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Application of the Rainfall–Runoff–Inundation Model for Flood Risk Assessment in the Mekerra Basin, Algeria

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Abstract: The Mekerra Basin in northern Algeria is highly vulnerable to severe flood events, such as those in October 1986 and September 1994, which caused significant damage to infrastructure and the environment. To address flood risk, this study applied the Rainfall–Runoff–Inundation (RRI) model to simulate hydrological processes and flood extents. The model was calibrated and validated using discharge data from these historical events. The sensitivity analyses identified hydraulic conductivity, suction head, and channel roughness as key parameters influencing flood peaks. The RRI model demonstrated a strong performance, achieving correlation coefficients of 0.97 and 0.94 for the 1986 and 1994 events, respectively. The model also produced R^2 values of 0.94 (calibration) and 0.89 (validation), with Percent Bias (PBIAS) values of 0.006 and 0.013, indicating minimal bias. Nash–Sutcliffe Efficiency (NSE) scores of 0.93 (calibration) and 0.86 (validation) confirmed its robustness in simulating event flows. This study represents the first application of the RRI model in the Mekerra Basin and highlights its utility for flood risk assessment in arid and semi-arid regions, offering critical insights for flood management and mitigation strategies.

Keywords: flood modeling; Rainfall–Runoff–Inundation (RRI) model; Mekerra Basin; sensitivity analysis; flood risk assessment; arid regions



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1. Introduction

Flooding represents a hazardous natural event that poses a serious threat to lives and livelihoods globally. It can cause significant property damage, including damage to homes, and contribute to environmental degradation [1–5]. Human activities, such as the gradual alteration of land cover for agricultural or urban purposes, coupled with recent shifts in climate conditions that concentrate rainfall over shorter periods, contribute to the accumulation and subsequent release of runoff water from upstream to downstream, thereby increasing the risk of flooding [6]. Additionally, flood risks have heightened due to human intervention, manifested in the population’s encroachment on drainage systems and the social and economic development of river basins [7].

All these conditions converge in North Africa, especially in northern Algeria. Characterized by a semi-arid climate and rugged topography, northern Algeria is composed of small watersheds with a short surface runoff concentration time [8]. The majority of the population, nearly 90%, is concentrated in coastal areas, engaging in significant human activities that impact river systems through urbanization and agriculture. Climate changes in this region are apparent, marked by an increased frequency of extreme events. This leads to more intense and concentrated rainfall, compacting the soil and diminishing permeability over time [9]. Inadequate vegetation exacerbates the situation, promoting high peak flows and elevating the risk of flooding [10]. Local governments reported that inundations affected almost all of the northern region of Algeria. Since the 1980s, these inundations have resulted in casualties surpassing a thousand deaths and leaving over 30,000 people homeless. The extent of material damage includes more than 3000 buildings that were either destroyed or damaged, with a financial loss estimated at nearly EUR 300 million in terms of property damage [11–13].

In response to the serious consequences generated by river overflow around the world, scientists have devoted significant efforts to employing various methodologies and instruments for the systematic observation, quantification, and simulation of flood propagation in rivers and watercourses, as well as their overflow onto adjacent lands. A valuable tool for flood analysis is the Rainfall–Runoff–Inundation (RRI) model, developed in 2012 by the International Center for Water Hazard and Risk Management (ICHARM) with the support of the United Nations Educational, Scientific, and Cultural Organization (UNESCO). Recognized for its effectiveness in forecasting and hazard mapping, the RRI model has been successfully applied across diverse climatic conditions and geographical regions [14–19]. Its versatility ranges from simulating large-scale flooding [20] to modeling smaller basin-specific hydrological processes [21].

To the best of our knowledge, the application of the RRI model in investigating catastrophic floods in Algeria has been limited or entirely absent. Consequently, this study serves as the first time that such a model was utilized in the examination of floods, with a specific focus on the Mekerra Basin in the northwest of Algeria. This region, inhabited by a population of 200,000 people, experiences recurrent floods, leading to dozens of casualties and significant damage to agricultural lands and infrastructure. Additionally, these events result in the displacement of hundreds of families [22].

Hydrological simulation models, which are based on rainfall–runoff relationships, are often employed as effective forecasting tools [23]. The outputs of the RRI model are critical for decision-making in flood risk management. The detailed flood maps and hydrological insights derived from the model assist water resource managers, urban planners, and policymakers in developing effective flood mitigation strategies. Furthermore, scenario analyses are conducted to evaluate the impacts of land use changes, infrastructure developments, and climate change projections on flood risks. This study represents the inaugural utilization of the RRI model in examining floods in Algeria, with a specific focus on the Mekerra watershed. The investigation was conducted through an extensive review of relevant literature. Consequently, this research will serve as the foundation for numerous later investigations and serve as a subject of inquiry to assess the efficacy of these models, particularly given the dearth of data in these places, both in terms of quantity and quality. The selection of the catastrophes that occurred in October 1986 and September 1994 as the two most severe flood events in the basin's history was motivated by our research. The aim of this study was to analyze the RRI model's performance in accurately reproducing flood characteristics such as peak discharge, runoff volume, flood depth, inundation extent, and flood duration in the Mekerra watershed by comparing the simulated results with the observed data. Examining the model calibration parameters along with conducting a sensitivity analysis will help in identifying both hydrological and meteorological risk factors

that could exacerbate flooding. The RRI model can be employed to develop forecasting scenarios and assess the impact of climate change. Ultimately, this study seeks to contribute to the knowledge base by sharing its findings with the scientific community, fostering a broader understanding of floods in similar contexts around the world.

