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Contribution of Hydrological Modelling to the Quantification of Surface Runoff in the Ungauged Watershed of the City of Bambey (Senegal)

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Abstract

In recent years, recurring floods in the city of Bambey have caused catastrophic consequences for the lives of the population. Bambey's vulnerability to flooding is exacerbated by a lack of measurement data, which makes it difficult to understand the hydrological phenomena of its watershed. The objective of this study is to use the HEC-HMS distributed model, which subdivides the watershed into several sub-basins, to quantify surface runoff from the ungauged watershed area of the city of Bambey. The method chosen in the Hec-Hms model is based on defining a production function and a function for converting rainfall into flow after creating the model watershed. The Green and Ampt infiltration model was used for the production function, and for transformation, the Snyder unit hydrograph model was chosen. Next, the meteorological model was created by selecting the SCS method to specify the hundred-year rainfall event at the Bambey weather station as the input rainfall for the simulation. Finally, before running the simulation, the model was carefully calibrated over a control period to ensure that the total flow reached the outlet of the watershed. This rigorous methodology made it possible to determine the water balance and the shape of the hydrograph for the watershed and its sub-watershed. The peak flow rate for the large watershed is 128.3 m^3/s, and the runoff coefficient is 27.26% over an area of 94.9 km^2. However, the water level is higher in the sub-watershed with hydromorphic soils and gravel beds on marl-limestone. The simulated unit hydrographs show a fairly short rise phase, a flood peak, and a longer fall phase.

Keywords

Watershed, Rainfall, Bambey, Modelling, Flow

1. Introduction

After a long period of drought since the 1970s, the Sahelian belt of West Africa has seen a trend towards increased rainfall since the 2000s. This observation is supported by studies conducted by Descroix et al. (2015) in Senegambia and the Middle Niger Basin, and especially by Nouarceur (2020) across the Sahel as a whole. In the current period, even though annual rainfall totals have not returned to the levels seen in the 1950s and 1970s, there has nevertheless been an increase in rainfall events with high daily cumulations (Vischel et al., 2015; Panthou et al., 2013; Panthou et al., 2014). This means that, although the total amount of rainfall is not yet equivalent to that of the past, the region is experiencing more and more episodes of intense rainfall, which increases the risk of flooding. In Senegal, despite the increase in the occurrence of floods in inland cities such as Bambey, Thies, Diourbel, Touba, Kaolack, Fatick, Louga, and Kaffrine, most urban hydrology studies focus on the Cape Verde peninsula (Bassel, 1996; Laaroubi, 2007; Diouf, 2011; Diouf et al., 2019; Dacosta, 2012). In Bambey, several major flooding events were observed between 2001 and 2020. In 2012, catastrophic floods destroyed homes, damaged farmland, and caused waterborne diseases. The phenomenon occurred in Bambey after consecutive rainfall from 9 to 11 August, with a total of 199 mm falling on waterlogged hydromorphic soils in the middle of the rainy season. Similarly, on 1 September 2016, heavy rainfall of 135 mm fell in Bambey, causing severe flooding in the eastern and southern districts. For a long time, research focused on soil (Bonfils & Faure, 1956; Charreau, 1961; Charreau & Nicou, 1971; Dancette, 1973; Dancette & Nicou, 1974) and agroclimatological studies (Dancette & Williot, 1971; Dancette, 1976; Dancette, 1983). However, with the pressing issue of flooding, it is urgent to broaden the scope to include hydrological studies.

Due to the lack of hydrological and hydrometric data, the use of rainfall-runoff modelling is an option for obtaining quantified data to improve the understanding of flooding in Bambey. The HEC-HMS hydrological modelling system, a semi-distributed conceptual model (Feldman, 2000) and mathematical model (Chea & Oeurng, 2017) developed by the US Army Corps of Engineers Hydrologic Centre, was used for rainfall-runoff simulation. The HEC-HMS model has been successfully applied in hydrological studies in Africa (Nandalal & Ratmayake, 2010; Najim & Halwathura, 2013). According to Ouedraogo et al. (2018) and Plata-Rocha et al. (2025), HEC-HMS is a high-performance hydrological modelling tool that integrates all stages of a rainfall-runoff simulation, from the delimitation of basins and sub-basins to the visualization of results. The use of HEC-HMS, therefore, remains simpler and more consistent in data processing, unlike many rainfall-runoff modelling tools that require tedious upstream work with other software for input data.

The aim of this article is to use the Hydrological Modelling System of the US Army Corps of Engineers Hydrologic Centre HEC-HMS to quantify the flow balance (flow, water depth, volume flow, runoff coefficient) and obtain the shape of the hydrographs of the Bambey watershed and sub-basins. The results obtained must be validated by field measurements to ensure the reliability of the chosen model. Once this validation has been carried out, the data can be used for more effective flood management in Bambey.

2. Data and Methods

2.1. Study Area

The study area is the Bambey watershed, an ungauged sub-basin of the Sine Saloum watershed covering an area of 95 km^2 in the north-west of this large hydrosystem (**Figure 1**). The morphological characteristics show an elongated basin with a topography reflecting very low relief (**Table 1**). According to Sall (1983), there is a topographical slope in this part of Senegal, running northeast to southwest, corresponding to the orientation of the Ogolian dunes. For Ndiaye (2016), the hydrographic network is severely degraded in the area and features temporary pools that form along the thalwegs during the rainy season.

