the natural hydrology. This necessitates assessment of their influence on hydrology at a catchment scale. However, such evaluations are particularly challenging in data-scarce regions such as the Chongwe River Catchment, where hydrometric records capturing conditions before and after structural modifications are limited. Therefore, we applied a 2D rain-on-grid approach in HEC-RAS to evaluate changes in high-flow responses to short-duration, high-intensity rainfall events in the Chongwe River Catchment in Zambia, where structural interventions have been implemented. The terrain was modified in HEC-RAS to represent 21 km of concrete drains and ten dams. Sensitivity analysis conducted on five key model parameters showed that parameters controlling surface runoff generation, particularly curve number, exerted the strongest influence on simulated peak flows, while routing-related parameters had a secondary effect. Model calibration and validation showed strong performance with  $R^2 = 0.99$ ,  $NSE = 0.75$  and  $PBIAS = -0.68\%$  during calibration and  $R^2 = 0.95$ ,  $NSE = 0.75$ ,  $PBIAS = -2.49\%$  during validation. Four scenarios were simulated to determine the hydrological effects of channel concrete-lining and dams. The results showed that concrete-lining of natural channels in the urban area increased high flows at the main outlet by approximately 4.6%, generated localized instantaneous maximum channel velocities of up to 20 m/s, increased flood depths by up to 11%, decreased lag times and expanded flood inundation widths by up to 15%. The existing dams reduced peak flows by about 28%, increased lag times, reduced flood depths by about 11%, and reduced flood inundation widths by up to 8% across the catchment. The findings demonstrate that enhancing stormwater conveyance through concrete-lining must be complemented by storage to manage high flows, while future work should explore nature-based solutions to reduce channel velocities and improve sustainable flood mitigation. Therefore, the study provides event-scale insights to support flood-risk management and infrastructure planning in rapidly urbanizing, data-scarce catchments.

**Keywords:** Chongwe catchment; HEC-RAS; 2D Rain-on-Grid Modelling; high flows; concrete-lining; stormwater drainage systems; structural modifications



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## 1. Introduction

Landscape disturbance resulting from urban expansion, land-use change, and climate-driven hydro-climatic variability has increasingly altered the hydrological dynamics of river catchments worldwide [1]. An estimated 13.6% of global forest area was lost or degraded between 2000 and 2020, largely driven by urban expansion and agricultural intensification, highlighting the scale of anthropogenic disturbance to catchment landscapes [2]. Such disturbances modify surface runoff generation, flow routing, and flood regulation functions, often prompting the implementation of structural interventions such as dam construction and the concrete-lining of natural channels. Climate change remains one of the global drivers influencing hydrological variability and extremes, with evidence indicating increasing flood and drought risks in many regions [1,3,4]. Globally, such events have displaced an estimated 22 million people annually since 2008, emphasizing the growing humanitarian extent of hydrological extremes [5]. In response to these combined pressures, particularly in rapidly urbanizing regions, engineered flood management measures have been widely adopted to enhance catchment resilience and protect critical infrastructure [6–8].

In response to these evolving climatic pressures, structural interventions have become central to national and regional adaptation strategies across many parts of the world. Governments and water management authorities are increasingly constructing dams, retention basins, and concrete-lined drainage systems to control floods and secure water supply for domestic and agricultural use [9]. While such measures play a vital role in safeguarding infrastructure and livelihoods, they also introduce significant alterations to natural hydrological regimes [6]. These modifications change infiltration capacity, channel roughness, and storage dynamics, thereby influencing the magnitude, timing, and duration of peak flows [10]. Previous studies have reported that channel concretization accelerates runoff concentration and reduces groundwater recharge, whereas dam construction alters downstream hydrographs [8,11,12]. Understanding the impact of these measures on runoff in a watershed is a critical aspect of water resource management and hydrological studies [13–15]. For instance, Huang et al. [16] demonstrated that increased structural modification by increasing imperviousness hindered the infiltration of runoff and caused it to flow directly into rivers, ultimately increasing both surface and channel runoff. Their findings gave implications for prioritizing measures in flood prevention and preparedness, such as the consideration of building arrangement, green infrastructure, and the Low Impact Development (LID) techniques.

Assessing the effects of interventions has become an essential component of modern watershed management and climate adaptation planning [17,18]. Researchers have employed approaches to evaluate the hydrological impacts of anthropogenic interventions in watershed systems. Studies such as those by Rose and Peters [19], Miller et al. [20] and Ress et al. [7] applied paired-catchment analyses to compare runoff responses between drained and undrained basins, demonstrating that artificial drainage increases surface runoff and shortens flow concentration times. More recent studies have advanced to process-based and data-driven frameworks that couple hydrological and statistical methods [21–23]. For instance, Song et al. [21] combined the SIMHYD rainfall–runoff model, the Budyko framework, and double-mass curve (DMC) analysis to quantify the hydrological alterations induced by mining in the headwaters of Chinese catchments, reporting consistent evidence of substantial flow modification across all methods. Similarly, Zhang et al. [22] used both DMC and hydrological modelling to assess irrigation and mining impacts in the Qing-shui River Basin, revealing significant declines in streamflow. While the DMC technique provides a simple means of detecting regime shifts, it cannot reproduce natural flow processes under non-stationary or structurally modified conditions, or during specific rainfall events [24]. In contrast, physically based hydrological models have demonstrated greater

capability to reproduce natural streamflow regimes because they incorporate watershed characteristics such as soils, slopes, land use, and climatic variables [21,25]. When integrated with hydraulic analysis, these models can effectively capture spatially distributed hydrological responses to observed rainfall events by accounting for both channel and catchment-scale flow dynamics [26].

HEC-RAS two-dimensional (2D) rain-on-grid modelling has emerged as a powerful approach for simulating coupled hydrologic–hydraulic processes by directly applying rainfall onto a two-dimensional computational mesh, thereby enabling dynamic interaction between surface runoff, catchment characteristics and channel flow [27]. Although this approach has been increasingly applied in floodplain and urban drainage studies [9,12,28], most existing applications addressing structural modifications at the catchment scale remain limited to single reservoirs or isolated urban drainage networks [29,30]. Consequently, the cumulative, catchment-scale hydrological effects of integrating urban concrete-lined channels together with multiple dams within a single modelling framework remain poorly explored. Moreover, while structural interventions are widely implemented for flood management, few studies have used event-based 2D modelling to jointly evaluate their impacts on peak flows, lag time, flood depth and inundation widths, which are critical indicators of downstream flood risk.

This study addresses these gaps by assessing the high-flow characteristics of the Chongwe River Catchment in Zambia using HEC-RAS 6.5, with particular emphasis on terrain modification to represent 21 km of urban concrete-lined channels and ten existing dams. Terrain modification is applied as a low-cost, transferable approach for incorporating engineered river infrastructure into freely available coarse digital elevation models (DEMs) with minimal field data, avoiding reliance on high-resolution topographic surveys, such as drone-based surveys, that are often unavailable or expensive to collect in data-scarce regions [17]. Using an event-based rain-on-grid modelling, the study evaluates the combined and individual effects of river channel concrete-lining and dam storage on peak discharge, lag time, velocity, flood depth and inundation width across multiple sub-catchment outlets. To the best of our knowledge, this is the first rainfall-event-based, catchment-scale HEC-RAS 2D assessment of structural flood-control interventions in the Chongwe River Catchment in Zambia. The results provide actionable evidence for flood-risk management by demonstrating how urban drainage upgrades and upstream storage interact to amplify or attenuate high flows, thereby supporting informed decisions on drainage design, dam operation and the integration of complementary nature-based solutions in rapidly urbanizing data-scarce catchments.

## 2. Materials and Methods

### 2.1. Study Area

This study was conducted in the Chongwe River Catchment, located in south-central Zambia between Latitudes 14.9° S and 15.5° S and the Longitudes of 28.2° E and 28.8° S (Figure 1). The catchment covers an area of approximately 1964 km<sup>2</sup> and encompasses parts of the towns of Lusaka, Chongwe, and Chisamba. The mean annual rainfall ranges from 750 mm to 930 mm [31]. As shown in Figure 2, rainfall peaks in January with an average value of 232 mm. Minimum and maximum air temperatures are approximately 8.2 °C and 32 °C, respectively [32]. The mean annual actual evapotranspiration is about 786 mm [33], which peaks in March with a mean of 99 mm (Figure 2). Topographically, the catchment is relatively flat, with elevations varying between 1041 m and 1421 m above mean sea level. According to the Food and Agriculture Organization (FAO) soil classification, the dominant soil types in the catchment are Luvisols and Acrisols [31]. Considering vegetation, the Miombo woodland is predominant, characterized by semi-evergreen trees

with a well-developed grass layer [33]. The Zambezi Escarpment zone, located in the catchment, is predominantly Mopane woodland, typically interspersed by patches of Munga woodland [34].

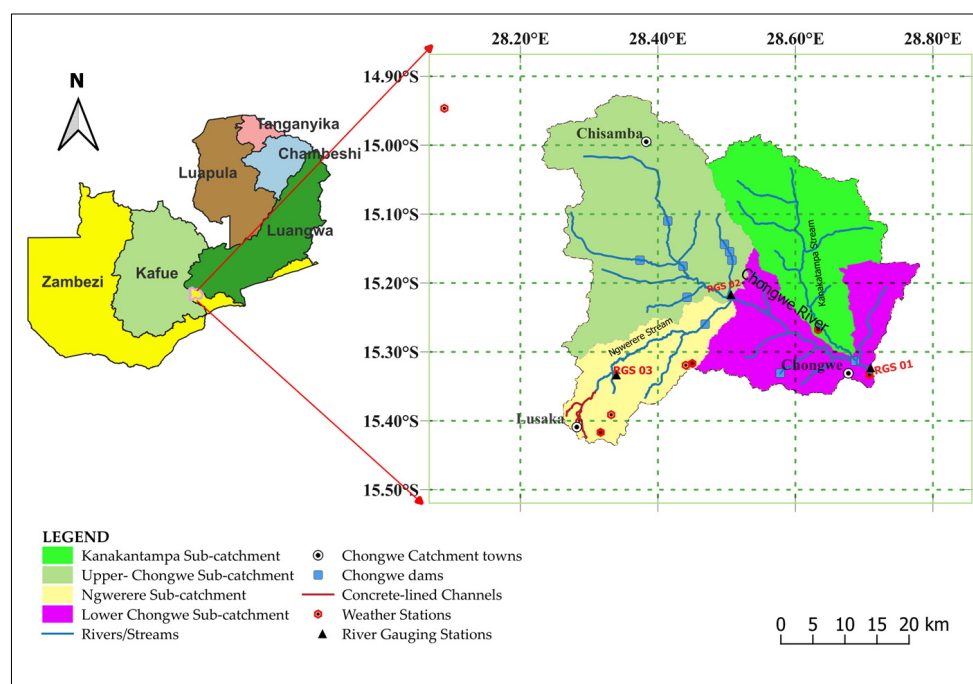


**Figure 1.** Location of the Chongwe River Catchment in Zambia showing sub-catchments, drainage features including rivers, concrete-lined channels and dams, as well as the locations of weather stations, river gauging stations and major towns.

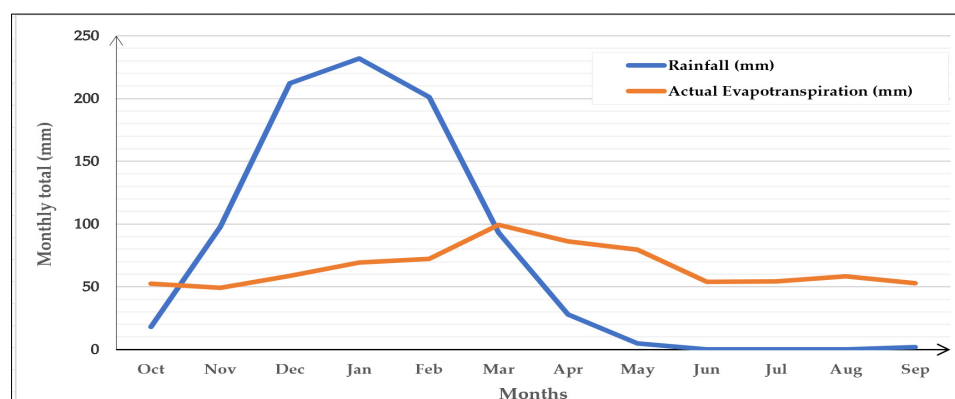


**Figure 2.** Averaged monthly rainfall (mm) and actual evapotranspiration (mm) of Chongwe Catchment.

The study area comprises four main sub-catchments (See Figure 1): Ngwerere, Upper Chongwe, Kanakantapa, and Lower Chongwe. Each sub-catchment has distinct land-use and hydrological characteristics influencing surface runoff generation and flood behaviour. The Ngwerere Sub-catchment, originating in urban Lusaka, represents the city's drainage outflow, where approximately 21 km of natural headwater channels have been concrete-lined to enhance flood conveyance from the city [35,36]. The Upper Chongwe Sub-catchment is dominated by commercial agriculture and contains the majority of irrigation infrastructure, hosting seven irrigation dams that support surface-water abstractions for crop production [37]. The Kanakantapa Sub-catchment reflects intensive rain-fed agriculture and livestock keeping associated with government farming blocks dominated by maize cultivation [38]. The Lower Chongwe Sub-catchment integrates flows from the



### 2.3. Data Collection and Sources

HEC-RAS 2D Rain-on-grid modelling involves incorporating geometric data to represent the hydrology and hydraulics of a river catchment. The datasets used in this study were acquired from multiple sources. The catchment boundary and river network were generated using the global watersheds tool [39]. The DEM (Figure 4) with 30 m resolution was obtained from the Japan Aerospace Exploration Agency (JAXA) [40]. The DEM provided essential topographic information for terrain processing and hydraulic geometry definition within HEC-RAS. To supplement the DEM in representing channels and dams, sample cross-sections at 16 locations (Figure 4) were collected from the Water Resources Management Authority (WARMA) and from field surveys using levelling and an Acoustic Doppler Current Profiler (ADCP v2.6) and used to modify terrain. Data on concrete-lined drainage channels, including layout and geometry (Figure 5), were obtained from the Lusaka City Council (LCC), and data on dams, including location and capacity, also shown in Figure 5, were sourced from the Department of Water Resources Development (DWRD), WARMA and Google Earth Pro. Ground-truthing surveys were conducted between December 2024 and June 2025 to verify channel geometry and dam locations.