2. Materials and Methods

2.1. Study Area

The Mekerra watershed is located in the northwestern region of Algeria, roughly 400 km from the capital, Algiers (Figure 1). Spanning an area of about 3000 km², the hydrographic network originates at an altitude of 1715 m above sea level. The main streamflow extends for 115 km until it reaches an altitude of 283 m. The flow direction shifts from the southern region, El Hacaiba, to the northern region, Sidi Ali Ben Youb (Figure 1).

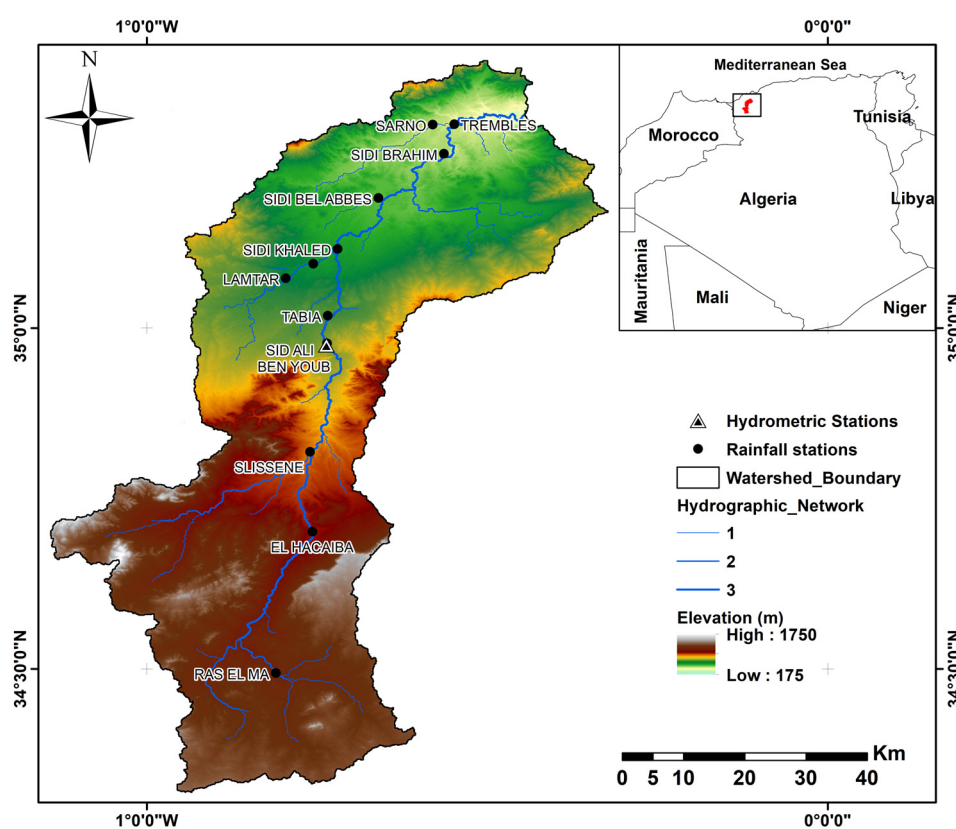


Figure 1. Location of Mekerra watershed and the main rainfall gauge stations.

The Upper and Central regions of the basin are densely populated and include major urban centers such as Sidi Belabbes and Sidi Ali Benyoub. These areas are further characterized by significant agricultural activity, which contributes to the basin's vulnerability to flood-related damages. From 1986 to 2009, Civil Protection services recorded 21 significant floods, resulting in human casualties and extensive damage to properties, agriculture, and infrastructure. The total documented damages included over 850 displaced families and 10 fatalities, highlighting the region's susceptibility to flood risks [24,25].

2.2. Rainfall and Runoff Climatology

The Mekerra Basin is characterized by a semi-arid climate, with hot and dry summers from April to August, and mild winters. The average yearly temperature hovers around 15 °C. Rainfall patterns exhibit significant spatio-temporal variability. The rainy season

typically occurs between October and March, with annual rainfall ranging from 198 mm in the southern portion of the basin to 311 mm in the northern portion [26].

Flood risks in the basin are influenced by storm-triggered runoff events, particularly during late summer and early autumn. From 1986 to 2009, 21 floods were recorded in the basin, with 12 of these occurring during by storm-triggered runoff events. These events highlight the relationship between intense, short-duration rainfall and rapid surface runoff. A discharge exceeding $100 \text{ m}^3/\text{s}$ often results in severe flooding, as observed in Sidi Belabbes during a flood event that caused one fatality and over 200 injuries. The highest recorded discharge in the basin, $808 \text{ m}^3/\text{s}$, occurred at Ras El Maa, which is upstream of the watershed. Overflow of the river was observed in nine zones along the Oued Mekerra, affecting multiple communities and further emphasizing the role of runoff in exacerbating flood risks [24,25,27].