The geology of the region is characterized by a substrate consisting of impermeable formations dating from the Lutetian period, with facies composed of marl and limestone interspersed with lateritic crusts (Tessier, 1952; Noel, 1975; Noel, 1978). The vegetation has suffered significant degradation with the expansion of cultivated areas and is currently dominated by a wooded steppe with a few species similar to those found in savannah areas. The climate belongs to the southern Sahelian region on the edge of the northern Sudanese region. The rainfall is concentrated between late June and October, mainly in July, August, and September, following the rise of the ITF (Intertropical Front) in the northern part of the Sahel, which, according to Sagna (1988), favours the intrusion of the African monsoon into Senegal.

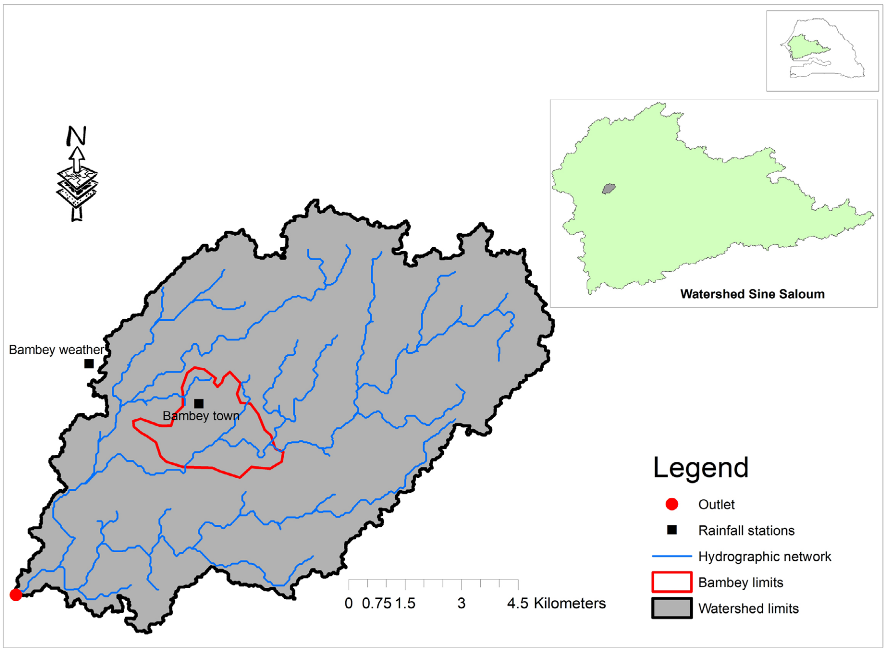


Figure 1. Geographical location of the Bambey watershed.

Table 1. Morphological characteristics of the watershed (Kc: Gravelius compactness index; L (km): length of the equivalent rectangle; I (km): width of the equivalent rectangle; Ip: Roche slope index; IG (m/km): overall slope index; Ds (m): specific elevation difference).

Area (km^2)	Length (km)	Kc	L (km)	I (km)	IP	IG (m/km)	Ds (m)
94.9	83.5	2.39	39.33	2.41	0.79	0.5	4.95

2.2. Topographical Data

The Digital Terrain Model covering the study area with a resolution of 12.5 m in GeoTIFF format in RTC (Radiometrically terrain-corrected) level was acquired using NASA ALOS PALSAR DEM radar images, which can be downloaded from the ASF (Alaska Satellite Facility) website via the link https://vertex.daac.asf.alaska.edu/en. The radar images are from the ALOS (Advanced Land Observing Satellite) mission of JAXA (Japan Aerospace Exploration Agency) from 2006 to 2011.

2.3. Daily Rainfall

In a context of climate change in the Sahel, which is increasing the frequency and intensity of extreme rainfall, it is better to analyse the hydrological behaviour of the catchment area in response to a hundred-year rainfall, even though ten-year rainfall has been tested by Ndiaye (2016) in the area with interesting results. The hundred-year rainfall thus assesses the highest risk of flooding, enabling better anticipation for managing the phenomenon and for measures to protect people and property. This option was even applied as part of the PGIIS (Integrated Flood Management Project in Senegal) in seven pilot cities, and return periods of 500 and 1000 years were also tested.

The daily rainfall data comes from the Bambey weather station, which is managed by the CNRA (National Centre for Agricultural Research) of Bambey and the ANACIM (National Civil Aviation and Meteorology Agency) of Senegal. The 98-year data sample (1923-2020) was used to determine the hundred-year rainfall frequency used in the hydrological model. This rainfall of 168 mm was obtained after adjusting the data using Pearson's incomplete truncated gamma distribution.

2.4. Types of Soil

The tropical ferruginous soils, clayey-humic marsh soils, hydromorphic soils with gravel beds on marl-limestone, and hydromorphic soils with temporary waterlogging are the four types of soils that cover the watershed. This information comes from the exploitation of the work of researchers at the CNRA in Bambey (Bonfils & Faure, 1956; Ganry & Gueye, 1992; Charreau, 1961; Charreau & Nicou, 1971; Dancette, 1973; Hamon, 1980). The infiltration characteristics of the dominant soil types will be used for hydrological modelling with HEC-HMS.

2.5. Methods

2.5.1. Creation of the Model Watershed

The approach consists of delineating the Bambey watershed after projecting the

DTM into HEC-HMS, with a resolution of 12.5 m covering the study area. Hec-Hms performs the delimitation and geospatial schematization of hydrological information in order to obtain the model watershed, also known as the useful project area (**Figure 2**).

