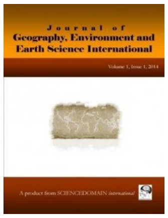

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A Copula-based Approach for Assessing Flood Protection Overtopping Associated with a Seasonal Flood Forecast in Niamey, West Africa

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Authors' contributions

This work was carried out in collaboration between all authors. Author AGD developed the methodology under the supervision of authors OS, HMS, NP, HK and JEP. Author KS assisted with the data analysis. All authors proof read the manuscript and contributed to the interpretation of the results.

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ABSTRACT

Flood is one of the most important natural disasters that cause huge loss of life and properties every year around the world. Moreover, the International Federation of the Red Cross and Red Crescent Societies pointed out that floods were by far the greatest cause of homelessness. In West Africa, many countries are damaged from flooding almost every season. Thus, this study aimed to set a seasonal flood forecast model and carried out an evaluation of the level of risk associated with each seasonal forecast. HEC-RAS (Hydrologic Engineering Centers River Analysis System) was used to develop a hydro-dynamical model of Niger river on a 160km reach (80km upstream to 80kmdownstream of Niamey), then a simple risk measure was used to calculate the probability of overtopping the flood protection dykes in Niamey. Results show that the hydro-dynamical model reproduced well the rating curve over the period 2009-2014. A subsequent copula analysis demonstrated a dependency between flow on the Niger river and flow on the Sirba River, the main tributary contributing to the seasonal flood at Niamey. The Gumbel copula was found to be the best among the tested 5 copulas to represent the dependency between peak flow on the main channel of the Niger River and concomitant flow on the Sirba river. It is found that for the six dykes the probabilities of being overtopped by the flood range from very high (100%) to relatively low (16.67 %) over the 34 years of simulation.

Keywords: Seasonal flood forecast; HEC-RAS model; dykes; copula; Niamey.

1. INTRODUCTION

Climate variability is known as a short-term deviation from the normal of the climate at a given place. Deviations affect parameters such as temperature, wind and precipitation. In different parts of the world, the climate is also distinguished by extreme weather events such as droughts, flooding, and so on. These extreme weather events cause recurrently worldwide significant human loss and economic disasters. This is the case, for example, of floods in the Sahel in West Africa. Climate change is thought to be the reason behind the increase in magnitude and frequency of extreme weather events such as droughts, intensive precipitations, floods, strong winds, storm surges that were reported in several recent publications [1,2]. The extreme events have severe consequences for societies in underdeveloped countries where the populations are more vulnerable due to their low adaptive capacity [3]; this fact was specifically detailed in the study by [4] who particularly emphasized on the lack of sustainable solutions for communities to fight against these calamitous phenomena.

Flooding can be defined as the overflowing by the water of the normal confines of a stream or other body of water, or accumulation of water by drainage over areas that are not normally submerged [5]. Different types of floods are mentioned in the scientific research works around the world and they can be categorized into 10 groups: Flash floods, fluvial (riverine) floods, single event floods, multiple event floods, seasonal floods, coastal floods, estuarine floods, urban floods, snowmelt floods, and ice-and debris-jam floods. Details of these floods are contained in [5-9].

Flood is one of the most important natural disasters which cause extensive loss of life and properties every year around the world. According to WMO statistics on the types of water-related natural disasters in the world [5], the damages related to floods have been more frequent and had a more economic impact on the population as compared to other extreme events during the last two decades. Indeed, the United Nations Educational, Scientific and Cultural Organization [10] showed in its water assessment program that 15% of deaths issued from natural disasters are due to flooding. For instance, the Asian continent was affected by 44% of flood disasters during the period 1987-1997, that led to the loss of 228 000 lives [11]. Moreover, the International Federation of the Red Cross and Red Crescent Societies (IFRC) pointed out that floods were by far the greatest cause of homelessness. In West Africa, many countries have been recently damaged by flooding: Burkina Faso and Niger have been hardly hit by heavy flooding in 2009 and faced many emergency situations. At least 30 people were killed and 350,000 displaced when torrential rains soaked much of West Africa in September 2009. In 2007, 300 people died and 800,000 were affected by the inundations [12]. It is particularly found that the Niger River and its tributaries (at upstream) always contribute to the flooding issue in Niger especially at Niamey city. Many dead and displaced populations were registered during such flooding events. In 2013, the economic losses induced by flooding in Niger were estimated to 32 billion FCFA [13].

Therefore, there is a great need to forecast flood in order to provide early-warning about impending flood to stakeholders to alert the population in order to reduce the probable losses. Seasonal flood forecasts are of prime importance for Niamey city due to its location at the banks of the Niger River. Seasonal flooding experienced annually by the city generate the displacement of the local population living near the river, economic loss and psychological impact on victims. It should be noted that Niamey is a city that lacks adequate resources, so the funds disbursed to aid the victims should have been invested in the development of the city in order to provide better living conditions to the population. Hence, the seasonal flood forecast should help Niamey city to avoid or to lessen the overall impacts of a flood and also by saving lives, livestock and property.

In a broad sense, flood-risk assessment combines a frequency analysis of extreme hydrological phenomena and an evaluation of the flood damages.

This article discusses the hydrological variability by assessing the potential damages of induced flood events over seasons. The development of a seasonal flood forecast model for Niamey city involves the development of a hydro-dynamical model of Niger at Niamey using HEC-RAS model and applying probability distributions to generate a probabilistic forecast for each year. Thus, the aim of this study is to develop a seasonal flood forecast model in Niamey and to quantify the probabilities of flood protection dykes to be overtopped. In attaining this objective a copula-based approach is chosen.

2. SEASONAL FLOOD FORECASTING APPROACH

The performance of an engineered flood protection system must be evaluated over the system's lifetime. Consequently, the hydrologic conditions can be described as a function of time, particularly if the river environment changes over time due to the impact of land-use change or because of climate perturbations. In order to tackle such issues, flood forecasting is needed to help to take the necessary and adequate measures to avoid such flood or to reduce its impacts. The critical part of any flood forecasting system is the hydrological model (i.e., rainfall-runoff model). It is for this reason that [14] considered the hydrological model as the element that ensures the success and efficiency of a flood forecasting system. Thus, the choice of the rainfall-runoff model is fundamental for flood forecasting attainment in order to produce the exact flood projections based on input data (hydro-meteorological and other data). Flood forecasters usually rely heavily on real-time data about rainfall and river water levels as well as rainfall forecasts [15]. But, there are uncertainties in long-range forecasts, noticeably biases in precipitation frequency (i.e., too many rainy days), and intensity (i.e., too small precipitation values). Thus bias correction of seasonal rainfall forecasts is essential before using them as inputs for hydrological models. To circumvent such process, we developed a new approach for seasonal flood forecast for Niamey city. The seasonal flood forecast model for Niamey city was developed based on the probabilistic forecasted streamflows. It involves the development of a hydro-dynamical model of Niger at Niamey using HEC-RAS model, and applying probability distributions to generate probabilistic forecast for each year. The developed seasonal flood forecast model is a tool that could help stakeholders to take adequate decision to reduce the resulting damages. Also, the quantification of probabilities of flood protection structures to be overtopped could help a lot to avoid high induced economic losses. Therefore, the main idea behind this seasonal flood forecast model is that any flood forecasting model or method has to consider the will of decision-makers and the wishes of the end-users (i.e., the riparian communities) of such flood estimates [16,17].

3. MATERIALS AND METHODS

3.1 Study Area

Two areas are considered in this study, namely, the Niger River at Niamey city for flood damages and the Sirba watershed (Sirba tributary) for flow prediction. Located in western Niger between longitudes 2°01' - 2°14' East and latitudes 13°25' - 13°36' North, Niamey is landlocked in the department of Kollo. It is bounded to the north-east by the rural town of Hamdallaye, at east and south by the rural town of Liboré and at west by the canton of Lamordé and the rural town of

Karma [18]. Niamey, capital of Niger, is built on both banks of the Niger River. The left bank houses the districts I, II, III, and IV; while the fifth district is on the right bank. These five districts give rise to a set of 96 quarters occupying a surface of 239.263 km^2 [18]. Fig. 1 presents the location and characteristics of Niamey city.

The development of Niamey falls within the administrative needs of the colonial authorities and subsequently of the Niger governments. The city spread diffusely without proper planning developments. Currently, the urban area at the right bank is experiencing unparalleled growth driven by ever-increasing rural exodus [19-20]. This spatial expansion meets the growing demographic needs. Its population increased from about 30,000 inhabitants in 1960 to 1,222,066 people in 2010, that is, from 1 to 8% of the total population in fifty years. This growing of the demographic weight confirms the importance of rural-urban migration and high annual population growth rate (3.3%) [21,22]. This high demographic and spatial pressure also generates land issues involving competition between housing, industry and agriculture, and the use of vulnerable space, for instance the Niger River bed without any prior planning. Thus, this work is carried out on the portion of the Niger River at Niamey in order to seek ways on how to tackle this flooding issue. The choice of Niamey city is motivated by the fact that the city experienced almost every year seasonal flooding which usually led to the displacement of the local population living near the river, and huge economic losses. Moreover, this area offers the opportunity to carry out such kind of study because the city undergoes an anarchic occupation and the population has the low fiscal revenue to cope with the issued consequences.