2.3. Rainfall–Runoff–Inundation (RRI) Model

Over the past decade, the RRI model has undergone significant advancements, resulting in a substantial body of academic literature. Developed by the International Center for Water Hazard and Risk Management (ICHARM) with support from UNESCO, the RRI model is a sophisticated two-dimensional hydrological and inundation model [28]. This model has demonstrated effectiveness in various hydrological contexts, including arid and semi-arid regions [14,22,28–30].

The RRI model considers distinct components of river channels and land surface slopes as discrete entities, assuming that the river channel and slope are co-located within a grid cell. Channel flow is simulated using the one-dimensional diffusive wave model, while runoff on the slope is simulated using the two-dimensional diffusive wave model [31].

The RRI model incorporates three flow scenarios or cases for each basin mesh, which are determined based on soil and land use characteristics. The three components of the hydrological model under consideration are (a) Only Overland Flow, (b) Vertical Infiltration Using the Green-Ampt Model Plus Infiltration Excess Overland Flow, and (c) Saturated Subsurface Plus Saturation Excess Overland Flow.

The mesh geometry was considered to be a rectangle. In terms of upstream contributing area in km^2 , the following pair of equations were employed to calculate the width and the depth of the river:

$$W = C_w A^{S_w}. \quad (1)$$

$$D = C_d A^{S_d}. \quad (2)$$

In this context, the variables D , W , A , C_d , S_d , C_w , and S_w represent the depth (in meters), width (in meters), area (in square kilometers), depth parameters, and width parameters, respectively.

2.4. Data Collection

2.4.1. Rainfall and Runoff Data

The rainfall measurements were conducted by the National Agency of Hydraulic Resources (ANRH), which is responsible for gauging stations and hydrometric measurements in Algeria. The study utilized daily data collected from 12 rainfall gauge stations for the period 1975–2003 (Figure 1), distributed across the watershed to capture the target flood events. Rainfall data from these gauges were interpolated across the watershed using the Thiessen polygon method for input into the RRI model, as recommended in the model's manual. To provide an overview of the rainfall variability in the basin, Figure 2 presents the timeline of average annual rainfall for the period of 1975–2003.

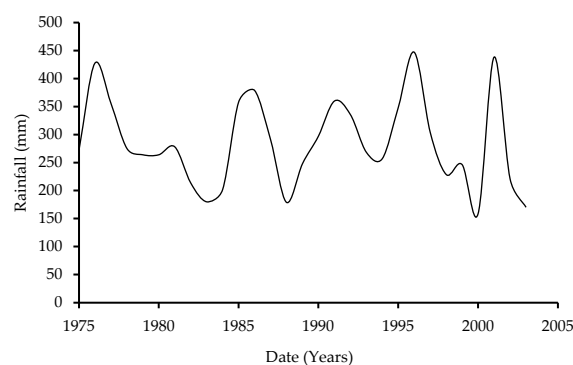


Figure 2. Temporal variability of average annual rainfall in the Mekerra Basin (1975–2003).

For the sensitivity analysis, data from only the Sidi Ali Benyoub gauging station (Figure 1) were considered. The calibration and validation of the RRI model were based on two significant flood events, which occurred in October 1986 and September 1994. These two events were selected due to the availability of runoff data, ensuring that the model’s calibration and validation could be accurately performed. The focus on these events allowed the model to effectively capture the rainfall–runoff dynamics and represent the peak flood characteristics during these periods.

A summary of the data used in this study is provided in Table 1, including details on the time period, frequency, unit, data source, missing data percentage, and the method used to handle gaps in the data. Data quality control and the process of filling in missing values were conducted using the reference value (RV) approach. These procedures were implemented through an R package named “reddPrec” that was developed using RStudio software (version 2022.07.2-567). Further details on the methodology can be found in [32].

Table 1. Description of input data.

Data Type	Time Period	Frequency	Unit	Source	Missing Data (%)	Gap-Filling Method
Rainfall	1975–2003	Daily	mm	ANRH	3%	RVs
Runoff	October 1986, September 1994	Hourly/Daily	m ³ /s	ANRH	/	/

2.4.2. Topographic and Watershed Data

Topographic data for this study were sourced from HydroSHEDS [33], including its flow direction and flow accumulation products. These datasets were essential for identifying stream networks and delineating watershed boundaries using Geographic Information Systems (GIS). The data were analyzed at a resolution of 30 s, providing a detailed and accurate representation of the terrain. The input data were prepared following the procedure outlined in the RRI model manual, which includes clipping the target river basin and adjusting the digital elevation model (DEM) and flow direction datasets to ensure compatibility with hydrological modeling. This preparation ensured the data’s suitability and reliability for the study objectives.