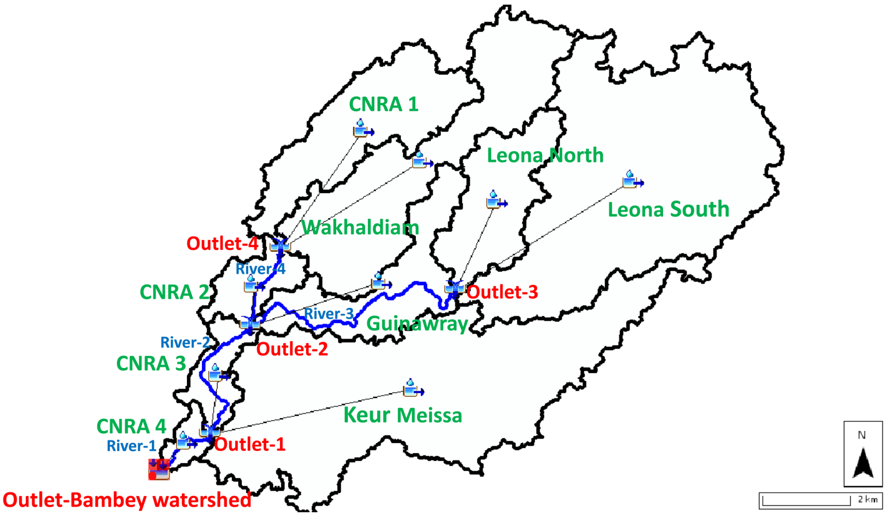


Figure 2. Conceptual scheme of the model watershed.

HEC-HMS then generates the sub-watershed areas of Leona North, Leona South, Wakhaldiam, Guinawray, CNRA 1, CNRA 2, CNRA 3, CNRA 4, and Keur Meissa with their physical and hydrological attributes essential for rainfall-runoff simulation (areas, methods for calculating losses, and transforming rainfall into runoff). The tributaries of the sub-watershed are shown in black, and the main rivers in blue. The four secondary outlets (confluences of tributaries of the sub-watershed) are represented by a blue arrow pointing downwards, the outlet of the Bambey watershed by a red point, and the sub-basins by blue horizontal arrows.

2.5.2. Definition of the Model Watershed

This involves defining the choice of infiltration loss method that will determine the production function of the dominant soil type in each sub-watershed (**Table 2**) and the method for converting rainfall into flow. The approach of Green and Ampt (1911), based on Darcy's law with the principle of conservation of mass, was used for losses, and Snyder's unit hydrograph method was used for the conversion of rainfall into flow (Snyder, 1938).

The equation of the Green and Ampt (1911) model is written as:

$$f_t = K\left[\frac{1+(\phi-\theta_i)S_f}{F_t}\right]$$

where K is the saturated hydraulic conductivity in mm/h; ϕ the porosity; θ_i the initial losses, which depend on the water conditions in the watershed; $(\phi-\theta_i)$ the volume of the water deficit; S_f a tabulated parameter expressing suction before wetting in mm; F_t represents cumulative losses over time; $\phi = \theta_i$ for saturated soils and $\theta_i = 0$ for drained soils.

The parameters of this model for each soil type have been studied by several authors (Rawls & Brakensiek, 1982; Rawls et al., 1983; Huber & Dickinson, 1988; Pitt, 1999). **Table 3** provides information on the parameters of the Green and Ampt (1911) model in the sub-basins based on the indications of Rawls et al. (1983).

Table 2. Distribution of soil types in the sub-watershed.

Sub-Watershed	Dominant Soil Types
Leona North	Hydromorphic soils with gravel beds on marl-limestone
Leona South	
Wakhaldiam	
Guinawray	
CNRA 1	
CNRA 2	
CNRA 3	Hydromorphic soils with temporary waterlogging
CNRA 4	
Keur Meissa	

Table 3. Green and Ampt parameters based on sub-basin soil textures (Rawls et al. 1983).

Soil Types	Hydraulic Conductivity	Pre-Wetting Sprinkling	Porosity	Initial Losses
Hydromorphic soils with gravel beds on marl-limestone	1.2	636	0.43	0
Hydromorphic soils with temporary waterlogging	4.3	449	0.398	0

The approach of Snyder's model is based on determining a transfer time and a peak coefficient for each sub-watershed (Snyder, 1938). The transfer time equation is written as:

$$t_L = 0.7517Ct\left(L \times L_{ca}\right)^{0.3}$$

where L is the length of the longest hydraulic path of the main watercourse for each sub-watershed in km, measured from the outlet to the crest line; L_{ca} the distance in kilometres between the main watercourse separating the outlet of the sub-watershed from its centre of gravity and Ct a parameter typically ranging from 1.8 to 2.2 that takes into account variations in slope and storage in sub-watershed.

The studies conducted in the province of Quebec, Canada, in 2010 by ESTRH (French Ecole Supérieure de Technologie en Ressources Hydriques) showed that the lowest Ct values correspond to the steepest slopes and the highest values to the gentlest slopes. As the slopes are very gentle in the Bambey watershed (**Table 1**), a *Ct* value of 2.2 was used to determine the delay time. The peak coefficient is a factor denoted Cp and varies between 0.4 and 0.8, depending on the retention capacity of the watershed (ESTRH, 2010). Lower values are generally associated with higher *Ct* values and vice versa. As the high *Ct* value (2.2) was used in calculating the delay time, the peak coefficient Cp corresponds to 0.4, i.e., the lowest value.