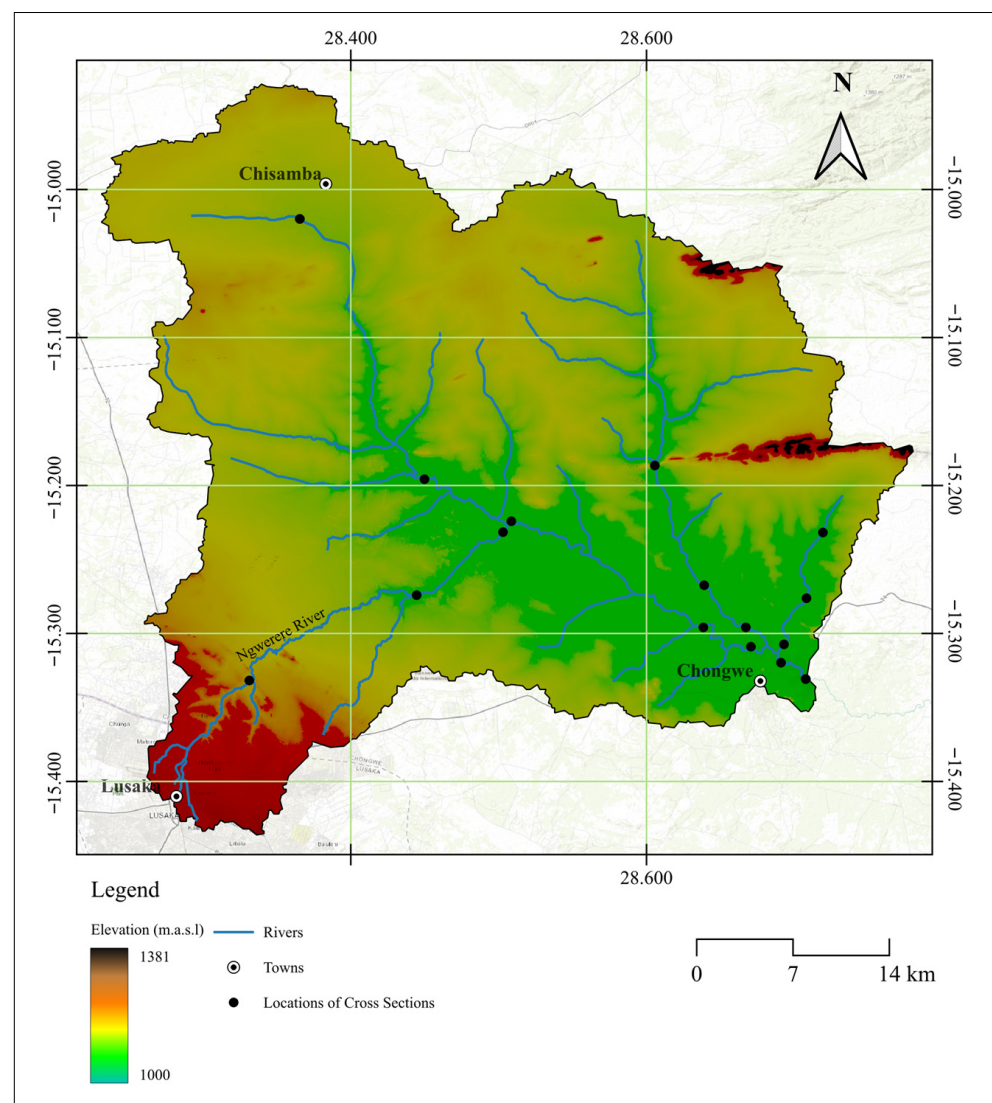


**Figure 4.** Digital Elevation Model and Location of Cross Sections.

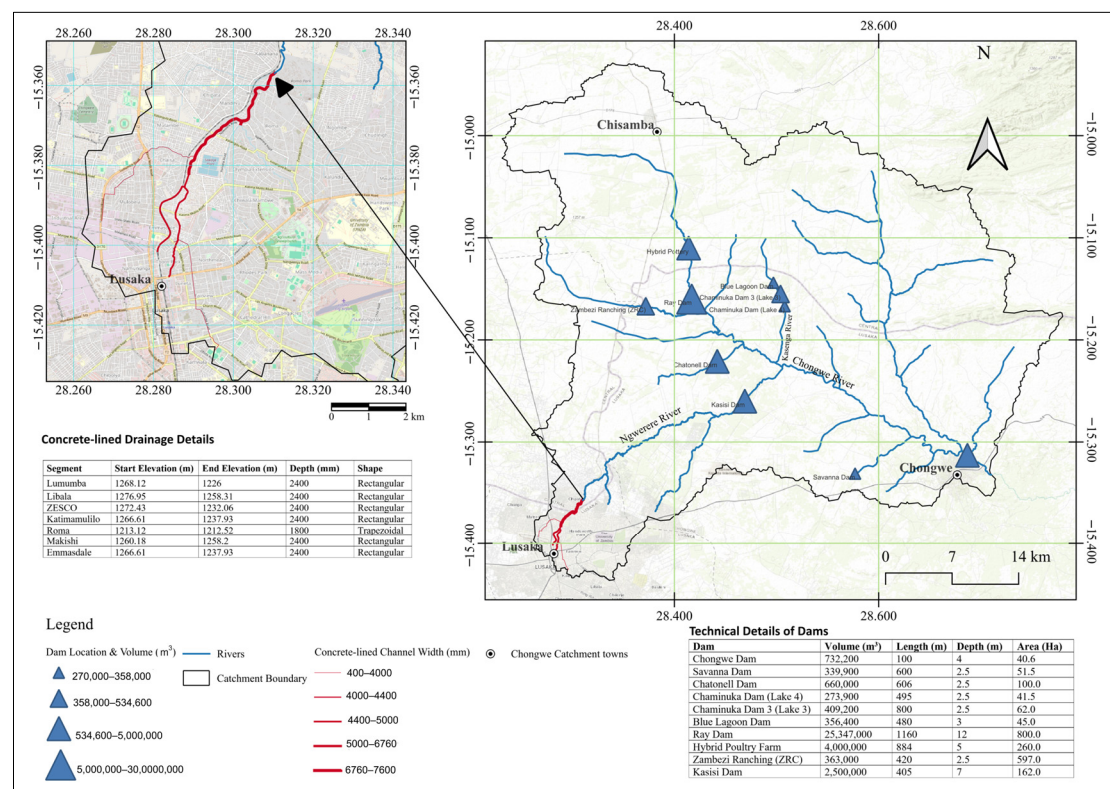


**Figure 5.** Location and details of the concrete-lined channel and existing dams.

To assign hydraulic properties to the computational cells in HEC-RAS, land-use/land-cover (LULC) and soil datasets are required. LULC (Figure 6a) was derived from the European Space Agency (ESA) WorldCover 2021 product with 10 m resolution accessed via Earth Map, based on Sentinel-1 and Sentinel-2 imagery while the soil dataset was obtained from the Hydrologic Soil Groups (HYSOGs250 m) database which provides a globally consistent gridded dataset of hydrologic soil groups (HSGs) with a geographic resolution of about 250 m [41]. Classification of HSGs (Figure 6b) was derived from soil-texture classes and depth-to-bedrock information provided by the FAO SoilGrids system [41]. The classification of the HSGs is described in Table 2. In addition, sub-hourly rainfall events at 15 min intervals were collected from the SASSCAL WeatherNet [40] at the Kenneth Kaunda International Airport and City Airport for the period October 2013 to February 2025 and used in the setting boundary conditions. Streamflow events at 15 min intervals were collected from the WARMA for the Great East Road Bridge Gauging Station (RG1 shown in Figure 1) and used for model calibration and validation.

**Table 2.** Description of Hydrologic Soil Groups [41].

| HSG | Description                                                        |
|-----|--------------------------------------------------------------------|
| A   | Low runoff potential (>90% sand and <10% clay)                     |
| B   | Moderately low runoff potential (50–90% sand and 10–20% clay)      |
| C   | Moderately high runoff potential (<50% sand and 20–40% clay)       |
| D   | High runoff potential (<50% sand and >40% clay)                    |
| A/D | High runoff potential unless drained (>90% sand and <10% clay)     |
| B/D | High runoff potential unless drained (50–90% sand and 10–20% clay) |
| C/D | High runoff potential unless drained (<50% sand and 20–40% clay)   |
| D/D | High runoff potential unless drained (<50% sand and >40% clay)     |

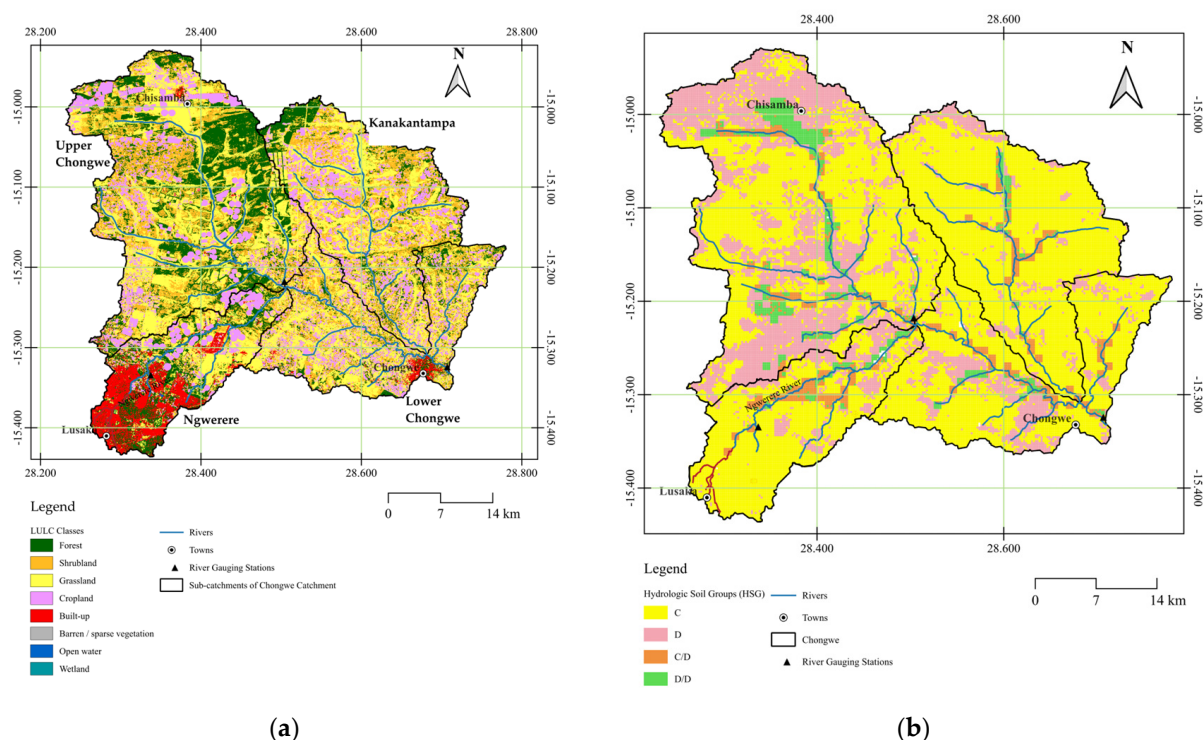


**Figure 6.** (a) LULC map of the Catchment; (b) Hydrological Soil Groups (HSGs) of the Catchment.

## 2.4. HEC-RAS Model Development

### 2.4.1. Terrain Processing

The terrain model forms the foundation for representing surface topography and flow pathways within the HEC-RAS 2D environment [42]. The 30 m DEM was pre-processed in Quantum Geographic Information System (QGIS) to ensure hydrological correctness and representation. However, the raw DEM did not represent the terrain below the water surface in the rivers and drainage channel geometry due to the DEM's coarse resolution. To improve this representation, 16 river cross-sections (Table S1 in Supplementary Data) from field surveys, Google Earth Pro and WARMA were integrated through terrain modification in RAS Mapper using a one-dimensional (1D) geometry. The 1D geometry incorporated major river confluences based on the extracted river network, allowing for consistent connectivity across primary channels. Since the cross-sections were few, the interpolation option [43] was used in HEC-RAS to estimate channel geometry between the available cross-section locations. The terrain modification channel and high ground tools in HEC-RAS were further applied to incorporate the geometry of concrete-lined drainage channels and dam walls, respectively, for better representation of channels and dam walls as recommended in the manual [43].

It should be noted that dams were represented solely through terrain modification of dam walls and associated storage rather than through explicit reservoir routing or operational modelling. Spillway rating curves, gate operations and controlled reservoir release rules were not simulated and dam effects on flood attenuation are therefore represented implicitly through static storage and topographic control. To isolate the influence of dam storage on high flows, dam-related simulations were conducted assuming low initial reservoir levels at the onset of the rainfall event, representing near-empty storage conditions and therefore maximum available attenuation capacity [29]. This assumption is justified by field observations indicating that most existing dams in the Chongwe Catchment are relatively small and are frequently observed to contain little water or to be dry, particularly outside periods of sustained rainfall due to over-abstraction [44,45]. Under this modelling

approach, the simulated dam impacts reflect potential flood attenuation under low initial storage conditions, whereas reduced attenuation would be expected under full-reservoir or spillway-controlled conditions. Figure 7 and Figure S1 in the Supplementary Section show part of the original terrain model and the modified terrain model.

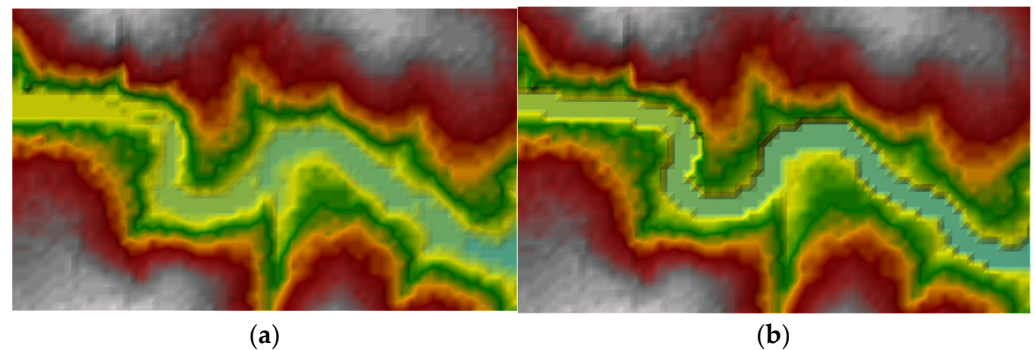


**Figure 7.** (a) Original terrain model; (b) Modified terrain model.

#### 2.4.2. Two-Dimensional (2D) Flow Geometry and Computational Mesh Setup

A 2D flow area (Figure 8) was developed to mimic the hydrological response of the Chongwe River Catchment during rainfall events. A well-developed mesh is essential for numerical stability and for accurately simulating inundation patterns and high-flow routing [46]. A general grid resolution of 100 m was applied to the wider floodplain areas to balance accuracy, stability, computational efficiency and run-time [47]. Breaklines were used to introduce higher-resolution meshes as low as 0.5 m around the drainage channels, rivers, confluences, bridges, and highlands to improve the representation of sharp hydraulic gradients and local flow dynamics. This refinement ensures that narrow drainage channels, as well as much wider river sections, are represented by multiple computational cells across their widths. The 2D flow area was updated, having 406,706 computational cells generated and formed the basis of the simulations. Figure S2 in the Supplementary Materials shows the summarized characteristics of the 2D flow area.

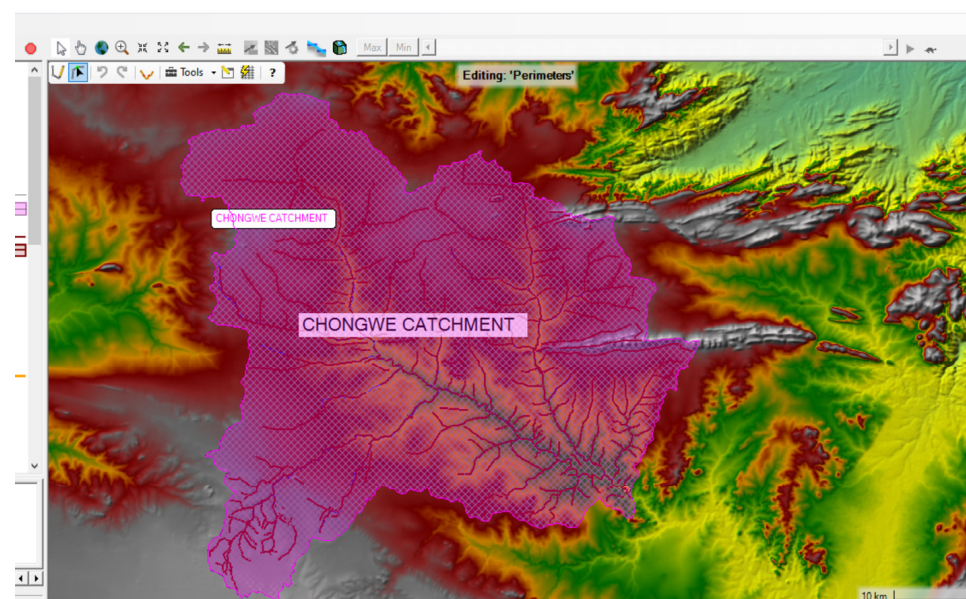


**Figure 8.** Developed computational mesh for 2D Flow Area (Red lines indicate breaklines; Background is the terrain model).