2.4.3. Land Use

The analysis in this study utilized land use data derived from Landsat imagery, specifically Landsat 5 Thematic Mapper (TM) data, for historical mapping of land use in 1986. The land types were categorized into three distinct classes (crops, rocks, and built areas), each with its own water-holding capacities, which is a crucial parameter in the RRI model. In arid regions, heavy rainfall on impermeable or clay soils can cause a surge in runoff. The lack of vegetation and decreased soil absorption capacity in flat terrains

further exacerbate the rapid accumulation of water, increasing the risk of flooding [34]. The rapid expansion of urban areas and changes in land cover lead to the transformation of many soils into non-porous surfaces, resulting in diminished soil infiltration capacity and increased runoff.

2.5. RRI Model Application

The RRI model, as described in [28], is a two-dimensional hydrological and inundation simulation tool tailored for analyzing rainfall-runoff and flood dynamics. Its development has prompted significant academic research, particularly underscoring its effectiveness in arid and semi-arid regions. The model has been successfully applied in a variety of contexts, including large-scale flood simulations, hazard mapping, real-time inundation forecasting, and thorough flood risk assessments at the river basin scale [20]. These applications illustrate the model's versatility in addressing diverse hydrological challenges.

In this research study, the RRI model was applied to simulate extreme flash floods in the Mekerra watershed following its calibration and validation using flow discharge data from different time periods, focusing on the severe flood events of October 1986 and September 1994, which lasted 20 h and 37 h, respectively, and are the most significant floods recorded in the basin's history. To provide a clear overview of the methodological steps, a flow diagram is presented in Figure 3, summarizing the processes of data preparation, model simulation, calibration, validation, and iterative parameter adjustments.

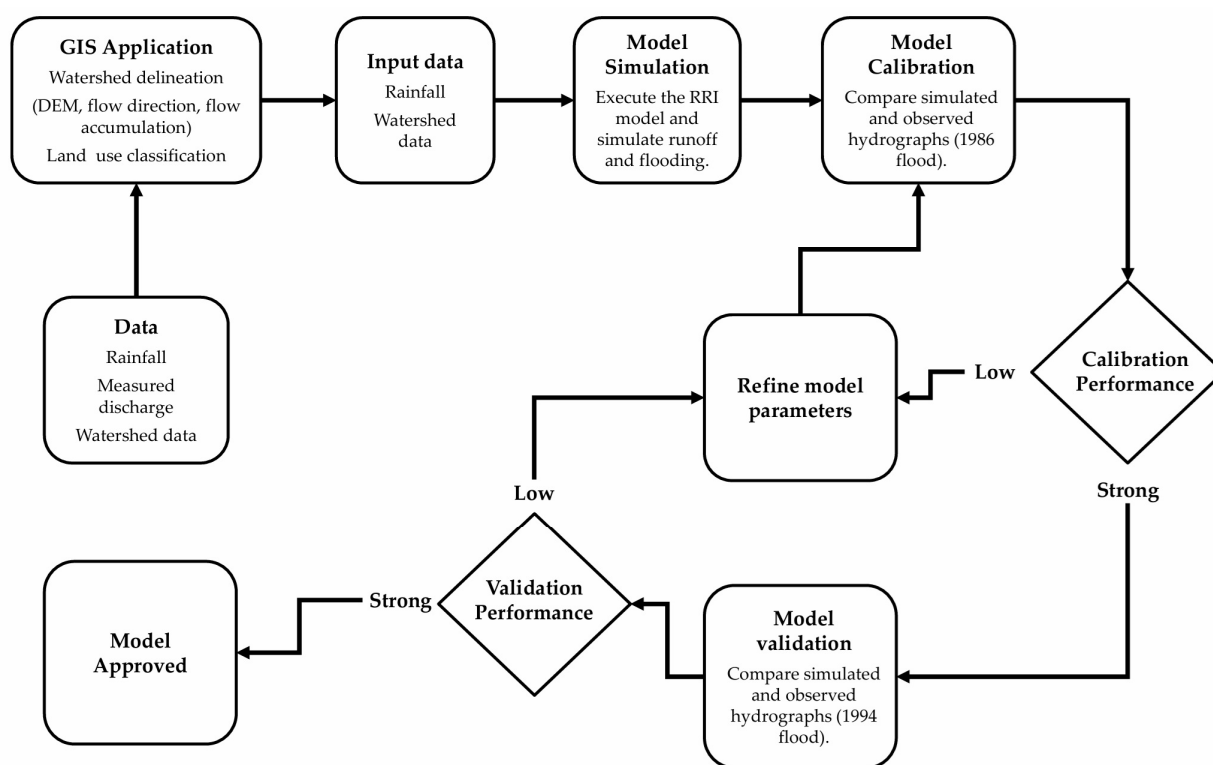


Figure 3. Flow diagram illustrating the methodology for applying the Rainfall-Runoff-Inundation (RRI) model in the Mekerra Basin study.

Model parameters were adjusted to match the observed data from historical flood events. This process involved fine-tuning parameters such as roughness coefficients, infiltration rates, and channel characteristics to minimize discrepancies between the simulated and observed data. The major sensitive RRI model parameter settings are indicated in Table 2.

Table 2. RRI cases and limits of operation of parameters.