2.5.3. Creation of the Weather Model

For each sub-basin, the rainfall used for the rainfall-runoff simulation must be specified. The weather model method developed by the US Soil Conservation Service (SCS) was chosen. It is based on a hypothetical type 1 rainfall distributed over 24 hours across the entire area of the watershed and sub-watershed. This option gives the fraction of the hundred-year rainfall (168 mm) at each time step (**Figure 3**), and here the choice is for a time step of one minute. Ideally, the meteorological model should use the hundred-year rainfall from stations that are well distributed spatially throughout the basin and its surroundings in order to take into account the heterogeneity of precipitation. However, this option may skew the results of the rainfall-runoff modelling because the other stations are quite far from the basin, and the sample of daily rainfall data from these stations covers a short period (most often from 1975 or 2000 onwards), and is therefore not representative of the rainfall characteristics of the catchment area.

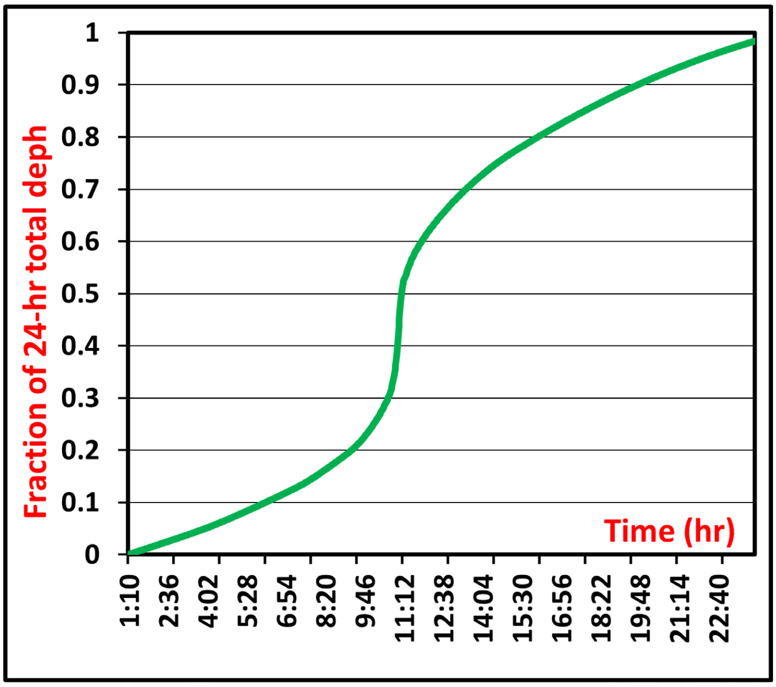


Figure 3. Hypothetical type 1 rainfall.

2.5.4. Simulation Calibration Parameters

The start date and time of the simulation must correspond to the start of the specified rainfall, and the end date and time must be chosen so that all runoff has reached the watershed outlet. The choice of a simulation start time at 00:00 and an end time beyond 24 hours allowed for good calibration for the rainfall-runoff modelling.

2.5.5. Running the Simulation

HEC-HMS first checks the input data in the model watershed (loss method and rain-to-runoff conversion), the meteorological input data (specified rainfall), and the calibration parameters (start and end times of the simulation). The simulation is therefore possible if HEC-HMS validates all of these steps.

3. Results and Discussion

3.1. Flow Balance

This balance is a very good indicator of the hydrological response of the ungauged watershed of the city of Bambey to a once-in-a-century rainfall event. The results of the hydrological modelling mentioned in Table 4 show that for an area of 94.9 km^2, the large basin produced a peak flow of 128.3 m^3/s with a runoff coefficient of 27.26%. At the sub-watershed level, the Keur Meissa basin, which covers an area of 27.4 km^2, has a runoff coefficient of 18.05%, while the Wakhaldiam sub-watershed, covering an area of only 13.3 km^2, has a runoff coefficient of 54.34%. Similarly, the Leona South watershed has a hundred-year flow rate of 39 m^3/s for an area of 26.5 km^2, which is higher than the peak flow rate of the Keur Meissa sub-watershed (21.2 m^3/s), which is slightly larger in size.

Table 4. Watershed runoff balance (A: area; P: centennial rainfall; Q: flow; L: water flowed; D: flow deficit; V: volume flow; C: flow coefficient).