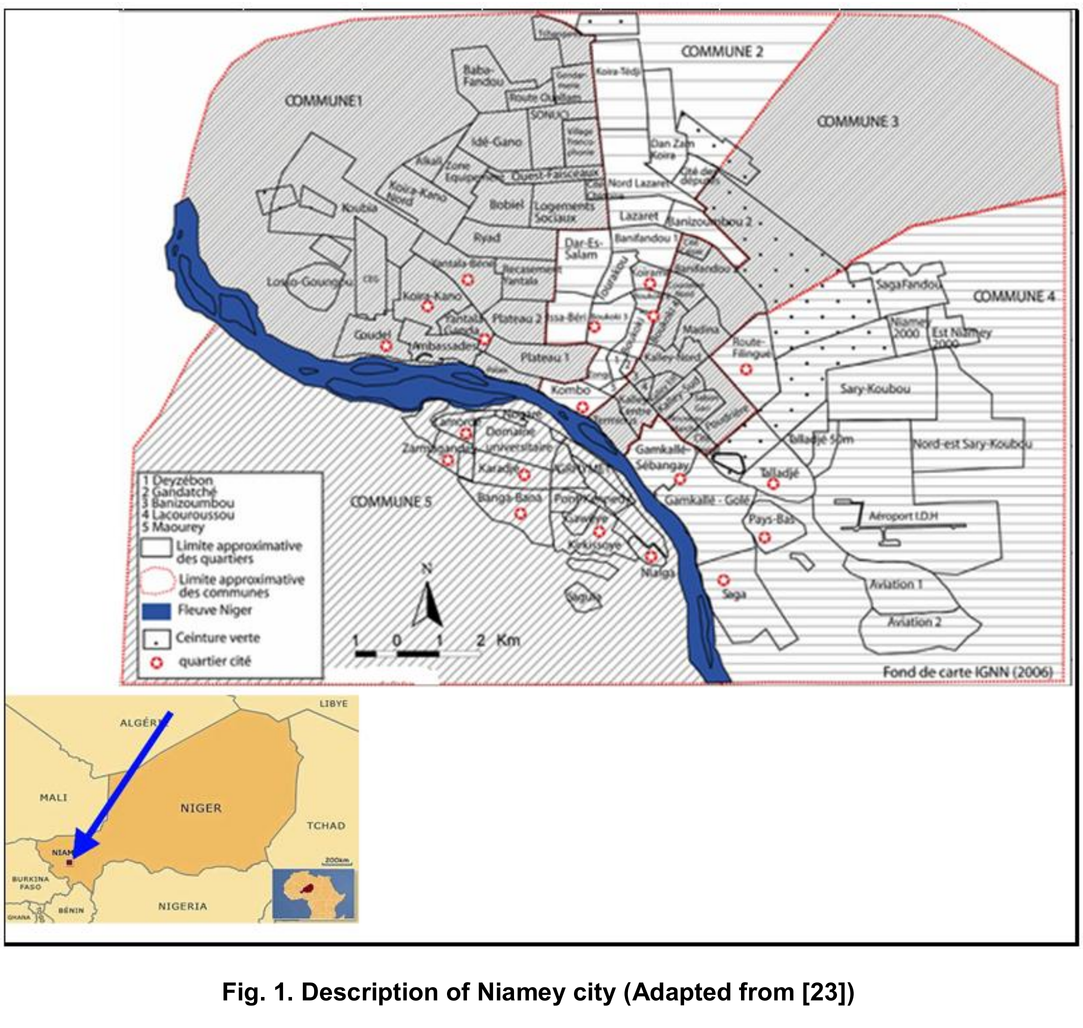

Fig. 1. Description of Niamey city (Adapted from [23])

Concerning the Sirba watershed, it is a transboundary watershed in between Burkina Faso and the Niger Republic. The Sirba watershed lies within the latitudes 12°55'54''–14°23'30''N and longitudes 1°27'W–1°23'42''E with an area of 38,750 km^2 [24]. The Sirba extends over three sub-climate zones based on the mean annual amount of rainfall decreasing from south to north: a southern Sudanian zone with mean annual rainfall between 700 and 800 mm, a northern Sudanian zone with mean annual rainfall ranging from 550 to 650 mm and a Sahelian zone with mean annual rainfall of 300 to 500 mm. The highest quantities of rainfall are observed during the months of July to September (JAS), regardless of the climate zone. The climate is generally characterized by the presence of two seasons: a dry season (October–April) due to the harmattan (dry hot wind) and a rainy season (May–September) due to the presence of the West African Monsoon (cold wet wind). The hydrographic network is relatively dense and consists of three main tributaries (Sirba, Faga and Yeli) as well as some small reservoirs from five dams with non-operated spillways (Fig. 2). Based on the description of the rainfall pattern, the hydrological regime in the Sirba watershed is a Sahelian type, while its vegetation formation is thorny and of a lightly wooded savannah [25]. The reason for choosing the Sirba basin is due to the fact that the Sirba tributary contributes to the local flood of Niger River. It is also one of the most important affluents of Niger River; and it is specifically chosen to predict the seasonal flows in order to develop the seasonal flood forecast model.

3.2 Modeling the Dependence of Flood Peak at the Kandadji and Garbe-Kourou Station Using Copulas

Let X and Y be random variables with distribution function F_X and F_Y. We called copula (2-dimensional) any distribution function C whose marginal bivariate is a uniform distribution on [0, 1]. In other words, C satisfies the four properties of a bivariate distribution function in addition to the following 4 equations:

$$C(x, y) = 0 \text{ if } x \leq 0 \text{ or } y \leq 0 \quad (1)$$

$$C(x, y) = 1 \text{ if } x \geq 1 \text{ and } y \geq 1 \quad (2)$$

$$C(x, y) = x \text{ if } y \geq 1 \quad (3)$$

$$C(x, y) = y \text{ if } x \geq 1 \quad (4)$$

Copula theory allows to model the dependence structure between variables independently of marginals [26]. It has been widely applied in various fields, such as biology [27] and Insurance and Reinsurance [28-32].

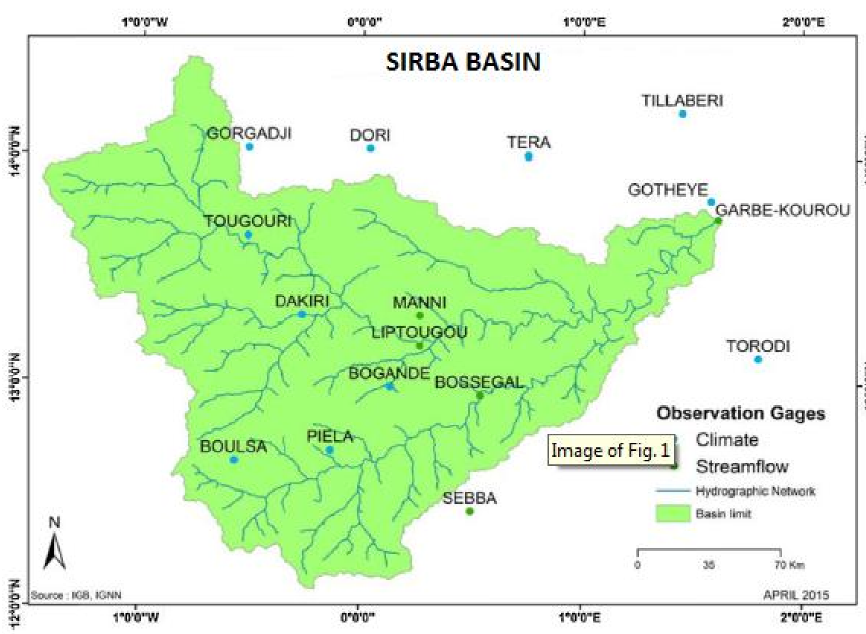

Fig. 2. Location of Sirba watershed (source: Gado Djibo et al., 2015)

In hydrology, [33] present two applications of copula: the first concerns the modeling of flow rates upstream and downstream of a river with tributary, and the second concerns the joint modeling of annual maximum flows based on the volume of runoff. De Michele C. et al. [34] used the Gumbel copula to model the positive dependence between the peak flow and flood volume. Zhang L and Singh VP [35] used bivariate copulas for frequency analysis of the variables: peak flow and volume of runoff, and flood volume and its duration.

In this study, the copula method is applied for the analysis of the dependence structure for a couple of streamflows at Kandadji and at Garbé-Kourou. This helps to check which flow station contributes more to the flooding occurring at Niamey city along the Niger River. This checking was made in 3 main steps detailed in the next paragraphs.