Parameter	Unit	Notation	Range	Cases ¹	Calibration		
					Crops	Land Use	Built Area
Channel roughness coefficient	$m^{-1/3}.s$	ns_river	0.015–0.04	a, b, c	0.015	0.015	0.015
Hillslope roughness coefficient	$m^{-1/3}.s$	ns_slope	0.15–1.0	a, b, c	0.15	0.15	0.15
Soil depth	m	soilepth	0.1–2.0	b, c	0.45	1	2.0
Soil porosity	-	gammaa	0.05–0.6	b, c	0.3	0.1	0.05
Vertical saturated hydraulic conductivity	ms^{-1}	Kv	6.54×10^{-5} 1.67×10^{-7}	b, c	1.67×10^{-7}	1.45×10^{-6}	x
Suction at the vertical wetting front	m	Sf	0.0495–0.3163	b, c	0.2185	0.2045	x
Lateral saturated hydraulic conductivity	$m.s^{-1}$	Ka	0.01–0.3	c	x	x	x
Unsaturation effective porosity	-	Gamma	0.02–0.4	c	x	x	x

¹ Cases: (a) Only Overland Flow, (b) Vertical Infiltration and Infiltration Excess Overland Flow, and (c) Saturated Subsurface and Saturation Excess Overland Flow.

The land use of the region is characterized by an arid mountainous area in the south, with sparse vegetation, and urban areas in the north. In such regions, the primary hydrological processes are governed by surface runoff and infiltration (Cases a and b in the model). The presence of impermeable surfaces such as rocks and built areas increases surface runoff, leading to rapid water accumulation. This is captured by the Manning's roughness coefficient (nriver), which represents the resistance to flow in the river channels, and the hillslope roughness coefficient (nslope), which defines the resistance in the overland flow across the land surface.

Additionally, in areas with small vegetation and soil often compacted by dry conditions, the ability of the soil to absorb water is limited. This is represented by parameters such as soil porosity (gammaa) and vertical saturated hydraulic conductivity (Kv), which control the rate of water absorption and the vertical movement of water through the soil. Case c, which involves saturated subsurface flow and saturation excess overland flow, was excluded from our analysis due to a drought occurring in the study area during the summer preceding the autumn rainfall.

The drought resulted in soils that were dry and unable to contribute significantly to subsurface saturation or excess overland flow, making it unnecessary for this case to be considered. As a result, the study focused on the scenarios where infiltration and surface runoff were the dominant contributors to flood dynamics.

3. Results and Discussion

3.1. Sensitivity Analysis

This study examined the sensitivity of the RRI model to key hydrological parameters, including hydraulic conductivity (ksv), Manning's roughness coefficient (nriver), and suction head (Sf). Each of these parameters significantly influences the timing, magnitude, and duration of flood peaks, highlighting the importance of accurate parameter calibration in flood modeling.

In Figure 4a, the parameter that was varied was hydraulic conductivity (ksv), which refers to a material's ability to transmit water and is essential for understanding groundwater flow and transport in aquifers. Low hydraulic conductivity leads to low water infiltration into the soil, causing accelerated and concentrated runoff [35]. For example, a hydraulic conductivity of $ksv = 1.67 \times 10^{-7}$ exhibited a sharp peak discharge of approximately 500 m³/s, occurring at around 20 h. In contrast, higher values of ksv (e.g., 6.54×10^{-5}) and the default ksv curve, which represents the initial uncalibrated parameter value used in the model, showed lower

peak discharges of around 120 and 100 m³/s, respectively. These lower peaks reflect a greater infiltration capacity, meaning more water is absorbed by the soil, reducing the intensity of surface runoff.