### 2.4.3. Hydraulic Cell/Face Properties and Water Losses

The hydraulic roughness and infiltration characteristics of the computational cells were defined to represent surface resistance and water losses during rainfall events. In HEC-RAS 2D, the hydraulic roughness of each cell was represented using Manning's  $n$ , assigned from the LULC layer and supported by literature recommendations [48]. The proportion of impervious area within each land-use class was also specified to account for areas where direct runoff dominates [49]. Classification polygons available under the LULC layer were used to assign Manning's  $n$  values to the concrete-lined drainage channels.

Water losses in HEC-RAS are computed using three available infiltration computation options: The Constant Deficit method, the SCS Curve Number method, and the Green-Ampt equation. Of these, the SCS Curve Number method was selected because it is widely applied in large-scale catchment studies, requires fewer site-specific soil hydraulic parameters compared to Green-Ampt, and provides a robust linkage between land use, soil type, and hydrologic response [50]. The input parameters for this method are the abstraction ratio, curve number and minimum infiltration (Table S2 in Supplementary Materials). These were assigned to the infiltration layer created by integrating the land use and soil characteristics as recommended by USDA SCS [43,49].

### 2.4.4. Setting of 2D Unsteady Flow Computations

#### (i) Computational Equations

HEC-RAS uses unsteady flow analyses to perform 2D simulations [42]. Unsteady 2D flood modelling advances in time the depth-averaged shallow-water Saint Venant's equations for a free surface over complex topography while exchanging water with rainfall, losses, and boundary fluxes under specified boundary conditions [43]. The governing equations used are as follows:

##### a. Continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = r - i \quad (1)$$

where  $h$  = water depth (m),  $u, v$  = depth-averaged velocity components in  $x$  and  $y$  directions (m/s),  $t$  = time (s),  $r$  = rainfall intensity applied (m/s) and  $i$  = infiltration rate into the ground (m/s).

##### b. Momentum (x and y) equations

$$\frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x}(hu^2 + 0.5gh^2) + \frac{\partial(huv)}{\partial y} = -gh S_{fx} \quad (2)$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial(huv)}{\partial x} + \frac{\partial}{\partial y}(hv^2 + 0.5gh^2) = -gh S_{fy} \quad (3)$$

where  $g$  = gravitational acceleration [9.81 m/s<sup>2</sup>] and  $S_{fx}, S_{fy}$  = friction slope components in  $x$  and  $y$  directions (dimensionless).

##### c. Manning friction slopes

$$S_{fx} = \frac{n^2 u \sqrt{u^2 + v^2}}{h^{4/3}}, \quad (4)$$

$$S_{fy} = \frac{n^2 v \sqrt{u^2 + v^2}}{h^{4/3}} \quad (5)$$

where  $n$  = Manning's roughness coefficient.

In this study, the Diffusion Wave option was adopted as the computational shallow-water equation (SWE) solvers to implement Equations (1)–(5) in HEC-RAS because it is well-suited to broad, mildly sloped floodplains and rainfall-driven sheet flow where inertial effects are small, providing stable, efficient runtimes for calibration, whereas the full-momentum variants are preferable where hydraulic controls or rapidly varied flow dominate [51,52]. In the Chongwe River Catchment, the modelling objective was to assess catchment-scale flood behaviour, including peak discharge, lag time, flood depth and inundation width, rather than structure-scale hydraulics. Detailed geometric information for local hydraulic controls, such as bridges and culverts, was limited, and these features were therefore not explicitly represented in the model. Under these conditions, the diffusion wave solver is considered appropriate for capturing the dominant floodplain and channel routing processes, while acknowledging that localized backwater effects associated with individual hydraulic structures may not be fully resolved. Similar diffusion wave formulations have been widely and successfully applied in large-scale floodplain inundation studies in data-scarce environments [28,47].

## (ii) Boundary Conditions (BCs)

### a. Normal depth

The normal depth boundary inputs the energy slope, which is used to calculate the normal depth with Manning's equation [43]. It is usually estimated using the channel slope. In this study, three (left, right and outlet) boundary condition lines (BCs) were drawn (Figure S3 in Supplementary Materials). The left and right boundaries approximate the watershed divide and were assigned a normal depth slope of zero to represent no-flow lateral boundaries and prevent lateral outflow from the model domain [53]. For the outlet BC, a value of 0.009 was estimated using Global Mapper Pro v26.0 [54] and applied to represent downstream flow conditions.

### b. Rainfall Events

In HEC-RAS, rainfall is introduced as a boundary condition to the 2D flow area. The rainfall events used as boundary conditions in this study were selected from the available 15 min interval rainfall records collected from the Sasscal Automated Station, which is located within the catchment. The rainfall events were selected based on: (i) frequent extreme rainfall events since our objective focuses on high flows, (ii) availability of corresponding observed hourly flow for model calibration and validation and (iii) a period after the implementation of the concrete-lined drainage system in Lusaka to focus on the current conditions. Based on these criteria, three rainfall events shown in Table 3 and Figure 9 were selected. The rainfall event of 9 January 2021 was used for model calibration. In line with best practices in event-based hydrological modelling, particularly in data-scarce contexts, a separate event of 12 January 2022 was selected for validation. The approach involving calibrating the model on one observed flood and validating on a different independent event has been widely applied in HEC-RAS-based flood modelling studies [47,55]. The 29 January 2025 rainfall was selected for scenario analysis to focus on the recent major observed floods in the catchment.

**Table 3.** Rainfall events for calibration, validation and scenario analysis.

| Event | Date            | Start Time<br>(HH: MM) | End-Time<br>(HH: MM) | Comment           |
|-------|-----------------|------------------------|----------------------|-------------------|
| 1     | 9 January 2021  | 01:00                  | 09:15                | Calibration       |
| 2     | 12 January 2022 | 07:45                  | 14:00                | Validation        |
| 3     | 29 January 2025 | 04:30                  | 09:15                | Scenario Analysis |

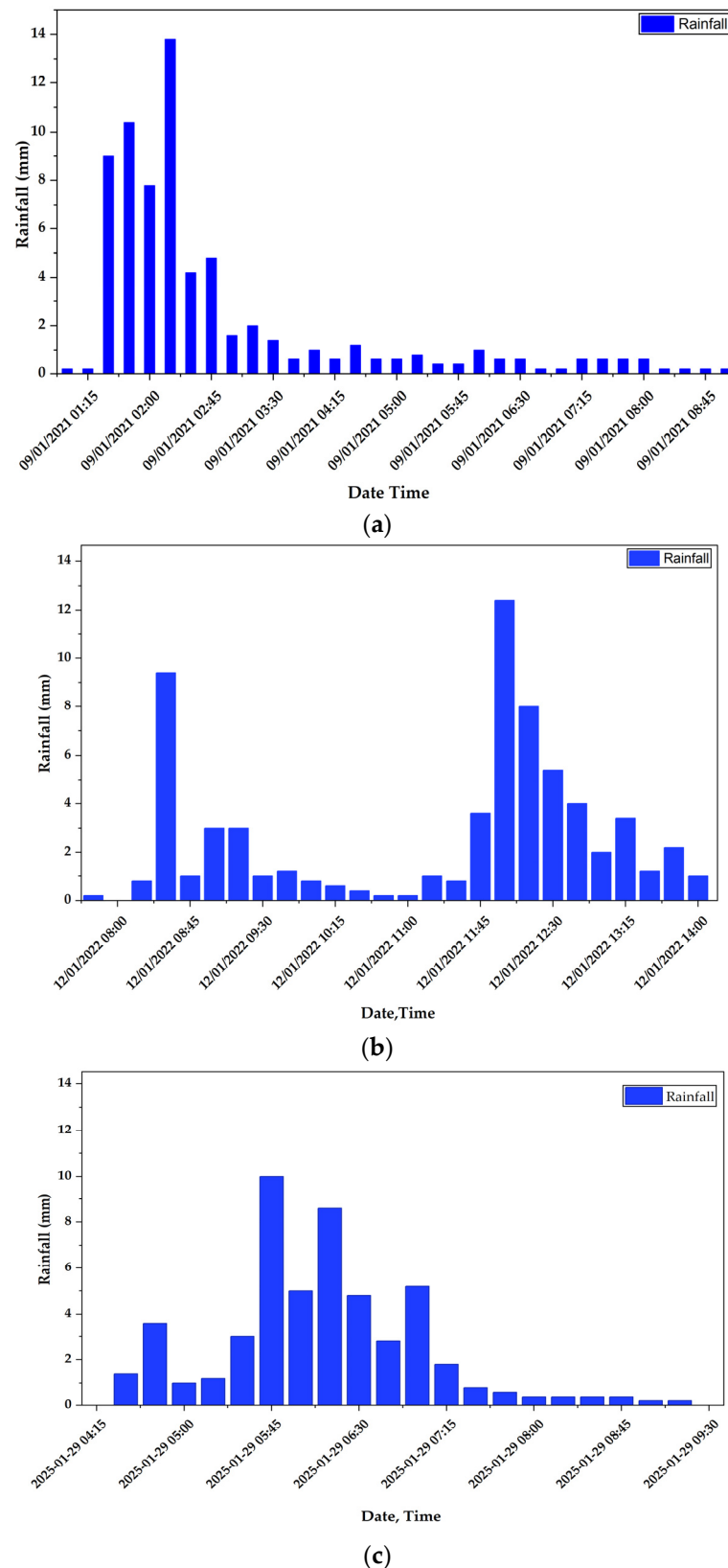


**Figure 9.** Rainfall hydrographs for (a) calibration, (b) validation and (c) scenario analysis.

In implementing the rainfall boundary condition, a spatially uniform rainfall distribution was applied over the 2D flow area. This assumption was adopted because available rainfall records indicate limited spatial variability at the catchment scale. Specifically, a comparison of monthly and annual rainfall records (1985–2024) from two rain gauges located

approximately 25 km apart within the catchment—Kenneth Kaunda International Airport (KKI) and Lusaka City Airport showed strong agreement, with coefficients of determination of  $R^2 = 0.95$  for monthly rainfall and  $R^2 = 0.84$  for annual rainfall (Figure 10a,b). These results suggest broadly similar rainfall patterns across the catchment and support the use of uniform rainfall for catchment-scale modelling. A similar assumption has been adopted in previous hydrological studies of the Chongwe Catchment, including Tena et al. [33], who applied the WEAP model for water balance analysis, and Chisola and Kuráž [45], who assessed long-term hydrological regime changes. Nevertheless, it is acknowledged that spatial variability at sub-hourly storm scales may influence localized runoff generation and the timing of flood peaks. This assumption, therefore, represents a source of uncertainty and future studies could incorporate spatially distributed rainfall inputs, such as weather radar, to further refine event-scale flood simulations where data availability permits.

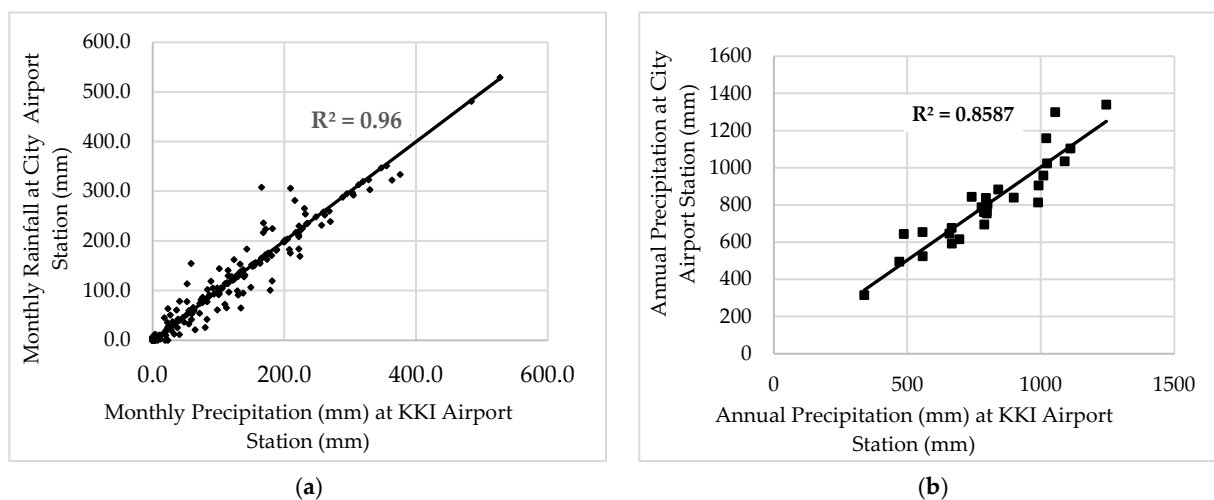


**Figure 10.** Scatter Plots and Comparison of the measured rainfall records at Kenneth Kaunda International (KKI) Airport and Lusaka City Airport for the period 1985–2024: (a) monthly comparison and (b) annual comparison.

#### 2.4.5. Sensitivity Analysis, Calibration and Validation of HEC-RAS 2D Model

A sensitivity analysis was performed to determine the influence of key model parameters, namely Manning’s roughness coefficient, percent impervious, curve number, initial infiltration rate and abstraction ratio, on the peak flow of the Chongwe River as informed by the HECRAS user manual [43]. A local one-factor-at-a-time (OAT) approach was adopted due to the computational cost of 2D simulations and its wide application in flood modelling studies [56]. The initial parameter values assigned from literature [48,49] were systematically perturbed by  $\pm 20\%$  while all other parameters were held constant to determine their influence on flows at the outlet of the Chongwe Catchment.

To determine the sensitivity of the parameters quantitatively, a normalized relative sensitivity index, which expresses the proportional change in model output relative to the proportional change in the perturbed parameter, was quantified [57]. This dimensionless measure, also referred to as the relative effect, allows direct comparison of parameters with different units and magnitudes and addresses limitations associated with absolute sensitivity measures such as the Morris OAT method [58,59]. The relative effect was computed using Equation (6) below.

$$\text{Relative effect} = \frac{\Delta Q/Q}{\Delta x/x} \quad (6)$$

where  $\Delta Q/Q$  is the relative change in peak flow and  $\Delta x/x$  is the relative change in the parameter.

Positive values of the relative effect indicate that an increase in the parameter leads to an increase in peak flow, while negative values indicate an inverse relationship. The magnitude of the relative effect reflects the relative importance of each parameter, with larger absolute values indicating higher sensitivity. Parameters were ranked based on the absolute value of the relative effect to identify dominant controls on peak flow generation within the catchment. A relative thresholding approach [60,61] was adopted to classify parameter sensitivity, whereby parameters with absolute relative effect values greater than 50% of the maximum observed absolute relative effect were categorized as highly sensitive, while those with values below 10% of the maximum were classified as having low sensitivity. Parameters falling between these thresholds were considered moderately sensitive. It is important to note that more comprehensive global sensitivity analysis methods, such as Sobol, exist [59,62]; however, they require extensive simulations that were not feasible in our study. It should also be noted that because parameters were perturbed individually using a one-factor-at-a-time approach, parameter interactions and equifinality were not explored, which represents a limitation of the sensitivity analysis of the study.

Calibration was performed manually by modifying the sensitive parameters and comparing simulated hydrographs with observed streamflow data at the Great East Road Bridge Gauging Station (RG1) [63]. Validation was subsequently performed using an independent rainfall event to test whether the calibrated model retained its predictive ability without further parameter adjustments. The simulation period for both calibration and validation runs was 48 h at 15 min intervals due to HEC-RAS limitations on the number of ordinates for the observed data to conserve computational run-time. The model performance during these runs was evaluated using three performance measures, namely, the coefficient of determination ( $R^2$ ), the Nash–Sutcliffe Efficiency (NSE), and the Percent Bias (PBIAS). The  $R^2$ , NSE, and PBIAS were calculated using Equations (7), (8) and (9), respectively.

$$R^2 = \frac{[\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)(Q_{s,i} - \bar{Q}_s)]^2}{[\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)^2][\sum_{i=0}^n (Q_{s,i} - \bar{Q}_s)^2]} \quad (7)$$

$$NSE = 1 - \frac{[\sum_{i=1}^n (Q_{o,i} - Q_{s,i})^2]}{[\sum_{i=0}^n (Q_{o,i} - \bar{Q}_o)^2]} \quad (8)$$

$$PBIAS = 100 \times \frac{[\sum_{i=0}^n (Q_{o,i} - Q_{s,i})]}{\sum_{i=0}^n Q_{o,i}} \quad (9)$$

where  $Q_{o,i}$  = observed discharge at time  $i$ ,  $Q_{s,i}$  = simulated discharge at time  $i$ ,  $\bar{Q}_o$  = mean of observed discharges,  $\bar{Q}_s$  = mean of simulated discharges and  $n$  = total number of observations.