3.2.1 Identification and adequacy of marginals

Eleven statistical distributions were applied and tested over the streamflow data series of Kandadji and Garbé-Kourou. The distributions are individually tested using the maximum likelihood method to compute the parameters of each distribution. The statistical criterion used to assess the goodness of fit is the Kolmogorov-Smirnov (Ks) test [36]. All statistical distributions were ranked based on the goodness of fit values, where the lesser value denotes a high rank. Additionally, the p-value is also used because the higher the p-value the lower the statistical value of the goodness of fit. This ranking helps to classify the probability distributions and eases the identification of the best distribution. The probability densities of the best fit were computed. More details on these tests are provided in [36] and [37]

3.2.2 Detecting dependency

To characterize and measure the dependence between flow at Kandadji and Garbé-Kourou, two criteria are used: the Spearman (ρ_s) and Kendall (τ) rank correlation coefficients. These two correlation coefficients are the most suitable as they only depend on the rank of each observation compared to Pearson correlation coefficient which depends on variables values. Furthermore ρ_s and τ are invariant under strictly increasing transformations of random variables X and Y.

In addition, distributions of ρ_s and τ are near normal distribution of average zero and respective variances $\frac{1}{1-n}$ and $\frac{2(2n+5)}{9n(n-1)}$. So random variables X and Y can be considered as dependent on α threshold, if: $\sqrt{(n-1)}|\rho_s| > z_{\alpha/2}$ and $\sqrt{\frac{9n(n-1)}{2(2n+5)}}|\tau| > z_{\alpha/2}$ respectively [38]. Therefore, the dependence parameter was estimated using the above conditions.

3.2.3 Selection and adequacy of the copula

Five copulas were used to find the dependence structure. They are t-copula, Gaussian copula, Frank copula, Gumbel copula, and Clayton copula. It consisted to compare the empirical values and the estimated values for the different copula. This comparison is made using the Kolmogorov-Smirnov test [39] to a threshold α. This test is recommended by several studies such as [40] and [41]. Also, the quantile-quantile (QQ) plot is performed after resampling because it helps to check ultimately if the convergences between the distribution of series being tested and those of reference are very obvious.

3.3 Hydro-dynamical Model Development for Niger River at Niamey

In this study, the hydraulic model HEC-RAS and HEC-GeoRAS associated to ArcGIS were used to study and evaluate flood flows and map flood zone along 160km upstream Niamey.

HEC-RAS, a one-dimensional, hydraulic-flow model was used to develop the hydro-dynamical of Niger River at Niamey. The HEC-RAS program has been developed by the US Army corps of Engineers since its inception in 1964, and different sub-programs have been continuously established. It was designed specifically for application in floodplain management and flood-insurance studies to evaluate floodway encroachment and to simulate estimated flood inundation [42,43]. This model is used worldwide. Indeed, [44] used HEC-RAS model to develop floodplain maps for an urban area in Segamat town in Malaysia. Using the model, the water surface profile of the river was plotted. Using HEC-RAS software, [45], evaluated the hydraulic behaviour of the flood. David LK [46] while studying flood for a period of 5 years in the United States, prepared flood zone maps. Knebl MR [47] using the hydrological model, HEC-HMS, and hydraulic model, HEC-RAS, and radar precipitation estimate (NEXRAD) in the basin of San Antonio, Central Texas, United States suggested logic model for flood, and compared the model with the summer 2002 flood. Results showed the model efficiency for regional-scale flood forecasting. Sighomnou D made flood hazard mapping for small watersheds near Baya Sea in Astore valley. For this purpose combination of WetSpa and HEC-RAS was used.

The HEC-RAS model was used to compute water-surface elevations and develop flood-inundation areas along the study area (Niger River at Niamey) for the flood discharges. Peak flows before august was used (1980-2013), and they are from two flow measurement stations, Kandadji (on Niger River) and Garbé-Kourou (exit of the Sirba watershed located at Niger River).

The steps in building the hydro-dynamical model, and the required data at each step, are briefly explained in the next paragraphs as they are standard steps. It consisted first of building the import file (digital terrain model (DTM) of the Niger River system) in the ArcInfo TIN (Triangular Interpolation Networks) format under HEC-GeoRAS environment. This helps setting-up analysis environment for HEC-GeoRAS. The geometry file containing the RAS layers and line themes were then created. It should be noted that two nodes were specified in this model, and also an adequate number of cross-sections cut lines. 6 levees were set in this model; these levees protect the city of Niamey against flooding from Niger River. The geometry data were then imported into HEC-RAS then the model was run for some simulations after entering flow data and boundary conditions. These simulations helped to obtain water surface profile and velocity data after processing.

The developed HEC-RAS model was calibrated to reproduce the last rating curve over the period 2009-2014 using the observed elevations data at Niamey and bathymetry data of Niger River. It is should be noted that during the calibration a leave-one-out cross-validation was used due to the short length of data used. A flood inundation map of Niamey city was generated after exporting the acquired data from the HEC-RAS simulations to HEC-GeoRAS, for GIS analysis of floodplain mapping.

3.4 Assessment of Potential Damages Related to the Seasonal Flood Forecasts

Economic loss assessment based on established vulnerability maps are crucial for West African Sahel especially the city of Niamey, as the recurrent flood events can lead to the loss of human lives and valuable properties. Also, another potential benefit resides in the thought of some specialists [7,8] who believe that remedial approaches and quick technical solutions are less effective for dealing with flood events than projected measures. With increased accessibility to digital information and the effectiveness of computer-based analysis, GIS has played an important role in hydrologic and hydraulic modelling. The main advantage of using GIS in modeling is the considerable potential for extracting digital information from a digital elevation model (DEM). Thus, while developing the hydro-dynamical of Niger River at Niamey the probabilistic forecast streamflows obtained are used to find the probabilities of overtopping the dykes protecting the city of Niamey against flood. These probabilities were obtained after running the hydro-dynamical model and considering the number of dykes (among the six) that each peak flow can overtop. These probabilities of overtopping the dykes explain the extent of the danger of floods at Niamey.

4. RESULTS AND DISCUSSION

4.1 Niger River HEC-RAS Model

The Niger River hydro-dynamical model was developed by combining HEC-GeoRAS and HEC-RAS computer programs to extract floodplain cross sections from the elevation contour data of the City of Niamey. A total of 988 cross sections were extracted along the study reach of 160 km. All cross sectional profiles were drawn and the longitudinal profile for each of the 34 years (1980-2012). Typical HEC-RAS cross sectional and longitudinal profiles obtained for the year 2012 are shown in Figs 3 and 4, respectively. The developed model contains 6 levees which were completely overflooded in 2007, 2009, 2010 and 2012, the years when Niamey actually underwent several. The floods were computed at all cross sections from the HEC-RAS model. An analysis of all those profiles showed that the year 2010 was the worst in terms of negative impacts on the City of Niamey, followed by the year 2012. This finding is justified by the records of the government through its early warning center. In addition, in 2012, the flood led to the collapse of more than 3,000 houses and 23,000 people affected [49].

Fig. 5 depicts the calibration of the seasonal flood forecast model. It can be easily seen that the model calibrated over the period 2009-2014