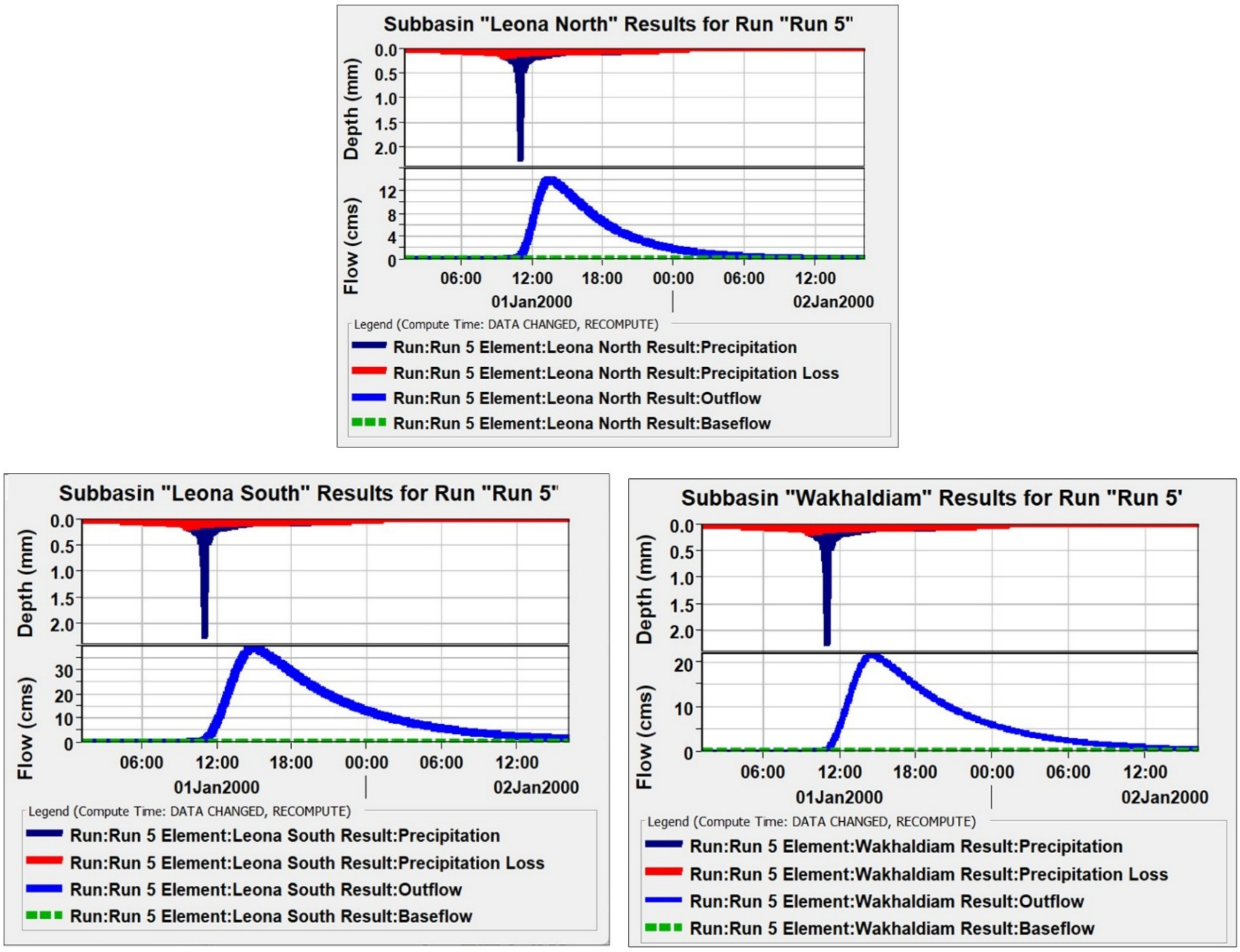
Watershed	A (km^2)	P (mm)	Q (m^3/s)	L (mm)	D (mm)	V (m^3)	C (%)
Bambey	94.9	168	128.3	45.8	122.20	4,348,300	27.26
Leona North	6.4	168	14	54.34	113.96	3,45,600	32.35
Leona South	26.5	168	39	54.34	113.96	1,412,200	32.35
Wakhaldiam	13.3	168	21.6	54.34	113.96	715,400	32.35
Guinawray	6.8	168	12.6	54.34	113.96	369,100	32.35
CNRA 1	8.6	168	15.5	54.34	113.96	467,100	32.35
CNRA 2	2.5	168	9	54.34	113.96	138,000	32.35
CNRA 3	2.3	168	4.6	30.32	137.98	70,800	18.05
CNRA 4	1	168	3.4	30.32	137.98	30,700	18.05
Keur Meissa	27.4	168	21.2	30.32	137.98	799,400	18.05

This observation shows significant variations, where smaller watershed can produce high peak flows and have higher flow coefficients than larger basins, suggesting that other factors influence the hydrological balance of the Bambey watershed and its sub-watersheds.

3.2. Form of Simulated Hydrographs

The simulated hydrographs effectively reflected Green and Ampt's (Green & Ampt, 1911) approach to modelling infiltration and Snyder's (Snyder, 1938) approach to the unit hydrograph (**Figure 4**). The Hec-Hms model also simulated hyetographs, separating the infiltrated volume in red and the net rainfall in blue, which will contribute to surface runoff. The decreasing curve of the infiltration regime to reach the submersion threshold depends on the form of the rainfall, which in this case is a centennial rainfall event, and above all on the texture of the hydromorphic soils in the sub-watershed.

This method was developed by Musy & Soutter (1991) and Musy & Higy (2004) at the Swiss Federal Institute of Technology in Lausanne (EPFL) in Switzerland in their work on the relationship between infiltration and runoff in watersheds. The hydrographs show a single flood peak separating a very short rising phase