It has been documented that (i)  $R^2$  is oversensitive to high extreme values, (ii) NSE cannot help in identifying model bias and differences in timings and magnitudes, and (iii) PBIAS can give a deceiving rating of model performance if the model overpredicts as much as it underpredicts [64]. Therefore, a combination of these performance measures, despite their weaknesses, was adopted in this study to be consistent with their widespread application in hydrological modelling by several authors [31,33,37,65]. The resulting performance statistics were evaluated using the classification criteria for hydrological models (Table 4) recommended by Moriasi et al. [64], similar to the approach followed by [55].

**Table 4.** Classification criteria for hydrological models [64].

| Goodness-of-Fit    | NSE                           | PBIAS (%)                           | R <sup>2</sup>                |
|--------------------|-------------------------------|-------------------------------------|-------------------------------|
| Very Good (V)      | $0.75 < \text{NSE} \leq 1.00$ | $\text{PBIAS} < \pm 10$             | $\text{R}^2 \geq 0.75$        |
| Good (G)           | $0.60 < \text{NSE} \leq 0.75$ | $\pm 10 \leq \text{PBIAS} < \pm 15$ | $0.70 < \text{R}^2 \leq 0.75$ |
| Satisfactory (S)   | $0.50 < \text{NSE} \leq 0.60$ | $\pm 15 \leq \text{PBIAS} < \pm 45$ | $0.60 < \text{R}^2 \leq 0.75$ |
| Unsatisfactory (U) | $\text{NSE} \leq 0.50$        | $\text{PBIAS} \geq \pm 45$          | $\text{R}^2 < 0.60$           |

#### 2.4.6. Simulation of Scenarios Represented in the Chongwe Catchment

To evaluate the influence of structural modifications on the hydrological behaviour in the Chongwe River Catchment, four simulation scenarios were designed and executed within the HEC-RAS 2D rain-on-grid framework. These scenarios represent a progression from the current, engineered catchment conditions toward increasingly naturalized states, enabling comparative assessment of the impacts of concrete-lined channels and irrigation dams on runoff generation and peak flow. The description and corresponding model actions applied in each scenario are summarized in Table 5. For each scenario, high-flow metrics including peak flow, lag time, flow velocity, flood depth and flood inundation width were extracted at the sub-catchment outlets. Peak flow was defined as the maximum discharge value of the simulated outlet hydrograph during the rainfall event. Lag time was defined as the time difference between the onset of the rainfall event and the occurrence of peak discharge at the corresponding outlet hydrograph and is reported consistently in hours (hrs). Flow velocity represents the instantaneous maximum cell-based velocity extracted from the 2D computational mesh within the channel domain during the simulation period. Flood inundation width refers to the maximum lateral extent of inundation measured perpendicular to the channel centerline at the outlet reach, derived from the maximum water depth map. The results of the scenarios were collected and observed at the outlets of the four sub-catchments.

**Table 5.** Simulated Scenarios.

| Scenario | Name                                          | Description                                                                                                                                               | HEC-RAS Action Tool                                                                                                   |
|----------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| 1        | Current Conditions (Concrete Channels + Dams) | Simulating the catchment as it is, with existing 21 km concrete-lined channels and 10 dams                                                                | Calibrated model and observed storm                                                                                   |
| 2        | Natural Channels + Dams                       | Simulating the peak flows before concrete-lining of the 21 km of the natural channels in Lusaka, and while observing the effect of dam storage            | Adjusting Manning's number of the classification polygons assigned to the concrete-lined channels to natural channels |
| 3        | Renaturalization: Natural Channels + No Dams  | Simulating the catchment under fully naturalized channels, representing a close to undisturbed channel flow response                                      | Through terrain modification using the channel tool at the dam walls                                                  |
| 4        | Concrete Channels, No Dams                    | Simulating a system with concrete-lined channels in Lusaka but without irrigation dams, to highlight the significance of storage in high flow conditions. | Combination of two actions above (2 and 3)                                                                            |

### 3. Results and Discussion

#### 3.1. Sensitivity Analysis

Sensitivity analysis was conducted using a local one-factor-at-a-time approach by evaluating the normalized relative effect, defined as the ratio of the relative change in simulated peak flow to the relative change in each perturbed parameter. Each parameter was perturbed individually while holding all others constant, and the resulting changes in peak flow at the catchment outlet were quantified following each 48 h HEC-RAS 2D simulation. While previous flood and inundation modelling studies have largely focused on the sensitivity of hydraulic parameters such as Manning's roughness coefficient during model calibration and inundation mapping, this study extends the analysis by evaluating hydrologic and surface-runoff-related parameters including curve number, percent impervious area, abstraction ratio and infiltration characteristics under event-based rainfall conditions [66,67]. The results of the relative effect analysis are presented in Table 6. Under this approach, parameters with larger absolute values of the normalized relative effect exert a stronger influence on simulated peak flow. The results indicate that curve number exhibited the highest sensitivity, with a normalized relative effect substantially larger than that of the other parameters, and was therefore classified as very highly sensitive based on the threshold criteria presented in Table 7. This highlights the strong influence of runoff generation processes on peak discharge under the applied parameter perturbation.

**Table 6.** Normalized Relative Effect Sensitivity Analysis Rankings.

| Parameter                          | Initial Value (x) | Perturbation ( $\Delta x$ ) | Initial Peak Flow ( $Q_i$ ) ( $m^3/s$ ) | Perturbed Flow ( $Q_f$ ) ( $m^3/s$ ) | Relative Effect | Absolute Relative Effect | Sensitivity Ranking |
|------------------------------------|-------------------|-----------------------------|-----------------------------------------|--------------------------------------|-----------------|--------------------------|---------------------|
| Manning's n                        | 0.064             | 0.013                       | 122.760                                 | 105.990                              | −0.673          | 0.673                    | Moderate            |
| % Impervious                       | 16.000            | 3.200                       | 122.760                                 | 145.89                               | 0.942           | 0.942                    | Moderate            |
| Curve Number                       | 86.310            | 10.090                      | 122.760                                 | 31.070                               | 3.810           | 3.810                    | Very High           |
| Initial Infiltration Rate (mm/hr.) | 1.300             | 0.260                       | 122.760                                 | 117.080                              | −0.231          | 0.231                    | Low                 |
| Abstraction Ratio                  | 0.200             | 0.04                        | 122.760                                 | 110.580                              | −0.496          | 0.496                    | Moderate            |

**Table 7.** Relative threshold criteria for classifying parameter sensitivity [61].

| Absolute Relative Effect Range (Relative to Max)     | Sensitivity Classification |
|------------------------------------------------------|----------------------------|
| Absolute Relative Effect > 1.905                     | Very High                  |
| $1.143 < \text{Absolute Relative Effect} \leq 1.905$ | High                       |
| $0.381 < \text{Absolute Relative Effect} \leq 1.143$ | Moderate                   |
| Absolute Relative Effect $\leq 0.381$                | Low                        |

Percent impervious area, Manning's roughness coefficient, and abstraction ratio exhibited moderate sensitivity, indicating a meaningful but secondary influence on peak flow magnitude. In contrast, the initial infiltration rate showed low sensitivity, suggesting that short-duration peak flows in the modelled event were relatively insensitive to moderate changes in infiltration capacity. Overall, the sensitivity results show that, under short-duration and high-intensity rainfall conditions, parameters controlling surface runoff generation and surface connectivity exert a dominant influence on simulated peak flow. In particular, curve number and percent impervious area exhibited the highest relative effects, indicating that peak discharge during event-based simulations is primarily governed by excess rainfall production rather than subsurface losses. Routing-related parameters, such as Manning's roughness coefficient and abstraction ratio, showed a moderate influence, while the initial infiltration rate had a comparatively low effect on peak flow magnitude.

### 3.2. Model Calibration and Validation

The HEC-RAS 2D model was calibrated over a simulation period of 48 h following a 15 min interval rainfall event using Manning's  $n$  and percent impervious for the hydraulic face properties under LULC classes and curve number, initial infiltration rate and abstraction rate under the infiltration layer. The model was evaluated against a continuous hydrograph comprising multiple time steps at 15 min intervals over the flood event, allowing for parameter adjustments to reflect model performance across a range of flow conditions, including the rising and falling limbs and peak flows. This ensured that calibration was not based on a single discharge value, but rather on the ability of the model to reproduce the full temporal dynamics of streamflow at the outlet. Table 8 presents the initial and calibrated Manning's  $n$  and percent impervious values (Land cover layer parameters), while Table S2 in the Supplementary Material presents the initial and calibrated values of curve number, initial infiltration rate and abstraction rate assigned to the infiltration layer.

**Table 8.** Initial and calibrated Manning's  $n$  & % impervious values.

| LULC Class |                 | Manning's $n$ |            | Percent Impervious % |            |
|------------|-----------------|---------------|------------|----------------------|------------|
| ID         | Name            | Initial       | Calibrated | Initial              | Calibrated |
| 1          | Shrubland       | 0.100         | 0.120      | 2.000                | 2.000      |
| 3          | Built-up Land   | 0.045         | 0.030      | 70.000               | 85.000     |
| 4          | Grassland       | 0.060         | 0.055      | 5.000                | 5.000      |
| 5          | Cropland        | 0.050         | 0.050      | 2.000                | 3.000      |
| 6          | Barren Land     | 0.040         | 0.030      | 0.000                | 0.000      |
| 7          | Wetland         | 0.120         | 0.120      | 0.000                | 0.000      |
| 8          | Open Water      | 0.025         | 0.025      | 0.000                | 0.000      |
| 10         | Forest          | 0.120         | 0.160      | 1.000                | 1.000      |
| 9          | Natural Channel | 0.035         | 0.035      | 1.000                | 1.000      |
| 2          | C * Drain       | 0.013         | 0.013      | 1.000                | 100.000    |

\* Concrete-lined drainage channels.

A graphical comparison of the simulated flow and the observed flow at the outlet of the Chongwe Catchment, shown in Figure 11, shows a good model prediction of the observed flow. The statistical computations of model performance during calibration were also conducted, in which  $R^2$ , NSE and PBIAS were found to be 0.99, 0.75 and  $-0.68\%$  respectively. The  $R^2$  value of 0.99 indicates that the model closely followed the overall temporal pattern of the hydrograph, capturing the trends of flood [68]. The NSE value of 0.75 obtained shows that the model reproduced observed flow magnitudes with reasonable accuracy, though it also suggests moderate discrepancies during peak flows [64]. The negative value of PBIAS indicates that the model overestimated the peak flows [68]; however, all the results of statistics obtained fall within the good to very good thresholds defined by Moriasi et al. [64].

The calibrated model parameters were used for the validation of flow using an independent rainfall event which occurred on 12 January 2022 and the corresponding observed flow event and the results are presented in Figure 12. The validation exercise achieved  $R^2$ , NSE and PBIAS of 0.95, 0.75, and  $-2.49\%$ , respectively.  $R^2$  and NSE were similar to calibration results; however, PBIAS shows that the model further overestimated the peak flows during validation compared to calibration. Overall, the HEC-RAS 2D simulations seem to capture the observed flow well, both during calibration and validation runs based on the recommendations of Moriasi et al. [64]. Although peak flows are slightly overestimated, the PBIAS values remain within acceptable limits for hydrological model performance and the bias is systematic across all scenarios. Therefore, relative differences between scenarios

remain meaningful for comparative assessment of the effects of channel concrete-lining and dam storage on high-flow behaviour.

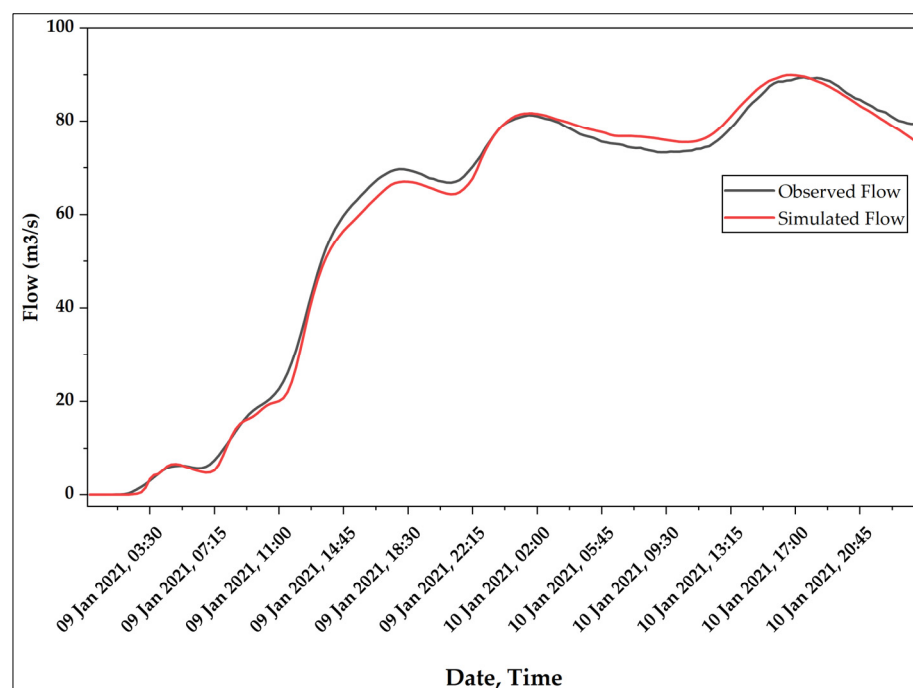


**Figure 11.** Sub-hourly (15 min) flow calibration results for gauging station RG1 located at Great East Road Bridge.

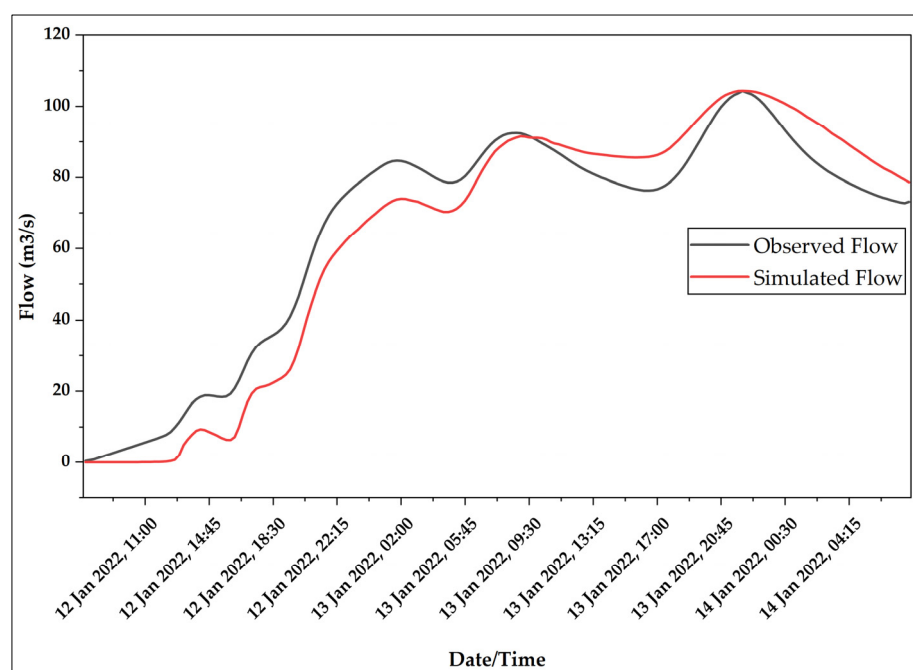


**Figure 12.** Sub-hourly (15 min) flow validation results for gauging station RG1 located at Great East Road Bridge.

### 3.3. Effects of Concrete-Lining of Natural Channels on High Flows

To segregate the hydrological effects of urban channel modification, Scenario 3, which represents a naturalized condition with unlined channels and no dam under the simulated rainfall event, was used as the baseline for comparison. Scenario 4 simulates the same catchment for the same rainfall event, but with 21 km of urban headwater channels of the

Ngwerere River in Lusaka replaced by a concrete-lined drainage channel. The difference between these two event-based scenarios, therefore, captures the response of the catchment to concrete-lining during an extreme rainfall event, rather than long-term hydrological change. The results showed that concrete-lining of 21 km of urban headwater channels significantly altered event-scale flood flows at the outlet of the Ngwerere sub-catchment, where urban drainage upgrades were implemented. A comparison between Scenario 3 (natural channels, no dams) and Scenario 4 (concrete-lined channels, no dams) showed that peak flow increased by 11% (from 49.44 m<sup>3</sup>/s to 54.91 m<sup>3</sup>/s), flood depth rose from 3.79 m to 3.88 m and flood inundation width expanded from 114 m to 117 m. Lag time decreased by 0.20 h, indicating faster runoff concentration response to a rainfall event. These changes are presented in Figure 13 and Table 9. It should be noted that the brief negative discharges observed at the initial stage of Figure 13 are associated with common numerical instability near wetting–drying fronts in 2D shallow-water solvers, where exaggerated friction forces under vanishing depths may even reverse the computed flow [69].

