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FLOOD RISK REDUCTION THROUGH THE ASSESSMENT OF FLOOD FORECASTING SYSTEM IN THE UPPER NIGER RIVER BASIN IN MALI.

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DEDICATION

To my beloved Father who passed away just 2 months after the beginning of the 6-months coursework at University of Abomey-Calavi, Benin Republic.

To my beloved Mother

My Brothers and Sisters

This work is yours

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Abstract

This work was based on the issue of flood risk reduction through the assessment of a flood forecasting system. First of all, an overview of the flood forecasting system already implemented in Africa, especially in West Africa is carried out. Secondly, the trend analysis of flood events as well as their relationship with extreme rainfall is performed in Bamako. Thirdly, the hydrological models are calibrated and validated using the observed rainfall data. And lastly, the flood forecasting system is implemented in order to mitigate the coming floods in the study area. It allows the population to take necessary advances against floods, reducing considerably the flood impacts.

HBV, HEC-HMS, SWAT, WRF-Hydro are the hydrological models the most used for the flood forecasting issues in Africa.

From 1982 to 2019, the flood events historical trend in Bamako has increased as well as the flood victims. The extreme rainfall indices (RX1 day, RX5 day, R99P, PRCPTOT, CWD) show the same trend increasing during the same period 1982 to 2019. Therefore, a strong relationship between flood occurrences and extreme rainfall is identified. Most of the years where floods occurred in Bamako correspond to the years of high rainfall value, especially for the R99P. However, it has been observed that the rainfall responsible for flood in Bamako is approximatively 47mm, which is far from being exceptional. It is in the range of normal to severely abnormal classes; meaning that there are other causes that should be added to the extreme rainfall leading to flood events. Non-maintenance of channels, building houses on the way of the river-bed in addition to the soil destruction, could be considered as the major causes to be linked to the extreme rainfall.

The flood forecasting system was explored in the study area through two hydrological models HBV and HEC-HMS. Both of the models are well calibrated and validated with satisfactory model efficiency values for the four days ahead NCEP rainfall data. Nash values are respectively 0.74, 0.76, 0.71, 0.62 for the 24h, 48h, 72h, and 96h ahead precipitation during the calibration and 0.82, 0.84, 0.77 and 0.76 during the validation for the HEC-HMS model respectively for the 24h, 48h, 72h and 96h ahead precipitation. For the HBV hydrological model, Nash values for the calibration are respectively 0.67, 0.86, 0.83, 0.80 for 24h, 48h, 72h and, 96h. During the validation, Nash values are 0.78, 0.78, 0.83, 0.80 for respectively 24h, 48h, 72h and 96h ahead precipitation. This interesting finding confirms the suitability of these models to be used for the flood forecasting system in the area. PoD and FAR indices calculated, gave satisfactory results of NCEP center data, and more success than false alarm rate was obtained. The knowledge of the forecasted rainfall can allow a better management of the Selingue dam, reducing floods impact and producing sufficient energy for the population.

Key word: Flood forecasting system, extreme rainfall, hydrological models, Koulikoro watershed Selingue dam.

Résumé

Ce travail était basé sur le problème de risque d'inondation à travers la mise en place du système de prévision d'inondation. Premièrement une revue littéraire du système de prévision d'inondation déjà mis en place en Afrique spécialement en Afrique de l'Ouest est évalué. Deuxièmement, l'historique des inondations ainsi que leur relation avec les pluies extrêmes sont analysés à Bamako. Troisièmement, les modèles hydrologiques ont été calibrés et validés par les données observées de pluie. Le quatrième et dernier objectif était basé sur la mise en place du système de prévision d'inondation dans le but de réduire considérablement l'impact des inondations futures. Il permet à la population d'être avertie et de prendre des décisions nécessaires pour se mettre à l'abri des impacts d'inondation.

Les résultats ont montré que beaucoup restent à faire en Afrique pour l'amélioration de la mise en place des systèmes d'alerte précoce. Car la plupart de ces systèmes sont obsolètes et ont besoin d'être améliorés.

De 1982-2019, l'évolution des inondations est croissante et cette croissance va de pair avec l'augmentation du nombre de victimes. Les extrêmes d'indice de pluie ont été obtenus avec un package appelé RClimDex du logiciel R. A part CWD les quatre autres indices de pluie extrême montrent tous une évolution progressive. Aussi il a été établi que la pluie responsable des inondations à Bamako est loin d'être une pluie exceptionnelle ce qui signifie que d'autres causes doivent être associées aux pluies pour provoquer les inondations. Ces causes peuvent être la non-maintenance des caniveaux, la destruction du couvert végétal et donc du sol etc…

Le système d'alerte précoce a été mis en place à travers les modèles hydrologiques HBV et HEC-HMS. Ces deux modèles utilisés pour la mise en place du système d'alerte précoce ont pu calibrer les données observées sur le terrain ainsi que les données de pluies futures obtenues grâce au NCEP (Centre National de la prédiction Environnementale). De valeurs satisfaisantes de NASH ont été obtenues durant toutes ces phases de calibrations et de validations. La qualité de NCEP a été évaluée avec les indices de PoD et FAR qui ont tous confirmé le fait que NCEP soit assez bon pour fournir les pluies de futures pour calibrer les modèles hydrologiques dans le système de prévision d'inondation. Ce système de prévision doit être associé au barrage de Sélingue pour mieux contrôler et réduire les risques d'inondation dans la zone d'inondation.

Mots clés : Système d'alerte précoce des inondations, pluies extrêmes, modèles hydrologiques, bassin du Niger à Koulikoro, barrage de Sélingue.

Introduction

De nos jours, les inondations sont des catastrophes dévastatrices les plus récurrentes avec beaucoup de victimes aussi bien en vies humaines qu'en perte de matériels. Au Mali, pratiquement chaque année, les inondations font des dégâts énormes. Non seulement des pertes en vie humaine sont à déplorer mais en plus elles sont accompagnées de beaucoup de pertes de matériels. Ces victimes, par faute de logement, sont souvent logées dans des cours d'école avec des conditions de vie et d'hygiènes qui laissent à désirer. De ce fait, plusieurs maladies apparaissent avec les inondations et font souvent plus de mal que l'inondation elle-même de façon directe. Le changement climatique incontestable de nos jours, associé très souvent à l'occupation anarchique du sol ainsi que le blocage des lits de cour d'eau sont cités comme les véritables causes de ces inondations fréquentes. Il est donc plus qu'urgent de trouver une solution à ce fléau qui détruit et la vie humaine et l'économie du pays. Deux types de méthodes sont utilisées pour atténuer les effets et impacts des inondations. Il s'agit des méthodes structurelle et non-structurelle. Les méthodes structurelles sont des méthodes qui prônent la mise en place des dykes, des réservoirs pour atténuer et réduire considérablement le volume d'eau pouvant inonder la partie située à l'aval. Le problème de cette méthode est la non prévision des inondations à l'avance et donc impossible pour la population de prendre des précautions nécessaires en avance pour réduire les impacts de l'inondation. Pire encore, cette méthode pourra même donner de faux espoirs aux populations, leur faisant construire dans une zone à risque d'inondation ; les dégâts ne peuvent donc qu'être catastrophiques lorsque l'inondation ait lieu. La méthode non-structurelle est celle basée sur le processus de prévision d'inondation. Ce processus consiste à utiliser les modèles hydrologiques, les calibrer et les valider sur les données de prévision de pluie. Cette méthode a pour avantage de prédire les inondations probables à venir et donc permettre à la population de prendre des mesures nécessaires pour atténuer les impacts liés aux inondations. C'est dans ce but que cette méthode a été mise en place afin de soulager la population contre les effets des inondations.

Dans la partie supérieure du bassin du fleuve Niger, très peu d'études ont concerné les problèmes liés aux inondations encore moins le système de prévision des inondations. La plupart des études avaient trait à l'hydrologie du bassin, l'effet du changement climatique sur le débit, l'étude sur le changement et l'utilisation des terres etc... La présente étude est donc d'une nécessité importante pour un problème d'actualité. Les modèles hydrologiques HBV et HEC-HMS sont les deux modèles utilisés pour la mise en place du système de prévision d'inondation dans la zone d'étude. Tous les deux ont été calibrés et validés avec des valeurs intéressantes de NASH. La mise en place de ce système de prévision d'inondation permettra non seulement de réduire les impacts liés aux pertes en vies humaines mais également à la sauvegarde de l'économie du pays.

Données

Les données utilisées dans cette étude sont de différentes natures. Dans un premier temps, les articles sur le système de prévision des inondations ont été utilisés. Ensuite des données de pluie, de température allant de 1982 à 2019 ont été utilisées pour mener à bien l'étude sur l'historique des inondations à Bamako ainsi que leur lien avec des pluies extrêmes. Et enfin des données de prévision de pluie de 24h, 48h, 72h, et 96h, pour la période s'étalant de 1993 à 2013 ont été téléchargées sur le site web de Copernicus à travers le centre NCEP. Ces données sont importantes et nécessaires pour le processus du système de prévision d'inondation.

Zone d'étude

Le fleuve Niger est le troisième grand fleuve d'Afrique (après le Nil et le Congo), tant par sa longueur (4 200 km) que par la superficie de son bassin théorique (2 000 000 km^2) qui occupe le cœur de l'Afrique de l'Ouest et une partie de l'Afrique Centrale. Son bassin géographique comprend d'immenses zones désertiques avec de vastes vallées en cours de fossilisation. Le bassin du fleuve Niger couvre les territoires de 10 pays africains et dans les proportions suivantes : Algérie 3 %, Bénin 2 %, Burkina Faso 4 %, Cameroun 4 %, Côte d'Ivoire 1 %, Guinée 6%, Mali 25 %, Niger 22 %, Nigeria 32 %, Tchad 1 % (Tefera, 2015). Le fleuve Niger joue un rôle crucial dans les pays qu'il traverse. Il fournit aux populations riveraines croissant rapidement de précieuses ressources en poissons dont l'exploitation jusqu'à une date récente était soutenable. Les plaines inondées du Fleuve sont utilisées de manière extensive pour de la culture du riz, du coton et, dans la zone septentrionale, celle du blé. Le fleuve Niger prend sa source sur le versant Sud du Fouta Djallon en Guinée, une zone montagneuse dont le point culminant est d'environ 1 000 mètres. Au départ, le fleuve et ses principaux affluents dévalent des pentes abruptes. Ensuite, peu avant son entrée au Mali il devient navigable de Kouroussa à Bamako, avant de s'étaler en un Delta Intérieur à la bordure méridionale du Sahara. La moyenne de son volume annuel y compris celui de son affluent le Bani, tourne autour de 55 milliards de m^3 approximativement. La plaine inondée du fleuve à mesure que le Niger coule le long de la bordure du Sahara, couvre une superficie moyenne d'environ 20 000 à 30 000 km^2. Pays enclavé et continental situé au cœur de l'Afrique de l'Ouest, le Mali dispose d’un patrimoine naturel exceptionnel comme le fleuve Niger qui y parcourt 1 750 km sur une longueur totale estimée à 4 200 km. La portion malienne du bassin du Niger est évaluée à 570 000 km^2 soit 48 % de la superficie totale du pays. Le fleuve forme une vaste zone d'inondation au centre du pays avant de décrire une boucle à l'entrée de la zone subdésertique. Le fleuve et ses affluents arrosent totalement ou partiellement, six des huit régions administratives du pays et le District de Bamako.

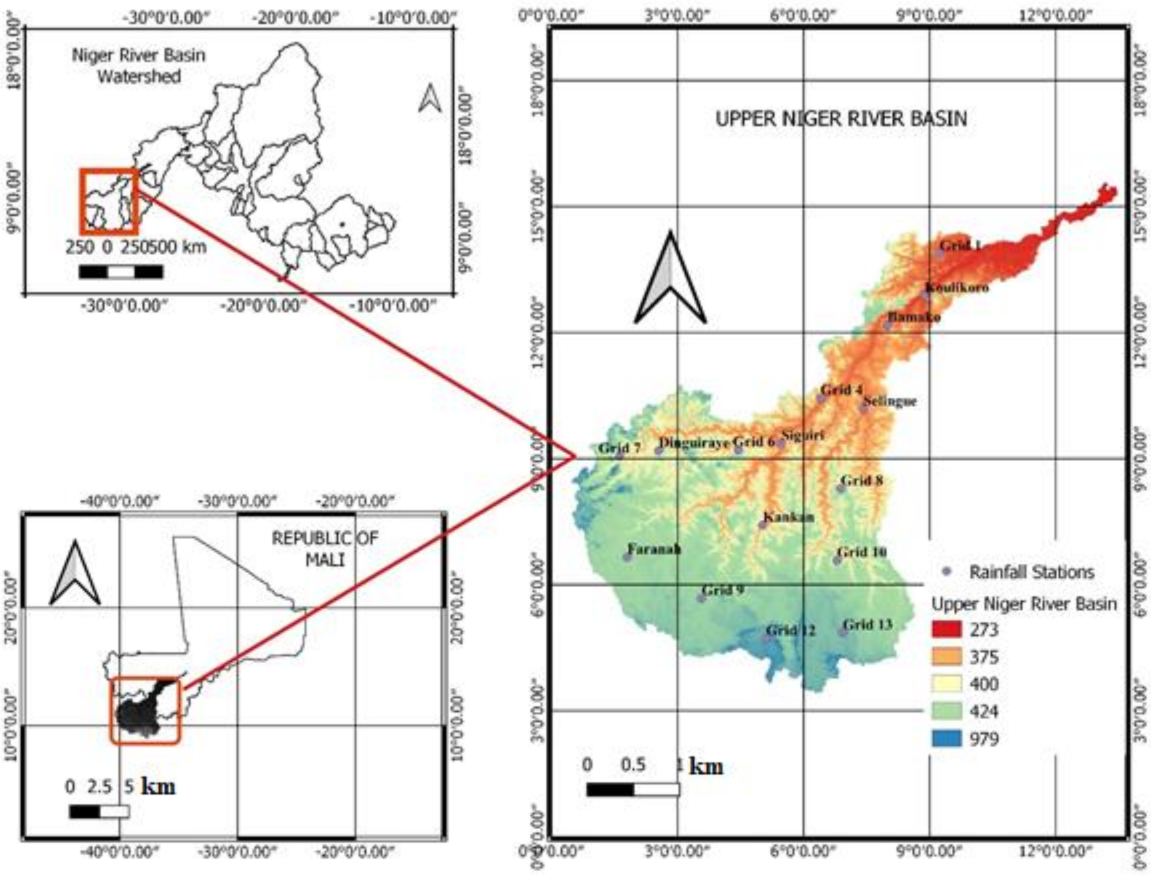

Figure 1 : La zone d'étude

Matériels et Méthodes

Pour que les objectifs fixés soient atteints, plusieurs matériels et méthodes ont été utilisés. Certains outils de recherche de documents scientifiques tels que Google scholar, Scopus ont été utilisés pour avoir des articles intéressants avec un facteur d'impact assez élevé. Ces articles ont été choisis selon leurs mots clés et en rapport direct avec le système de prévision d'inondation. Les articles traitent les problèmes liés aux inondations dans le monde, dans l'Afrique et plus particulièrement dans l'Afrique de l'Ouest. Certains de ces articles analysent les différentes méthodes utilisées pour lutter contre ou du moins réduire les effets et impacts liés aux inondations.

Les indices de pluie extrême ont été obtenus grâce à un package du logiciel R appelé RClimDex. Plusieurs indices sont inclus dans ce RClimDex, cependant juste cinq (5) sont utilisés pour cette étude. Au préalable, la non-stationnarité de ces données est analysée à travers le test de Pettitt, aussi l'analyse de tendance est faite avec Modified Mann-kendall. Le logiciel Hyfran-Plus est utilisé pour avoir les périodes de retour des inondations. Deux modèles hydrologiques pluie-débit HBV et HEC-HMS sont utilisés pour mettre en place un système de prévision d'inondation. Ces modèles sont utilisés sous la forme globale et ont été calibrés et validés avec les données observées dans un premier temps, ensuite recalibrés et revalidés par les données de Copernicus de prévision de pluie de 4 jours en avance.

Résultats et Discussions

Les résultats obtenus sont de diverses natures. Premièrement la revue littéraire a permis de connaitre les types de modèles hydrologiques utilisés en Afrique dans le domaine de la prévision des inondations. Aussi l'Afrique, malgré le fait qu'elle soit durement frappée par l'effet de l'inondation, semble ne pas être très avancée en matière de prévision d'inondation pour atténuer les impacts de celles-ci. Il a été observé aussi que la plupart des méthodes de prévision d'inondation en Afrique sont obsolètes et ont besoin d'être améliorées. Malgré les conséquences liées aux inondations, l'Afrique semble être en retard en ce qui concerne les modèles hydrologiques de réduction des impacts d'inondation. Cependant, quelques modèles déjà utilisés dans certains pays sont à noter. SWAT est utilisé au Sénégal, en Egypte, en Tanzanie, tandis que HEC-HMS est mis en place au Burundi, en Ethiopie en Egypte. Tefera en 2015 a utilisé le modèle HEC-HMS au Nigeria.