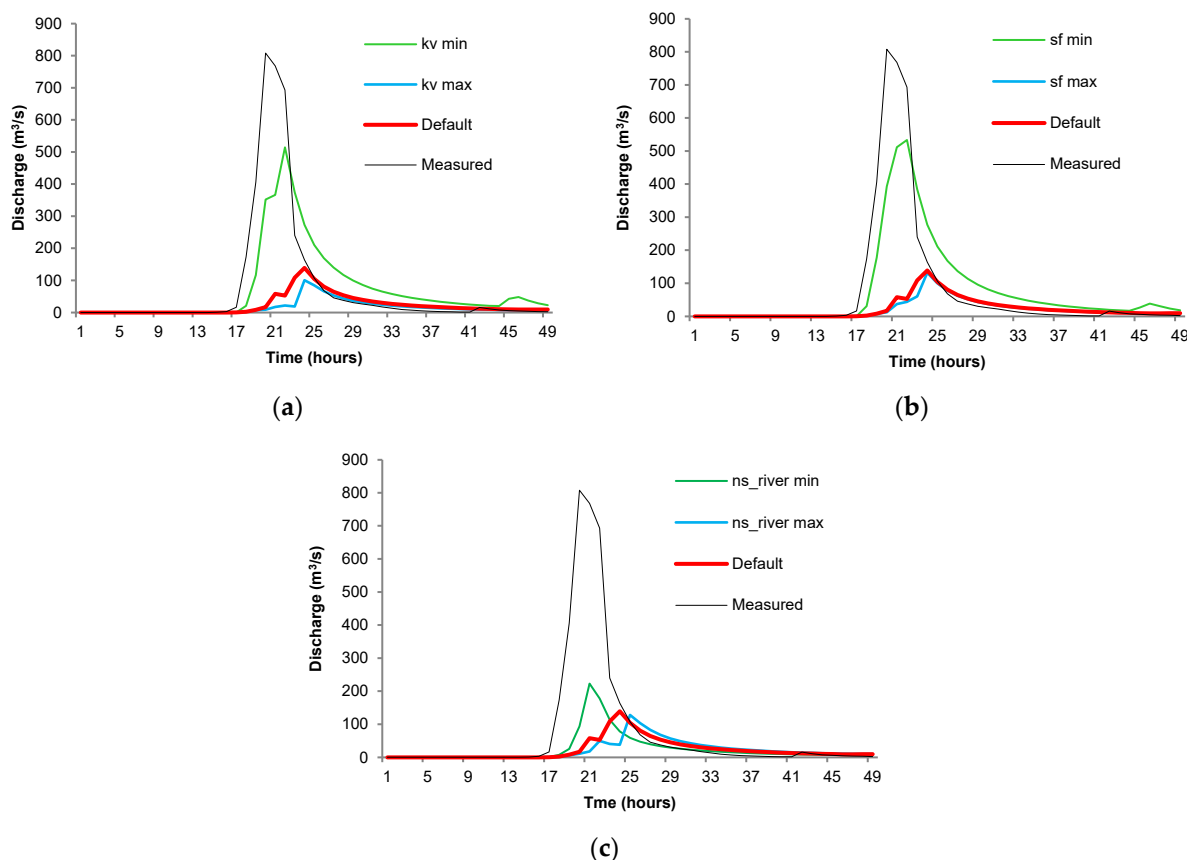


Figure 4. Simulated hydrograph variations for the Mekerra flash flood event (Sidi Ali Ben Youb flow gauge station) under different RRI parameter configurations: (a) vertical saturated hydraulic conductivity (Ksv), showing how a higher Kv value reduces flood peaks through enhanced infiltration; (b) suction at the vertical wetting front (Sf), illustrating the impact of soil water retention on surface runoff; and (c) channel roughness coefficient (ns_river), emphasizing the role of flow resistance in moderating flood peaks.

Many studies have utilized the RRI model to understand and predict flood events, conducting detailed sensitivity analyses to identify key parameters. For instance, a study conducted in Wadi Samail, Oman, identified the channel roughness coefficient (nriver) and hillslope roughness coefficient (nslope) as the most significant parameters, followed by soil depth (d) and soil porosity (ϕ) [14]. Similarly, our sensitivity analysis highlighted the importance of hydraulic conductivity (ksv), Manning’s roughness coefficient (nriver), and suction head (Sf), which were crucial in accurately simulating the flash flood events in Mekerra.

In another study conducted in Yangon City, Myanmar, the RRI model was used to simulate flood events, and the sensitivity analysis focused on lateral saturated hydraulic conductivity (ka) and soil depth (hd) [18]. The results showed significant differences in these parameters due to the geological characteristics and climate zones of Myanmar.

Figure 4b shows the variation in Manning’s roughness coefficient (nriver) for river flow in Mekerra. Manning’s n is a critical parameter for estimating flow resistance; a lower roughness results a faster water movement and more concentrated flood peaks [36]. An nriver value of 0.015, corresponding to a lower roughness coefficient, had the sharpest and highest peak of around 200 m³/s, whereas a high roughness coefficient showed high flow

resistance, resulting in energy losses. Manning's coefficient (n) plays a vital role in the computation of flood discharge and velocity distribution [37].

Figure 4c analyzes how the suction head (S_f) parameter impacts the generated hydrograph. S_f is a parameter associated with soil infiltration characteristics. It measures the pressure difference in the soil resulting from its moisture content, which indicates the soil's ability to resist the force of gravity and retain water [38]. During flooding, suction head plays a crucial role in determining the speed and efficiency of water infiltration into the soil. A higher suction head generally indicates greater water absorption by the soil. Conversely, a lower suction head may result in increased surface runoff. For instance, the data shows that when $s_f = 0.0495$, representing a lower suction head, there was a peak discharge of approximately $500 \text{ m}^3/\text{s}$, while when $s_f = 0.3163$, it led to a much lower peak of around $100 \text{ m}^3/\text{s}$.

According to results from the sensitivity analysis, the simulated hydrographs underestimated the measured flow because the sensitivity analysis was conducted using the single-variable testing method, where only one parameter was adjusted during each simulation while all the other parameters were kept at their default settings. Although parameters such as vertical saturated hydraulic conductivity, suction at the vertical wetting front, and channel roughness coefficient exhibited significant variations in the hydrograph between their maximum and minimum values, other parameters, including hillslope roughness coefficient, soil depth, and soil porosity, did not demonstrate a substantial impact on the hydrograph.