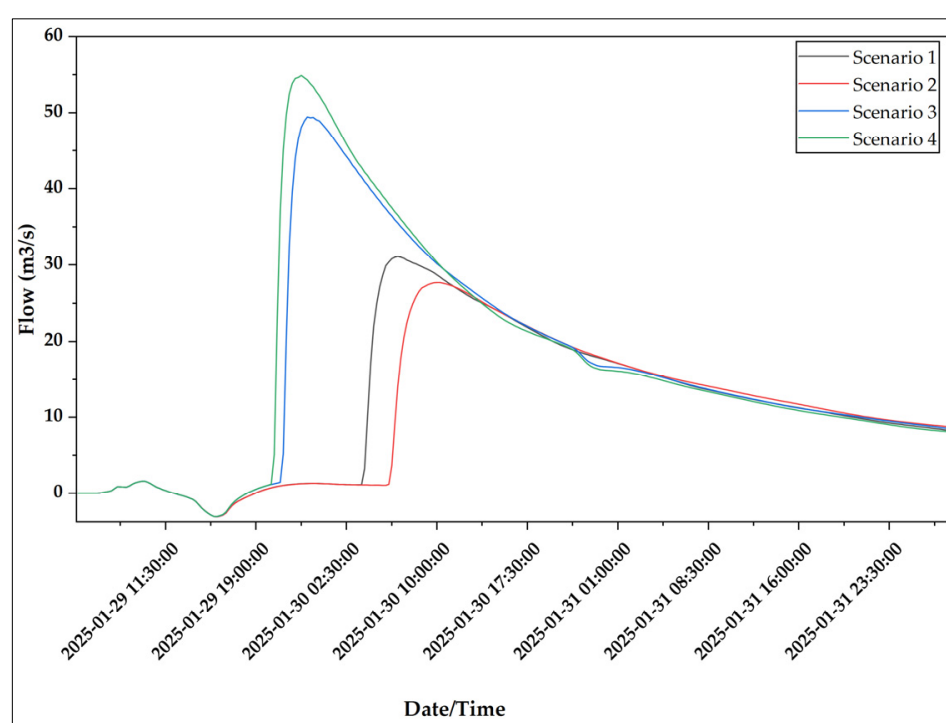


**Figure 13.** High flow characteristics at the Ngwerere outlet for different scenarios.

**Table 9.** Summary of Flow Characteristics at Ngwerere Outlet for the four scenarios.

| Scenario | Peak Flow (m <sup>3</sup> /s) | Lag-Time (h) | Maximum Flood Depth (m) | Flood Inundation Width (m) |
|----------|-------------------------------|--------------|-------------------------|----------------------------|
| 1        | 31.14                         | 25.00        | 3.44                    | 110.00                     |
| 2        | 27.72                         | 28.15        | 3.37                    | 105.00                     |
| 3        | 49.44                         | 17.30        | 3.79                    | 114.00                     |
| 4        | 54.91                         | 17.50        | 3.88                    | 117.00                     |

Historically, flooding has been a recurrent problem in Lusaka due to rapid urban expansion, encroachment into floodplains and inadequate stormwater drainage infrastructure [37,70]. Prior to the concrete-lining of natural urban channels, flood events were frequently reported during intense rainfall events, causing damage to roads, informal settlements, and public infrastructure [70]. These challenges prompted the adoption of channel-lining as a means of rapidly conveying stormwater through densely urbanized

areas during storm events [36]. However, while channel concrete-lining improves flow conveyance within modified reaches, it also fundamentally alters natural flow resistance. Therefore, under the model set-up, the observed increases in peak flow and flood inundation width under scenario 4 can be attributed to the reduction in channel surface roughness and the lack of natural detention associated with concrete-lining. Natural channels typically slow flow through resistance provided by vegetation and irregular geometry and they also facilitate infiltration and temporary storage [71]. In contrast, concrete-lined channels are hydraulically efficient, allowing rapid flow conveyance while limiting infiltration and subsurface storage interactions [20].

This is supported by the results shown in Figures 14 and 15, in which the localized instantaneous maximum velocity outputs across the concrete-lined main drainage channel were extracted for both the concrete-lined and natural channel scenarios and compared. Minor discontinuities are observed in the results at some junctions in Figure 15a,b, likely due to the exclusion of secondary drainage features not captured in the river network datasets used in terrain modification. These visual discontinuities did not affect the hydraulic continuity of the main channels and had no notable impact on the overall simulation results. The results showed that in the concrete-lined channels, instantaneous maximum velocities increased and ranged between approximately 8 m/s and 20 m/s across the channel width. In the natural channel scenario, instantaneous maximum velocities were lower than 5 m/s.

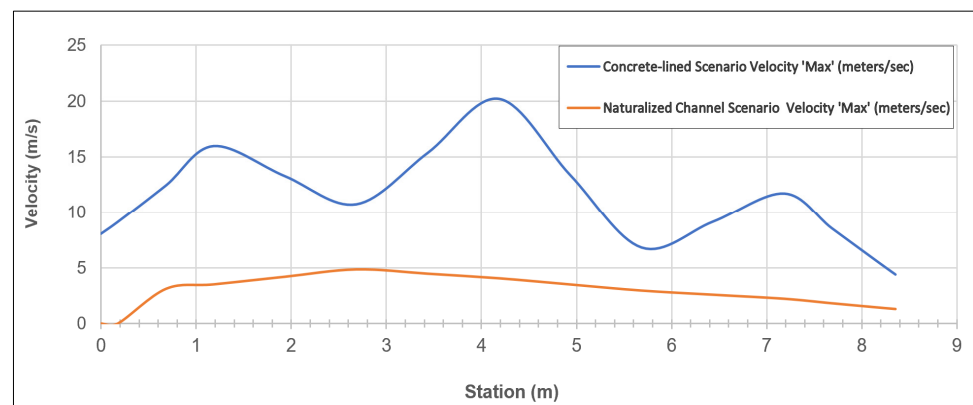


**Figure 14.** Comparison of instantaneous maximum velocities in a naturalized channel and a concrete-lined channel at Kasangula Road Bridge (KRB in Figure 15).

The 2D model was executed using a stable timestep of 1 min that satisfied the Courant–Friedrichs–Lewy (CFL) stability condition with a computational mesh designed to balance numerical stability and representation of key hydraulic features. A coarser grid of 100 m was applied across the wider floodplain, while locally refined cells of 2 m resolution were introduced along river channels and concrete-lined drainage channels using breaklines to better resolve channel geometry and flow acceleration. Under these conditions, the reported velocities of up to approximately 20 m/s represent localized instantaneous maximum values occurring within confined, smooth concrete-lined sections during high flow conditions. Such increases in instantaneous maximum flow velocity are in line with the reported findings of Fletcher et al. [72], who presented that increased imperviousness and enhanced hydraulic connectivity in urban areas lead to elevated stream power and rapid flow acceleration during extreme rainfall events. Although these velocities exceed typical natural-channel conditions, they are physically plausible for short-duration peak flows in confined concrete-lined channels and indicate elevated erosive and structural risk associated with such drainage systems.

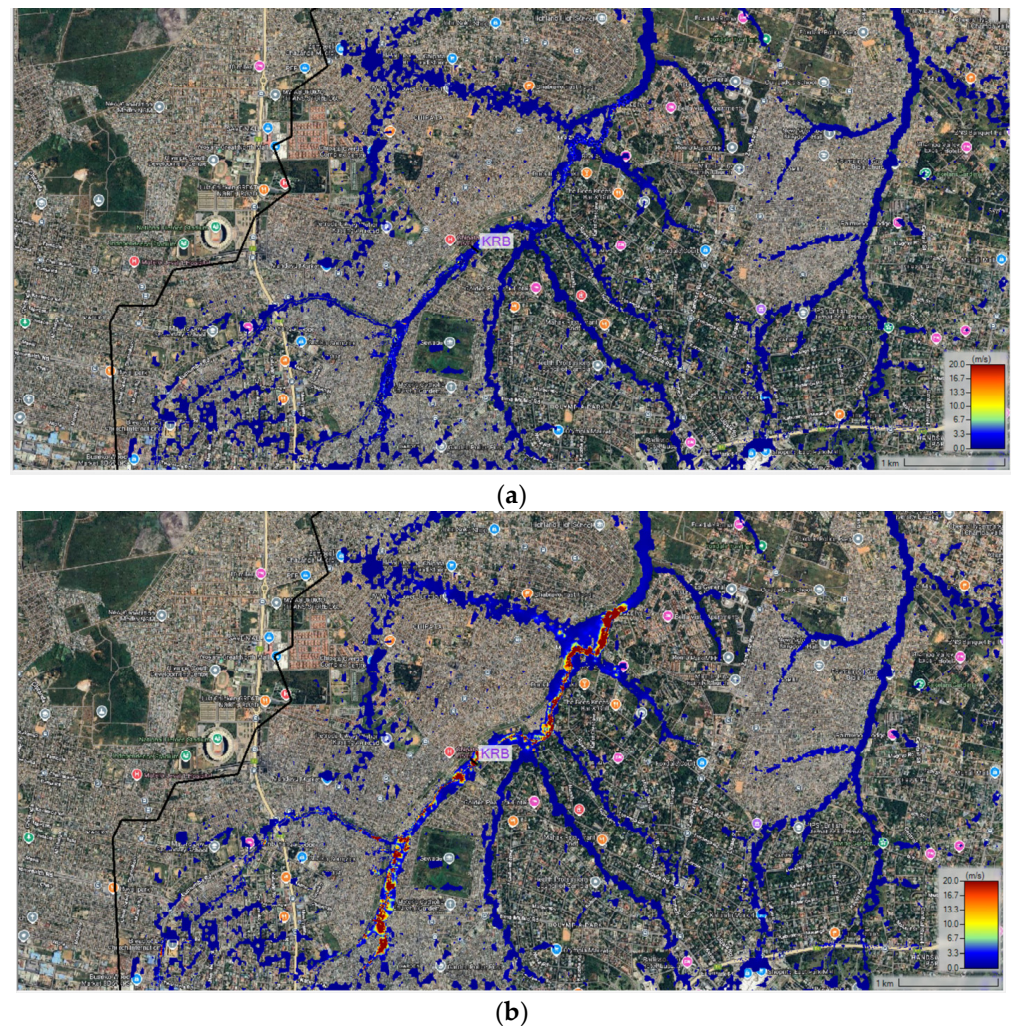


**Figure 15.** Comparison of maximum velocities along: (a) Naturalized channel (Scenario 3) and (b) Concrete-lined channel (Scenario 4) in Lusaka.

Similar hydrological responses to concrete-lining have been reported in other highly urbanized catchments. For example, in the Bukit Timah catchment in Singapore, Palanisamy and Chui [73] showed that concrete-lined drainage canals increased runoff volumes contributing to downstream flood risk. Their study demonstrated that such hydraulic efficiency necessitates complementary mitigation measures, such as low-impact development techniques to restore infiltration and reduce peak flows. Beyond hydrological impacts, studies in other urban catchments have shown that concrete drainage infrastructure can also alter runoff water quality through geochemical interactions between stormwater and concrete surfaces. For example, Wright et al. [74], based on observations from urban catchments in Melbourne, Australia, reported elevated pH, alkalinity, and calcium concentrations in streams receiving runoff conveyed through concrete-lined drainage systems. This suggests that, in addition to increased flood magnitudes downstream, concrete-lining in the Chongwe Catchment may also have implications for runoff quality and stream health, necessitating further investigation in future studies.

The observed increase in instantaneous maximum velocities in the concrete-lined channel can be explained by Manning's equation, which relates velocity to the roughness coefficient, channel slope, and hydraulic radius [75]. When the Manning's  $n$  value is lowered, the flow experiences less frictional loss and accelerates accordingly. In addition, smoother channel geometry reduces small-scale surface irregularities and localized storage effects relative to natural channels, contributing to more efficient flow conveyance [48].

Furthermore, concrete channels are often more directly connected to impervious urban surfaces, which increases both the velocity and volume of runoff entering the drainage channel system. As a result, the flow becomes more concentrated, contributing to elevated flood levels and wider flood inundation widths at the catchment outlet under the modelled conditions.

At the main Chongwe River outlet, the downstream influence of upstream concrete-lining was also evident, although the magnitude of hydrological changes was less pronounced. Comparing Scenario 4 (concrete-lined, no dams) with Scenario 3 (natural channels, no dams) showed that peak flow increased by 4.6% from 73.60 m<sup>3</sup>/s to 77.00 m<sup>3</sup>/s, while lag time decreased by approximately 1.25 h (Figure 16 and Table 10). The smaller change at the main outlet reflects the larger catchment size and longer flow routing distance, which reduces the influence of localized urban channel modifications. Under the same scenario comparisons, the maximum flood depth increased slightly from 1.99 m to 2.22 m, while the flood inundation width expanded from 102 m to 104 m. The spatial differences in flood depth distribution and inundation width along the Chongwe outlet reach are illustrated in Figures 17 and 18, respectively. The quantitative changes are summarized in Table 10.

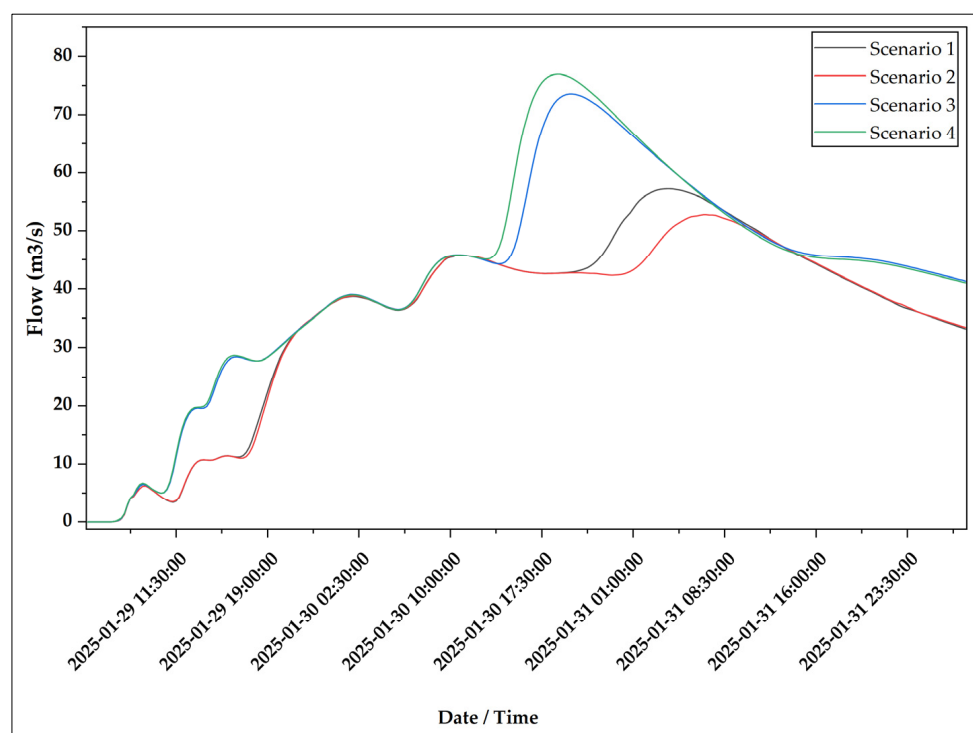


Figure 16. High flow characteristics at Chongwe main outlet for different scenarios.