Les inondations à Bamako de 1982 à 2019 sont toutes liées à des pluies extrêmes. Tous les indices montrent une évolution positive exceptée CWD. Il existe donc un lien solide entre les pluies extrêmes et les inondations. Cependant, la plupart de ces pluies extrêmes, causant les inondations à Bamako, ne sont pas dans la classe des pluies exceptionnelles. Ce qui signifie que la pluie responsable pour l'inondation à Bamako n'est pas une pluie exceptionnelle, d'autres causes doivent être associées à ces pluies extrêmes pour provoquer les inondations. Les causes remarquées sont pour la plupart des causes liées au non entretien des caniveaux, au blocage des lits de fleuves ainsi qu'au changement de l'utilisation des terres associé à la dégradation du sol.

Sarr et Camara (2017) ont mis en exergue une diminution de la pluviométrie dans le Sahel. En même temps nous constatons une augmentation du débit dans la même région. C'est ce qui est appelé le « paradoxe du Sahel ». Larbi et al. 2018 ainsi que Sarr et Camara (2017) attestent dans leurs travaux de recherche une augmentation du débit respectivement au Ghana et au Sénégal. Cependant, Tazen et al. 2019 au Burkina Faso ont trouvé un résultat contraire. Les résultats de Tazen montrent une évolution négative des extrêmes d'indice de pluie. La relation entre les pluies extrêmes et les inondations, établie à Bamako, a été observée dans plusieurs pays notamment en Egypte et au Bangladesh respectivement par Nashwan et al. (2019) et Sarfaraz et al. (2019).

Deux modèles hydrologiques HBV et HEC-HMS ont été calibrés et validés avec de valeurs de NASH satisfaisantes. Ces mêmes modèles ont été à nouveau réutilisés dans le processus de prévision du système d'inondation. Les données de prévision de pluie du NCEP ont été utilisées pour recalibrer et revalider ces modèles hydrologiques. Des valeurs intéressantes de NASH obtenues, ont permis de conclure à la possibilité de ces modèles hydrologiques d'être utilisés comme des modèles de prévision d'inondation dans la zone d'étude. En Afrique les exemples de système de prévision d'inondation ne sont pas nombreux surtout en Afrique de l'Ouest. Cependant, certains auteurs ont mené des études intéressantes sur la prévision d'inondation notamment au Togo (Komi et al., 2017).

Conclusion

Ce travail traite les mécanismes de mise en place en vue de la réduction des risques d'inondation au Mali. La partie supérieure du Niger appelée Haut Niger est la partie où cette étude est localisée.

Quatre objectifs spécifiques majeurs ont été abordés dans cette étude. Le premier consistait à faire une revue de littérature en vue de voir les différents moyens de réduction des inondations à travers les modèles hydrologiques mis en place dans les pays de la sous-région. Il a été observé que l'Afrique est à son tout début en cette matière vue le nombre assez faible des modèles hydrologiques mis en place contre les inondations et cela malgré le taux élevé des cas d'inondations en Afrique. L'autre difficulté rencontrée est la non-volonté de partage des informations relatives aux questions d'inondations entre les pays transfrontaliers.

Le second objectif avait trait aux relations entre les extrêmes pluviométriques et la série d'inondations qui ont eu lieu dans le passé. Les résultats ont montré une nette corrélation positive entre les pluies extrêmes et les inondations à Bamako de 1982 à 2019. Cependant, les pluies extrêmes ne doivent être considérées comme les seules responsables de ces inondations car ce ne sont pas les pluies extrêmement fortes c'est à dire « exceptionnelles » qui sont responsables de ces inondations.

Les troisième et quatrième chapitres traitent les mécanismes de mise en place du système d'alerte précoce des inondations. Le troisième chapitre a consisté en la calibration et validation de deux modèles hydrologiques (HBV et HEC-HMS) avec les données d'observation de pluie, de débit et d'évapotranspiration. Le quatrième et dernier chapitre a vu la mise en place définitive du système d'alerte précoce d'inondation avec la calibration et validation à nouveau des dits modèles avec cette fois-ci des données de satellite de pluie du NCEP obtenues via un site de téléchargement des données satellitaires nommé COPERNICUS. Les données de 24h, 48h, 72h et 96h en avance ont été obtenues sur ce site dans la période allant de 1993 à 2013. La calibration avec ces données témoigne à suffisance la capacité pour ces modèles d'être utilisés pour un travail similaire dans la même zone d'étude avec des données de pluie future (24h, 48h, 72h, 96h etc…en avance) du même site, ce qui permettra d'avoir une idée claire de probables inondations à venir dans un future très proche. La connaissance de cette information est capitale pour sauver et les personnes et leurs biens des catastrophes liées aux inondations.

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List of acronyms and abbreviations
UNDP: United Nations Development Program

NRB: Niger River Basin

UNRB: Upper Niger River Basin

HEC-HMS: Hydrologic Engineer Center Hydrologic Modelling System

HBV: Hydrologiska Byrans Vattenbalansavalelning

SWAT: Soil and Water Assessment Tool

NCEP: National Center for Environmental Prediction

WAM: West African Monsoon

ITCZ: Intertropical Convergence Zone

IND: Inner Niger Delta

WWAP: World Water Assessment Program
CHIRPS: Climate Hazards Groups InfraRed Precipitation with Station data

PoD: Probability of detection

FAR: False Alarm Rate

CSI: Critical Success Indices
RX1: Annual maximum 1-day rainfall
RX5: Annual maximum 5-day rainfall
R99P: Annual number of extremely wet day with rainfall amount greater than 99th percentile
CWD: Cumulative wet day
TX10: Cool day frequency
TX90: Warm day frequency
TN10: Cool night frequency
TN90: Warm night frequency
WSDI: Warm spells
ETCCDMI: Expert team for climate change detection monitoring and indices.
FFWS: Flood forecasting and warning system
FFS: Flood forecasting system
WRF-Hydro: Weather Research and Forecasting Hydrological model
SWAT: Soil water assessment and tool
WMO: World meteorological organization

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CHAPTER 1: GENERAL INTRODUCTION

This chapter presents the context-problem statement and literature review in sections 1 and 2 respectively. Research questions and objectives are detailed in the sections 3 and 4. The sections 5, 6 and 7 present the hypothesis of the objectives, the novelty and the scope of the thesis respectively. The expected results and the outline of the thesis end this chapter.

1.1. CONTEXT AND PROBLEM STATEMENT

With climate change, flood occurrences are more frequent nowadays in Africa in general and in Mali, a West African country, in particular. Damages to the populations related to flood basically in terms of loss of human live, economical loss, infrastructure destruction, school shutdown, etc. are jeopardizing the livelihood of the affected populations. What are the best ways to avoid and minimize flood risks, and its associated damages? The current study is undertaken to investigate the causes of the flooding in Bamako and propose ways to reducing the risk and alleviating the sufferance of the exposed populations.

The damages suffered by the populations at each flood occurrence in Mali are terrible. The exposed populations faced issues such as displacements, diseases, properties loss and deaths. Schools are therefore used as shelters with all its consequences (school shutdown, unsanitary conditions, sexual aggressions, violence on women and children, health issues, etc.). The problem of relocation of these victims will appear at each time of flooding, most of the time the resume of school will be delayed because of the occupation of the classrooms by flood victims. The spread of diseases throughout the whole country will occur quickly, enhancing the number of deaths. Mali has a weak capacity to cope with these concerns. The economic impacts are part of the flood events consequences that are very damageable for the whole country. For a country with a weak economy, these losses will increase the economic impacts. When floods occur, lot of important materials are lost. A lot of infrastructures, hospitals, schools, roads, are destroyed. A country like Mali regularly hit by floods, associated by catastrophes like deaths, diseases, losses of persons; it is unfortunate that there is any study that has been done on this topic for the best of our knowledge. Thus, it is more urgent that scientists decide to deeply study this problem of flood especially in Mali a country which is more vulnerable due to its weak mean of adaptation. Flood can be considered when the level of water overflows its normal channel, entering a new land of crop or habitat (Hounkpe, 2016). This event is proved to be natural phenomenon (generally due to the climate change), but nowadays, its frequency appearance and high magnitude are caused by the implication of human activities. The environment impact is important to point it out because according to many authors, the climate change will continue and so its impact especially on floods. It has been demonstrated by some authors that the intensity as well as the magnitude of the climate are supposed to increase (CRED, 2012; Ntajal et al., 2017).

Flood is the most devastating hydro-meteorological hazards worldwide which affects people life socio-economic and ecological system. Flood hazards are the most common and destructive of all disasters and are a constant threat to life and property. European commission perceived flood risk as the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment cultural heritage and economic activity associated with a flood event (Ntajal, et al. 2017). Floods are one of the most common and widely distributed natural risks to life and property. Damage caused by floods on a global scale has been significant in recent decades (Jonkman and Vrijling, 2008). In 2011, floods were reported to be the third most common disaster, after earthquake and tsunami, with 5202 deaths and affecting millions of people (CRED,2012). River, coastal, and flash floods can claim human lives, destroy properties, damage economies, make fertile land unusable and damage the environment. Flood is causing damage everywhere it occurs, but it is also obvious that the damages caused in Africa are higher than the ones noticed in developed countries due to their capacity to cope with it. Many economic activities can be affected by flooding events, among them are agriculture, fisheries, navigation, power production, industries, etc. The loss of these activities can influence the economic prosperity of a community region or a country. That is why in the view of reducing the damage of flood, the implementation of flood forecasting models as well as flood hazard map is useful. The objective of flood hazard map is to provide to the population with the information on the range of possible damage and the disaster prevention activities. The effective use of hazard map can decrease the magnitude of disaster. Most of the studies done in the study area were related to the flow dynamic, flow regime, climate change and its impact on the flow dynamic in the Niger River Basin. Very few literatures related on flood issues were available. This study comes to fill the gap and help the population to better cope with this issue by implementing the hydrological model in the process of flood forecasting system.

1.2.LITERATURE REVIEW

Flooding is among the most devastating events in the world occurring regularly with high intensity and magnitude. The impacts noticed in Africa are more catastrophic because of the weak means of adaptation in comparison to the remaining part of the world. Climate change is the central point of this event. Many authors published a lot of papers about the reality of the climate change, especially the impacts which may occur (Aich et al., 2016; Mahe et al., 2005, Mariko et al.,2003, Al-Gamal et al., 2009, Andersen 2005; Wilcox et al. 2018). Between 1985 and 2005, over 112000 people lost their life and more than 354 million were affected with approximately 520 billion euros in financial damages (Thiemig et al. 2011). According to United Nations Development Program (2004), almost 200 million of people in more than 90 countries are exposed to catastrophic flood events every year. Kundzewicz (2008) argued the increasing of the flood events occurring in the future due to climate change and the steady increase of population as well as of urbanization. It was noticed in Africa during the last years, the increasing of the occurrence of severe flood events affecting millions of people and hampering economic development in the region, exerting enormous pressure on the affected countries (Thiemig et al. 2011). The climate change which is increasing everywhere in the world is to be the main factor leading to the flood. Because of the climate change, a change in rainfall frequency and intensity which leads to the flood become frequent. According to the studies carried out by Mahe et al. (2005) in the Upper Niger River Basin, the trend of rainfall has not been clarified but the rainy season July, August, September are the months in which there is an intense quantity of precipitation. Considerable effort has been put into the mitigation of flood-induced damages in Africa over the last decade. During this period, several number of institutions and research dedicated to dealing with flood management have increased everywhere in Africa. Lot of number of floods have been recorded during the last decade in comparison to those observed in the last 50 to 60 years ago (Mahe et al. 2005). Very few studies regarding to the extreme rainfall have been done in Mali. As already cited above, for a such crucial and important phenomenon, few documents are available concerning the flooding in Mali.

Aich et al. (2016) led a study based on the time series analysis of flood across the Niger River Basin. They found out a consistency between the annual maximum discharge (AMAX) and the climatic decadal pattern. Among the three sub-regions concerned by the study, the Sahelian showed an unstable AMAX meaning the difference existing between the flood behavior among the three regions, Sahelian presenting the mostly affected area by flood. The Inner Niger Delta has delayed the timing of flood in the downstream because of the retention processes. The entire basin presents a positive trend of the statistics damage since the beginning of 1980s; with the Middle Niger being the area the most affected.

The impact of climate change on streamflow in four large African River Basins (Niger River, Upper Blue Nile River, Limpopo River and Oubangui River) has been carried out (Aich et al., 2014). Despite the uncertainty, the impact of climate change is noticeable in discharge both mean and extreme high and low. The Niger river and Limpopo showed the highest magnitude of trends. For the temperature, all the models agree on the concept of its rising over the whole continent. The

Niger River Basin (NRB) and the Limpopo are located in this area of the most extreme temperature increase. The model agreement for the precipitation is much lower. A negative precipitation trend in the headwaters in the West of the River and a positive precipitation trend in the eastern part of the River are the divided areas of the Niger River according to the repartition of the precipitation trend. The NRB shows a higher discharge sensitivity of climate change. An increase of 25% of precipitation results in approximatively 90% of discharge increase while almost 50% annual discharge decrease corresponds to the 25% precipitation decrease (Aich et al., 2014).

The increase in the annual maxima of daily rainfall is more attributable to stronger storm intensities 80% than to more frequent storm occurrences 20% (Chagnaud et al., 2022).

Generally, the dry areas of Sahelian and Sudanian are more sensitive to the climatic and land use changes, with high flood events probability occurrences. A scenario with continuing transformation of natural vegetation into agricultural land and urbanization intensifies the flood risk in all parts of the NRB, while a “regreening” scenario can reduce flood magnitude to some existent. The effect of climate change impact has been more important than the land use changes impact (Aich et al., 2016).

Liersch et al., (2019) carried out a study in the Upper Niger River Basin based on the water resources planning. They highlighted the need of Mali and Guinea to build new dams for the hydropower and irrigation purposes in order to meet population need. 7% corresponding to the irrigation demand may increase to one third in 2045. Despite the construction of new dams such as Fomi and Moussako, the irrigation demand for the 2045 would not be satisfied but at least the gap can be reduced from 36 to 14%. The implementation of these dams will not be without any consequence in the River. It will reduce by 40% the discharge, consequently the inundated area of the Inner Niger Delta will be reduced by 21%.

The Niger River, with its 1700km in Mali for a total of 4200km, is a natural inheritance for Mali, a country located in the central part of the West Africa. The Niger River in Mali covers an area of 570000 km^2, 48% of the total area of Mali. The river crosses six regions in Mali plus the capital Bamako.

The Niger River basin has a great importance in West Africa for many reasons. It is the river which crosses 10 countries in Africa and lot of activities are occurring inside this basin to support the economy of these countries. Important natural resources are located in the area where the river crosses through. Mali, one of these countries crossed by the NRB, is greatly dependent on it because of the fact that its economy, mainly based on agriculture, livestock and fishing are related to these natural resources. According to the FAO, the most part of the NRB is located in Nigeria (25.7%), Mali (25.5%), and Niger (24.8%). According to Mahe et al. (2005), the NRB evolution of flow is as follow: from 1920-1950, that is the period of high flow in Niger River basin, the 1960 period was underlined by the beginning of the flow drop. From 1970, an important flow drop record in the whole West Africa has been noticed (Mahe, et al., 2005). The flow increasing in

Sahelian region is due to the surface state regarding especially to the augmentation of the crop areas and bare soils against the natural vegetation areas (Mahe et al., 2005) and also to the increasing of the fast runoff (Descroix et al., 2009). The drought period of 1970 modified considerably the river flow at all stations. Since 40 years, the NRB brings less amount of water in the Sahel areas; however, this Sahel produces more due to the fact of the soil surface degradation (Mahe et al., 2005). The regional climate evolution should continue to modify the river hydrodynamic. However, it seems that the coming arrangements especially on the upstream of the basin will impact seriously the flooding of the Inner Delta of NRB (Mahe et al., 2005). Mahe (2005) demonstrated that the years 1993 has been a typical dry period (728 m3/s) and the year 1994 has been the wet year (1445 m3/s), while the yearly average is in the order of 1000 m^3/s. The tremendous difference in monthly discharge between the dry season (December-July) and the wet season (August-November) is evident.