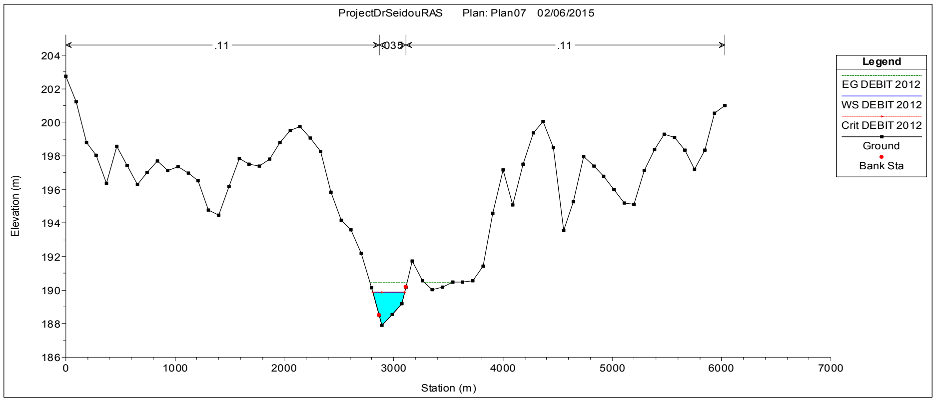

Fig. 3. Example of a cross sectional profile for the year 2012 streamflow

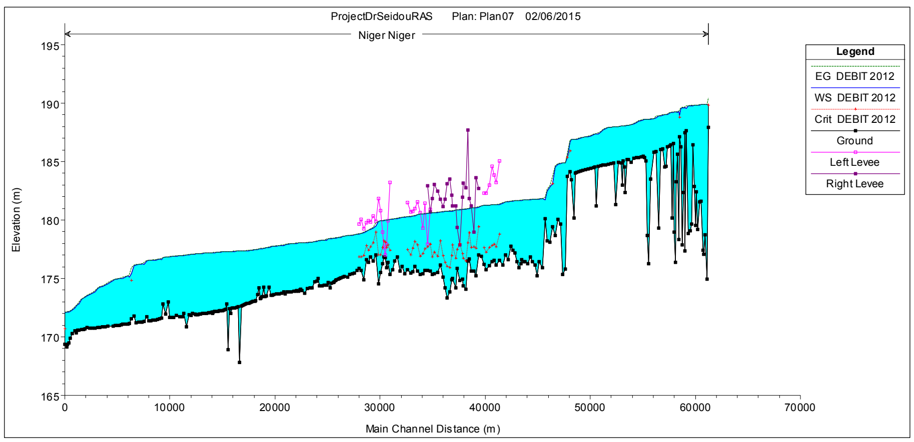

Fig. 4. A longitudinal profile of Niger River at Niamey for 2012 flows

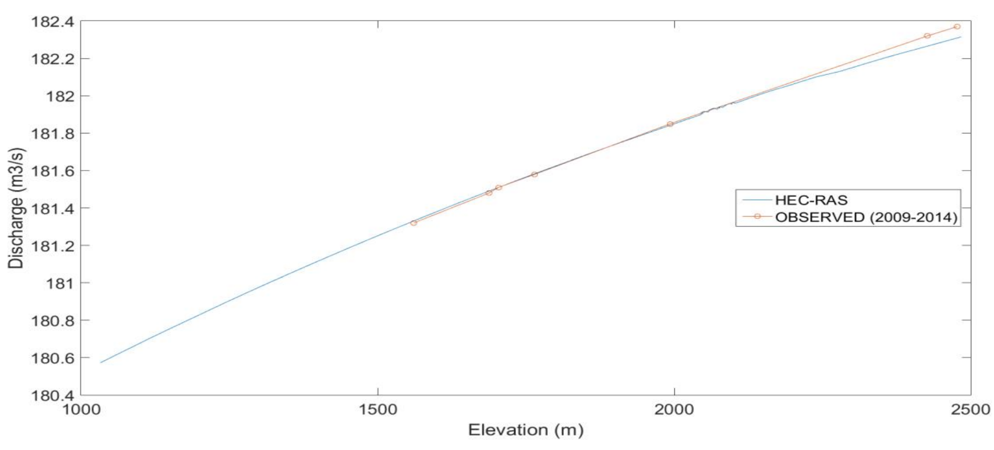

Fig. 5. Calibrated seasonal flood forecast model: simulated (blue) and observed (red)

reproduces almost perfectly the last rating curve over the indicated period. The two curves match well confirming how satisfactory the calibration is.

This is the first model for Niger River developed using the HEC-RAS model. However, the limitations and errorsassociatedwith developing flood-inundation areas are dependent on the topographic data, hydrologic data, and one-dimensional hydraulic modeling used in a floodplain study.

4.2 Kandadji and Sirba Streamflows Dependency on Flooding at Niamey

4.2.1 Goodness of fit test

The streamflow peaks at Garbé-Kourou and Kandadji were analyzed over the period 1980-2013. The best fit was obtained with the generalized Pareto (GPAR) distribution for flows at Garbé-Kourou (Fig. 6) while the Log-Pearson III distribution (LP-III) was found as the best fit for flows at Kandadji (Fig. 7). These distributions were the best at 95% confidence interval. It can be seen on these figures that all the observations align with the fit and fall within the confidence range.

The Figs. 8 and 9 present the tested distribution for comparing the 11 probability distributions for flows at Kandadji and Garbé-Kourou, respectively. In addition, Table 1 presents the results for the statistical distributions that gives the best fit.

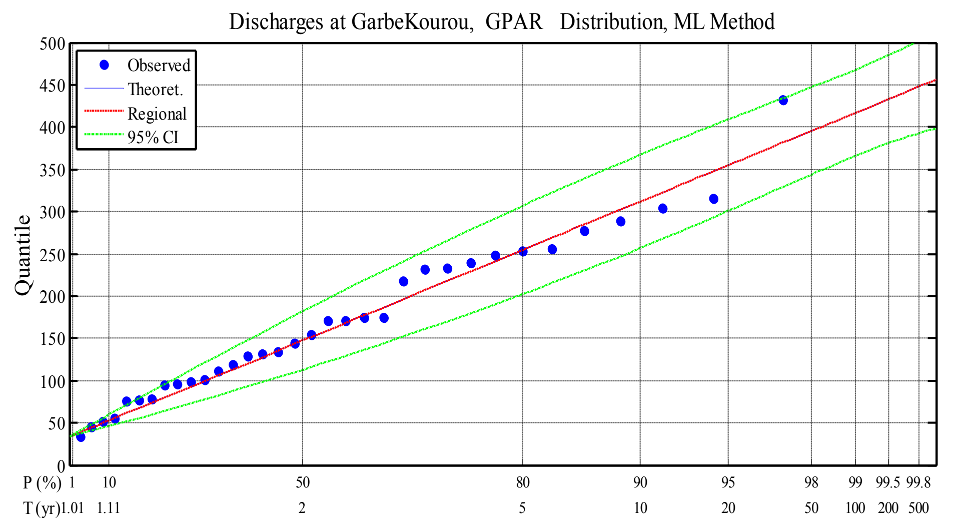

Fig. 6. Best probability distribution fit (GPAR) for streamflow peaks at Garbé-Kourou

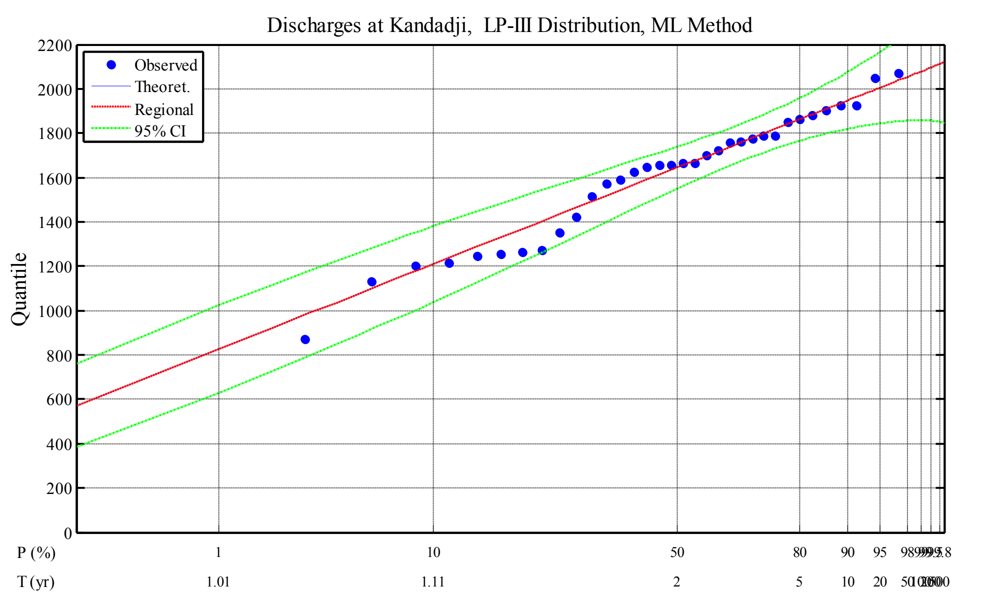

Fig. 7. Best probability distribution fit (LP-III) for streamflows at Kandadji

Table 1. Parameters of the best fitted distributions for streamflows peaks at Kandadji and Garbé- Kourou based on KS test

Distribution	KS test		Parameters
	Statistic test	p-value	
Log-Pearson III (LP-III)	0.10	0.846	γ=7.66; α=-0.13; β=2.22
Generalized Pareto (GPAR)	0.07	0.913	e=33.22; α=189.88; k=0.43

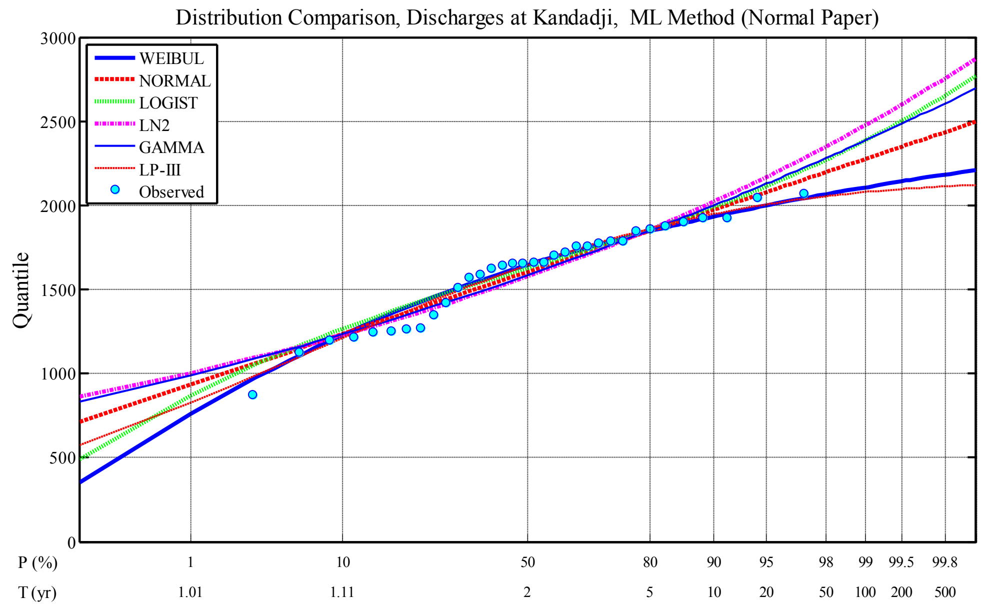

Fig. 8. Distribution comparison of 6 probability distributions for streamflow peaks at Kandadji