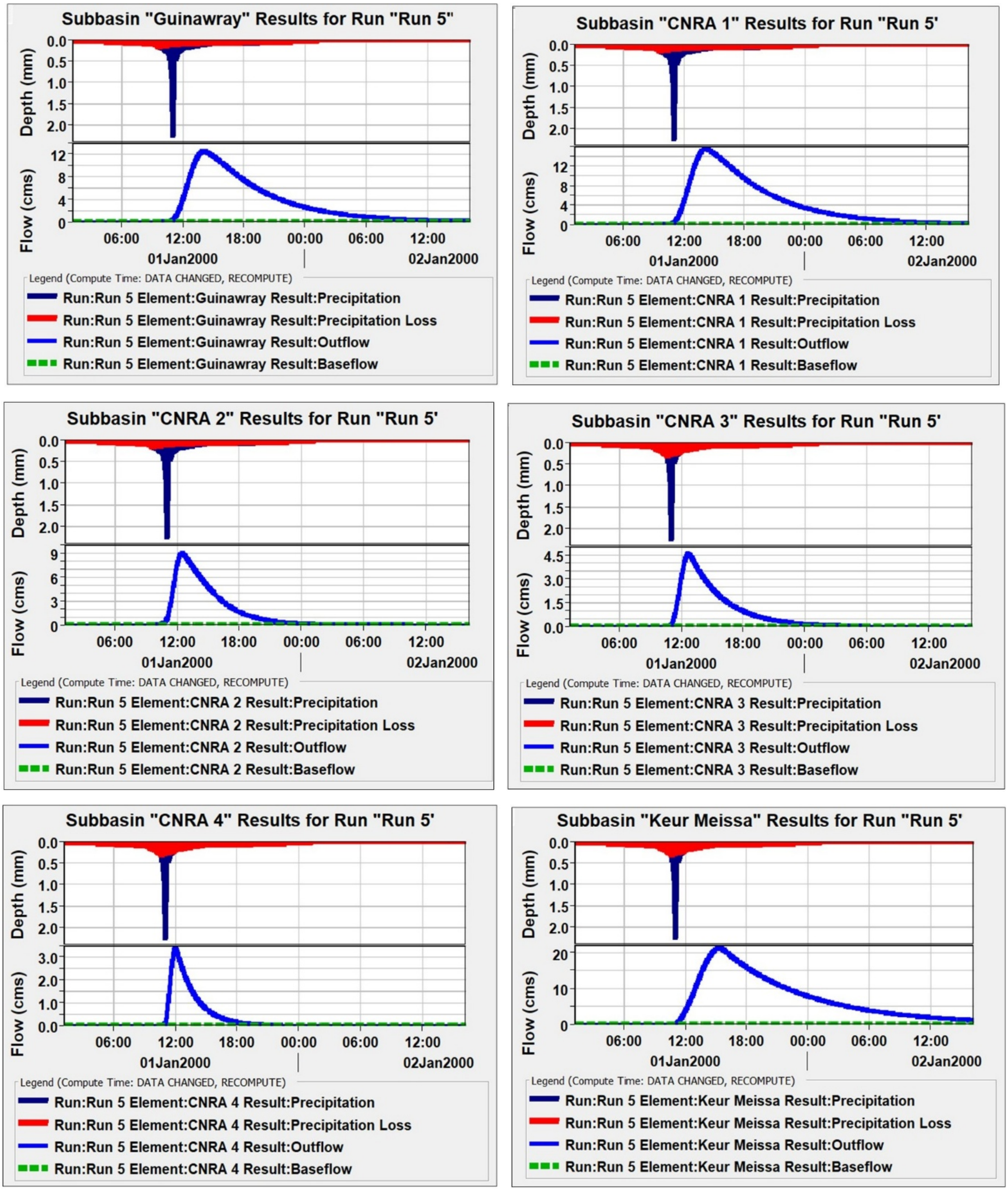
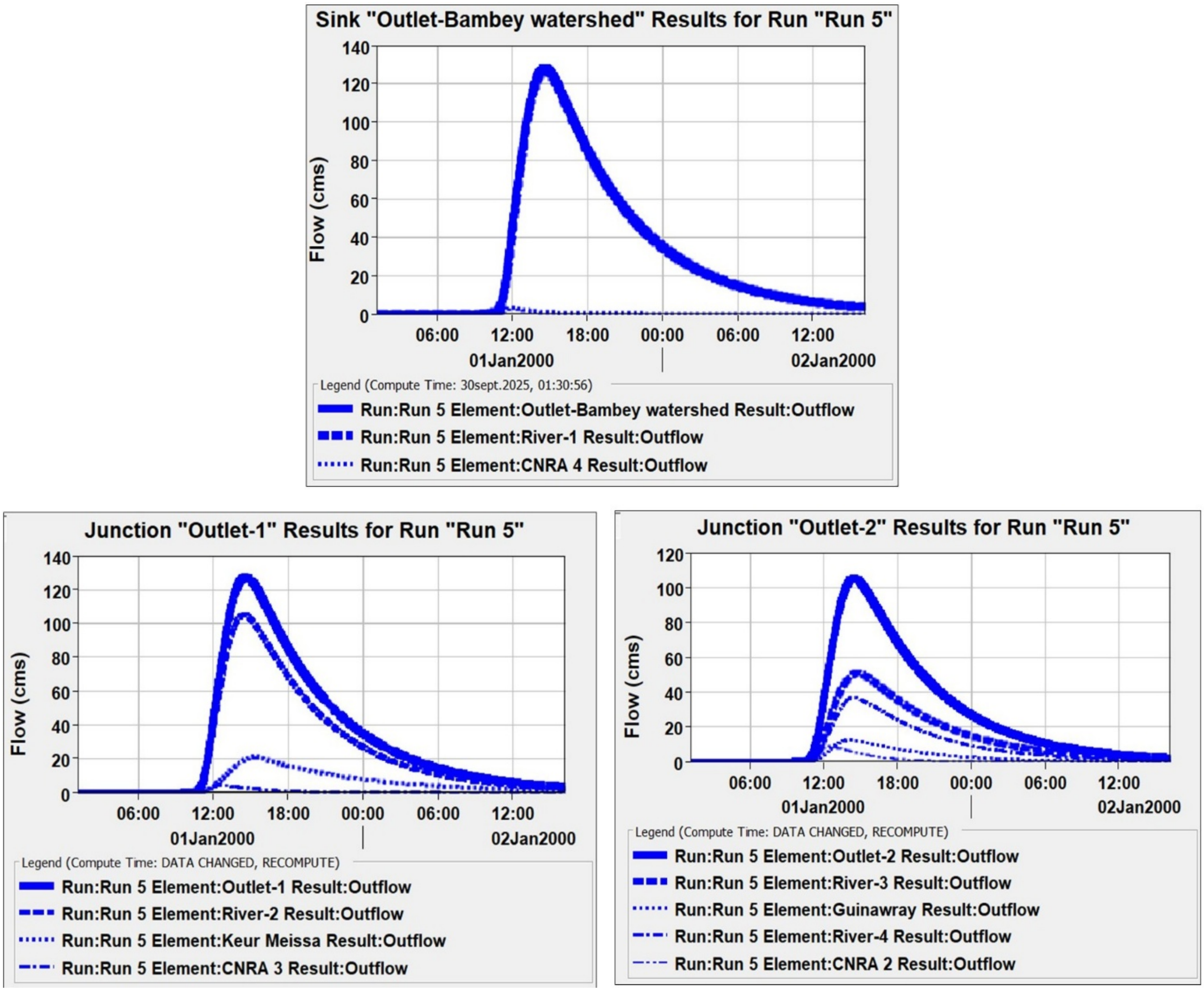