In Mali there are four climatic zones in the basin area and rainfall ranges from 1500 mm in the south to less than 50 mm in the north. The water in the Niger River is partially regulated through dams. The Sélingué dam on the Sankarani River, built in 1982, is mainly used for hydropower generation, but also allows the irrigation of about 60,000 ha under double cropping. Two diversion dams, one at Sotuba in the city of Bamako, and one at Markala, just downstream of Ségou, are used to irrigate the area of the Office du Niger (equipped area of about 54,000 ha) (Mahe et al., 2005). The flood when it occurs in Koulikoro watershed, can have devastating damages in the downstream. The main city affected is Bamako, it is becoming each year. Lot of people are affected and the poorer people are the most important. There are a lot who will stay homeless after the events, the government by default of relocation will locate them in the classrooms with bad dirty of life conditions. The infrastructures damaged are important and in most of the cases, the roads are not usable leading to a huge traffic. According to the population one of the causes is the non-maintenance of the gutters, the non-maintenance of the infrastructures and also the random building of houses in the river bank.

1.2.1. Climate

Tropical climate is the climate of the basin in Mali through which annual rainfall varies from less than 200mm in the North to more than 1100mm in the South. Dry climate extends from 5 months in the South part to 9 months in the North. Winter climate begins from April-May and ends in October-November.

Four agro-ecological areas from South to the North are determined by the annual height of the rainfall as well as the seasonal duration of rainfall.

- Guinea-soudanian area annual rainfall of 1100mm located in Sikasso, the Upper Niger River, 8 months of rainfall occur in this area.
- Soudanian area located from Bamako to Segou, the annual rainfall varies from 1100 to 600mm with 6 months of rainfall from Mai to October.

- The Sahelian area located in Mopti, it is recognized by Inner Niger Delta area. The annual rainfall varies from 600 to 200mm with just 3 months of rainfall.
- The extreme Sahelian or desert area with an annual rainfall less than 100mm and just 2 months of rainfall is located in extreme Northern part of Mali, Tombouctou.

Since 1970, African continent suffers a rainfall deficit that has had lot of damages in the hydrology of some rivers.

1.2.2. Flood history in Africa

Floods are one of the catastrophes with regular occurrences, that affect many regions around the world, damaging properties and economies, harming human health and causing losses of life. Dilley et al. (2005) reported that more than one-third of the world's land area is prone to flooding affecting 82% of the global population. According to EM-DAT (2015), floods are responsible of nearly half of the deaths and one-third of all economic losses. The twentieth century has been hit by more than 5000 major hydrological disasters in the world where 3.5 billion people were affected, 7 million of persons lost life and around $650 billion USD of economic losses (CRED, 2014). All major natural disasters combined, flood-related disasters alone are responsible of 22% of total deaths, 24% of total economic losses and 51% of the total people are suffering of flood impact. According to Alfieri et al. (2014), 54 millions of people in the World are exposed to yearly river flood. ICHARM (2009) reported that during the period of 1900-2006, floods accounted for about 30% of the total number of natural disasters, 19% of the total fatalities and more than 48% of the total number of people affected. Out of the 72% of the total economic damages caused by the natural disasters, 26% of the damages were flood related (ICHARMv, 2009). According to the international disaster database, flood occurs more frequently than all other types of natural hazards across the globe and accounts for 39% of all disasters arising from natural hazards since 2000 with 94 million people affected every year in the world. In its 2008 note, UNESCO stated that half of the deaths and nearly one-third of all economic losses from natural hazards worldwide are due to floods. Africa is the third continent the most affected by flood after Asia and Europe. The climate change along with the urbanization and an increasing African population, make flood risks certain to occur frequently. The reliability to forecasting has increased in the recent years due to the integration of meteorological and hydrological modeling capabilities, improvements in data collection through satellite observations, and advancements in knowledge and algorithms for analysis and communication of uncertainties. Climate change and the steady increase in the population as well as the urbanization, land use change, deforestation, sea level rise, population growth in the flood-prone area will increase the number of vulnerable people to flood disasters up to two billion in 2050 as the flood occurrence is going to increase in the future (Kundzewicz, 2008, Bogardi, 2004; ICHARM, 2009; Vogel et al., 2011).

Floods happen generally when there is a heavy rain associated with severe thunderstorms, hurricanes, tropical storms enhanced by melted ice, and glaciers water or snow water flowing over ice sheets or snowfields. It appears in geomorphological low-lying areas. The extreme rainfall in addition to the reduced water-holding capacity of the soil are the main origin of more severe floods in Sahelian countries (Descroix et al. 2018; Mahe et al. 2005). The conversion of the savannah into cereals fields, forest destruction for farming, trees cutting down for firewood in addition to the transformation of flood-prone area to new human settlements due to the population growth are the major causes of the occurrence of flood, leading to increase catastrophic flood impacts (Tiepolo and Tarchiani 2016; Foriollo et al. 2017).

West Africa is one of the regions the most negatively impacted by flood events. According to EM-DAT, Africa comes just after Asia and Europe, in terms of human life losses due to flood events. However, due to its weak means of recovery, Africa is severely affected by the flood events. According to OCHA (2020), in West and Central Africa, 465 people lost life because of flood, 1.7 million of people were touched, 94000 displaced and 152000 people stayed houseless. The densely populated low-and middle-income countries where exposure and vulnerability are the highest, are the places where flood victims are important and located (Dottori et al. 2018; UNISDR & CRED 2015). In Africa, the majority of the countries hit by the flood are located in the Eastern part, Nigeria being the exception. Some Arabian countries are severely impacted by the flood events. Researches showed that the issue of flood will continue to increase both in frequency and magnitude (Nka et al.,2015; Ntajal et al., 2017). These losses are expected to increase in the future due to the climate change, land use change, deforestation, rising sea level and population growth in flood-prone areas leading to two billion by 2050 the number of vulnerable people to flood disasters in the world (Bogardi 2004, ICHARM 2009, Vogel et al., 2011).

Many researchers link the causes of floods to climate change attributed to the anthropogenic actions such as urbanization, and land use change. Because of these causes, it is obvious that flood events are expected to occur more frequently in the future as well the damages associated to it.

1.2.3. Hydrological modelling for flood purposes

In order to alleviate, mitigate and adapt to the flood events, there are some solutions that have to be put in practice. These solutions, when implemented and applied, can give accurate, timely, precise and understandable forecast information, alerts, and may help to reduce the flood impacts (Perera et al., 2019). Structural and non-structural methods are the widely methods used for the flood adaptation. The structural methods such as Dam, levees and embankments allow sometimes to adapt flood events by reducing the water level. However, the main issues will be the maintenance cost of these infrastructures and also their incapacity to stand the coming floods in the future. The structural methods against flood issues can be misleading to users, because it gives hope to population to build in the flood prone area and develop their activities at these places (Haile et al. 2013a). In fact, just 25 to 55% of reduction in flood damages are noticed when the structural methods are implemented (Bubeck et al., 2012, Kreibich et al., 2005; Kreibich and Thieken, 2009). The non-structural methods are the ones that are currently used by the hydrologists; it is based on the flood forecasting through hydrological models. Non-structural measures provide more reversible and less-expensive mechanisms to reduce flood risk than structural actions (DiFrancesco and Tullos 2014). The non-structural methods are not only the most effective in term of flood risk management measures, but also the methods with an important accuracy and increased amount of flood damages reduction (UNISDR, 2004) in addition to more reversible and less-expensive mechanisms to reduce flood damages (Di Francesco and Tullo, 2014). The implementation of flood forecasting and early warning systems, the building of population awareness and preparedness, urban planning, discouraging human settlements in flood-prone areas and the development of local institutional capacities as well as forecasting methods development should be appropriate actions to carry out. The flood prediction models are very important due to their ability to provide the forecasted data from short-term to long-term depending on the need. The importance of advanced systems for short-term and long-term prediction for flood and other hydrological events is strongly emphasized to alleviate damages (Pitt, 2008). However, because of the climate condition and nature dynamic, the prediction of flood lead time and occurrence location is complex to do. Floods modeling and forecasting are useful to manage and prepare for the extreme flood events. The World Meteorological Organization stated that due to the improved flood forecasting models, there is an important decrease in the number of losses of life, however, economic losses have increased over the past 50 years.

The accuracy of flood forecasting depends on the quality of meteorological forecast and on the performance of the hydrological model. Meteorological models are designed to mimic water and energy cycles in the atmosphere and land. Hydrological models are designed to emulate water and energy cycles that occur over and within the land surface (Roundy et al. 2019). The outputs of the meteorological models are used to force the hydrological models. Various hydrological models are currently used to forecast flooding events. Two main types of models are widely used worldwide: deterministic/stochastic and data driven models. In Africa, several studies have been done using deterministic models for flood forecasting issues. The physical models required lot of input data associated, making its use complicated while data driven models required less data and there is no need for physical equations and parameters, or catchment characteristics leading to the static of the model which cannot evaluate the changes such as land use land change (Quenum et al. 2022). Despite the impacts and catastrophes induced by flood, West Africa is unfortunately not well documented in that topic. For the best of our ability, the hydrological models used in West Africa are not very important and no one exists in Mali. However, the mostly models used for the purposes of flood forecasting are HEC-HMS, HBV, SWAT, WRH-Hydro. The importance of these models are their ability to predict the floods allowing to reduce the damages of flood events, especially in terms of losses of life.

1.3.RESEARCH QUESTIONS

Question 1:

What is the state of the flood forecasting system implemented in Africa and especially in some West African countries?

Question 2:

What is the main cause responsible for the flood occurrence and intensity in the study area?

Question 3:

Among the flood forecasting system already implemented in the surrounding countries, which one could fit better in the study area?

1.4.THESIS OBJECTIVES

1.4.1. MAIN OBJECTIVE

The main objective of this work is to analyze the flood risk reduction means in place in Mali and propose ways out through the implementation of flood forecasting system in the Upper Niger River Basin in Mali (Koulikoro watershed).

1.4.2. SPECIFIC OBJECTIVES

SO1: Investigate the current state of flood forecasting hydrological models used in the region especially in West Africa with the forecasting systems.

SO2: Investigate flood trend events in Bamako (from 1982-2019) and its relationship with extreme rainfall based on historical flood information and rainfall time series.

SO3: Calibrate and validate the hydrological models HBV and HEC-HMS.

SO4: Implement the flood forecasting system with hydrological HBV and HEC-HMS models.

1.5.HYPOTHESIS

In Africa especially in West Africa, the undeveloped flood forecasting system leads to detrimental consequences to the population.

The lack of rainwater drainage system in Bamako in addition to the extreme rainfall are the causes of the flash flooding these past three decades.

HBV and HEC-HMS model better the flash flood risk in the UNRB.

Both of the hydrological models (HBV and HEC-HMS) contribute better to the flood forecasting system in the UNRB.

1.6.NOVELTY

Flood forecasting through hydrological models can allow to reduce considerably the impact of flood events in terms of population life. Even if the infrastructures can be touched but more lives could be safe. This study has been able to implement two type of hydrological models in the study area, Upper Niger River Basin in Koulikoro. These models showed good results of calibration and validation, so they are suitable to be used for flood purposes in the study area. For the best of our knowledge, any hydrological model especially in Koulikoro watershed has been put in place for flood purposes. The implementation of the hydrological models in order to improve flood risk in the area is the novelty of this work and can contribute to the safe of population life. Moreover, with that information, Selingue dam, located in the upstream of the study area, can be well managed.

1.7.SCOPE OF THE THESIS

The thesis was implemented in order to find solution of flood concerns in the Upper Niger River Basin in Mali (Koulikoro watershed). Flood events cannot be avoided, however, through the hydrological model tools for flood forecasting, its damages can be reduced considerably. Flood forecasting system implemented in Africa in general and West Africa in particular is investigated. This is done in order to have an overview of the flood forecasting system already implemented in the region and try to implement such kind of system in our study area.

After, a trend analysis of flood events in relationship with the extreme rainfall in Bamako is done.

The last part consists of implementing a flood forecasting system in the study area. Two hydrological models (HBV, HEC-HMS) are used. Both of them gave satisfactory results of model efficiency during the calibration and validation of forecasted rainfall of NCEP, downloaded from Copernicus website.

This finding is interesting in the way it can reduce considerably the impacts of flood by alerting the population several days in advance. Also, the Selingue dam, located in the upstream of the outlet, be well manage what will contribute to the reduction of flood occurrence especially due to the Selingue dam spillway.

1.8.EXPECTED RESULTS AND BENFITS

This study aims to highlight the usefulness of the hydrological models in order to mitigate the flooding damages. At the end of this study, first of all, the information of flood related to Bamako would have been known. The rainfall threshold above which flood will occur in Bamako would have been known. A peer review of literature would have been done in order to know the different hydrological models in flood forecasting implemented in Africa. It allows to know which type of hydrological models for flood forecasting will suit the best to be implemented in Mali. The benefit is that the population will be given a tool allowing them to be informed about the coming floods, what will allow them to be protected for the flood damages reducing the number of victims. Again, the results will be more benefit to the authorities who can use it for the best application.

1.9.OUTLINE OF THE THESIS

The thesis is divided into eight following chapters:

Chapter 1 describes the literature review made up of problem statement, research questions, main and specific objectives, the research hypothesis, the novelty of the thesis, the scope of the thesis, the expected results and benefits of the thesis.

Chapter 2 gives details on the study area. In this chapter, more details of localization, relief, vegetation, climate, hydrology, soil, land use demography are given.

Chapter 3 describes the overall data, materials and methods uses.

Chapters 4, 5, 6 and 7 account for the details of each specific objective result.

Chapter 8 presents the general conclusion and perspectives.

CHAPTER 2: STUDY AREA

Section 1 presents the localization and the relief of the basin. The climate and the hydrology of the river basin are presented in the sections 2 and 3 respectively. The soil, land use, the vegetation are provided in sections 4 and 5 respectively. The last section deals with the demography, environmental social and economic activities.

2.1.Localization and Relief

The Niger River Basin (Fig.1), with an area of about 2 million km^2, is the third longest river in Africa after the Nile and Congo Rivers respectively the first and second longest Rivers. The length of Niger River is about 4200 km (Tefera, 2015). It is located between latitude 5˚S to 22˚N and longitude 11˚30’ W to 15˚E. Andersen et al. (2005) stated that the Niger River Basin crosses through ten (10) African countries (Algeria, Benin, Burkina Faso, Cameroun, Chad, Cote d’Ivoire, Guinea, Mali, Niger, Nigeria) and covers approximately 7.5% of Africa continent surface area (Tefera, 2015). The geographic heterogeneity of the land it flows through, ranges from arid deserts to moist mountain forests. Its location between the arid Sahara Desert and the equator however results in the curious fact that only approximately 59% (1.27 million km^2) of the area is actually contributing to the river’s discharge (Aich, 2015). Still the Niger is vital for the agriculture, economy and cultural identity of the riverine nation’s societies (Aich, 2015). The Niger River Basin, according to the topographical and hydrological characteristics is divided into four (4) sub-basins: The Upper Niger spreads from Guinea to Mali, the Central Delta located within the central region of Mali called Mopti, the Middle Niger in Niger Republic and the Lower Niger located in Nigeria.

Figure 1: Niger River Basin (Tefera, 2015)

The Upper Niger River Basin, also named Koulikoro watershed (Fig. 2) is where the study is performed, it covers a surface area of 120000 km^2, and is located between 7°00' and 12°00'West and 8°30' and 13°00' North. It encompasses three countries: Guinea (65%), Mali (30%) and Cote d'Ivoire (5%). The altitude varies from 1479 m to 265 m at the outlet of the basin (Dezetter et al., 2010). Koulikoro watershed is located in the Southern part of Mali. The relief decreases from Guinea where the basin starts to Mali. The outlet is located in Koulikoro just 60 km from Bamako, the capital of Mali.