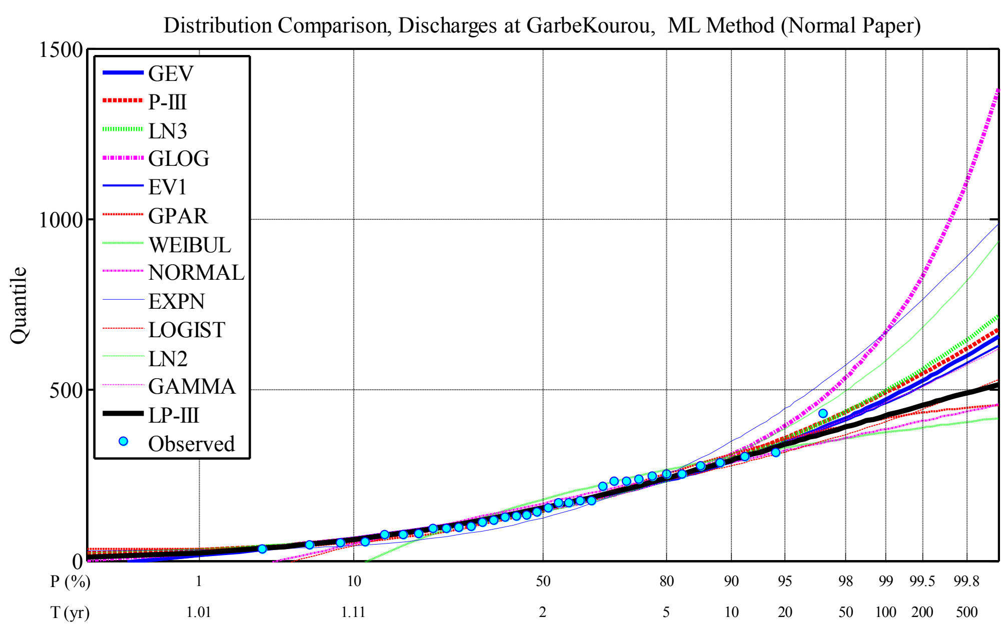

Fig. 9. Distribution comparison of 11 probability distributions for streamflow peaks at Garbé-Kourou

4.2.2 Copula analysis

The dependence between streamflows at Kandadji and Garbé-kourou was measured by calculating the rank correlation coefficients of Spearman and Kendall. These coefficients were 0.447 and 0.385 respectively.

To estimate the dependence parameter, the hypothesis of independence between the streamflows at Kandadji and Garbé-Kourou was tested using the Spearman and Kendall rank coefficients obtained. It was found on one hand for the Spearman coefficient that $\sqrt{(n-1)}|\rho_s| = 2.52 > 1.96\ (z_{\alpha/2})$, and on the other hand for the Kendall coefficient $\sqrt{\frac{9n(n-1)}{2(2n+5)}}|\tau| = 151.78 > 1.96\ (z_{\alpha/2})$. These values correspond to $z_{\alpha/2}$ at α=5% threshold. $z_{\alpha/2}$ was obtained from the table of Z-test at α=5%.

These values indicate that the hypothesis of independence between these two variables is to be rejected, thus there is dependence between these streamflows.

About the suitability of the copula, the data were transformed to the copula scale (unit square) using appropriate cumulative distribution function (CDF) to transform X (streamflows at Garbé-Kourou) to U and Y (streamflows at Kandadji) to V, so that U and V have values between 0 and 1. The best distribution for X is the generalized Pareto distribution, while Log-Pearson III distribution is the best distribution for Y. Fig. 10 shows a scatter-plot of the initial streamflows data of Kandadji and Garbé-Kourou, and Fig. 11 displays the transformed streamflows to unit in order to be fitted.

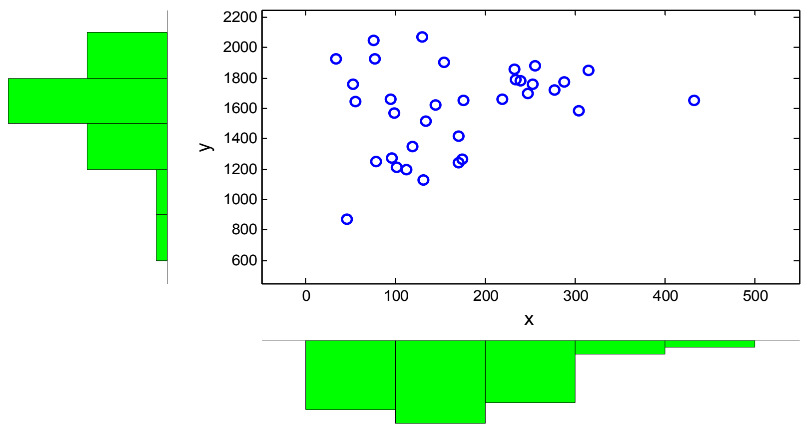

Fig. 10. Scatter plot of observed streamflows at Garbé-kourou (X) and Kandadji (Y)

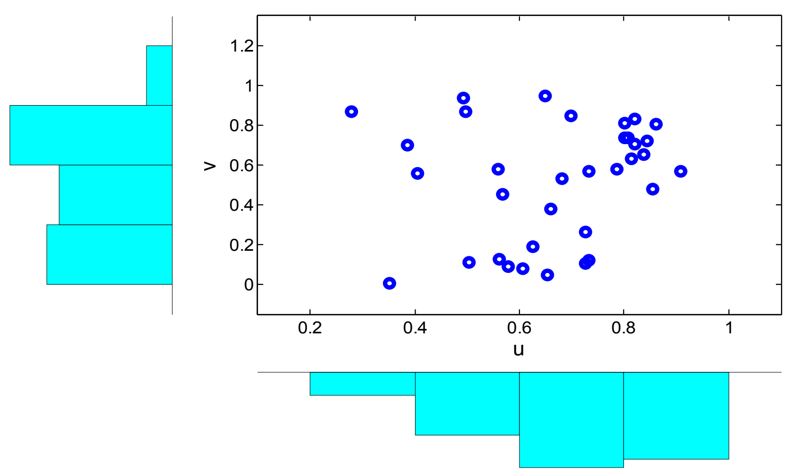

Fig. 11. Cumulative distributions of streamflows at Garbé-kourou (U) and Kandadji (V)

After transforming these data to unit, each of the five copulas was fitted to the obtained couple (U, V) by generating first a random sample from the corresponding copula (Usim, Vsim). Thereafter, using the appropriate inverse cumulative distribution function, the previous couple (Usim, Vsim) was transformed to Xsim, Ysim, so that to transform the random sample back to the original scale of data.

Figs. 12 to 16 present the fitted copula and the transformed copula back to the initial scale for t, Gaussian, Gumbel, Frank and Clayton copulas, respectively. It is observed on the lower panels of those figures that there is dependence between the streamflows. They also showed that the scatter plots are mostly located on the positive parts of the axes.