Figure 4. Simulated hydrographs of the sub-watershed.

from a fairly long falling phase. In their study of rainfall-runoff events, Musy and Higy (2004) determined the pattern of the unit hydrograph as characteristic of the sub-watershed of the Bambey watershed, with a flood curve, a drawdown curve, and a dry curve. This approach makes it possible to distinguish between surface runoff and subsurface runoff or hypodermic runoff after soil drying.

The United States Soil Conservation Service method used as an option in the meteorological model for hydrological simulation confirmed Rodriguez's (Rodriguez, 1999) approach for constructing the unit hydrograph (**Figure 5**). The simulated unit hydrographs reflected the key elements of his approach, which is based on unit rainfall in time and space, a response from the catchment area to this rainfall that corresponds to the unit hydrograph, and finally, a linear response reflecting the affinity and additivity links between the rivers in the sub-watershed.

This relationship of affinity and additivity is perfectly illustrated in **Figure 5** with the hydrograph at the outlet of the large watershed, which is the sum of the hydrographs of the sub-watershed and secondary outlets. This means that the hydrographs of the sub-watersheds of Leona North, Leona South, Wakhaldiam, Guinawray, CNRA 1, CNRA 2, CNRA 3, CNRA 4, and Keur Meissa can be combined additively to form the hydrograph of the Bambey watershed.



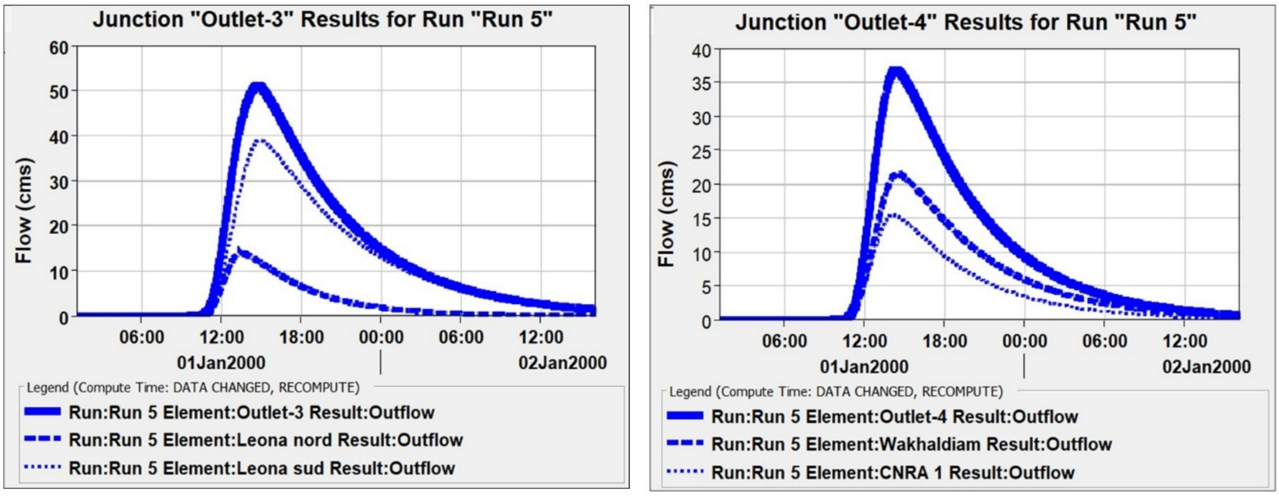


Figure 5. Hydrographs of secondary outlets and the Bambey watershed.

The unit hydrograph, although useful for modeling the hydrological response of a watershed to a unit rainfall, nevertheless has significant limitations. However, in this study, given the small size of the Bambey watershed (94.9 km^2), the uniformity of the centennial rainfall (168 mm) across its entire surface area may be accurate, especially in the sub-basins, which all have a surface area of less than 30 km^2 and even less than 5 km^2 in some cases. The highly debatable criterion here is the principle of linearity, i.e., that peak flow is proportional to rainfall intensity and that the concentration time remains constant. This hypothesis does not apply to the Bambey watershed. In fact, Ndiaye (2016) mentions that surface runoff in the region is organized within the hydrographic network only after one or more intense rainfall events, which first fill the ponds and then cause runoff through the phenomenon of communicating vessels. In this case, the concentration time is closely linked to the filling threshold of the ponds that will contribute to surface runoff. The previous water conditions in the basin, particularly consecutive showers that moisten hydromorphic soils before heavy rainfall, can also play a decisive role in the hydrological response of the sub-watershed. In this case, according to Descroix (2018), organized surface runoff only occurs once the soil is saturated, and this is referred to as saturation runoff or Cappusian behaviour rather than Hortonian behaviour. Thus, the complexity of hydrological responses in the Bambey watershed and its sub-watershed makes it impossible for the processes that depend on them to be linear. Added to this is the influence of land use, with crop areas in this part of the Senegalese peanut basin.