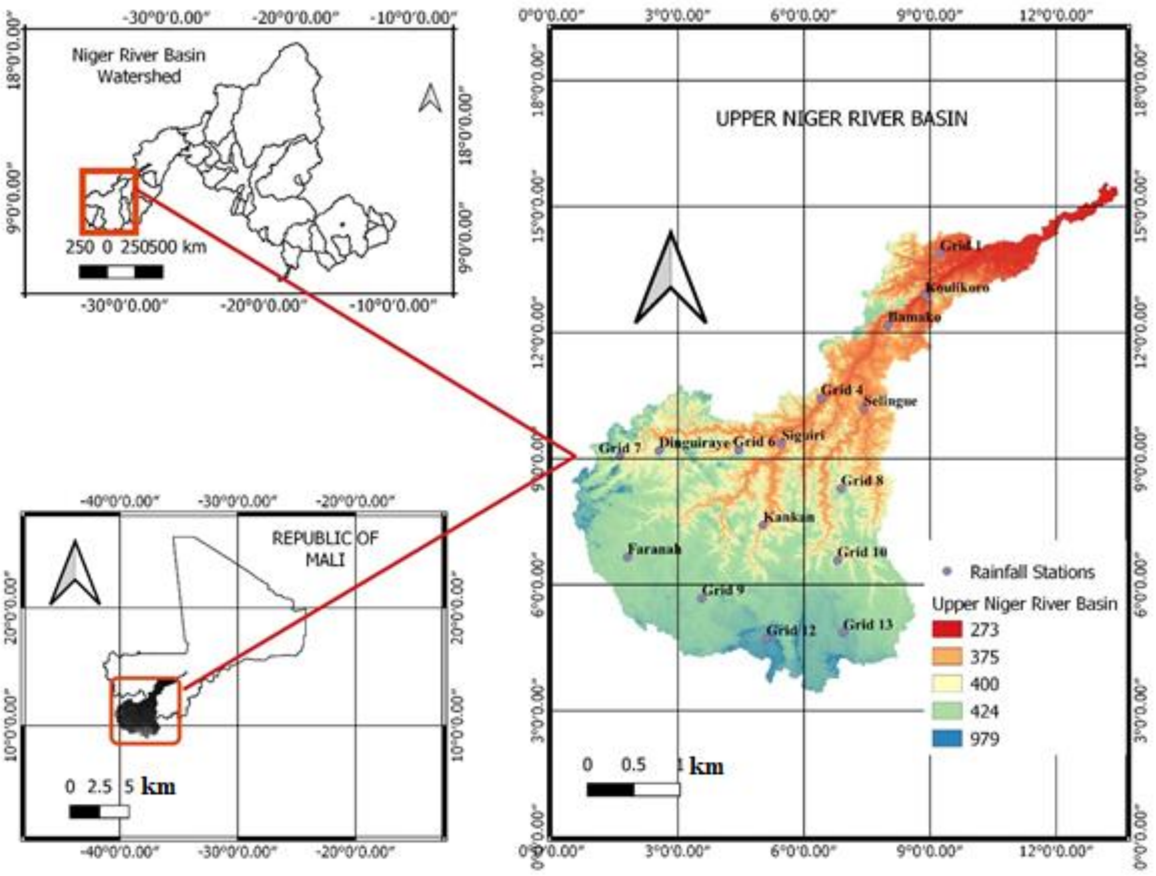

Figure 2: Upper Niger River Basin (Koulikoro watershed)

2.2.Climate

The climate of Niger River Basin (NRB) depends on the West African Monsoon (WAM) system. WAM is also controlled by the movement of the Intertropical Convergence Zone (ITCZ) which causes the typical tropical seasonal cycle of dry and rainy seasons (Tefera, 2015). WAM has a very distinct, high inter-annual rainfall variability. These variations are characteristics of West Africa (Sahel region). Due to the meridional gradient of WAM, three to five different eco-climatic zones are commonly distinguished over West Africa, and the NRB has a share to each one. They range from the arid North at the bend of the Niger (Saharan, < 150 mm/a), the semiarid desert zone (Sahelian, 150-300 mm/a), the semi-arid tropical (Sudano-Sahelian 300 - 750 mm/a), and pure tropical zones (Sudanian/Sudanese 750-1200 mm/a) to the transitional tropical zone (Guinean, > 1200 mm/a) (Fig.3) (Tefera, 2015). The Sahelian part of the Niger River Basin presents a high temperature in the whole basin between 28°C to 30°C while in the other parts, the temperature ranges from 24°C to 28°C (Tefera, 2015).

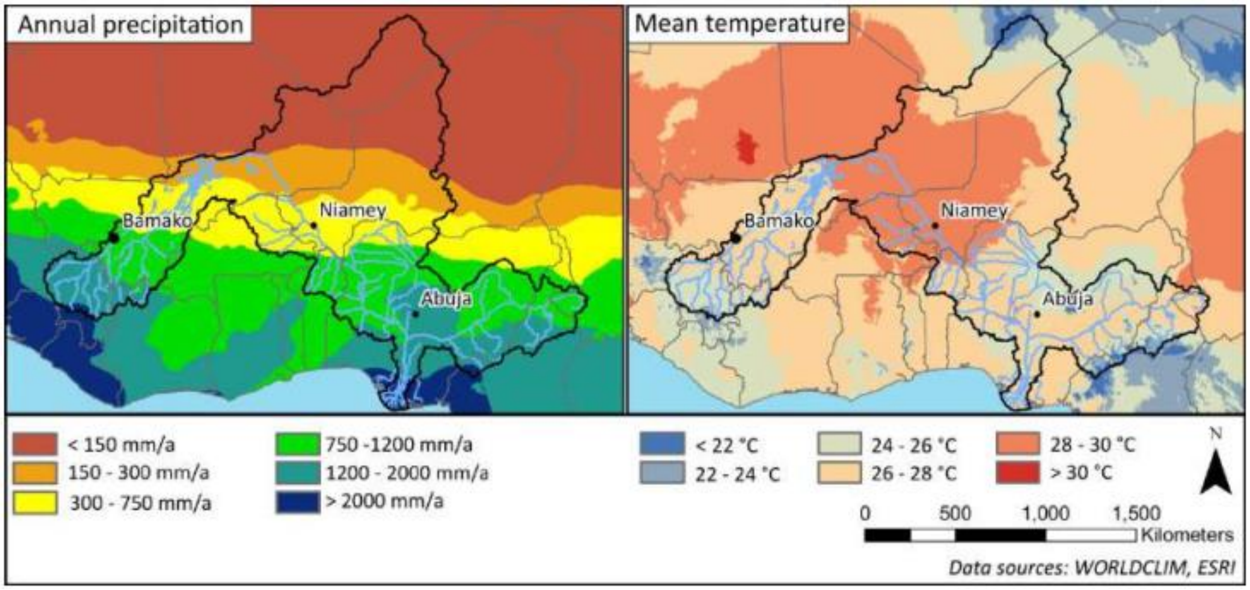

Figure 3: Annual precipitation and mean temperature of the Niger River Basin (Tefera, 2015)

The statistical analyses have been applied to these different stations in order to know and see the evolution of the rainfall throughout the whole country along the Upper Niger River Basin in Mali. The average and the anomaly analyses were applied to all of the stations and the different graphs obtained have helped us to understand the rainfall evolution.

From the Southern part (Selingue, with a maximum monthly rainfall equal to 300mm; Bamako 262,35mm and Katibougou or Koulikoro 254,83mm) to the central part (Mopti, with a maximum monthly rainfall equal to 179,18mm) a decreasing of rainfall intensity is noticed (Fig.4). Whereas one single peak is observed throughout the whole country of Mali where the month of high value is July for Selingue and Bamako and August for Katibougou (or Koulikoro) and Mopti. Mannkendall and Pettitt' test and Sens's slope tests were applied to these data. All stations display an increasing trend (Mann kendall test) of rainfall from 1990 to 2019. The rainfall intensity started to increase from the year 2000 till 2019.

Mali is a West Africa country with just one rainfall season and a very few period of rainfall occurring in just four mouths (June, July August, September). From 1960 to now 2020, according to many authors (Mahe et al., 2005, Mariko et al., 2003; Dezetter et al., 2010), the climate has changed due to the variation of the rainfall. During the decade 1960 to 1969, the rainfall was intense in Mali but from 1970 the break was noticed and after this period of break, the rainfall has never reached the intensity of the one of 1960. Adding this to the increasing of the population, and the high important of water that is lost due to evaporation in the Inner Delta Niger, we need to implement a strategy in place that will allow the population to better adapt to the challenges they are facing because of water scarcity as well as the decreasing of rainfall in the region.

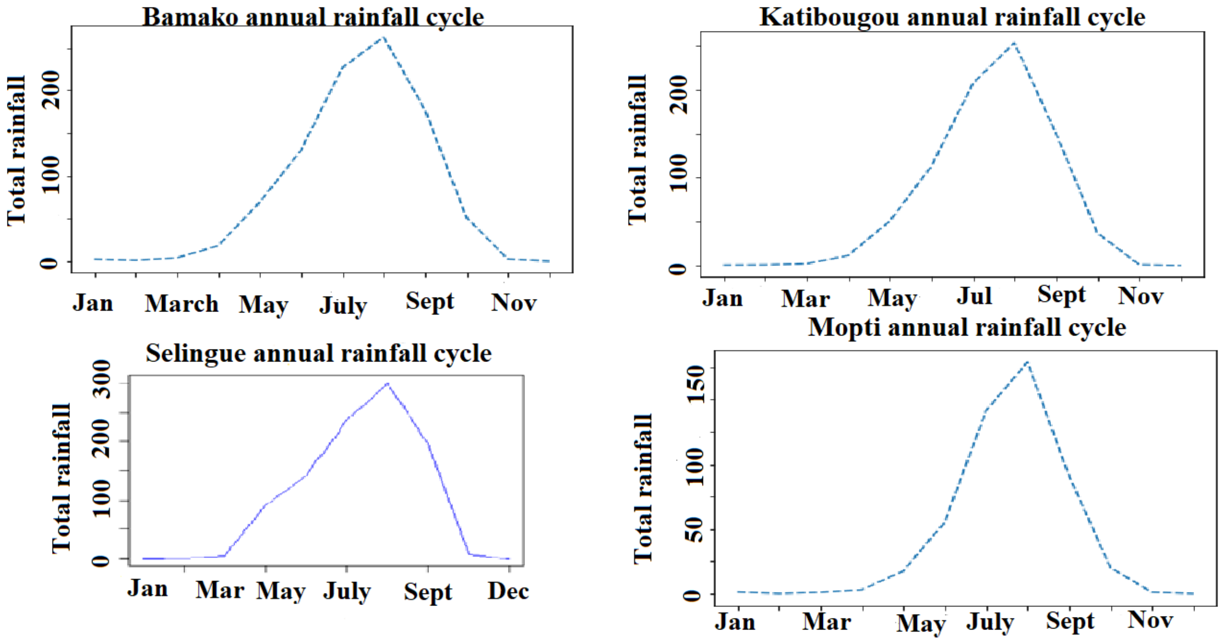

Figure 4: Annual rainfall cycle at Koulikoro watershed

In the same way, rainfall anomalies have been done in order to highlight the period of high and low rainfall in the study area (Fig.5). Four stations in Mali have been chosen (Bamako, Katibougou or Koulikoro, Selingue and Mopti). All the figures show an increasing of rainfall from 1990 to 2019, in otherwise the period 1990 to 2000 correspond to the low rainfall period in Upper Niger River Basin while the 2000 to 2019 period correspond to the wettest period.

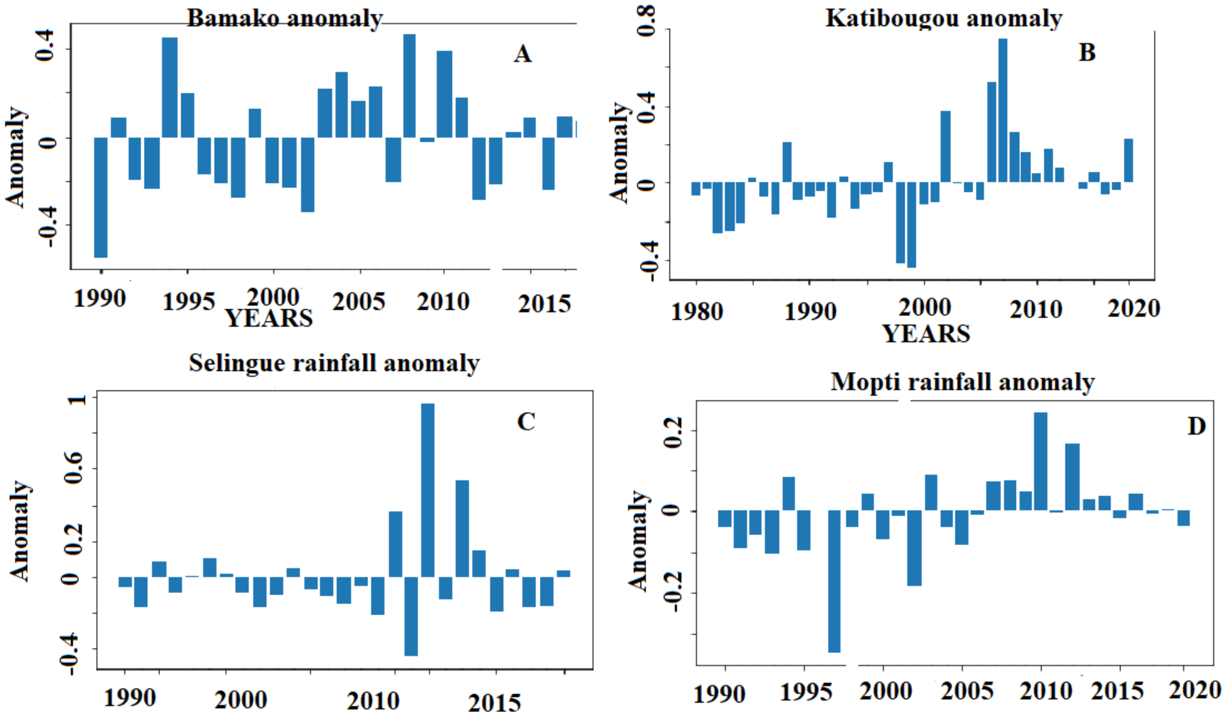

Figure 5: Rainfall anomaly of the Study area

Five extreme temperatures indices were used for the calculation of the extreme indices: TX10, TX90, TN10, TN90, WSDI which are respectively cool day frequency, warm day frequency, cool night frequency, warm night frequency and warm spells.

The analysis of the graphs obtained from these extreme indices of temperature shows an increasing trend of temperature.

The cool day frequency TX10P, as well as the cool night frequency TN10P present a downward trend from 1982 to 2019 in the graph (Fig.6). This means that the weak temperature (cool temperature) during the day is decreasing from 1982 to 2019, and in other senses, it means that the temperature is increasing during the day. However, we notice an upward trend of the warm temperature during both the day and night (Fig.6). The warm spell which is defined in the Table 1 as an annual account of days with daily temperature greater than 90th percentile presents also an increasing trend (Fig.6). This means that the temperature is increasing both during the day and night from the study period from 1982 to 2019.

The cool night temperature graph (Fig.6) shows a decreasing trend from 1982 to 2019 meaning that the night of the period of 1982 was cooler than the night of nowadays. The temperature has then increased.

When analyzing the warm night temperature graphs (Fig.6) from the same period, we notice an increasing trend meaning that the temperature is more increasing during the night in the period of 2019 than in 1982.

So when we combine all of these extreme indices of temperature, it appears that the temperature is increasing from the period 1982 to 2019 both during the day and night. Because not only the cool period has decreased but also the warm period has increased. The climate has then changed from this 30 years' period of time.

The Mann kendall trend tests are in the same line with these results (Table 1).

Table 1: Mann kendall trend tests

Indices	P-Values	Z values	Sen's slope	Tau	S	Var(S)
TN10P	0.001	-3.22	-0.32	-0.36	-257	6327
TX10P	0.03	-2.20	-0.19	-0.25	-176	6326
TN90P	0.01	2.76	0.21	0.31	221	6327
TX90P	0.02	2.36	0.13	0.26	189	6327
WSDI	0.04	2.01	00	0.19	139	4697

(Larbi et al., 2018; Mouhamed et al., 2013) have found similar results respectively in his work done in Vea catchment, one of the sub-basin of White Volta Basin in Ghana where positive trend was obtained for the warm day, warm night and warm spell temperature and Senegal.