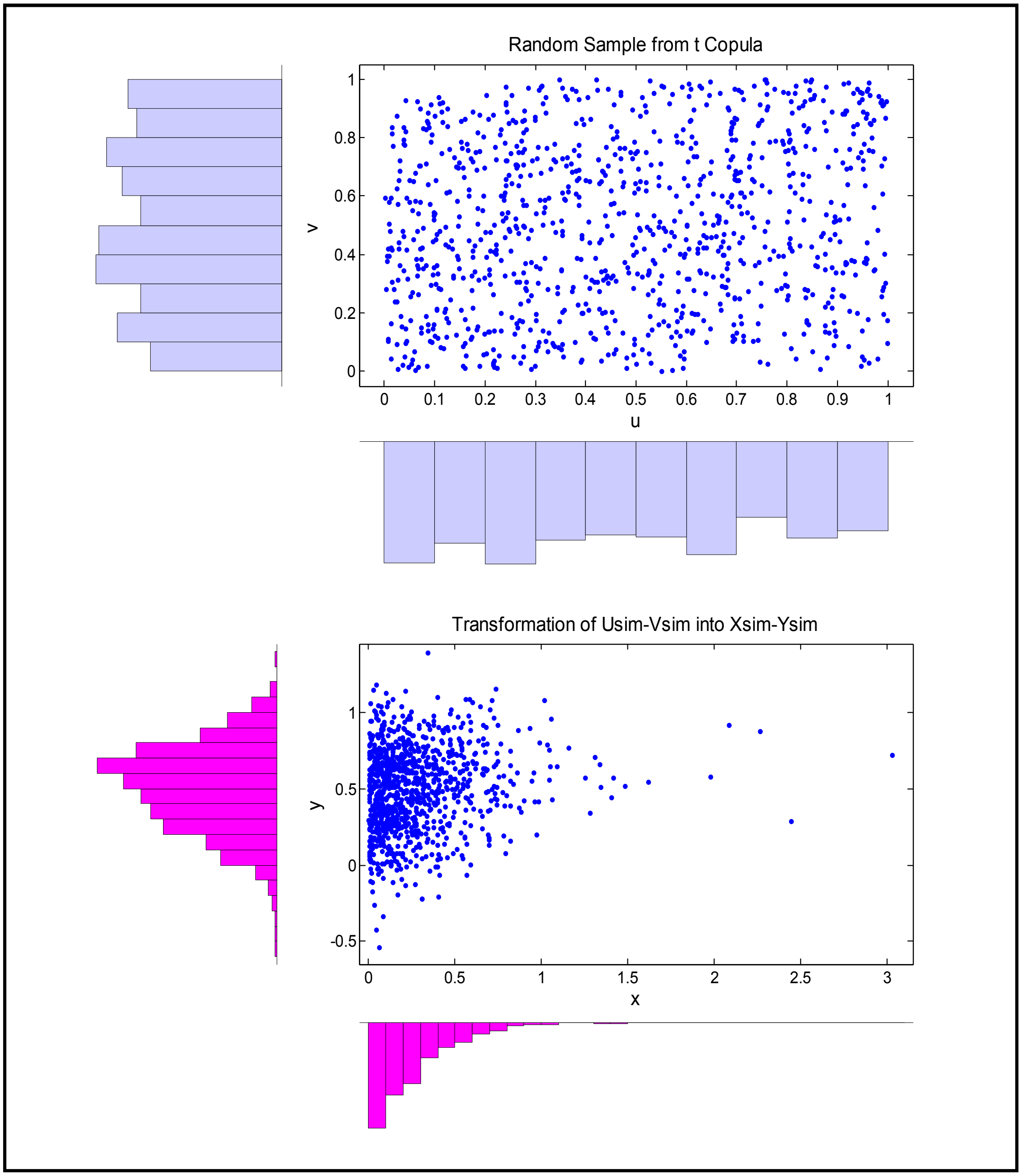

Fig. 12. Fitted *t* copula using random sample (upper panel) and transformed copula back to the initial scale (lower panel)

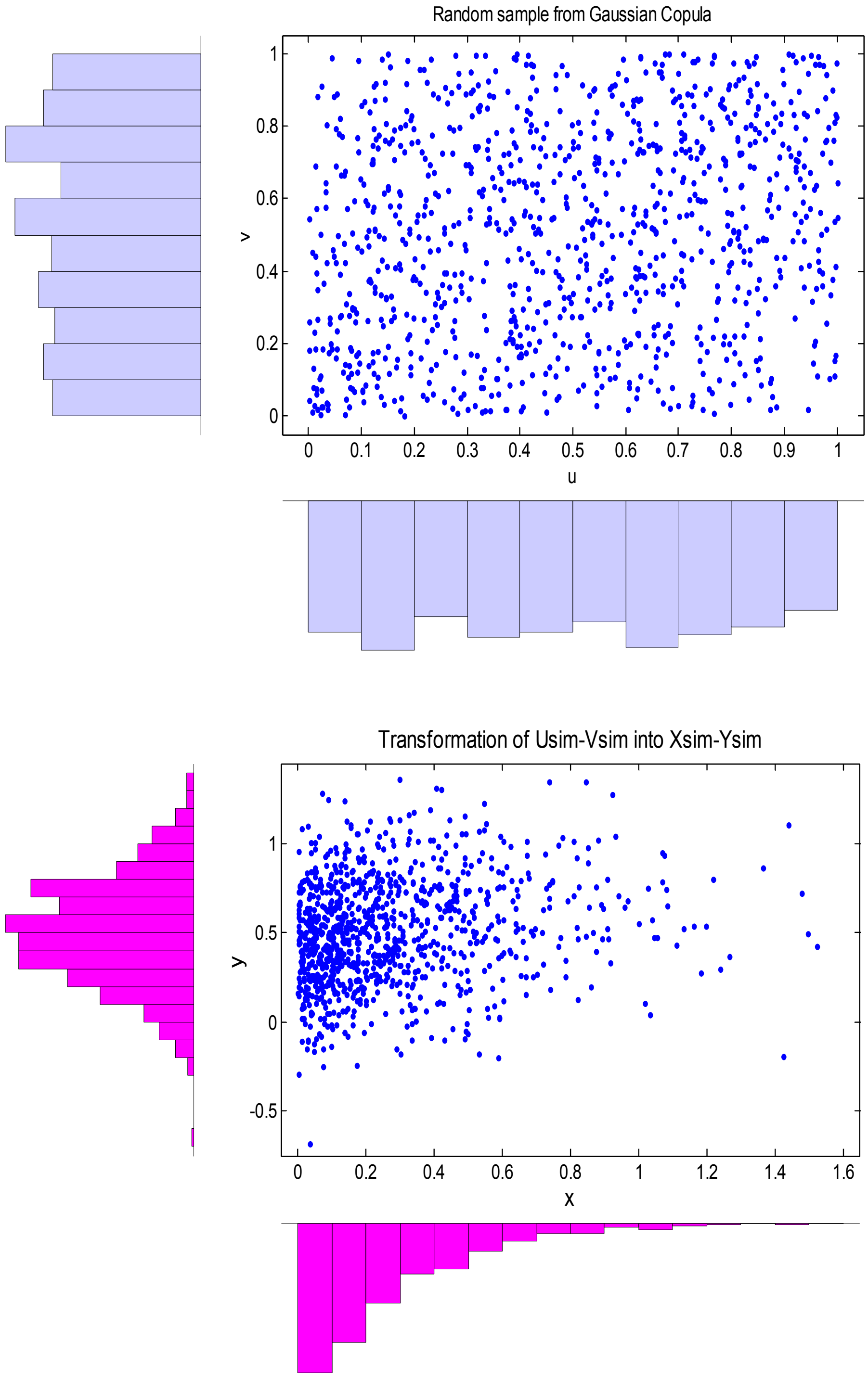

Fig. 13. Fitted Gaussian copula using random sample (upper panel) and transformed copula back to the initial scale (lower panel)

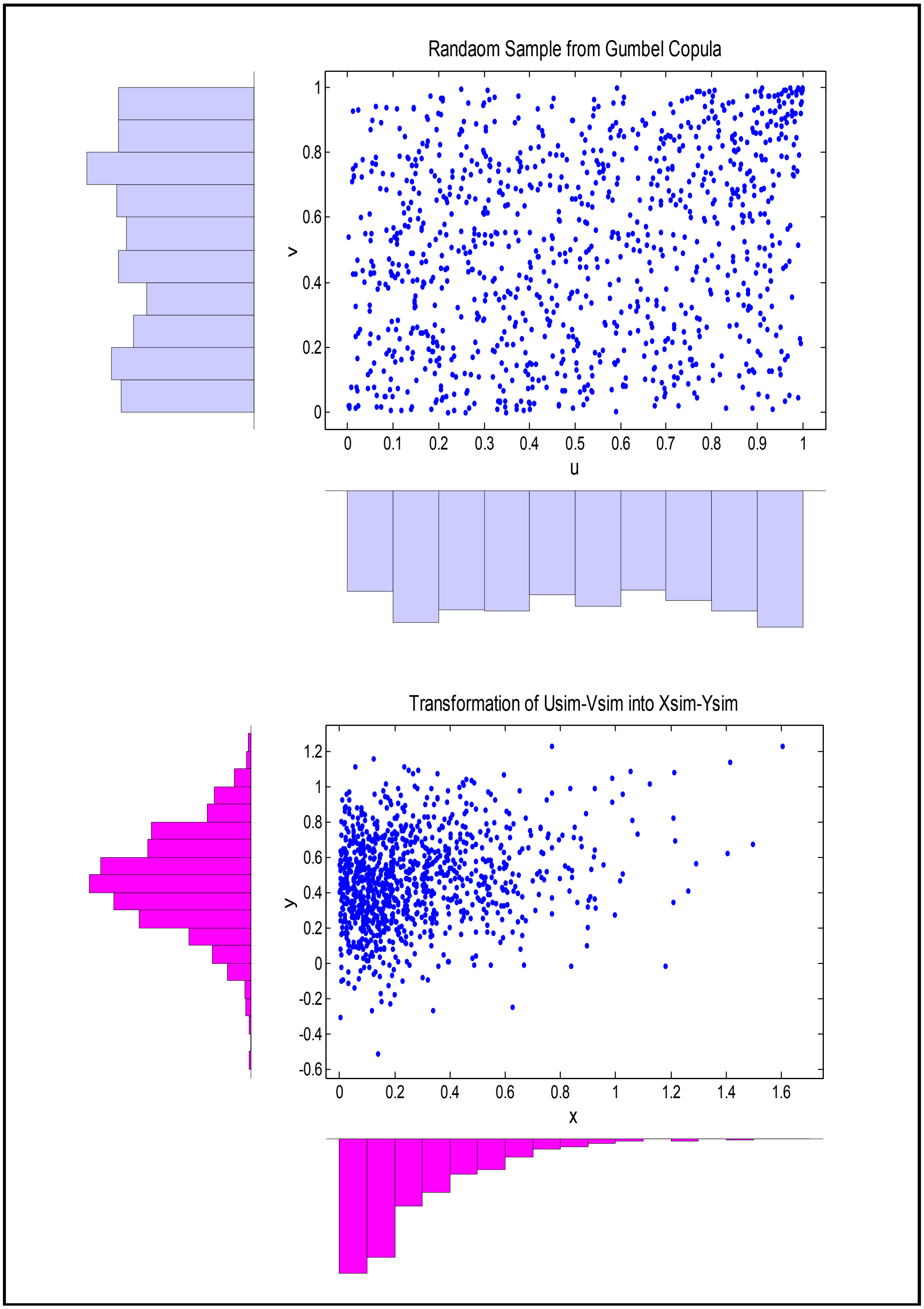

Fig. 14. Fitted Gumbel copula using random sample (upper panel) and transformed copula back to the initial scale (lower panel)