Table 10. Summary of Flow Characteristics at Chongwe main outlet for the four scenarios.

| Scenario | Peak Flow (m <sup>3</sup> /s) | Lag-Time (h) | Maximum Flood Depth (m) | Flood Inundation Width (m) |
|----------|-------------------------------|--------------|-------------------------|----------------------------|
| 1        | 57.25                         | 46.00        | 1.81                    | 100.00                     |
| 2        | 52.82                         | 49.25        | 1.77                    | 98.00                      |
| 3        | 73.60                         | 38.25        | 1.99                    | 102.00                     |
| 4        | 77.00                         | 37.00        | 2.22                    | 104.00                     |

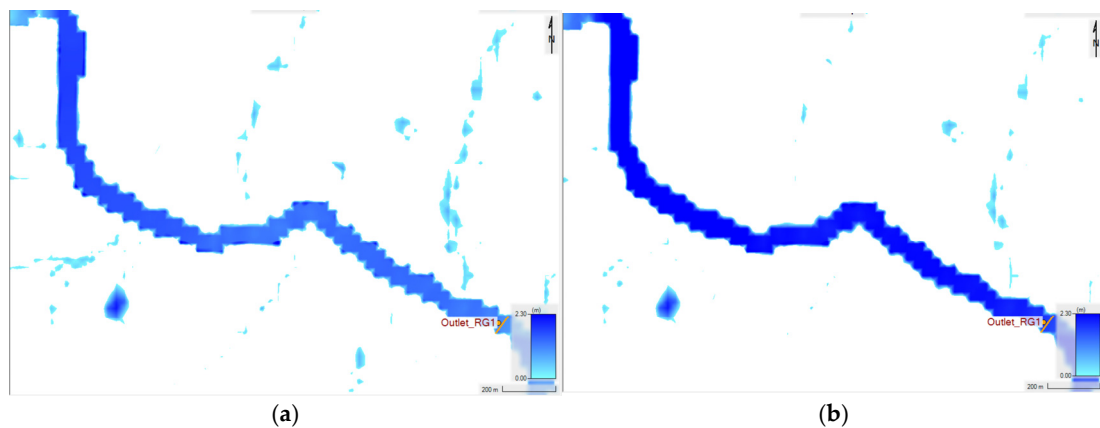


**Figure 17.** Comparison of maximum flood depth distribution in RAS Mapper at the Chongwe River (RG1) Reach under (a) natural channel conditions without concrete-lining (Scenario 3) and (b) concrete-lined channel conditions in Lusaka City (Scenario 4).

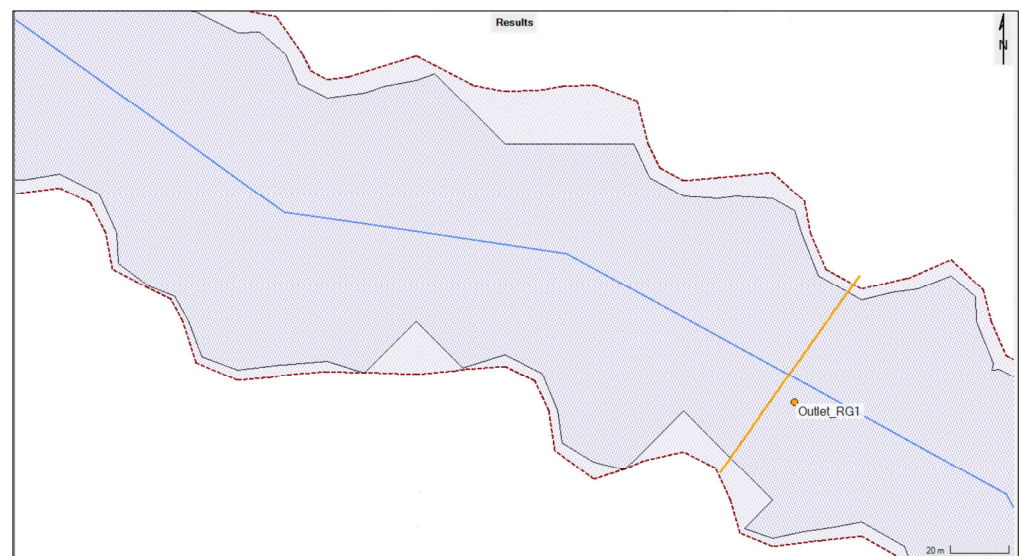


**Figure 18.** Overlay comparison of flood inundation boundaries in RAS Mapper at the Chongwe River Outlet (RG1) Reach for Scenario 3 (natural channels, shown by the black solid line) and Scenario 4 (concrete-lined channels, shown by the red dashed line).

The simulated downstream changes in the high flows (Figure 15) suggest that even localized structural modifications, such as concrete-lining within a single urban sub-catchment, can have cascading effects at the catchment scale. The accelerated routing of stormwater reduces the time available for the natural hydrological processes, thereby increasing the timing and inundation widths of downstream flooding during high-flow conditions. This effect is further reflected in the flood depth and inundation maps (Figures 17 and 18), where concrete-lined channels are associated with increased flow movement leading to increases in flood depth and inundation width at the Chongwe River outlet reach. These findings highlight the importance of considering system-wide hydrologic connectivity when designing urban drainage interventions. Our findings are consistent with studies such as Ress et al. [7], who reported increased peak flows when natural channels are replaced by engineered stormwater drainage systems. While these findings are out of a 15 min interval rainfall event-based modelling, they support the findings of Chisola and Kuráž [45] who analyzed long-term streamflow time-series and reported an increase in streamflow during wet seasons and a reduction in dry season, suggesting a decrease in lag time, similar to our results. Tena et al. [37] attributed rising wet-season flows to

the rapid expansion of buildings and road infrastructure in Lusaka. Our study adds new evidence by showing that the observed increases in flow in wet seasons may further be linked to the construction of the 21 km concrete-lined drainage system (the Bombay drain) in Lusaka, which enhances runoff concentration and accelerates peak-flow delivery to the Chongwe River.

### 3.4. Effects of Dam Storage on High-Flows

To evaluate the effects of dam storage on high flows, Scenario 2 (natural channels with dams) was compared with Scenario 3 (natural channels without dams) at the outlets. This comparison isolates the hydrological influence of existing irrigation and water supply dams while keeping the surface channel characteristic constant. The results showed that dam presence reduced peak flows and delayed flood wave propagation across the Chongwe River Catchment. At the Ngwerere outlet, peak flow decreased by 44%, from 49.44 m<sup>3</sup>/s in Scenario 3 to 27.72 m<sup>3</sup>/s in Scenario 2. Lag time increased by approximately 11 h, from 17.05 to 27.93 h, while flood depth and inundation width decreased by 11% and 8%, respectively (Figure 13 and Table 9). These changes can be attributed to the presence of the Kasisi Dam on the Ngwerere River, which stores stormwater and thus delays and reduces downstream flow volumes during high-flow conditions. The dams temporarily store inflowing stormwater during peak rainfall periods and release it gradually through outlet structures [76]. Consequently, when dams are removed under Scenarios 3 and 4, this attenuation effect is lost and a larger proportion of event runoff is transmitted directly downstream, leading to higher and earlier peak discharges, reduced lag time, and increased flood depths and inundation width. As defined in the model setup, if a comparable rainfall event were to occur when the reservoirs are already at or near full supply level, the available storage for flood attenuation would be substantially reduced and a greater proportion of inflowing floodwaters would be routed downstream, resulting in increased peak discharge, reduced lag time, and enhanced downstream flood depths and inundation width [77].

A similar pattern was observed at the Upper Chongwe outlet, where the presence of upstream dams reduced high-flow magnitudes. Peak flow decreased by 35%, from 14.73 m<sup>3</sup>/s under Scenario 3 (no dams) to 9.64 m<sup>3</sup>/s under Scenario 2 (with dams), as shown in Figure 19 and Table 11. The sharp rise in flow observed when dams are removed in Scenarios 3 and 4 reflects the loss of upstream storage, particularly following the removal of seven major irrigation dams with a storage capacity of over 31.4 million cubic metres (Figure 5). Under dam-present conditions, the runoff is stored and released more gradually, which smooths the hydrograph and reduces peak flows. In contrast, when there are no dams, runoff generated by the rainfall event is routed directly downstream, resulting in a faster and more abrupt increase in discharge at the outlet. In addition, the maximum flood depth decreased from 1.71 m to 1.52 m, while flood inundation width contracted from 89 m to 80 m, demonstrating the capacity of upstream storage to reduce flood levels and downstream flood inundation. In contrast to other sub-catchments, the lag-time response at the Upper Chongwe outlet showed a marked decrease, from 56.45 h in the no-dam scenario to approximately 13 h when dams were present. This behaviour reflects the proximity of multiple dams, including the Ray Dam, to the outlet. Under the present dam conditions, flows reaching the outlet are dominated by outflows from the dam that respond more rapidly once reservoir levels rise. When the dam is removed in the simulation, inflows must travel the entire natural channel system, resulting in longer flood-wave travel times. Under full-reservoir conditions, spillway-controlled outflows would be initiated earlier and convey higher downstream discharges, thereby diminishing the flood-attenuation benefits observed under the low initial reservoir conditions assumed in this study.

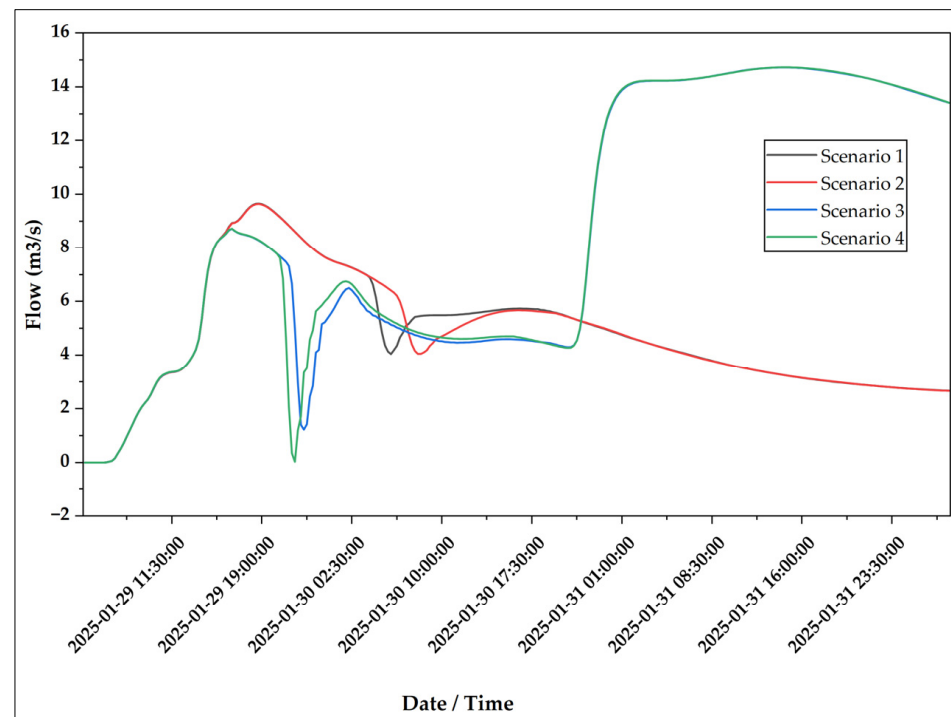


Figure 19. High flow characteristics at the Upper Chongwe outlet for different scenarios.

Table 11. Summary of Flow Characteristics at Upper Chongwe Outlet for the four scenarios.

| Scenario | Peak Flow (m <sup>3</sup> /s) | Lag-Time (h) | Maximum Flood Depth (m) | Flood Inundation Width (m) |
|----------|-------------------------------|--------------|-------------------------|----------------------------|
| 1        | 9.65                          | 13.00        | 1.15                    | 101.00                     |
| 2        | 9.64                          | 13.00        | 1.11                    | 97.00                      |
| 3        | 14.73                         | 56.45        | 1.50                    | 105.00                     |
| 4        | 14.74                         | 57.00        | 1.59                    | 108.00                     |

This finding is similar to the findings of Olariu et al. [78] in the Siret River Basin, who demonstrated that the influence of dams is strongest closest to the dam, then decreases downstream as the river system recovers its natural state. Therefore, the hydrograph is dominated by dam releases rather than natural channel routing. This finding calls for the need for multiple hydrograph observation points along the river; otherwise, near-dam outlets observations only can give a misleading picture of catchment response in structurally modified basins [79].

At the Main Chongwe outlet, the combined effect of all the 10 upstream dams produced a 28% reduction in peak flow from 73.60 m<sup>3</sup>/s (Scenario 3) to 52.82 m<sup>3</sup>/s (Scenario 2). Lag time increased from 38.25 h to 49.25 h, a 29% delay in flood wave arrival at the outlet. The maximum flood depth decreased by 11% and the flood inundation width narrowed by 4% (Figure 16, Table 10). Under the simulated conditions, these results show that 10 dams across the Chongwe Catchment play a substantial role in attenuating extreme flow events during short-duration, high-intensity rainfall. While previous assessments in the catchment have focused primarily on monthly or annual streamflow trends [37,80], the present event-based simulation highlights the sub-hourly influence of dam infrastructure on high-flow regulation rather than long-term hydrological change. The findings suggest that current dams provide effective mitigation of flash flood peaks and that their hydrological influence is both location-dependent and event-specific.

### 3.5. Integrated Effects of Concrete-Lining of Natural Channels and Dam Storage

The integrated effects of urban concrete-lining and dam storage were assessed by comparing Scenario 1 (concrete-lined channels with existing dams) against the naturalized Scenario 3. This comparison captures the effect of structural modifications introduced for flood management in the Chongwe Catchment. At the Ngwerere outlet, peak flow decreased by 43%, from 54.91 m<sup>3</sup>/s in Scenario 3 to 31.14 m<sup>3</sup>/s in Scenario 1. Flood depth dropped by 11%, from 3.88 m to 3.44 m, and flood inundation width narrowed by 6% from 117 m to 110 m. Lag time increased by 43%, suggesting a delayed runoff response despite the presence of the 21 km of concrete-lined drains in Lusaka. This shows that dam storage plays a significant role in reducing the peak-increasing effects associated with channel concrete-lining and in moderating the downstream flood response.

At the Main Chongwe outlet, the integrated influence of structural measures was similarly evident (Figure 16 and Table 10). Peak flow decreased from 76.99 m<sup>3</sup>/s (Scenario 3) to 57.25 m<sup>3</sup>/s (Scenario 1), representing a 26% reduction. Lag time increased by 24%, while flood depth and flood inundation width reduced by 10% and 4%, respectively. The overlay comparison of the flood inundation boundaries depicting the integrated influence of concrete-lining and dams is shown in Figure 20. These results reflect the cumulative regulating effect of multiple dams situated in the Ngwerere, Upper Chongwe and Lower Chongwe sub-catchments, which capture and store water over time and thus lessen the flood wave arriving at the outlet for the simulated event [76]. It should be noted that if similar rainfall events were to occur under full-reservoir conditions, the flood storage effects would be reduced, resulting in higher peak flows, shorter lag times and increased flood depth and inundation width as spillway-controlled outflows become dominant under such conditions [77].