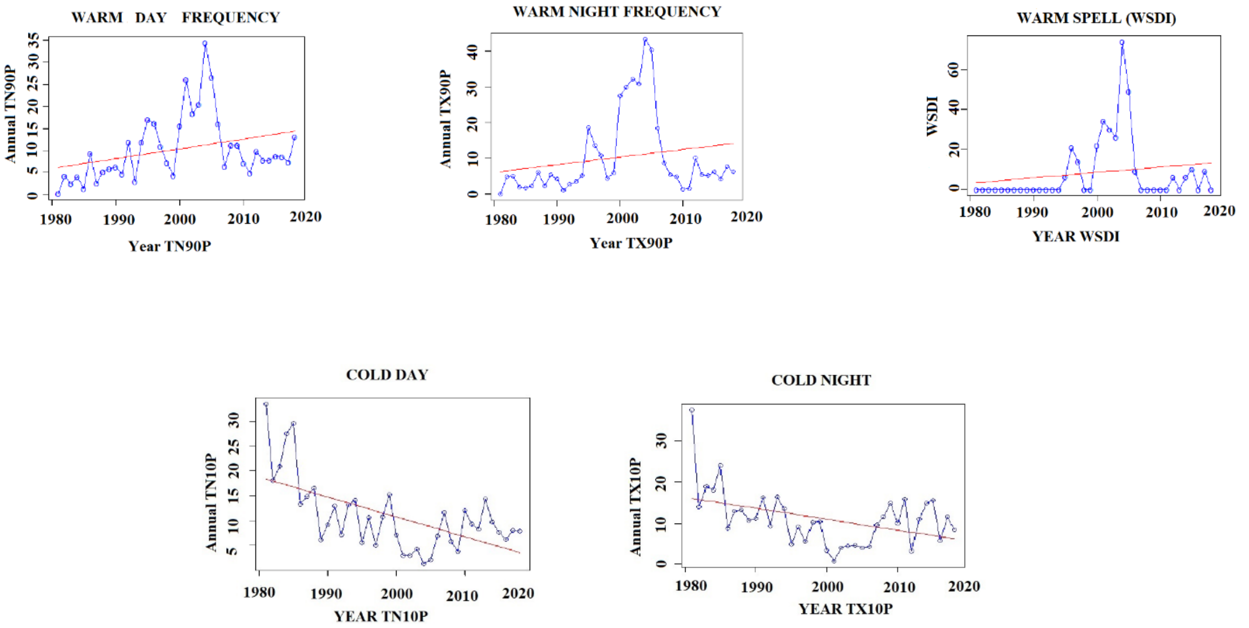
WARM DAY FREQUENCY
WARM NIGHT FREQUENCY
WARM SPELL (WSDI)
COLD DAY
COLD NIGHT

Figure 6: Extreme temperature frequency of Bamako

2.3.Hydrology

The NRB presents different flow regimes within the whole basin. Andersen et al. (2005) and Ogilvie et al. (2010) have proven that there are six main hydrographic regions in the NRB. The

Upper Niger Basin is a typical tropical headwater with an extensive network of tributaries. During the rainy season, the peak flow from Guinea reaches the Central Delta 4200 km downstream. The Inner Niger Delta (IND) has an area of 20000 to 30000 km^2. During the flooding period in Guinea, the annual flood forms a huge marsh which can cover a surface area of over 80000 km^2 in the IND.

One of the characteristics of Niger River and its confluents is the inter-annual and inter-seasonal discharges variability. In fact, the hydrology of the confluents depends on the climatic factor of the basins located in Guinea. The contrast of seasonal discharge variation between the rainy period (between July and November) and the dry period is very important. The important discharge started from the end of June. The discharge increase is fast. The peak is attained between late September and early October for the Upper Niger at Koulikoro. 805m^3/s of the discharge flows out between August and end of October except the flow in Inner Niger Delta where the flow is reduced due to the topography. In Mali, there are four climatic zones in the basin area and the rainfall ranges from 1500 mm in the south to less than 100 mm in the north. The water in the Niger River is partially regulated through dams. The Sélingué dam on the Sankarani River, built in 1982, is mainly used for hydropower generation, but also allows the irrigation of about 60,000 ha under double cropping. Two diversion dams, one at Sotuba in the city of Bamako, and one at Markala, just downstream Ségou, are used to irrigate the area of the Office du Niger (equipped area of about 54,000 ha) (Mahe et al., 2005).

Hydrological data have been collected from the National Directorate of Hydraulic in Mali. After computing, the data showed that in the year1960 the discharge was very important. The discharge decreases considerably from approximatively 2500 m^3/s in 1960 to less than 750m^3/s in 1990 (Fig.7). From 1990 to 2019 the discharge seems increasing (750m^3/s in 1990 to 1300 m^3/s in 2019) little bit but without reaching the level of 1960 (Fig.8). This analysis is done for all stations located in Mali. Two major break points are obvious, the year 1970 and 1990 where an important drop of discharge is noticed. In sum, from 1960 to 2019 the flow discharge is decreasing in the Upper Niger River Basin area.

Same analyses are made by the anomaly graphs of the same station of Koulikoro (Fig.9) and (Fig.10).

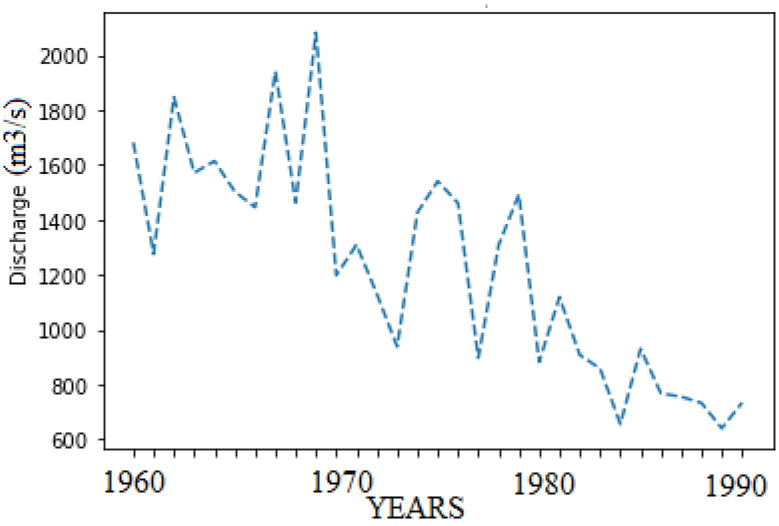

Figure 7: Koulikoro discharge 1960-1990

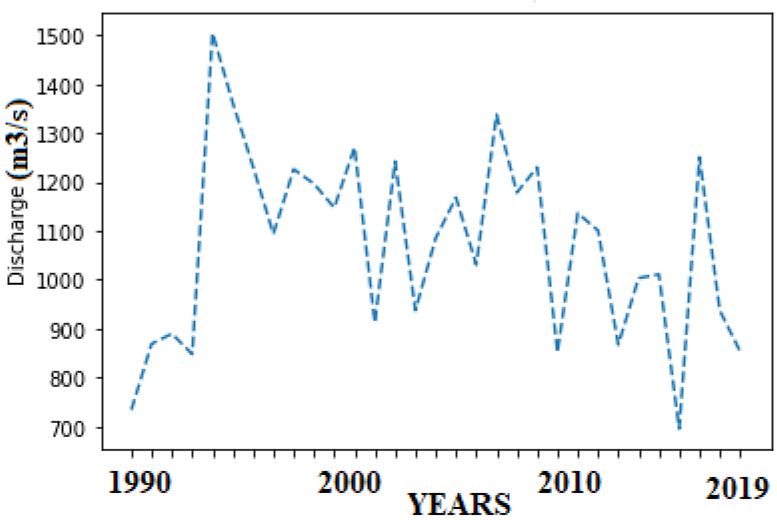

Figure 8: Koulikoro discharge 1990-2019

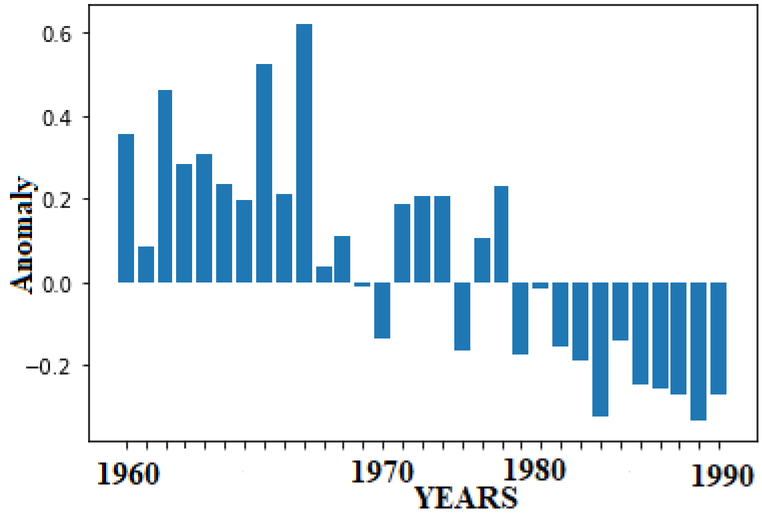

Figure 9: Anomaly discharge 1960-1990

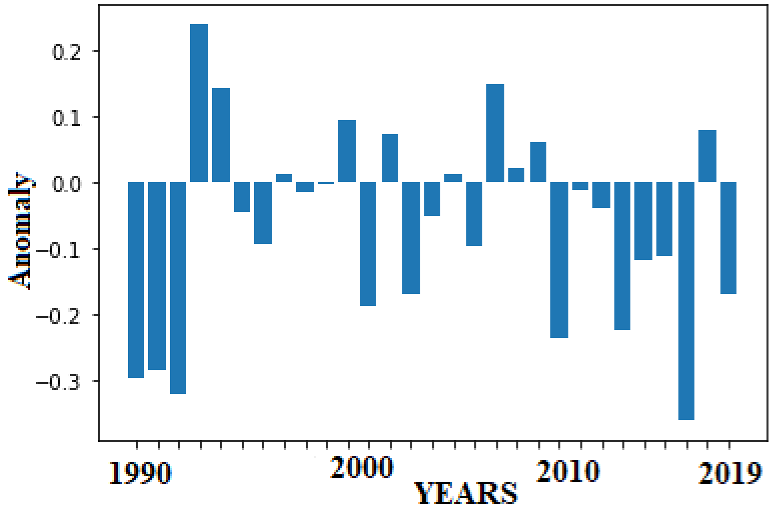

Figure 10: Anomaly discharge 1990-2019

2.4.Geology, hydrogeology and soil

The basin under investigation is located in the West Africa Craton, one of the five (5) cratons of the Precambrian basement of Africa whose crystalline rocks make up foundation of the basin where the basin is not overlain with sediment deposits (Tefera, 2015). Despite the fact that the rocks are crystalline and impervious, it is noticed a vast groundwater aquifer in the Niger River Basin (inter-granular aquifers) mainly in the tertiary, quaternary and recent deposits of the IND (Wright et al., 1985). Despite the high potential of groundwater resources, the quantity of withdrawal of groundwater is estimated to be very low (World Water Assessment Program (WWAP), 2009).

The West African soils are old and deep compared to European soils because of the fact that the African soils were not covered by the glaciers during the glacial periods. The feralitic soils are dominant in West Africa. The soil fertility is limited because of its high content in iron and low content in silica. With regard to the hydrological characteristics, feralitic soils feature high porosity and permeability despite their relatively high clay content due to micro-aggregates and bioturbation (Wiese, 1997). Typical of tropical soils are the hardened lateritic layers that result from ferrous oxides and can hinder or impede agriculture. Locally bleached layers of feralitic soils occur where water stands periodically, for example around the IND.

2.5.Vegetation

From the Guinea to Nigeria the Niger River flows through several types of vegetations (Fig.11). The Guinean part of the basin, because of the important quantity of rainfall, is characterized by the savanna forest mosaic. In Mali, especially in the Inner Niger Delta, the River flows through the West Sudanian savana composed of long grasses and aquatic plants. The bushland, characteristic of the Sahelian acacia savanna represents the vegetation type in the northern part of the basin. The vegetation is assessed to be deteriorated due to human being behavior. Despite the effort to vegetate many parts of the Sahel and Sudano-Sahelian ecozones, many other parts remain deteriorated (Kaptué et al., 2015). The climate change is playing an important role in vegetation degradation but the human intervention seems to be the most significant driver of destruction of vegetation which has a great impact in runoff and indirectly in flooding events.

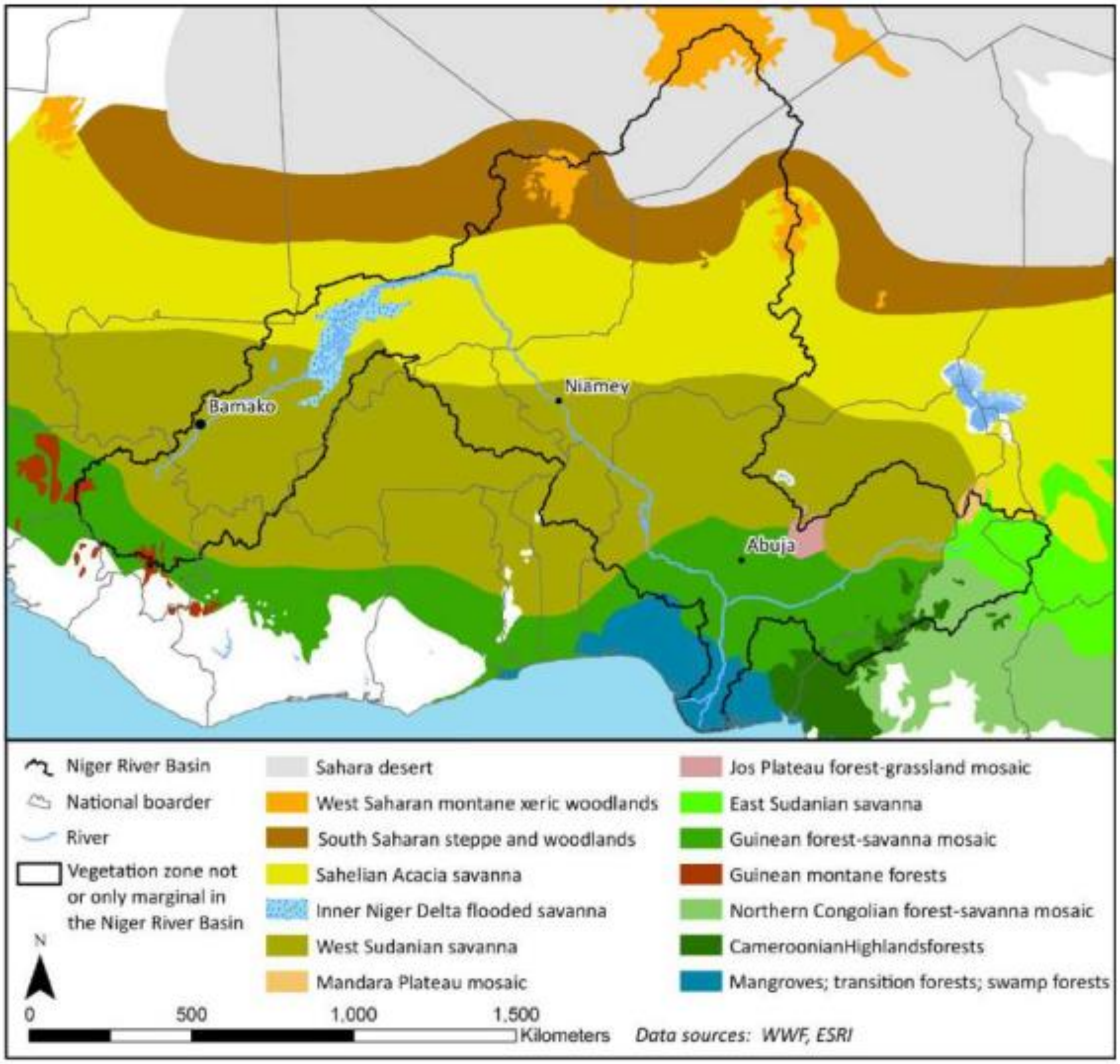

Figure 11: Vegetation of the Niger River Basin (Tefera, 2015)

2.6.Demography, environmental, social and economic activities

The main activity of the population living in the Niger River Basin is agriculture. This agriculture is highly dependent on rainfall; it is a rain-fed agriculture. Only 20% of 2.5 million ha of the arable land are exploitable. Five major reservoirs for the hydropower purposes are at use in the basin: Selingue (Mali), Kainji, Jebba, Shiroro (all three in Nigeria) and Lagdo (Cameroon). Beside the agriculture use of the NRB, the population uses it as a way of transportation for themselves and their goods. The NRB with its length of 4200km, is navigable in its most part; the stretch between Koulikoro (Mali) until IND in Mopti admits larger boats transportation during the rainy sea.

2.7.Partial conclusion:

This chapter deals with the localization and relief, climate, hydrology, soil and land use, vegetation demography environmental social and economy activities. Koulikoro watershed, the study area is located in the Upper part of the Niger River Basin in Mali. The Upper Niger River Basin starts from Guinea Republic to Mali Republic. The most part is located in Guinea where the rainfall is important in comparison to Mali. The discharge decreases from Guinea to Mali especially in the Inner Niger Delta zone where the evapotranspiration is important also the morphology of the soil does not allow quick flow of the rainfall. The vegetation in Guinea is made of savanna forest whereas in Mali we notice lot of long grasses and bushland in the Northern part. Population economy is depended on this River. Agriculture is the major activity in the area. This is facilitated by the Selingue dam and other small dam used for the irrigation purposes. Some other also are doing the fishing activities.

CHAPTER 3: DATA, MATERIALS AND METHODS

This chapter describes the data, materials and methods used for this research.

All data used are presented in the section 3, from the first specific objective data in section 3.1 to the data for the fourth specific objective in section 3.4.

While all the materials used are presented in the section 4, the last part of this chapter concerns the methods used to get the results that are contained in section 5.

3.1.DATA

3.1.1. S.O.1 Data Investigation of flood forecasting system implemented in Africa and sub-region

The data collected to perform this work are scientific papers. More than eighty documents have been used. Most of them have been downloaded from google scholar, web of sciences, Scopus, and represent a wealth of important information needed for the attainment of S.O.1.