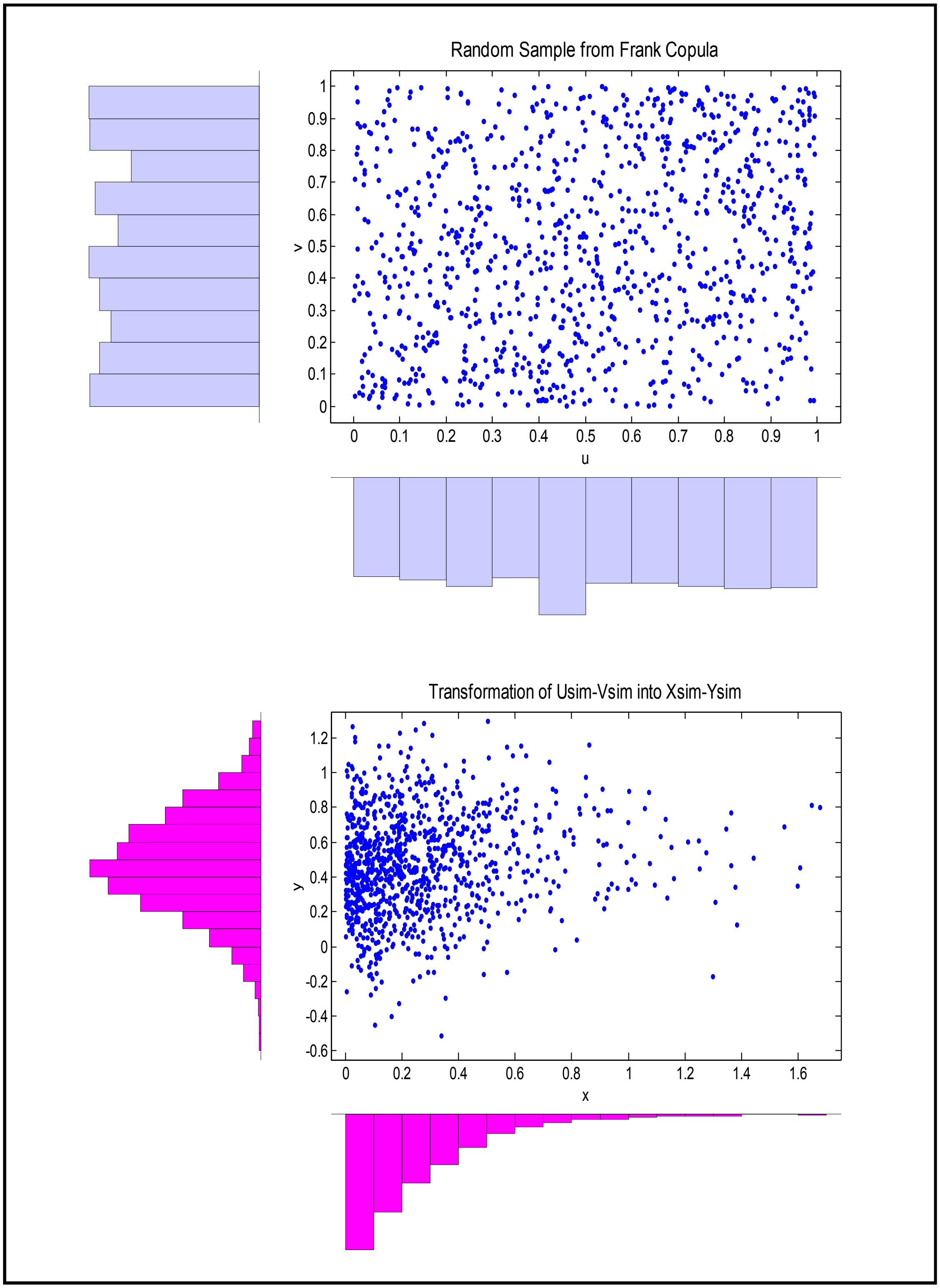

Fig. 15. Fitted Frank copula using random sample (upper panel) and transformed copula back to the initial scale (lower panel)

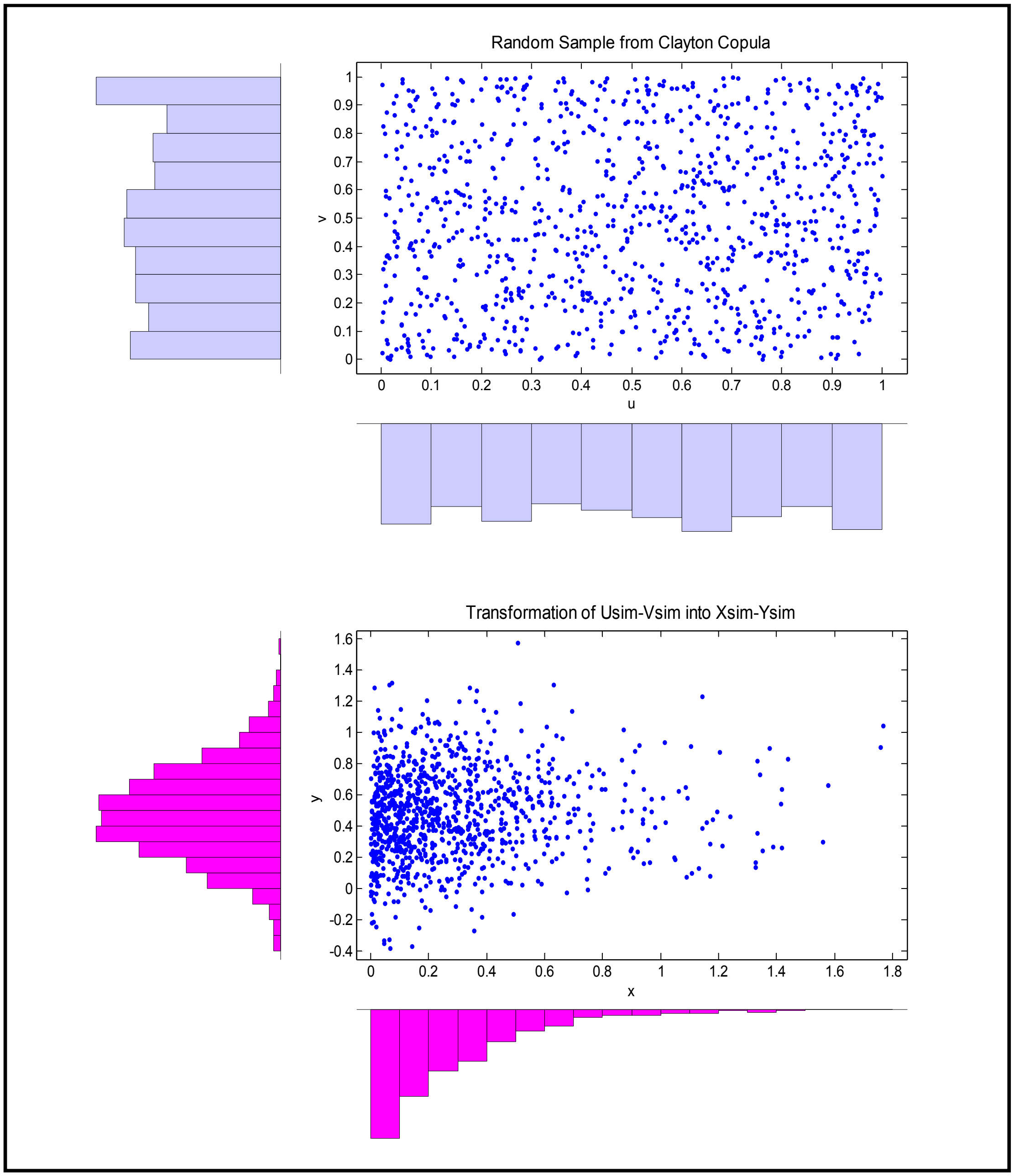

Fig. 16. Fitted Clayton copula using random sample (upper panel) and transformed copula back to the initial scale (lower panel)

The great difficulty is to choose the copula that best capture the dependency between data structures. To choose the copula that models the best observations, a comparison is made by a Kolmogorov-Smirnov. Therefore, the analysis of the 5 copulas based on the Kolmogorov-Smirnov test show that the Gumbel copula is the best as it has the lowest statistic value (0.0310) and highest p-value (0.7161) as shown in Table 2. Moreover, regarding the value of Spearman and Kendall rank coefficients, the Gumbel copula was found as the best with 0.71 and 0.80, respectively. However, the final selection was based on the QQ-plots (Fig. 17) as after resampling they allow ultimately to decide. Examining these figures, it is obvious that the Gumbel copula gives the best fitting compared to the remaining 4 copulas.