The results demonstrate that variations in these parameters significantly influence flood peak timing, magnitude, and duration, providing valuable insights into the underlying hydrological processes. Lower k_{sv} values resulted in rapid runoff and sharp flood peaks, reflecting the behavior of impermeable soils such as clay. Conversely, higher k_{sv} values enhanced infiltration, reducing flood intensity and delaying peak discharge, underscoring the importance of soil permeability management.

Similarly, Manning's roughness coefficient played a pivotal role in moderating flow velocity. Smoother channels, characterized by lower n_{river} values, produced sharper and higher flood peaks due to faster water movement. In contrast, increasing the channel roughness, such as through the presence of vegetation, dissipated flow energy and reduced peak discharges, emphasizing the importance of natural flood control mechanisms. The suction head parameter further illustrates the interaction between soil retention capacity and runoff. Soils with lower S_f values retained less water, increasing surface runoff, while higher S_f values reduced runoff through improved water retention, highlighting the importance of soil conservation practices.

3.2. Calibration and Validation Results

The RRI model demonstrated satisfactory performance in simulating flash flood events within the Mekerra Basin, as reflected by its calibration and validation metrics in Table 3. The high correlation coefficients (0.97 for the 1986 event and 0.94 for the 1994 event) indicate a strong agreement between the observed and simulated data. Similarly, the Nash–Sutcliffe Efficiency (NSE) values of 0.93 and 0.86 for the calibration and validation events, respectively, reflect the model's ability to capture the timing and magnitude of peak discharges. These results are consistent with previous studies in the Mekerra Basin using the MERCEDES model, where NSE values exceeding 0.80 were reported as a benchmark for acceptable model performance [26]. Additionally, a study employing the Runge–Kutta Discontinuous Galerkin (RKDG) finite element scheme to model historical floods in Wadi Mekerra reported a high accuracy, with a discharge difference of only 1.17% during the 1983 flood event [22].

Table 3. RRI model performance metrics for calibration and validation.

Performance Characteristic	Calibration (1986 Event)	Validation (1994 Event)
Correlation Coefficient	0.97	0.94
r^2	0.94	0.89
PBIAS	0.006	0.013
NSE	0.93	0.86

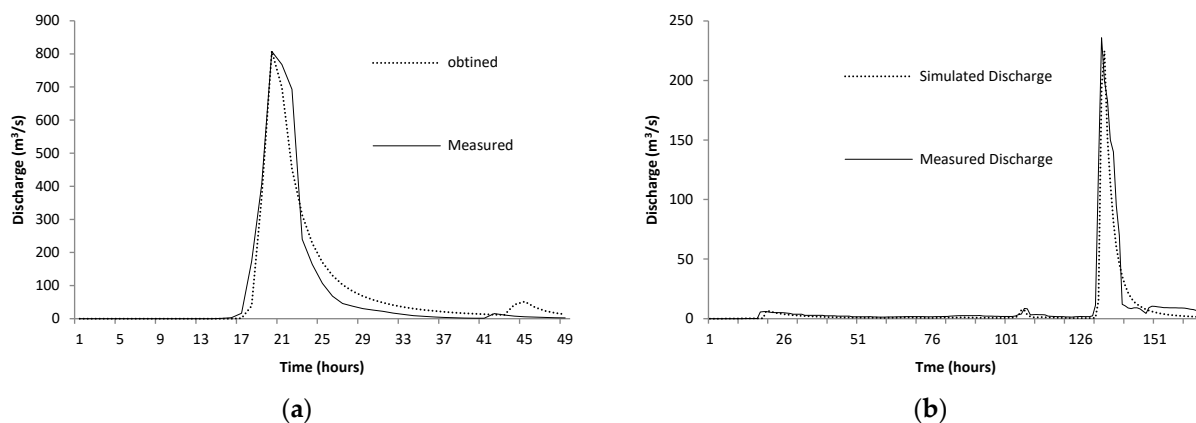
Additionally, Ref. [27] employed two hydraulic modeling schemes, the Van Leer Finite Volume method and the Petrov–Galerkin method, to simulate the 1983 and 1995 flood events in Wadi Mekerra. For the 1983 event, the Van Leer method achieved a relative error of 4.96%, while the Petrov–Galerkin method resulted in an error of 14.65%. For the 1995 event, the relative errors were 0.24% and 1.64% for the Van Leer and Petrov–Galerkin methods, respectively.

However, despite the positive results obtained using the RRI model in this study, there are areas for improvement. Notably, the model tended to overestimate flood volumes during the 1986 calibration event (by 8.2%) and underestimated them during the 1994 validation event (by 24.3%). These discrepancies suggest that while the model captures general flood behavior well, it may struggle with precise volumetric estimates across different events.

3.3. Simulation of Mekerra Flash Flood Event

Floods have caused considerable destruction over the past four decades. The most severe flood occurred on 04 October 1986 in Sidi Bel Abbas, with a flow rate of 800 m³/s, causing three deaths, almost 1000 homeless people, and affecting 530 individuals and 200 families.