3.1.2. S.O.2 Data: Investigation trends in flood events in Bamako and its relationship with extreme rainfall based on historical flood information and rainfall time series.

The data used for this specific objective include daily rainfall and temperature data and flood events information. The observed daily rainfall data at Bamako gauge station were obtained from Mali Meteorological Agency for the period 1990-2020. Due to limited number of years of station rainfall data at the Bamako station, rainfall data at 5km spatial resolution from the Climate Hazards Group Infrared Precipitation with Station data CHIRPS for the period 1982-2019 was extracted for Bamako location and used. Bamako rainfall station data was used to validate the CHIRPS data at monthly scale. The flood events information was obtained from documents provided by the Civil Protection Directorate and through the Emergency Events Database (EM-DAT) website (https://www.emdat.be/). The different dates of the floods as well as the damages caused were extracted from the documents. The main causes of the flood were noted as well as the number of deaths and injuries. Given that the Civil Protection Directorate is created recently, flood events before the creation of their directorate are not taken into account. To compensate for this gap, others sources (such as articles, newspapers) were used for the extraction of this kind of information.

Rainfall and temperature data

The climatic data used for this objective are rainfall and temperature daily data from 1980 to 2019. The daily rainfall data were collected from the national directorate of Mali-Meteo. CHIRPS satellite data from 1980 to 2019 were downloaded and used. Given that the Mali-Meteo data, was not well representative and with enormous missing data, CHIRPS data was definitely used for the study. The daily minimal and maximal temperatures data were collected through the CHIRPS satellite for the same period as the rainfall data.

Civil protection directorate/EM-DAT website

Information related to the victims of flood events were collected from this directorate as well as the economic information and human live loss. This civil protection directorate because of its new age, does not have enough flood events information especially those before its creation. For that reason, EM-DAT Website has been used to collect additional flood victim information to be completed with those obtained with Mali Civil Protection Directorate.

3.1.3. S.O.3 Data Calibration and validation of hydrological models HBV and HEC-HMS for the flood forecasting system purpose/

Rainfall data, evapotranspiration as well discharge data were used as an input to force the HEC-HMS and HBV hydrological models for the flood forecasting analysis. The rainfall data was collected from Mali-Meteo agency for the period ranged from 1990 to 2004. Daily temperature data, collected from this same website (https://www.ncei.noaa.gov/) on June 22th, 2022, was used to get the evapotranspiration data through the Hargreaves method (Hargreaves and Samani 1982). The discharge data was provided by the National directorate of hydraulic in Mali. The DEM at 30m resolution was downloaded from the United States Geological Survey (USGS) website (https://www.usgs.gov/). These data have been used to calibrate and validate the models in the area of study.

3.1.4. S.O.4 Flood forecasting system implementation through HBV and HEC-HMS in Koulikoro watershed

Forecasted rainfall data used for this study has been downloaded from the Copernicus website. Two original centers National Center for Environmental Prediction (NCEP) and UK Meteorological office of United Kingdom (UK Met office) have been chosen to download the forecasted rainfall data. The hindscast years data range from 1993 to 2013 are downloaded from Copernicus website. In contrary to the UK Met Office where just four (4) days were available for the download, all the 30 days were available for the downloading for the NCEP center. The lead-time hour chosen were 24 hours, 48 hours, 72 hours and 96 hours ahead.

3.2.MATERIALS

3.2.1. S.O.1 Materials: Data Investigation of flood forecasting system implemented in Africa and sub-region

This specific work has been done using the scientific papers published in important high factor journals. For that purpose, the papers used as data have been obtained through scientific website where interesting papers can be obtained.

3.2.2. S.O.2: Materials Investigation trends in flood events in Bamako and its relationship with extreme rainfall based on historical flood information and rainfall time series.

RClimDex

ClimDex is a Microsoft Excel based program that provides an easy-to-use software package for the calculation of indices of climate extremes for monitoring and detecting climate change. It was developed by Byron Gleason at the National Climate Data Centre (NCDC) of NOAA, and has been used in CCl/CLIVAR workshops on climate indices from 2001. The original objective was to port ClimDex into an environment that does not depend on a particular operating system. It was very natural to use R as our platform, since R is a free and yet very robust and powerful software for statistical analysis and graphisms. It runs under both Windows and Unix environments. In 2003 it was noticed that the method used for computing percentile-based temperature indices in ClimDex and other programs resulted in inhomogeneity in the indices series. A fix to the problem requires a bootstrap procedure that makes it almost impossible to implement in an Excel environment. This has made it more urgent to develop this R based package.

RClimDex (1.0) is designed to provide a user friendly interface to compute indices of climate extremes. It computes all 27 core indices recommended by the CCl/CLIVAR Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) as well as some other temperature and precipitation indices with user defined thresholds. The 27 core indices include almost all the indices calculated by ClimDex (Version 1.3). This version of RClimDex has been developed under R 1.84. It should run with R 1.84 or a later version.

A main objective of constructing climate extremes indices is to use it for climate change monitoring and detection studies. This requires that the indices be homogenized. Data homogenization has been planned but is not implemented in this release. Current RClimDex only includes a simple data quality control procedure that was provided in ClimDex. As in ClimDex, we require that data are quality controlled before the indices can be computed.

Table 2: Rainfall indices with unit and index description

Index	Unit	Index description
RTOT	Mm	Annual total rainfall from wet days (a wet day has rainfall >1mm)
R1mm	Days	Annual number of wet days
SDII	Mm/day	Mean rainfall amount on wet day
R10mm	Days	Annual number of days with daily rainfall greater or equal to 10mm
R20mm	Days	Annual number of days with daily rainfall greater or equal to 20mm
CWD	Days	Maximum number of consecutive wet days
RX1day	Mm	Annual maximum 1-day rainfall
RX5day	Mm	Annual maximum 5-day rainfall

R95P	Days	Annual number of very wet days with rainfall greater than 95th percentile of 1971-2000 daily rainfall
R99P	Days	Annual number of extremely wet days with rainfall amount greater than 99th percentile of 1971-2000 daily rainfall
R95pTOT	Mm	Cumulative rainfall amounts due to 95p
R99pTOT	Mm	Cumulative rainfall amounts due to R99p
R95pPROP	%	Percentage of annual total rainfall amount due to R95p
R99pPROP	%	Percentage of annual total rainfall amount due to R99p

Modified Mann-Kendall Test

The trends data was evaluated using the modified Mann-Kendall test. This test takes into account the effect of autocorrelation in the data. The effect of autocorrelation in the data affects the power of the classical Mann-Kendall statistical test by introducing outliers, and the effect of positive autocorrelation increases the risk of rejecting the type 1 error (overestimated trends), while the effect of negative autocorrelation increases the risk of rejecting the type 1 error (underestimated trend). Therefore, an additional contribution to the Mann-Kendall test was made to take into account this autocorrelation phenomenon. The trends in the hydrometric data series were evaluated using the modified Mann–Kendall test (Hamed et al., 1998), which is a non-parametric test used in several studies. The choice of this test was justified by the fact that it takes into account the effect of autocorrelation in the data. The principle is based on a modification of the (S) statistic in the MK test. Based on this principle, a modified version of the original MK test was proposed (Hamed et al., 1998), in which the variance of the statistic test is modified to account for autocorrelation in the series and the statistics to adjust the variance, as follows

Var(S)= $\frac{1}{18}(n(n-1)(2n+5))\frac{n}{ns}$

where ns* is the effective number of observations to account for autocorrelation in the data

$$\frac{n}{ns*} = 1 + \frac{2}{n(n-1)(n-2)}\sum_{s=1}^{m} \quad (n-s)$$

The modified Mann–Kendall trend test was implemented using the package “modifiedmk” (Sandeep et al., 2022) on R software and the null hypothesis ('() corresponding to “no trend” and the alternative hypothesis ('1) corresponding to the presence of a trend in the series at a significance level of 5%.

3.2.3. S.O.3/S.O.4: Materials Calibration and validation of hydrological models BHV and HEC-HMS for the flood forecasting system purpose/ Flood forecasting system implementing through HBV and HEC-HMS in Koulikoro watershed

QGIS/Arc-GIS
This software was used in order to preprocess the data to be used for the HEC-HMS model. ArcGis has firstly served to clip the study area part of the DEM data downloaded from USGSS with the shapefile of the study area catchment (Upper Niger River Basin). The curve number, one of the important HEC-HMS parameters for the model calibration and validation, has been determined through the ArcGIS. ArcGIS 10.2 version was the one used in this study.

HEC-HMS
The HEC-HMS software was developed by Hydrologic Engineer Center (HEC) of the US Army Corps of Engineers (Fig.12). This rainfall-runoff model is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is widely used as a practical rainfall runoff model in various areas (Ali et al. 2011; Caruso et al. 2013; Halwatura and Najim 2013; Sanyal et al. 2014) HEC-HMS conceptualizes the watershed into a network of subareas connected by channel links. This mathematical model will simulate precipitation-runoff and routing processes in natural or controlled watershed. The spatial data from HEC-GeoHMS could be imported to the HEC-HMS, and the model shall predict flow, stage, and timing for the basin based on the given meteorological dataset and land use information. HEC-HMS uses various hydrologic analysis procedures for continuous or event-based analysis for hydrologic analysis. There are three main components in the HEC-HMS model: basin model, meteorological model, and control specification. The basin model consists of the elements of the basin and sub-basins, the connectivity, and runoff parameter. The meteorological model contains the rainfall and evaporation data, while control specifications consists of the start/stop timing and calculation intervals for the run.

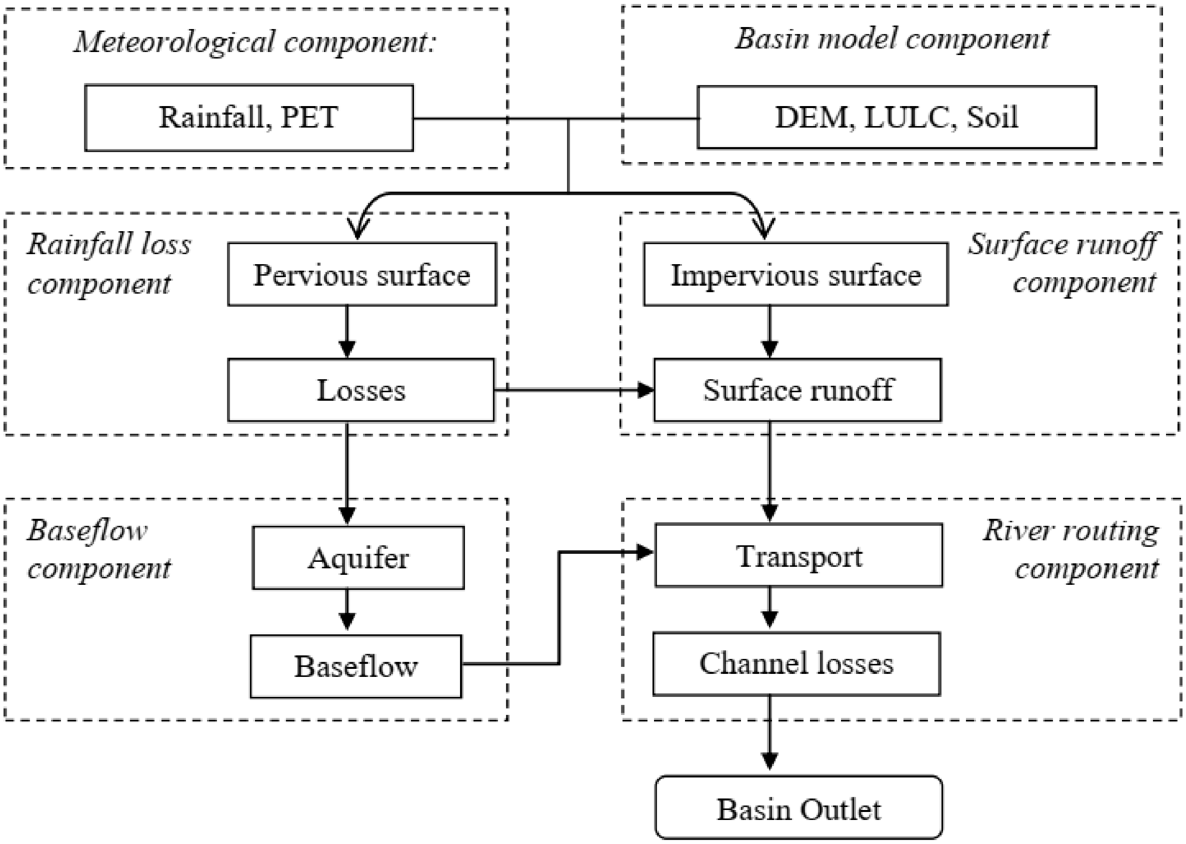

Figure 12: Scheme of rainfall runoff modeling in HEC-HMS (Adapted from HEC-HMS user's manual document)

HEC-GIS

GIS is one of the options that exists in the HEC-HMS model. It is at the interface of the “Component” and the “Parameters” option in HEC-HMS. This GIS option in HEC-HMS model has been used for the remaining preprocessing analysis. With this option, the fill sink, flow accumulation, flow direction and as well the watershed delineation and the sub-basins of the catchment were provided.

HBV

The HBV (Hydrologiska Byråns Vattenbalansavdelning) model (Fig.13) is a conceptual model of catchment hydrology, which was originally developed by Lindström et al. (1997) at the Swedish Meteorological and Hydrological Institute. HBV has been developed by the SMHI (Swedish Meteorological and Hydrological Institute). The structure of HBV components is shown by (Fig.13). Over each catchment or sub-catchment, losses are removed from precipitation and transformed through the soil moisture routine function into runoff.

Soil moisture routine

This is a parameter that takes into account the soil water quantity. In fact, it gives information on the soil permeability. Two parameters are included inside: the FC and LP and BETA. The increasing of the value of these parameters favors the decreasing of the peak of the simulated graph.

Response routine parameter

This is the parameter that plays on the peak of the simulated graph. It is made up of three parameters KO, K1 and K2 which are respectively high, medium and low flow. The increasing graph peak is proportional to the increasing of these parameters value.

Routing routing parameter

This parameter informs the time the rainfall takes to reach the outlet. MAXBAS is the name of the model parameter.

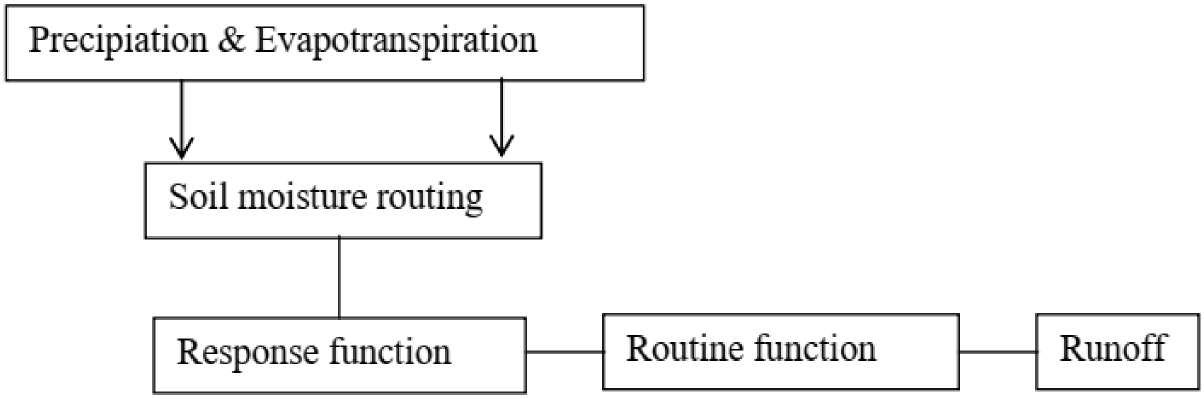

Figure 13: HBV model components structure (Adapted from HBV user's amnual)

3.3.METHODS

3.3.1. S.O.1 Methods: Collect data on flood forecasting system implemented in Africa and sub-region

More than eighty documents have been exploited. Most of them have been downloaded from google scholar in the journal indexed under Scopus, web of sciences. The keywords like extreme rainfall, flood events, climate change, flood forecasting and early warning system in Africa, flood events mitigation and adaptation in Africa have been the indices used to search most of the papers used for this literature review. The importance was given to the high impact factor of the journal where the papers used, are published. Also, the most recent years of publication have been one of the conditions of the papers to be used. The topic of these papers was based on the flood forecasting and warning system implemented in Africa in general and West Africa in particular.

3.3.2. S.O.2 Methods: Investigate the trends in flood events in Bamako and its relationship with extreme rainfall based on historical flood information and rainfall time series.