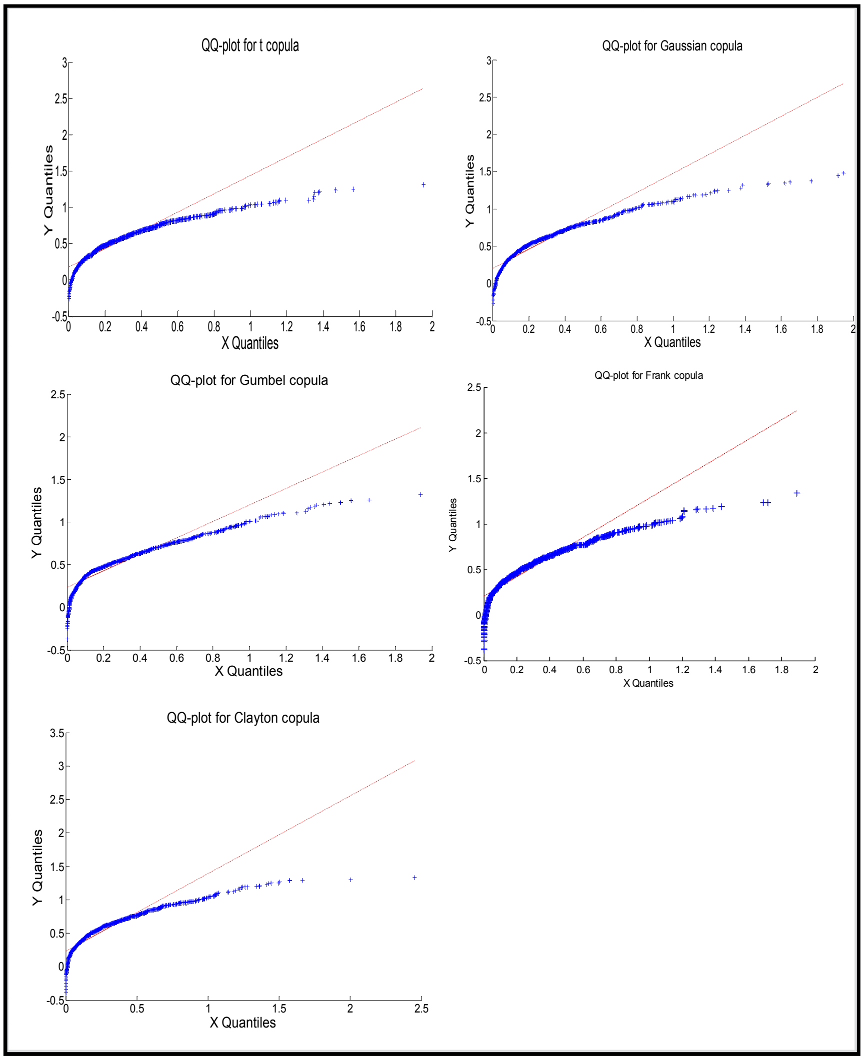

Fig. 17. QQ-plot for the five copulas

Table 2. Criteria table for the choice of copula

Copulas	Ks (test statistic)	Ks (p-value)	Spearman rank coefficient	Kendall rank coefficient	Dependence hypothesis (H)
t	0.0370	0.4931	0.15	0.6370	H_0 accepted (H=0)
Gaussian	0.0420	0.3344	0.22	0.1762	H_0 accepted (H=0)
Gumbel	0.0310	0.7161	0.71	0.80	H_0 accepted (H=0)
Frank	0.0620	0.0410	0.57	0.4567	H_0 rejected (H=1)
Clayton	0.0390	0.4253	0.14	0.7143	H_0 accepted (H=0)

4.3 Flood Risk Evaluation

After analyzing the floodplain, model results also indicate that the present protection system set in the Niger River at Niamey did not retain the floods throughout the sections of the city. It was observed that most of the dykes protecting the city of Niamey were overtopped by the different floods that occurred. The results also indicate that most of floods overtopped the levees reach on the upstream. However, it is noteworthy that in 1984 no dyke was endangered to be exceeded by the mean flow. For the six dykes, it is found that the probabilities of being overtopped by flows are very high (100% to 16.67 %) as shown in Table 3. For instance, the likelihood of exceeding these dikes show that the years 2010, and 2012 that experienced inundation events have flooding probabilities (66.7%, 33.3%) higher compared to other years. These results are in accordance with the period of high droughts experienced in the Sahel and with the wetting periods characterized by rainfall recovery in the region. Thus, two groups of years were found: the years of the great dryness with floods that do not overflow from the developments and the recent years of rainfall recovery with stronger intensities which generate floods with very high probability of having submerged irrigated lands.

These probabilities were obtained after running the hydro-dynamical model and considering the number of dykes (among the six) that each peak flow can overtop. These probabilities of overtopping the dykes explain the extent of the danger of floods at Niamey. However, these results may be improved by using more detailed topographic data, such as LIDAR (Light Detection and Ranging), in the future [50].

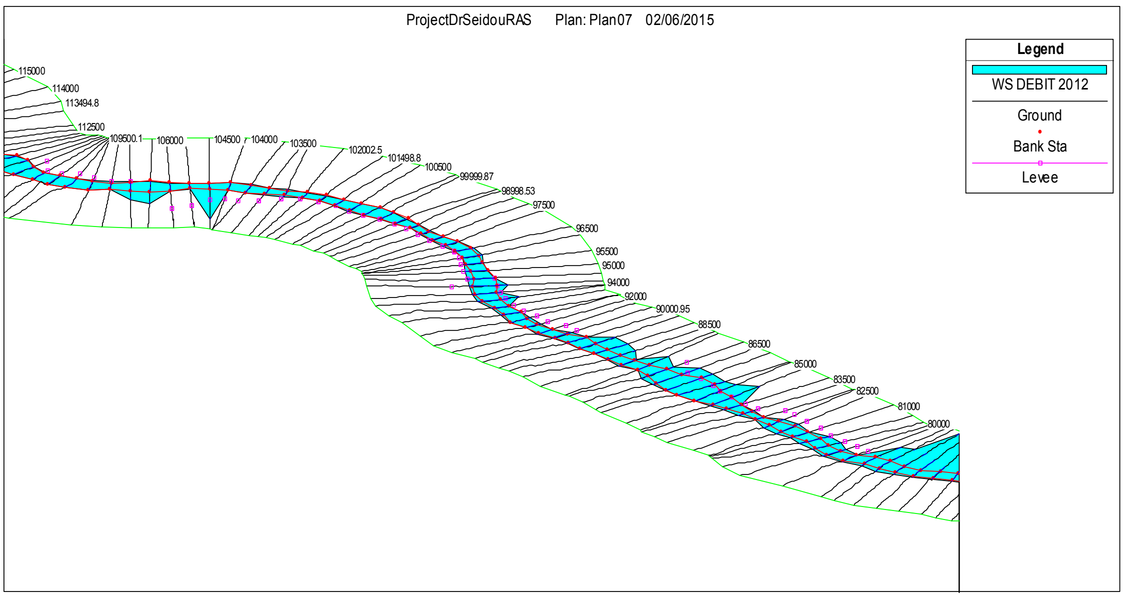

Fig. 18. Simulation of levees overtopping from the hydro-dynamical model of Niger River at Niamey

Fig. 19. Impact of flooding by overlaying the floodplain on Google Earth image of Niamey

Table 3. Probabilities of overtopping dykes for some specific yearly peak flows before August

Peak flows	Number of levees overtopped	Probability of levees to be overtopped (%)
1981	1	16.67
1984	0	0
1998	5	83.33
1999	4	66.67
2003	5	83.33
2010	6	100
2012	6	100

Fig. 18 shows an example of a floodplain generated from the Niger River HEC-RAS model based on the 2012 flows with the different cross sections. In Fig. 19 one can observe some agricultural areas and houses within the floodplain after its overlapping t over a GoogleEarth image of Niamey.

5. CONCLUSION

A seasonal flood forecast model was developed in this study for the city of Niamey. It involved the building up of a hydro-dynamical model of Niger River at Niamey based on HEC-RAS model and the use of a simple risk measure to calculate the probability of overtopping the flood protection dykes in Niamey. The results show that the seasonal forecast model reproduced well the rating curve over the period 2009-2014. The Gumbel copula was found to be the best among the 5 copulas after comparing them based on the Kolmogorov-Smirnov test and the QQ-plot. It showed that a dependency between streamflows at Kandadji and Garbé-Kourou based on the rank correlation coefficients of Spearman and Kendall coefficients. It is found that for the six dykes the probabilities of being overtopped by the flood are very high and varying from 100% to 16.67%. The next steps of this work in addition to the seasonal flood forecast model coupled to copula analysis is to carry out a probability risk assessment. This could constitute a good tool for decision makers in Niamey, and also be used to tackle the flood issue faced by several West African countries.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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