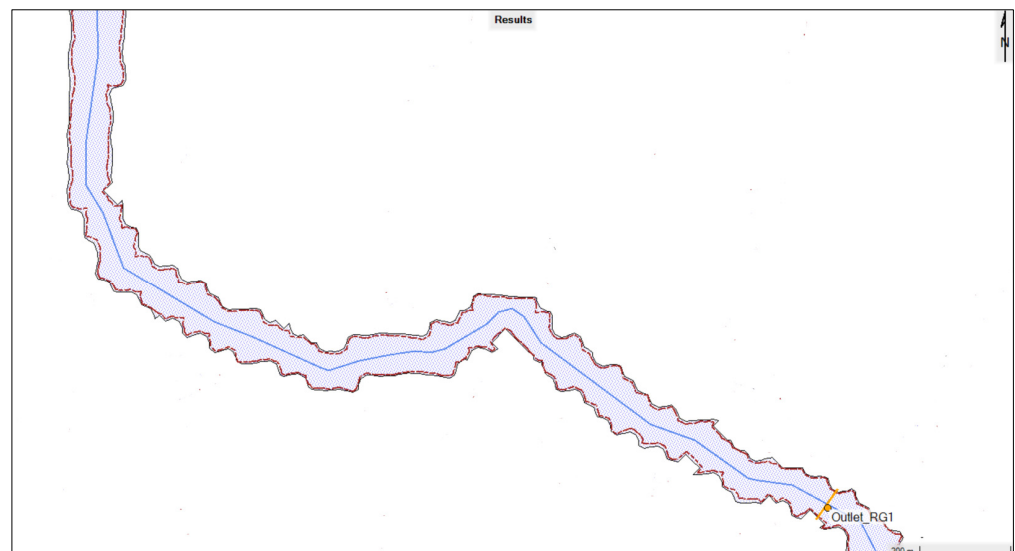


**Figure 20.** Overlay comparison of flood inundation boundaries in RAS Mapper at the Chongwe River (RG1) Reach for Scenario 3 (natural channels, shown by the black solid line) and Scenario 1 (concrete-lined channels with dams shown by the red dashed line; the blue line shows the river centreline).

The overall hydrological behaviour across all four scenarios demonstrated that although concrete-lining alone tends to accelerate and increase flow magnitudes, dam storage counteracts these effects by storing some volume of the flow [81]. This hydraulic buffering effect is supported by previous studies [82,83], which demonstrate that dams reduce both the magnitude and timing of peak flows, particularly when positioned close to areas of rapid runoff generation. Despite these reductions, flow velocities within the concrete-lined sections remained high, ranging from 8 to 20 m/s, far exceeding those recorded under

natural-channel conditions. This presents a continued risk of downstream erosion and structural damage during high-flow conditions, even when peak volumes are reduced downstream. This underscores the need for a hybrid flood management approach, which includes Nature-based Solutions (NbS) such as vegetated swales, wetlands and green spaces to reduce instantaneous maximum velocities, enhance infiltration, and increase catchment resilience. Integrating NbS alongside existing hard infrastructure may offer a more sustainable solution to managing urban flood risks in rapidly developing catchments like Chongwe [17].

### 3.6. Modelling Assumptions and Uncertainty

It should be noted that the event-based simulations presented in this study assume a spatially uniform rainfall distribution across the Chongwe River Catchment. While this simplification is supported by the strong agreement observed between long-term rainfall records from the two rain gauges located in different parts of the catchment, spatial variability at sub-hourly storm scales may still occur, particularly during convective rainfall events in urban areas [84]. Such variability can influence localized runoff generation and the timing of flood-wave propagation, potentially affecting the magnitude and arrival time of simulated peak flows at specific sub-catchment outlets. In this study, the differences observed between modelling scenarios are mainly driven by changes in channel roughness, drainage efficiency, and upstream storage associated with concrete-lined channels and dams. As a result, uncertainties related to rainfall spatial variability are unlikely to alter the overall direction of the simulated impacts of the structural interventions at the catchment scale, which is the primary focus of the analysis. Consequently, the uniform rainfall assumption is considered reasonable for evaluating relative differences between structural modification scenarios, although it introduces uncertainty in localized flow responses. Future studies could reduce this uncertainty by incorporating spatially distributed rainfall inputs derived from weather radar when such datasets become available for the catchment.

Additional sources of uncertainty arise from terrain representation and model parameterization. The use of a 30 m digital elevation model, combined with terrain modification techniques and interpolated cross-sections, may introduce uncertainty in channel geometry and localized flow dynamics, particularly within narrow or engineered channels. Furthermore, parameter uncertainty remains due to the application of a screening-level one-factor-at-a-time sensitivity analysis, which does not explicitly account for parameter interactions or equifinality. These limitations are inherent to event-based hydrologic-hydraulic modelling in data-scarce catchments and should be considered when interpreting the results.

## 4. Conclusions and Recommendations

This study used a 2D rain-on-grid HEC-RAS event-based modelling approach to evaluate the influence of concrete-lining of natural channels and dam storage on high-flow behaviour in the Chongwe River Catchment. The results reflect short-duration, event-scale flood responses that are relevant for flood assessment and planning in data-scarce catchments. Sensitivity analysis was conducted successfully and showed that, under the simulated short-duration rainfall event, parameters controlling surface runoff generation and surface connectivity, particularly curve number and per cent impervious area, exerted the strongest influence on simulated peak flows, while routing-related parameters had a secondary effect. The developed model performed well with  $R^2 = 0.99$ ,  $NSE = 0.75$ , and  $PBIAS = -0.68\%$  for calibration, and  $R^2 = 0.95$ ,  $NSE = 0.75$ , and  $PBIAS = -2.49\%$  for validation. This shows that the model is suitable for event-based flood modelling in the Chongwe Catchment and similar catchments. The study demonstrated that the

concrete-lining of 21 km of natural drainage channels in Lusaka increased high flows by approximately 4.6% at the main catchment outlet and generated localized instantaneous maximum flow velocities of up to approximately 20 m/s within the urban drainage system under the simulated rainfall event.

On the other hand, the 10 existing dams reduced peak flows by about 28% and increased lag times by 24%, while flood depth and flood inundation width were reduced by 10% and 4%, respectively. However, the magnitude of these mitigation benefits is strongly dependent on initial reservoir storage conditions, with reduced attenuation expected under full-reservoir or spillway-controlled conditions. This highlights their important role in reducing the magnitude of flash floods during short-duration, high-intensity rainfall events. From a planning perspective, these results highlight the limitations of concrete-lining as a stand-alone flood management measure. Future urban planning should incorporate downstream storage infrastructure, such as dams, alongside major drainage upgrades to effectively capture stormwater and mitigate the high-flow impacts associated with the concrete-lining of natural channels. The results further point to opportunities for incorporating complementary nature-based solutions (NbS) such as vegetated swales, wetlands and floodplain buffers to reduce flow velocities, enhance infiltration and improve overall catchment resilience.

The limitations of the study include: (i) the use of event-based simulation rather than continuous long-term modelling, which does not capture seasonal hydrological variability or dam operation dynamics; (ii) simplified river channel representation due to sparse cross-section data and manual interpolation, which may introduce geometric uncertainty in modified channels and dam structures; and (iii) the assumption of uniform rainfall distribution across the catchment, which may overlook spatial rainfall variability during localized storms. Future research could also benefit from continuous modelling over longer periods to quantify the effects of dams under a wider range of hydrometeorological conditions. For sub-catchments such as Kanakantapa, where no significant structural modifications were observed but rain-fed agriculture is predominant [31], further assessment of land management and soil conditions is needed to guide the selection of suitable interventions across the Chongwe River Catchment.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/hydrology13020065/s1>, Table S1: Cross-Sections and Elevations; Table S2: SCS Curve Number Method Input Parameters; Figure S1: Sample Terrain Modification; Figure S2: 2D Flow Area Characteristics; Figure S3: Three Normal Depth Boundary Lines Regulating Flow Out of The Catchment.

**Author Contributions:** F.M. designed the methodology, performed the modelling and analysis, interpreted the results, and prepared the original draft of the manuscript. H.M.M., J.M.G. and C.W.M. supervised the research and design of the methodology, provided guidance throughout the modelling and interpretation stages, and contributed to the review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** Data is contained within the article, or Supplementary Material; however, the model files developed can be obtained from the corresponding author upon reasonable request.

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## Abbreviations

|         |                                                                                         |
|---------|-----------------------------------------------------------------------------------------|
| 2D      | Two-Dimensional                                                                         |
| ADCP    | Acoustic Doppler Current Profiler                                                       |
| CFL     | Courant–Friedrichs–Lewy                                                                 |
| DAAD    | German Academic Exchange Service                                                        |
| DEM     | Digital Elevation Model                                                                 |
| DMC     | Double-Mass Curve                                                                       |
| DWRD    | Department of Water Resources Development                                               |
| ELM     | Eulerian–Lagrangian Method                                                              |
| ESA     | European Space Agency                                                                   |
| FAO     | Food and Agriculture Organization                                                       |
| HSG     | Hydrologic Soil Group                                                                   |
| HEC-RAS | Hydrologic Engineering Centre—River Analysis System                                     |
| HEC-HMS | Hydrologic Engineering Centre—Hydrologic Modelling System                               |
| IDF     | Intensity–Duration–Frequency                                                            |
| JAXA    | Japan Aerospace Exploration Agency                                                      |
| JKUAT   | Jomo Kenyatta University of Agriculture and Technology                                  |
| LCC     | Lusaka City Council                                                                     |
| LID     | Low Impact Development                                                                  |
| LULC    | Land Use/Land Cover                                                                     |
| NSE     | Nash–Sutcliffe Efficiency                                                               |
| NbS     | Nature-Based Solutions                                                                  |
| OAT     | One-factor-At-a-Time                                                                    |
| PBIAS   | Percent Bias                                                                            |
| PRISM   | Panchromatic Remote-Sensing Instrument for Stereo Mapping                               |
| QGIS    | Quantum Geographic Information System                                                   |
| RAS     | River Analysis System                                                                   |
| RG1     | Great East Road Bridge Gauging Station                                                  |
| SASSCAL | Southern African Science Service Centre for Climate Change and Adaptive Land Management |
| SCS     | Soil Conservation Service                                                               |
| SWE     | Shallow Water Equations                                                                 |
| SWE-EM  | Shallow Water Equations—Explicit Momentum                                               |
| SWE-LIA | Shallow Water Equations—Local Inertia Approximation                                     |
| USACE   | United States Army Corps of Engineers                                                   |
| WARMA   | Water Resources Management Authority                                                    |
| WEAP    | Water Evaluation And Planning System                                                    |
| ZMD     | Zambia Meteorological Department                                                        |

## References

1. IPCC. *Climate Change 2022—Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK, 2022. [\[CrossRef\]](#)
2. Potapov, P.; Hansen, M.C.; Pickens, A.; Hernandez-Serna, A.; Tyukavina, A.; Turubanova, S.; Zalles, V.; Li, X.; Khan, A.; Stolle, F.; et al. The Global 2000–2020 Land Cover and Land Use Change Dataset Derived From the Landsat Archive: First Results. *Front. Remote Sens.* **2022**, *3*, 856903. [\[CrossRef\]](#)
3. Li, Z.; Li, W.; Li, Z.; Lv, X. Responses of Runoff and Its Extremes to Climate Change in the Upper Catchment of the Heihe River Basin, China. *Atmosphere* **2023**, *14*, 539. [\[CrossRef\]](#)

4. Gray, L.C.; Zhao, L.; Stillwell, A.S. Impacts of climate change on global total and urban runoff. *J. Hydrol.* **2023**, *620*, 129352. [CrossRef]
5. National Geographic Society. The Influence of Climate Change on Extreme Environmental Events. Available online: <https://education.nationalgeographic.org/resource/influence-climate-change-extreme-environmental-events/> (accessed on 1 June 2024).
6. Dunn, S.M.; Mackay, R. Modelling the hydrological impacts of open ditch drainage. *J. Hydrol.* **1996**, *179*, 37–66. [CrossRef]
7. Ress, L.D.; Hung, C.L.J.; James, L.A. Impacts of urban drainage systems on stormwater hydrology: Rocky Branch Watershed, Columbia, South Carolina. *J. Flood Risk Manag.* **2020**, *13*, e12643. [CrossRef]
8. Gao, Y.; Sarker, S.; Sarker, T.; Leta, O.T. Analyzing the critical locations in response of constructed and planned dams on the Mekong River Basin for environmental integrity. *Environ. Res. Commun.* **2022**, *4*, 101001. [CrossRef]
9. Natarajan, S.; Radhakrishnan, N. An Integrated Hydrologic and Hydraulic Flood Modeling Study for a Medium-Sized Ungauged Urban Catchment Area: A Case Study of Tiruchirappalli City Using HEC-HMS and HEC-RAS. *J. Inst. Eng. (India) Ser. A* **2020**, *101*, 381–398. [CrossRef]
10. Onchi-Ramos, K.; Rodríguez-Cuevas, C.; Couder-Castañeda, C.; Padilla-Pérez, D.A. Flood Risk Assessment of the Garita River in the Urban Zone of San Luis Potosí City, by Hydrodynamic Modeling. *Sci. Rep.* **2024**, *14*, 15891. [CrossRef]
11. Kanema, E.M.; Gumindoga, W. Effects of changing climate on the groundwater potential: A case of Chongwe and Rufunsa Districts along the Chongwe River Catchment, Zambia. *Phys. Chem. Earth* **2022**, *127*, 103192. [CrossRef]
12. Zainal, N.N.; Abu Talib, S.H. Review paper on applications of the HEC-RAS model for flooding, agriculture, and water quality simulation. *Water Pract. Technol.* **2024**, *19*, 2883–2900. [CrossRef]
13. Zhao, B.; Xin, T.; Li, P.; Ma, F.; Gao, B.; Fan, R. Regulation of Flood Dynamics by a Check Dam System in a Typical Ecological Construction Watershed on the Loess Plateau, China. *Water* **2023**, *15*, 2000. [CrossRef]
14. Mwelwa, D.; Mwaanga, P.; Nguvulu, A.; Tena, T.M.; Taye, G. Assessment of catchment water resources allocation under climate change in Luwombwa sub-catchment, Zambia. *Heliyon* **2024**, *10*, e39962. [CrossRef] [PubMed]
15. Mwelwa, D.; Tena, T.M.; Nguvulu, A.; Mwaanga, P.; Taye, G. Surface water availability in ungauged catchments of Sub-Saharan Africa: A case study from Luwombwa sub-catchment, Zambia. *Water Sci.* **2025**, *39*, 42–57. [CrossRef]
16. Huang, S.; Gan, Y.; Chen, N.; Wang, C.; Zhang, X.; Li, C.; Horton, D.E. Urbanization enhances channel and surface runoff: A quantitative analysis using both physical and empirical models over the Yangtze River basin. *J. Hydrol.* **2024**, *635*, 131194. [CrossRef]
17. Mudenda, F.; Mwangi, H.; Gathenya, J.M.; Maina, C.W.; Tena, T.M. Structural and nature-based solutions for resilient watershed systems: A systematic review of watershed modelling approaches and global datasets. *J. Water Clim. Change* **2025**, *16*, 2084–2110. [CrossRef]
18. Tena, T.M.; Nguvulu, A.; Mwelwa, D.; Mwaanga, P. Assessing Water Availability and Unmet Water Demand Using the WEAP Model in the Semi-Arid Bweengwa, Kasaka and Magoye Sub-Catchments of Southern Zambia. *J. Environ. Prot.* **2021**, *12*, 280–295. [CrossRef]
19. Rose, S.; Peters, N.E. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): A comparative hydrological approach. *Hydrol. Process.* **2001**, *15*, 1441–1457. [CrossRef]
20. Miller, J.D.; Kim, H.; Kjeldsen, T.R.; Packman, J.; Grebby, S.; Dearden, R. Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *J. Hydrol.* **2014**, *515*, 59–70. [CrossRef]
21. Song, X.; Sun, W.; Zhang, Y.; Song, S.; Li, J.; Gao, Y. Using hydrological modelling and data-driven approaches to quantify mining activities impacts on centennial streamflow. *J. Hydrol.* **2020**, *585*, 124764. [CrossRef]
22. Zhang, M.; Stodolak, R.; Xia, J. The impact of the changes in climate, land use and direct human activity on the discharge in Qingshui River Basin, China. *Water* **2021**, *13*, 3147. [CrossRef]
23. Zimba, H.; Kawawa, B.; Chabala, A.; Phiri, W.; Selsam, P.; Meinhardt, M.; Nyambe, I. Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *J. Hydrol. Reg. Stud.* **2018**, *15*, 149–170. [CrossRef]
24. Gao, P.; Li, P.; Zhao, B.; Xu, R.; Zhao, G.; Sun, W.; Mu, X. Use of double mass curves in hydrologic benefit evaluations. *Hydrol. Process.* **2017**, *31*, 4639–4646. [CrossRef]
25. dos Reis, A.A.; Weerts, A.; Ramos, M.-H.; Wetterhall, F.; dos Santos Fernandes, W. Hydrological data and modeling to combine and validate precipitation datasets relevant to hydrological applications. *J. Hydrol. Reg. Stud.* **2022**, *44*, 101200. [CrossRef]
26. Loots, I.; Smithers, J.C.; Kjeldsen, T.R. Quantifying urban land cover imperviousness as input for flood simulation using machine learning: South African case study. *Water Sci. Technol.* **2025**, *91*, 1141–1156. [CrossRef]
27. Urzică, A.; Mihu-Pintilie, A.; Stoleriu, C.C.; Cîmpianu, C.I.; Huțanu, E.; Pricop, C.I.; Grozavu, A. Using 2D HEC-RAS modeling and embankment dam break scenario for assessing the flood control capacity of a multireservoir system (Ne Romania). *Water* **2021**, *13*, 57. [CrossRef]