Several methodologies are used for this study. Details of each methodology are the following:

Station and CHIRPS rainfall comparison

The performance of the CHIRPS data in reproducing the observed rainfall at Bamako station was first evaluated over the period 1990-2020. The software R was used to make the plot at monthly scale for both the station and CHIRPS data in order to validate the CHIRPS data. Statistical indicators such as efficiency criterion of Nash-Sutcliffe (NSE) (Nash & Sutcliffe 1970) (equation 1), Correlation Coefficient (R) and Mean Bias Error were used to evaluate the quality of the CHIRPS data. NSE is a measure to evaluate the squared differences between the observed and simulated values using the following equation:

$$NSE = 1 - \frac{\Sigma\ (Qobs - Qsim)2}{\Sigma\ (Qobs - Qo)2} \qquad (1)$$

Here Qobs means the observed discharges while Qsim is the corresponding simulated value. The variables Qo is the mean value of the observed discharge. The NSE can vary from minus infinity to1. A value of 1 denotes a perfect match of predicted and measured values and values above 0.7 usually mean satisfactory fit. A value of 0 for the deviation in balance means no difference in amount between the measured and simulated values.

Analysis of rainfall stationarity

The rainfall data was subjected to a homogenization process using the Khronostat package. A check for inhomogeneity is necessary to avoid biases, spurious trends and erroneous interpretations of the rainfall data series. To detect the break points in the times series, rupture detection tests such as Pettitt (Pettitt, 1979), Buishand (Buishand, 1982), and Lee & Heghinian (Lee & Heghinian, 1977) were used which are included in the software Khronostat. For the randomness test, auto correlogram and auto-correlation Rang test have been used at the 5% significance level. The Khronostat software was applied to the annual maximum daily rainfall to analyze the stationarity and to detect potential break points in the time series. At 5% significance level, six statistical tests were applied; autocorrelation, Rang, Pettitt, Buishand, Lee & Heghinian, Hubert. For the independence test, the calculated values of autocorrelation coefficient were mostly within the confidence interval meaning that the time series are independent.

Rainfall extreme indices selection and description

The rainfall indices related to frequency, intensity and duration were calculated from the daily rainfall time series over the study period 1982-2019 in order to investigate the relationship between extreme rainfall and flood events. In this study, five extreme precipitation indices established by the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI) and recommended by the World Meteorological Organization-Commission for Climatology (WMO-

CCI), were computed for each of the stations (Min et al., 2011). Table 3 provides a description of the five ETCCDI precipitation indices selected for this study. For the percentile-based index of extremely wet days (R99p), the methodology uses bootstrapping to calculate the values for the base period so that there is no discontinuity in the time series of the indices at the beginning or end of the base period. The R99p, RX1day and RX5day indices characterize the magnitude of intense rainfall events whereas CWD is applied to assess the frequency of rainfall extreme.

Table 3: Rainfall extreme indices description

Indices	Unit	Index description
CWD	days	Maximum number of consecutive wet days
RX1DAY	mm	Annual maximum 1-day rainfall
RX5DAY	mm	Annual maximum consecutive 5-days rainfall
R99p	mm	Annual total rainfall when RR >99 percentile
PRCPTOT	mm	Annual wet-day rainfall total

Extreme rainfall indices computation and trend analysis

The RClimDex package in R software was used to compute the extreme rainfall indices for the period 1982-2019. The daily rainfall data was used for the calculation of the five selected rainfall extreme indices. These indices enabled the assessment of the changes in extreme rainfall events (Aguilar et al., 2009; Griffiths et al., 2003; Hangnon et al., 2015; Hountondji et al., 2000).

Trend analysis of the selected indices was performed using the Modified Mann-Kendall (MK) trend test. The MK test, a widely used statistical analysis for trend detection in extreme climate indices and hydro-climate analysis (Larbi et al. 2018) assumes a null hypothesis (Ho) that there is no trend which is tested against the alternative hypothesis (H1) of the presence of a trend.

3.2.5. Historical flood event analysis in Bamako

The flood event data in Bamako in the previous years were collected from both the civil protection directorate and EM-DAT website. These data gave some information related to flooding such as date of occurrence in Bamako since the 1988, damages caused etc. The software R was used to make a bar plot to better understand the evolution of this flood information based on the damage it has caused.

Return period and classification of the maximum daily rainfall

The relationship between extreme rainfall and flood is detected from the return period estimated using different distributions for the analyses of extreme events. They are used to estimate maximum rainfall associated with different return periods. In frequency analysis of extreme precipitation events, the hydrological probability distribution that best represents the trend of maximum daily rainfall data can be determined using functions such as Generalized Extreme Values, Gumbel, Log-Pearson type III, Normal and Pearson type III (Tazen et al., 2019). For this study, three statistical methods were used namely the Generalized Extreme values (GEV), the Gumbel and the Log-Pearson type III distributions. According to Tazen et al. (2019), these distributions performed well with the methods of momentum and maximum likelihood for parameter estimation. For consistency purposes, the parameters of the three distributions have been estimated using the momentum approach implemented in HYFRAN software. For the choice of the best method, the Chi-square test was used as well as the Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC). The best method was the one presenting the lower value of AIC and BIC. Table 4 presents the classification of the different return periods with their corresponding attributed classes according to Tazen et al. (2019). It allows to know if the rainfall causing the flood is very exceptional (i.e. occurring every 100 years), exceptional (every 50 to 100 years), severely abnormal (every 10 to 50 years), abnormal (every 5 to 10 years) and normal (every 5 years).

Table 4: Return period with its corresponding attributed classes (Vandiependbeeck, 1997)

Return period (in Year)	Attributed classes to extreme events
$T \geq 100$	Very exceptional
$50 \leq T < 100$	Exceptional
$10 \leq T < 50$	Severely abnormal
$5 \leq T < 10$	Abnormal
$T < 5$	Normal

Relationship between extreme rainfall and flood events

Urban flash flooding is highly correlated with extreme rainfall, and given that the indices allow the assessment of changes in extreme rainfall, there is therefore a link between urban flash flood and these indices. The data on the historical flood events collected from the national directorate of civil protection and the EM-DAT website was plotted in order to identify the different years where floods have occurred in Bamako. The annual flood events were then compared with the annual maximum 1-day rainfall (RX1 day) index computed for Bamako to investigate any coincidence between the years of the reported flood events with RX 1 Day. The annual maximum consecutive 5-days rainfall (RX 5 day) index was also taken into consideration in verifying whether there was any influence or not. At the end, a threshold value above which flood may occur was determined.

3.3.3. S.O.3 Methods: Calibrate and validate the hydrological models BHV and HEC-HMS for the flood forecasting system purpose

Hydrological modeling

Canopy-interception represents precipitation that is captured on trees, shrubs, and grasses. When precipitation occurs, it first fills canopy storage. Only after this storage is filled that precipitation becomes available for filling other storage volumes. Water in canopy interception storage is held until it is removed by evaporation. In the loss method, infiltration rate is considered through curve number as well as the percentage of impervious area of the basin. In this method, it is considered that all land and water in a watershed can be categorized as either: directly-connected impervious surface or pervious surface. Directly-connected impervious surface in a watershed is that portion of the watershed on which all contributing precipitation runs off with no infiltration, evaporation, or other volume losses. Precipitation on the pervious surfaces is subject to losses. Impervious area percentage is catchment characteristics estimated using soil type and land use and cover data.

Canopy

Canopy is one of the components that can be included in the subbasin element and can represent the presence of the plants in the landscape. Plants intercept precipitation, reducing the amount of the precipitation that arrives on the ground surface. Intercepted water evaporates between storm events. Plants also extract water from the soil and release it to the atmosphere in a process called transpiration.

Simple Canopy

This method is a simple representation of a plant canopy. All precipitation is intercepted until the canopy storage capacity is filled. Once the storage is filled, all further precipitation falls onto the ground surface or to the soil if no representation of surface is included. All potential evapo-transpiration will be used to empty the canopy storage until the water in the storage has been eliminated. The potential evapotranspiration is multiplied by the crop coefficient to determine the amount of evapotranspiration in the canopy storage and later, the surface and soil components. Only after the canopy has been deflated, will unused potential evapotranspiration will be used by the surface and soil component.

Surface method

The surface is one of the method that can be included in the subbasin element. It is intended to represent the ground surface where water may accumulate in surface depressional storage. The depressional storage of an impervious surface such as parking lot is generally close to zero. Precipitation through-fall from the canopy, or direct precipitation if there is no canopy, impacts the surface. Surface runoff will begin when the precipitation rate exceeds the infiltration rate and the surface storage is filled. Precipitation residing in the surface storage can infiltrate after precipitation stops and is subject to the evapo-transpiration.

The simple surface is a method of a simple representation of the soil surface. All precipitation or precipitation through-fall that arrives on the soil surface is captured in storage until the storage capacity is filled. Water in surface storage infiltrates into the soil whenever it is present in the storage. That is, water will infiltrate even when the storage capacity is not full. Surface runoff will be generated when the storage capacity is filled, and the precipitation through-fall exceeds the of infiltration rate.

Loss method

While a subbasin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together, the actual infiltration calculations are performed by a loss method contained within the subbasin. A total of twelve different loss methods are provided. Some of the methods are designed primarily for simulating events while other are intended for continuous simulation. All of the methods conserve mass.

a. Curve Number

The soil conservation service, Curve number method implements the curve number methodology for incremental losses (NSCR, 2007). The SCS curve number loss method should only be used for event simulation. Originally, the methodology was intended to calculate total infiltration during a storm. The program computes incremental precipitation during a storm by recalculation the infiltration volume at the end of each time interval (NSCR, 2007).

Soil moisture accounting loss

The soil moisture accounting loss method uses three layers to account for continuous changes in moisture content throughout the vertical profile of the soil. Using the soil moisture accounting method allows for continuous simulation. It should be used in combination with a canopy method that will extract water from the soil in response to potential evapo-transpiration computed in the meteorologic model. The soil layer will dry out between precipitation events as the canopy extracts soil water. There will be no soil water extraction until a canopy method is selected. It may also be used in combination with surface method that will hold water on the land surface. The water in surface storage infiltrates to soil surface. The infiltration rate is determined by the capacity of the soil layer to accept water.

The soil moisture accounting loss methods uses three layers to represent the dynamic of the movement of water in the soil. It should be used in conjunction with the canopy method and surface method. The soil layer will dry out during between precipitation events as the canopy extracts soil water. There will be no soil water extraction unless a canopy method is selected. The surface layer holds precipitation and allows it to infiltrate after the rain has stopped. Infiltration is generally reduced if no surface method is selected.

SCS Unit Hydrograph

The Soil Conservation Service (SCS) unit hydrograph method defines a curvilinear unit hydrograph by first setting the percentage of the unit runoff that occurs before the peak flow (NRCS, 2007). A triangular unit hydrograph can then be fit to the curvilinear unit hydrograph so that the total time base of the unit hydrograph can be calculated. The standard unit hydrograph is defined with 37.5% of unit runoff occurring before the peak flow. This definition corresponds to a peak rate factor of 484 which incorporates the percentage of unit runoff before the peak, calculated total time base, and unit conversions when applying the equations within the US Customary unit system (NRCS, 2007).

The percentage of unit runoff occurring before the peak flow is not uniform across all watersheds because it depends on flow length, ground slope, and other properties of the watershed. By changing the percentage of unit runoff before the peak, alternate unit hydrographs can be computed for watersheds with varying topography and other conditions that affect runoff. The percentage of runoff occurring before the peak is reflected in the peak rate factor (PRF). It has been found that flat watersheds typically have a lower PRF that may be as small as 100. Steeper watersheds have a larger PRF that may range up to 600. The default unit hydrograph has a PRF of 484. Unit hydrographs with specific peak rate factors are defined in the National Engineering Handbook (NRCS, 2007). A very specific case of the unit hydrograph for flat coastal watersheds is known as the Delmarva unit hydrograph (Welle, Woodward, and Moody, 1980). The standard lag is defined as the length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph. Examination of the equations used in deriving the curvilinear unit hydrograph show that the lag time can be computed as the duration of unit precipitation divided by two, plus 60% of the time of concentration.

ArcGIS/QGIS

ArcGis 10.8 version was used for the preprocessing analyses.

After the setup of the model, there are some parameters that have to be added to the model for its calibration. The Curve Number as well as the time of concentration are among those parameters that have been determined through the ArcGis software.

The input data of the model such as the rainfall and the evapotranspiration have to be the average of the whole different sub-basins. To do so, the Thiessen polygon were performed in order to get an average value for the input data. The formula was applied to obtained the average value of the rainfall and evapotranspiration. The discharge of the outlet which is Koulikoro station was used for the model calibration and validation. The Hargreaves method is used to compute the evapotranspiration calculation (Hargreaves, 1982).

HEC-GIS

This is one of the various options into the HEC-HMS version 4.5. It has a lot of under-options allowing to perform different tasks. From the coordinate system, fill sink, flow direction, flow accumulation, drainage etc… to the delineation of the catchment, all of these parameters are obtained. It is the final result of this point, the catchment delineated, that will be used for the calibration and validation. The sub-basin will be created as the last point of the geo-preprocessing.

HEC-HMS

HEC-HMS 4.5 is the software used for the calibration and validation for the purpose of flood forecasting analysis. After creating a new project, the DEM file clipped in ArcGIS was called inside the software. The preprocessing steps done, performed by the HEC-GIS already mentioned in the previous section, the compilation of the different inputs data starts.

Meteorological models, control specification, times-series data are the three main options in HEC-HMS for the hydrological modeling processes. In the meteorological models, climatic data (Precipitation, evapotranspiration) as well as the hydrological data (discharge) are put in the model.

The control specification served to put in place the beginning and the end of the running time. The period 1991 to 1995 was used for the model set up and calibration; and the period 1996 to 2000 for the model validation. The third option, the Time series data, allows to insert the rainfall, evapotranspiration as well discharge data for the same period.

Five sub-basins were generated after model preprocessing, but for this study, HEC-HMS has been used as a Lumped simple model. For that reason, the five sub-basins were merged to a single basin for the remaining of the hydrological modeling. Four parameters were used for this study: Simple Canopy, Simple Surface, Loss, Transformation. Simple canopy was used for the canopy calculation. Simple surface for the Surface parameter. SCS curve number was used as the loss parameter and SCS unit hydrograph as Transformation parameter. For the precipitation, specified hyetograph was chosen, specified evapotranspiration has been adopted for evapotranspiration.

HBV

The simple version of HBV such as the lumped model was used to simulate the discharge of flood events from the 1990 to 2000 in Mali. The input data are daily precipitation, temperature and discharge in the same folder called "PTQ" and the second folder called "EVAP" contains the daily evapotranspiration both of the folders are inside another one called "DATA". These different data must have the same date and then the same number of lines otherwise we will get an error in the running.

3.3.4. S.O.4 Flood forecasting system implementation through HBV and HEC-HMS in Koulikoro watershed

The methods used to achieve the objective are the following. First of all, the forecasted 4-ahead rainfall are rearranged in a way the models require it to be used for the hydrological modeling. Flood forecasting system can be split into several steps. After models calibration and validation, the forecasted rainfall will be used as input with evapotranspiration, discharge data by the models calibrated and at the end, the information will be broadcasted. The data obtained from the NCEP center on Copernicus website, are preprocessed with R software. This software allows to change the format NetCDF to CSV. The hydrological models such as HBV and HEC-HMS are recalibrated and revalidated with new parameters values. HBV and HEC-HMS have been recalibrated and revalidated with new values of the parameters.

The satellite rainfall data from Copernicus after calibration and validation are analyzed through Probability of detection (PoD) and False alarm rate (FAR) and critical success indices (CSI) in order to see whether the satellite rainfall is data that can be used for future studies. If the value of PoD is superior to the FAR values, the satellite data is meaningful and can be used for such kind of analysis.

PoD and FAR two indices used in this study are calculated following these formulae:

$$\text{PoD}=\text{HR}=\frac{A}{A+C} \qquad \text{FAR}=\frac{B}{B+A}$$

Where a is the PoD the success events (predicted and occurred), c corresponds to the missed events (not predicted but occurred) and b represents the false alarm FAR (predicted but not occurred).

After the calculation of both PoD and FAR, for the analysis to be completed and meaningful, the PoD should be divided by the FAR in order to know whether the model has to be used for further studies also if it has any adding value. The value superior to 1 means the PoD value is higher than the FAR value and then the model is meaningful for the analysis. Another criteria Critical Success Indices (CSI) is chosen for this study. The choice of this criteria is due to the fact that it takes into account both PoD and FAR in its formula which is:

CSI= $\frac{A}{A+B+C}$

3.4.Partial conclusion

The data used for this research work are made up of hydrological, meteorological as well as climatic data. Satellite image DEM for the study area is used also for hydrological modeling aspect. The flood forecasting requires the use of forecasted rainfall data which have been downloaded from the Copernicus website. For these data to be used, some materials were necessary. R-software from which several packages like RClimDex, Modified Mann-Kendall have been useful for the extreme rainfall indices and trend analysis respectively, Hyfran-plus for the analysis of extreme rainfall return period, the hydrological models HBV and HEC-HMS for the scope of the flood forecasting analysis, have been necessary for the work. Several methods were applied to these data through the materials. The extreme rainfall analysis as well as the relationship between extreme rainfall and flood events in Bamako has been carried out. The water balance through the calibration and validation of the model in the study area by HBV and HEC-HMS models is done. Lastly, the flood forecasting through the usefulness of the hydrological models has been done, allowing to reduce considerably the impact of coming floods.