3.3. Discussion

In practice, the Hec-Hms model options do not take into account the vegetation aspect described by Albergel (1987), Mahé and Olivry (1999), Mahé et al. (2005), and Descroix et al. (2012) in the production of runoff in the Sahel. In fact, in the Sahelian watershed of Niger and Burkina Faso, researchers have noticed an increase in runoff during droughts, with above-average mortality among woody plants. Descroix et al. showed that this hydrological paradox, which manifests itself in an increase in runoff coefficients, is linked to land clearing, which leads to the fragility of the soil cover in the region (Descroix et al., 2012; 2015). The intensity of rainfall falling on areas with very little vegetation cover and the alternation between dry and wet seasons lead to the formation of crusts, which explain the differences in the soils' susceptibility to runoff (Casenave & Valentin, 1988; Casenave & Valentin, 1989; Sighomnou et al., 2013). In the Senegalese peanut basin where Bambey is located, the loss of natural vegetation due to intensive agriculture is very visible, according to Pélissier (1966) and Ndong (1996). Consequently, factors that may trigger an increase in flow coefficients are noted in the area.

However, Bonfils & Faure (1956) and, above all, Ganry & Gueye (1992) have described very significant hydromorphic phenomena in the area, resulting in total waterlogging for certain types of hydromorphic soils. Also, Ndiaye (2016) reports on the presence of highly clayey and elastic cements called montmorillonites in the soils of Bambey, which swell on contact with rainwater and significantly reduce the rate of infiltration. The influence of soil factors on surface runoff in Bambey was discussed by researchers from the CNRA agro-climatological laboratory between 9 and 11 August 2012, where a total of 199 mm of rainfall, including 113 mm between the night of 9 and 10 August and 83 mm between the night of 10 and 11 August, flooded the city of Bambey. However, in Lambaye, a town in the northwest outside the basin, these researchers noted that there were no significant floods, despite a cumulative rainfall of 215 mm during the same period, but falling on tropical ferruginous soils (K = 210). As a result, the relatively low hydraulic conductivity (K = 1.2) for hydromorphic soils with gravel beds on marl-limestone resting on an impermeable geological base dating from the Lutetian period (Tessier, 1952; Noel, 1975; Noel, 1978) appears to play a decisive role in increasing peak flows and flow coefficients for the sub-watershed of Leona North, Leona South, Wakhaldiam, Guinawray, CNRA 1, and CNRA 2.

4. Conclusion

The increase in flooding phenomena has been observed in Bambey since the beginning of the 2000s, as in many cities in Senegal. However, despite this alarming observation, its watershed has not been measured (lack of hydrometric data), and understanding of the hydrological phenomena that cause these floods remains very limited. In this study, hydrological modelling was used to quantify surface runoff from the watershed and sub-watershed using the Hydrological Modelling System of the US Army Corps of Engineers Hydrologic Center. The approach used is based on the creation of a model watershed, the definition of a production function using the Green and Ampt method, which uses soil infiltrability, and a function for converting rainfall into flow using Snyder's unit hydrograph method. The Bambey meteorological centennial frequency rainfall was simulated using the US SCS method, considering it as a hypothetical type 1 rainfall with a 24-hour distribution over the entire area of the watershed and sub-watershed at one-minute intervals. This allowed the model to be calibrated between the start of this rain and a sufficient time to allow the total flow to reach the outlet.

The results of the flow balance show for the large basin a peak flow of 128.3m^3/s and a flow coefficient of 27.26% for an area of 94.9 km^2. The water flow indicates that it was influenced by the hydraulic conductivity (K) of the soil types and not by the surface area. This is evidenced by the flow coefficient of the Wakhaldiam sub-basin (54.34%), which has hydromorphic soils with gravel beds on marl-limestone (K = 1.2), even though it is smaller than the Keur Meissa sub-basin (18.05%), which is dominated by hydromorphic soils with temporary waterlogging (K = 4.3). Consequently, in the Bambey watershed and its sub-watershed, surface runoff is influenced more by soil texture.

The form of the simulated hydrographs of the sub-watershed is the hydrological response of part of the unit rainfall injected into the HEC-HMS model. This volume fraction represents the net rainfall that resulted in surface runoff after its intensity exceeded the infiltration limits of hydromorphic soils. The hydrographs show a single flood peak separated by a short rise phase and a longer fall phase. The hydrograph at the outlet of the Bambey watershed reflects the cumulative flow rates of the sub-watershed and secondary outlets, even though the linearity of surface runoff is highly debatable.

In summary, the results obtained make a valuable contribution to the knowledge of hydrological information in the Bambey watershed. The same approach can be applied to Senegal's unknown urban watersheds in order to better understand the mechanisms of surface runoff formation and thus better design the hydraulic structures that will be used operationally for the technical management of floods, the occurrence of which has increased significantly in recent years.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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