Figure 5a,b depict hydrographs illustrating the hydrological events that occurred in October 1986 and September 1994. These events represent the most severe catastrophic incidents, characterized by significant losses of life and substantial economic damage within the watershed.

**Figure 5.** Simulation of Mekerra flash flood event: (a) RRI model calibration results for 1986 event; (b) RRI model validation results for 1994 event.

Both occurrences are characterized as flash floods. The 1986 event was dedicated to calibrating the RRI model, while the 1994 event served to validate the RRI model. For both events, the rise in water levels was rapid, occurring in less than 4 h, transitioning from an almost negligible base flow to a peak flow of 808 m³/s for the calibration event and 236 m³/s for the validation event. Both events exhibited remarkable increases, with an astonishing surge of over 400 m³/s per hour for the first event and nearly 188 m³/s for the second.

The calibration model simulated flood lasted only 21 h, from around 10 to 20 h. The water input from the flood was 13.46×10^6 m³ (observed) compared to the 14.57×10^6 m³

simulated by the RRI model, resulting in an overestimation of 8.2% compared to the observed flood. The flood rising flow lasted less than 4 h, with an observed volume input of about 37% compared to 30% in the simulated values. When evaluating water volumes over a moving 3 h time window, the critical input was the one corresponding to the interval 1 h before the peak and 1 h after. This window corresponds to the high potential for the river to overflow. During the critical window of the calibration flood, the water input represented 53.0% of the total input from the observed values and 46.4% from the simulated values, generating an error of only −5.4%.

The validation flood lasted 37 h, with an estimated volume of water discharged quantified at $5.23 \times 10^6 \text{ m}^3$ in the observed values and $3.96 \times 10^6 \text{ m}^3$ in the simulated values, resulting in an underestimation of approximately −24.3%. The contribution of water volume during the critical window was around 42.6% in the observed values and 51.8% in the simulated values. The error gap was only −8.0%.

The differences in the characteristics of the 1986 and 1994 flood events may explain the observed discrepancies in the volumetric estimates. The 1986 flood, which was shorter in duration and more intense, appeared to align more closely with the model's calibration parameters. The rapid rise in water levels and higher peak discharge likely suited the parameters that were optimized for intense flash floods. Conversely, the longer-duration of the flood of 1994, characterized by a slower increase in flow rates and lower peak discharge, probably necessitated adjustments to account for sustained infiltration, subsurface contributions, and prolonged runoff processes. These variations in peak discharge and flood duration suggest that event-specific attributes significantly influence the model performance and emphasize the need to refine parameters to enhance adaptability across diverse hydrological conditions.

4. Conclusions

The current study represents the first application of the Rainfall–Runoff–Inundation (RRI) model in the Mekerra Basin, a flood-prone area in northern Algeria. Through rigorous calibration and validation using data from significant flood events in 1986 and 1994, this research demonstrated the RRI model's effectiveness in simulating flood dynamics in semi-arid regions, achieving high correlation coefficients of 0.97 and 0.94 for the respective events.

The sensitivity analyses identified three critical parameters influencing flood peaks: hydraulic conductivity, suction head, and channel roughness. Lower hydraulic conductivity values (1.67×10^{-7}) produced sharp peak discharges of approximately $500 \text{ m}^3/\text{s}$, while higher values (6.54×10^{-5}) resulted in lower peaks around $120 \text{ m}^3/\text{s}$, demonstrating this parameter's significant impact on runoff behavior. Similarly, Manning's roughness coefficient showed substantial influence, with lower values (0.015) producing sharper peaks around $200 \text{ m}^3/\text{s}$.

The model demonstrated strong performance metrics, with Nash–Sutcliffe Efficiency (NSE) values of 0.93 for the calibration and 0.86 for the validation, and R^2 values of 0.94 and 0.89, respectively. However, notable discrepancies emerged in the volumetric predictions: the model overestimated the 1986 flood volume by 8.2% ($14.57 \times 10^6 \text{ m}^3$ (simulated) vs. $13.46 \times 10^6 \text{ m}^3$ (observed)) and underestimated the 1994 flood volume by 24.3% ($3.96 \times 10^6 \text{ m}^3$ (simulated) vs. $5.23 \times 10^6 \text{ m}^3$ (observed)).

The model showed significant disparities in performance due to the distinct characteristics of the flood events. The 1986 flood was characterized by an intense, short duration of 21 h with a peak discharge of $808 \text{ m}^3/\text{s}$, while the 1994 event had a longer duration of 37 h with a lower peak discharge of $236 \text{ m}^3/\text{s}$. These fundamental differences in flood behavior challenged the model's ability to accurately simulate both events using a single parameter set. The study also faced other limitations that should be considered when

interpreting the results. Data availability constraints, particularly the reliance on only two historical flood events for the calibration and validation, impacted the model's robustness. Temporal resolution limitations in rainfall data affected the model's ability to capture rapid flood onset. The semi-arid nature of the region and limited ground-truth data introduced uncertainty into the parameter estimation.

Looking ahead, research efforts should focus on enhancing the model's capabilities through several key improvements. While satellite-derived rainfall data could help address precipitation data gaps, it remains essential to have observed flood event data for model updating.

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