28. Neal, J.C.; Fewtrell, T.J.; Bates, P.D.; Wright, N.G. A comparison of three parallelisation methods for 2D flood inundation models. *Environ. Model. Softw.* **2010**, *25*, 398–411. [\[CrossRef\]](#)
29. Gruss, Ł.; Głowski, R.; Wiatkowski, M. Modeling of water flows through a designed dry dam using the HEC-RAS program. *ITM Web Conf.* **2018**, *23*, 00012. [\[CrossRef\]](#)
30. Rizaldi, B.; Idfi, G.; Suwarno, E.; Mujiyono. Design of drainage system on industrial area Kampung Cina, Dobo City, Aru Islands Regency, based on Eco drainage using with HEC-RAS 4.0. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *669*, 012038. [\[CrossRef\]](#)
31. Tena, T.M.; Mudenda, F.; Nguvulu, A.; Mwaanga, P.; Gathenya, J.M. Analysis of River Tributaries' Streamflow Contribution Using WEAP Model: A Case of the Ngwerere and Kanakatampa Tributaries to the Chongwe River in Zambia. *J. Water Resour. Prot.* **2021**, *13*, 309–323. [\[CrossRef\]](#)
32. Nick, A. *Groundwater Resources for Lusaka and Selected Catchment Areas*; Ministry of Energy and Water Development: Lusaka, Zambia, 2015.
33. Tena, T.M.; Mwaanga, P.; Nguvulu, A. Hydrological modelling and water resources assessment of Chongwe River Catchment using WEAP model. *Water* **2019**, *11*, 839. [\[CrossRef\]](#)
34. Chabwela, H.; Chomba, C.; Chabwela, B.; Muyumbana, N. Vegetation Structure and Condition of the Head Water Palustrine Dambo Eco-System in the Upper Catchment of the Chongwe River, Central Zambia. *IAR J. Agric. Res. Life Sci.* **2021**, *2*, 55–74.
35. MCC. *Improving Water, Sanitation, and Drainage in Zambia: Partial Progress on Strengthening Service Delivery and Financial Sustainability*; Millennium Challenge Corporation: Washington, DC, USA, 2020.
36. LWSC. *Lusaka Water Sanitation and Drainage Project*; Lusaka Water Supply & Sanitation Company: Lusaka, Zambia, 2013.
37. Tena, T.M.; Mwaanga, P.; Nguvulu, A. Impact of land use/land cover change on hydrological components in Chongwe River Catchment. *Sustainability* **2019**, *11*, 6415. [\[CrossRef\]](#)
38. JICA. *Basic Design Study Report on New Agricultural Village Development Project in Kanakantapa Area, Lusaka Province in the Republic of Zambia*; Japan International Cooperation Agency: Tokyo, Japan, 1991.
39. Matthew Heberger. *Global Watersheds (Web Application)*, version 2022; Matthew Heberger: Richmond, CA, USA, 2022.
40. Japan Aerospace Exploration Agency. *ALOS World 3D 30 meter DEM*, version 3.2; Japan Aerospace Exploration Agency: Tokyo, Japan, 2021. [\[CrossRef\]](#)
41. Ross, C.W.; Prihodko, L.; Anchang, J.Y.; Kumar, S.S.; Ji, W.; Hanan, N.P. *Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling*, version 1; ORNL Distributed Active Archive Center: Oak Ridge, TN, USA, 2018. [\[CrossRef\]](#)
42. Hoppe, A. Simulation of Flooding and Flood Mitigation in the Town of Söderköping Using HEC-RAS an Investigation of Floods and Mitigation Measures. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2024.
43. USACE. *HEC-RAS User's Manual*; USACE: Washington, DC, USA, 2024.
44. Chomba, I.C.; Sichingabula, M.H. Sedimentation and Its Effects on Selected Small Dams East of Lusaka, Zambia. *Mod. Environ. Sci. Eng.* **2016**, *1*, 325–340. [\[CrossRef\]](#)
45. Chisola, M.N.; Kuráž, M. Patterns and Implications of Hydrologic Regime Change in Chongwe River, Zambia. *J. Geogr. Geol.* **2016**, *8*, 1. [\[CrossRef\]](#)
46. Lima Neto, O.C.; Ribeiro Neto, A.; Alves, F.H.B.; Cirilo, J.A. Sub-daily hydrological-hydrodynamic simulation in flash flood basins: Una river (Pernambuco/Brazil). *Ambiente Agua—Interdiscip. J. Appl. Sci.* **2020**, *15*, e2556. [\[CrossRef\]](#)
47. Akiyanova, F.; Ongdas, N.; Zinabdin, N.; Karakulov, Y.; Nazhbiyev, A.; Mussagaliyeva, Z.; Atalikhova, A. Operation of Gate-Controlled Irrigation System Using HEC-RAS 2D for Spring Flood Hazard Reduction. *Computation* **2023**, *11*, 27. [\[CrossRef\]](#)
48. Chow, V.T. *Open Channel Hydraulics*; McGraw-Hill: New York, NY, USA, 1959.
49. USDA SCS. *Urban Hydrology for Small Watersheds*; United States Department of Agriculture: Washington, DC, USA, 1986.
50. Ficklin, D.L.; Abatzoglou, J.T.; Robeson, S.M.; Dufficy, A. The Influence of Climate Model Biases on Projections of Aridity and Drought. *J. Clim.* **2016**, *29*, 1269–1285. [\[CrossRef\]](#)
51. Sarker, S. Separation of Floodplain Flow and Bankfull Discharge: Application of 1D Momentum Equation Solver and MIKE 21C. *CivilEng* **2023**, *4*, 933–948. [\[CrossRef\]](#)
52. Bates, P.D.; Horritt, M.S.; Fewtrell, T.J. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *J. Hydrol.* **2010**, *387*, 33–45. [\[CrossRef\]](#)
53. Borst, R. Evaluating the Effect of Nature-Based Solutions on Urban Runoff Using Hydraulic Modelling: A Case Study in Sekondi-Takoradi, Ghana. Master's Thesis, University of Twente, Enschede, The Netherlands, 2023.
54. Blue Marble Geographics. *Global Mapper Pro*, version 26.0; Blue Marble Geographics: Hallowell, ME, USA, 2024.
55. Zeiger, S.J.; Hubbart, J.A. Measuring and modeling event-based environmental flows: An assessment of HEC-RAS 2D rain-on-grid simulations. *J. Environ. Manag.* **2021**, *285*, 112125. [\[CrossRef\]](#)
56. Tang, Z.; Chu, J.; Zhou, Z.; Zhou, T.; Yuan, K. The Sensitivity Analysis of Parameters in the 1D–2D Coupled Model for Urban Flooding. *Appl. Sci.* **2025**, *15*, 2157. [\[CrossRef\]](#)
57. Lenhart, T.; Eckhardt, K.; Fohrer, N.; Frede, H.-G. Comparison of two different approaches of sensitivity analysis. *Phys. Chem. Earth Parts A/B/C* **2002**, *27*, 645–654. [\[CrossRef\]](#)

58. Pianosi, F.; Beven, K.; Freer, J.; Hall, J.W.; Rougier, J.; Stephenson, D.B.; Wagener, T. Sensitivity analysis of environmental models: A systematic review with practical workflow. *Environ. Model. Softw.* **2016**, *79*, 214–232. [\[CrossRef\]](#)
59. Osuch, M. Sensitivity Analysis of the Flow Routing Model for the Middle River Vistula-Multi-method Approach. In *Stochastic Flood Forecasting System: The Middle River Vistula Case Study*; Springer International Publishing: Cham, Switzerland, 2015; pp. 109–128. [\[CrossRef\]](#)
60. Zhang, Z.; Liao, W.; Chen, H.; Mantini, D.; Ding, J.-R.; Xu, Q.; Wang, Z.; Yuan, C.; Chen, G.; Jiao, Q.; et al. Altered functional-structural coupling of large-scale brain networks in idiopathic generalized epilepsy. *Brain* **2011**, *134*, 2912–2928. [\[CrossRef\]](#)
61. McColgan, P.; Blom, T.; Rees, G.; Seunarine, K.K.; Gregory, S.; Johnson, E.; Durr, A.; Roos, R.A.C.; Scahill, R.I.; Clark, C.A.; et al. Stability and sensitivity of structural connectomes: Effect of thresholding and filtering and demonstration in neurodegeneration. *bioRxiv* **2018**. [\[CrossRef\]](#)
62. Thomas Steven Savage, J.; Pianosi, F.; Bates, P.; Freer, J.; Wagener, T. Quantifying the importance of spatial resolution and other factors through global sensitivity analysis of a flood inundation model. *Water Resour. Res.* **2016**, *52*, 9146–9163. [\[CrossRef\]](#)
63. Afzal, M.A.; Ali, S.; Nazeer, A.; Khan, M.I.; Waqas, M.M.; Aslam, R.A.; Cheema, M.J.M.; Nadeem, M.; Saddique, N.; Muzammil, M.; et al. Flood Inundation Modeling by Integrating HEC–RAS and Satellite Imagery: A Case Study of the Indus River Basin. *Water* **2022**, *14*, 2984. [\[CrossRef\]](#)
64. Moriasi, D.N.; Gitau, M.W.; Pai, N.; Daggupati, P. Hydrologic and water quality models: Performance measures and evaluation criteria. *Trans. ASABE* **2015**, *58*, 1763–1785. [\[CrossRef\]](#)
65. Ndhlovu, G.Z.; Woyessa, Y.E. Streamflow Analysis in Data-Scarce Kabompo River Basin, Southern Africa, for the Potential of Small Hydropower Projects under Changing Climate. *Hydrology* **2022**, *9*, 149. [\[CrossRef\]](#)
66. Belay, H.; Melesse, A.M.; Tegegne, G.; Kassaye, S.M. Flood Inundation Mapping Using the Google Earth Engine and HEC-RAS Under Land Use/Land Cover and Climate Changes in the Gumara Watershed, Upper Blue Nile Basin, Ethiopia. *Remote Sens.* **2025**, *17*, 1283. [\[CrossRef\]](#)
67. Alipour, A.; Jafarzadegan, K.; Moradkhani, H. Global sensitivity analysis in hydrodynamic modeling and flood inundation mapping. *Environ. Model. Softw.* **2022**, *152*, 105398. [\[CrossRef\]](#)
68. Bennour, A.; Jia, L.; Menenti, M.; Zheng, C.; Zeng, Y.; Barnieh, B.A.; Jiang, M. Calibration and Validation of SWAT Model by Using Hydrological Remote Sensing Observables in the Lake Chad Basin. *Remote Sens.* **2022**, *14*, 1511. [\[CrossRef\]](#)
69. Liang, Q.; Marche, F. Numerical resolution of well-balanced shallow water equations with complex source terms. *Adv. Water Resour.* **2009**, *32*, 873–884. [\[CrossRef\]](#)
70. YEC. *Study Report on National Water Resources Master Plan in the Republic of Zambia*; Yachiyo Engineering Co., Ltd.: Tokyo, Japan, 1995.
71. Velísková, Y.; Dulovičová, R.; Schügerl, R. Impact of vegetation on flow in a lowland stream during the growing season. *Biologia* **2017**, *72*, 840–846. [\[CrossRef\]](#)
72. Fletcher, T.D.; Andrieu, H.; Hamel, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Adv. Water Resour.* **2013**, *51*, 261–279. [\[CrossRef\]](#)
73. Palanisamy, B.; Chui, T.F.M. Rehabilitation of concrete canals in urban catchments using low impact development techniques. *J. Hydrol.* **2015**, *523*, 309–319. [\[CrossRef\]](#)
74. Wright, I.A.; Davies, P.J.; Findlay, S.J.; Jonasson, O.J. A new type of water pollution: Concrete drainage infrastructure and geochemical contamination of urban waters. *Mar. Freshw. Res.* **2011**, *62*, 1355–1361. [\[CrossRef\]](#)
75. Sarker, S. A Short Review on Computational Hydraulics in the Context of Water Resources Engineering. *Open J. Model. Simul.* **2021**, *10*, 1–31. [\[CrossRef\]](#)
76. Lempérière, F. Dams and Floods. *Engineering* **2017**, *3*, 144–149. [\[CrossRef\]](#)
77. Khoeun, R.; Sor, R.; Chann, K.; Phy, S.R.; Oeurng, C.; Sok, T. The Impacts of Dams on Streamflow in Tributaries to the Lower Mekong Basin. *Sustainability* **2024**, *16*, 6700. [\[CrossRef\]](#)
78. Olariu, P.; Cojoc, G.M.; Timovan, A.; Obreja, F. The future of reservoirs in the Siret River Basin considering the sediment transport of rivers (Romania). *GEOREVIEW* **2014**, *24*, 66–75. Available online: <https://georeview.usv.ro/article-6-vol-24-1-2014/> (accessed on 2 February 2026).
79. Peter, S.J.; De Araújo, J.C.; Araújo, N.A.M.; Herrmann, H.J. Flood avalanches in a semiarid basin with a dense reservoir network. *J. Hydrol.* **2014**, *512*, 408–420. [\[CrossRef\]](#)
80. Nguvulu, A.; Shane, A.; Mwale, C.S.; Tena, T.M.; Mwaanga, P.; Siame, J.; Chirambo, B.; Lungu, M.; Mudenda, F.; Mwelwa, D.; et al. Surface Water Quality Response to Land Use Land Cover Change in an Urbanizing Catchment: A Case of Upper Chongwe River Catchment, Zambia. *J. Geogr. Inf. Syst.* **2021**, *13*, 578–602. [\[CrossRef\]](#)
81. Erhui, L.; Mu, X.; Zhao, G.; Gao, P.; Sun, W. Effects of check dams on runoff and sediment load in a semi-arid river basin of the Yellow River. *Stoch. Environ. Res. Risk Assess.* **2017**, *31*, 1791–1803. [\[CrossRef\]](#)
82. Sang, J.; Gatheny, M.; Ndegwa, G. Evaluation of reservoirs as flood mitigation measure in Nyando basin, western Kenya using swat. *Editor. Advis. Board* **2007**, *18*, 231–239.

83. Acheampong, J.N.; Gyamfi, C.; Arthur, E. Impacts of retention basins on downstream flood peak attenuation in the Odaw river basin, Ghana. *J. Hydrol. Reg. Stud.* **2023**, *47*, 101364. [[CrossRef](#)]
84. Torelló-Sentelles, H.; Villarini, G.; Koukoula, M.; Peleg, N. Impacts of urban dynamics and thermodynamics on convective rainfall across different urban forms. *Urban Clim.* **2025**, *62*, 102499. [[CrossRef](#)]

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