CHAPTER 4: EVALUATING THE CURRENT STATE OF FLOOD FORECASTING MODELS FROM LOCAL TO REGIONAL LEVELS.

This review has focused on recent models and techniques applied in flood forecasting and flood warning system in Africa and particularly West Africa. In the present study, the current state-of-the-art in flood forecasting and flood warning system in Africa is deeply reviewed, and evaluated. Various hydrological models currently used in Africa and especially in West Africa for flood forecasting purposes are analyzed for their strengths and weaknesses.

Flood events occurrences and frequencies in the world are of immense threat to the stability of the economy and life safety. Africa continent is the third continent the most negatively affected by the flood events after Asia and Europe. Eastern Africa is the most hit in Africa. However, Africa continent is at the early stage in term of flood forecasting models development and implementation. Very few hydrological models for flood forecasting are available and implemented in Africa for the flood mitigation. And for the majority of the cases, they need to be improved because of the time evolution. Flash flood in Bamako (Mali) has been putting both human life and the economy in jeopardy. Studying this phenomenon, as to propose applicable solutions for its alleviation in Bamako is of a great concern.

4.1.The state-of-the-art of flood forecasting models and applications

There are several types of flood forecasting models and criteria for their classification. The catchment models used for flood forecasting may be classified according to the components in figure 14. Thus, the models may be classified depending on the way the catchment processes are represented either deterministic or data driven; or the way the catchment is spatially discretized such as lumped or distributed (Jain et al. 2018; WMO 2011). Deterministic models solve a set of equations representing the different watershed processes that produce a single model output for a given set of parameters (Jain et al., 2018). In contrast, data-driven models have the capability to simulate the random and probabilistic nature of inputs and responses that govern river flows (Jain et al. 2018). The type of model employed in a particular application depends largely on the primary processes that produce runoff and their spatial and temporal extent, spatial coverage and resolution of data, and catchment features (Kauffeldt et al. 2016). However, the state of the art operational and research on flood forecasting systems around the world are increasingly moving towards using ensemble probabilistic forecasts, known as Ensemble Prediction Systems (EPS), rather than single deterministic forecasts, to drive their flood forecasting systems (Cloke & Pappenberger 2008; Ramos et al. 2013; Alfieri et al. 2014).

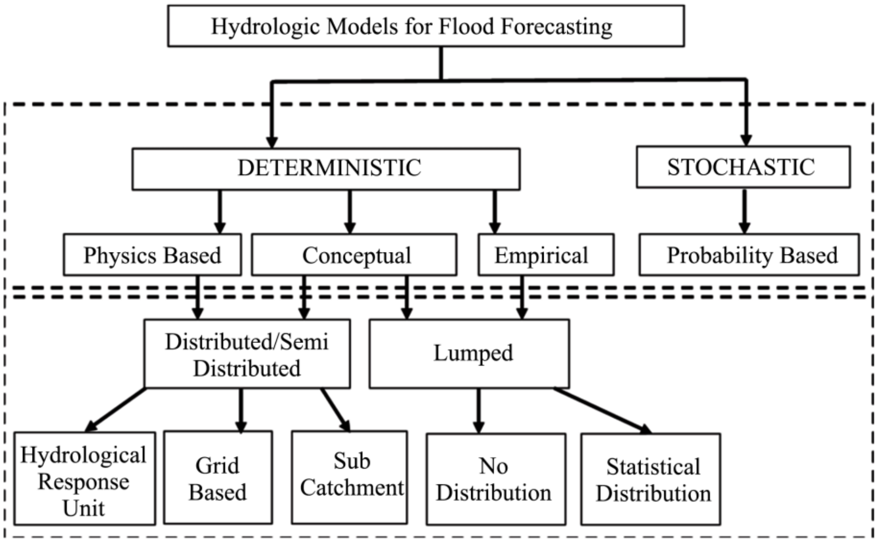

Figure 14: Classification of models used for flood forecasting based on model structure and type (reference: WMO,2011b)

The purpose of a flood forecasting and warning system (FFWS) is to alert in advance, the general public and concerned authorities of an impending flood, and with as much reliability as possible. Many factors can influence the quality of a flood forecasting system. Most of these factors rely on the constituents' quality of the system. The main constituents of the flood forecasting and warning system are: the input data (hydrological and meteorological data), forecasting, modeling, and dissemination of information to the end users.

The input data are used to force the hydrological models in the modeling process. They are climatic data obtained through the meteorological models.

The meteorological data, also called climatic data, are used to force the hydrological model. The main climatic data are precipitation and temperature which are frequently used by rainfall-runoff models in flood forecasting processes. Sometimes, the rain gauge data may not be enough in flood forecasting processes, especially when it is about the small catchment where the lead time is short. In that case, it becomes urgent to incorporate the Numerical Weather Precipitation (NWP) data in order to get forecasted rainfall. This data is important when carrying out a flood forecasting and warning system study. The input data of NWP has improved significantly nowadays, and has consequently improved the forecasting system extending the lead time to more than 15 days.

After the setting up of hydrological rainfall-runoff model, the calibration step begins. For that purpose, the discharge data, also called hydrological data are required. Many rainfall-runoff data used the discharge data in the flood forecasting modeling processes. In fact, the hydrograph resulting from the meteorological data will be compared to the observed discharge data for the calibration processes. Therefore, the quality of data such as rainfall and discharge, real-time measurement and forecasted is very important for the system.

The choice of the model is very important and depends on the aim of the research. This step is very crucial and need to be treated with great care. Several types of models exist. The choice of the models is important and will have an impact in the results. Deterministic and data driven models will not provide the same result, also lumped, semi-distribute and physical-based models will not give the same detailed output for the flood forecasting. Their use depends on the type of result that is required. So based on the issue, a specific model that suits better will be used to solve the issue of interest.

The last point of the flood forecasting and warning system is the dissemination of the information which is how to disseminate the results to the population in order to alert them about the coming floods and a need to take live saving decisions to avoid the catastrophes. This step is very important and everything depends on it. Not only the information has to be communicated on real time, allowing the population to evacuate and also the information has to be accurate for the people to trust the future messages. The accuracy of the information is very important for the reliability of the population to the communicated warnings. Henonin et al. (2013) compared the flood forecasting and warning system to a house building processes. While input data corresponds to "the foundation", the data collection to "the wall", the modeling processes to the "openings" and the warning is associated to "the roof" of the house. Like for the house architecture, the sustainability of the flood forecasting system relies on the combination of these different components. The quality of the system as well as the warning that will be launched to the people, depends on the quality of these components as well as their interconnection. None of them should be neglected.

4.1.1. Hydrological models for flood forecasting

According to Jain et al. (2018), catchment models are classified based on several criteria. The two main criteria are based on the way catchment processes are presented and the way catchment is spatially discretized. The models are deterministic or data driven regarding the catchment processes and lumped or distributed according to its spatial discretization. A third type of catchment model is based on the rainfall estimate and lead time.

The type of the models employed in a particular application depends largely upon the primary processes that produce runoff and their spatially and temporary extent, spatial coverage and resolution of data, and catchment features.

4.1.1.1.Physical based models

This is a mathematically idealized representation of the real phenomenon. This is also called mechanistic models that include the principles of physical processes. It uses state variables which are measurable and are functions of both time and space. The hydrological processes of water movement are represented by finite difference equations. It does not require extensive hydrological and meteorological data for their calibration but the evaluation of large number of parameters describing the physical characteristics of the catchment are required (Abbott et al. 1986). In this method huge amount of data such as soil moisture content, initial water depth, topography, topology, dimensions of river network etc. are required. Physical models can overcome many defects of the other two models because of the use of parameters having physical interpretation. It can provide large amount of information even outside the boundary and can be applied for a wide range of situations. Hydrological European System (SHE)/MIKE SHE model is an example.

Vischel et al. (2008) carry out a study in South Africa based on the implementation of the TOPographic Kinematic AProximation Integration (TOPKAPI) model for the first time in Africa in the Liebenbergsvlei catchment (4725 km^2). The TOPKAPI model, a physically-based distributed rainfall-runoff model, has been successfully applied in several countries in the world. The TOPKAPI model, applied in the Liebenbergsvlei catchment, showed good results and ability in modeling the river discharges at a small (6h) time-step with a limited adjustment of the parameters and low computation times.

A study based on modeling of flood hazard extent in data scarce area has been carried out by Komi et al., (2017) in Togo Republic especially in the Oti River basin. In the study, the hydrological model LISFLOOD was used for the flood modeling. The statistical tools showed a good result of the model (NASH 0.87 and 0.94 respectively for the calibration and validation processes) which means that the LISFLOOD model is a reliable tool for the flood modeling in the region.

Ansah et al. (2020) carried out a study in Ghana investigating the meteorological dynamic for the heavy rainfall that resulted in flood in Kumasi and Accra. The WRF-Hydro model was used to perform this study. It has been concluded that the floods occurring over the study area are non-meteorologically induced. Anthropogenic activities such as buildings on water ways and chocked drainage systems were responsible for the floods.

4.1.1.2.Conceptual models

This model describes all of the hydrological component processes. It consists of a number of interconnected reservoirs which represent the physical elements in a catchment in which they are recharged by rainfall, infiltration and percolation and emptied by evaporation, runoff, drainage etc. Semi empirical equations are used in this method and the model parameters are assessed not only from field data but also through calibration. Large number of meteorological and hydrological records is required for calibration. The calibration involves curve fitting which makes the interpretation difficult and hence the effect of land use change cannot be predicted with much confidence.

Many conceptual models have been developed with varying degree of complexity. Stanford Watershed Model IV (SWM) is the first major conceptual model developed by Crawford and Linsley in 1966 with 16 to 20 parameters.

Tefera (2015) has used the hydrological model HEC-HMS in his master thesis in order to be set-up and evaluated for flood forecasting in the Benue basin in Nigeria. The model has been integrated with GIS through HEC-GeoHMS. The model performance was satisfactory with NASH=0.5 for the calibration period and very good during the validation for some years of validation and poor for other years.

Hoedjes et al. (2014) performed a study in Kenya based on a conceptual flash flood early warning system for Africa. CREST (Coupled Routine and Excess Storage) distributed model is used in combination with the TMPA and rainfall forecast in Kenya for the purpose to generate the flood forecast in Kenya up to 10 days in advance. The results obtained were satisfactory and allowed to considerably reduce the impact of flood events through the implementation of the early warning system.

Assoumpta and Aja (2021) carried out a flood forecasting study in Rwanda using quantitative precipitation forecast and hydrological model in the Sebeya catchment. HBV hydrological model was used to perform the study and gave good results. It has been demonstrated that the number of hits is inversely proportional to the lead time.

HEC—RAS, a physical-based software on the fully De Saint Venant Equation was used to perform the study carried out in the Sirba River, the Middle Niger River basin (Massazza et al. 2019). The main goal was to assess the flood hazard in the Sirba River basin, in Niger. At the end of this work, the important output has been the availability of the data for the implementation of the early warning system and to provide the flood hazard map.

Adem et al. (2016) in Ethiopia, performed a study based on flood forecasting and stream flow simulation of the Upper Awash River Basin using Geospatial Stream Flow Model (GeoSFM). The GeoSFM gave satisfactory results with NASH values comprised between 0.67 and 0.70 respectively for the calibration and validation while the values of the coefficient of determination range between 0.60 and 0.65 respectively for the calibration and validation.

The flood impacts were very important in Mozambique with any flood control mitigation response. The Stream Flow Model (SFM), semi-distributed hydrological model was used as a flood forecasting tool to reduce flood impacts in the region (Artan et al. 2002).

The Centre for Ecology and Hydrology (IHE) developed a flow forecast model for the Somalian part of the Juba Shabelle River Basin, called Somalia FFM. The system uses upstream measurements and simple regression equations to predict river levels and flows at the key gauging stations. Fry et al. (2002) stated the reliability of the system for flow forecasts with a lead time of up to 1 week.

4.1.1.3.Empirical models

These models are observation-oriented models that take only the information from the existing data without considering the features and processes of hydrological system and hence these models are also called data driven models. It involves mathematical equations derived from concurrent input and output time series and not from the physical processes of the catchment. These models are valid only within the boundaries. Unit hydrograph is an example of this method. Statistically based methods use regression and correlation models and are used to find the functional relationship between inputs and outputs. Artificial neural network and fuzzy regression are some of the machine learning techniques used in hydro informatics methods.

Al-Zu'bi et al. (2010) developed the Takagi-Sugeno fuzzy model to estimate the Nile River flow at the Dongola station in Sudan. The performance of the model was assessed using observed discharge records of almost two decades. The results of the training and testing phase had a high VAF (variance-accounted-for) value indicating good modeling capacities. Within the study, it is demonstrated that the fuzzy model is able to represent the river flow at Dongola better than traditional modeling approaches and outlined the potential of their approach to provide accurate forecasts, in time and quantity.

4.1.1.4.Stochastic/Probabilistic models

Stochastic models reflect techniques based on time-series analysis, which have become very popular in hydrology (Box et al. 2016). Stationary stochastic models such as Auto Regressive Moving Average (ARMA) and non-stationary models such as Auto-Regressive Integrated Moving Average (ARIMA) can provide adequate representation of the dynamics of the RR process at large timescales, monthly or seasonal; parameters of these models have some physical interpretations in those cases. The success of these models can be attributed mainly to their simple mathematics, small computational requirements and their ability to reliably reproduce hydrographs. In the context of operational flood forecasting, ARMA models are mainly used for error correction.

(2006) carried out a study in Egypt in the Nile River basin based on flood forecasting. He used the statistical forecasting approaches (ARIMA models) for flood prediction with analysis of the historical inflow data. All the analyses of results proved the model suitability in forecasting the incoming floods to the lake Nasser upstream the high dam. Consequently, the statistical model could be used to predict the incoming flood during the period from year 2005 until the expected national project implemented at year 2017.

4.1.1.5.Ensemble forecasts

This type of flood forecast takes into account different aspects leading to an accurate early warning system. For the system to be accurate and reliable, the prerequisites are: accurate and high-resolution weather forecasts, availability of accurate ground observations for data assimilations, due consideration to the hydrological and meteorological aspect of the flooding, skilled personnel to interpret and issue timely warnings, effective communication of warnings signals to the most vulnerable sections of the population. The first points to be considered are the precipitation forecast data which have to be an accurate range of acceptable resolution. Thanks to the NWP, precipitation forecast data can be downloaded with precision and used as an input data to force hydrological models. The main source of uncertainties that may disrupt the result of the flood forecasting comes from the inaccuracies of the precipitation forecast (Hapuarachchi et al. 2011; Seo et al. 2017). The bias correction is needed to overcome this concern. The hydrological models, rainfall-runoff models are used to compute and to run the discharge output. The final point is to issue the flood information to the vulnerable and other type of population that are in the flood-prone area. Most of the African countries are at the earlier stage of the flood forecasting system development. This type of ensemble forecasting is not well developed and implemented in several African countries.

4.1.1.6.Data driven model/machine learning

Jain et al (2018) provide the capability to simulate the random and probabilistic nature of inputs and responses that govern the river flows. Data driven models are often referred to as black-box models because they depend on the statistical or cause-effect relationship between hydrologic variables without considering the physical processes that underlies the relationship (Luchetta and Manetti 2003). Data driven models can include stochastic models and non-linear time series models. An interesting application of data-driven techniques is to improve the real-time forecasts issued by deterministic lumped rainfall-runoff models, in which the catchment response is simulated by a conceptual model and the residuals are simulated by an ARMA model.

Practical applications of the data-driven models for flood forecasting are still lacking chiefly due to two reasons: data-driven models do not account for the changing dynamics in the physics of the basin over the time (land use change pattern, aggregation/disaggregation), the parameters of data-driven models are completely dependent on the range of the data (maximum, minimum) used for the calibration. The machine learning methods are an example of data-driven models' tools that are becoming popular and quicker to develop with minimal inputs. Contrary to the physical and numerical models that are unsuitable for the short-term prediction, the machine learning models are able to simulate both the short-term and the long-term prediction forecasts. Moreover, the easiest way to implement the model, associated to the low computation cost, as well as the fast training, validation, testing and evaluation with high performance compared to the physical models make it more accessible to the users. Also, according to Agudelo-Otalora et al. (2018); Kratzert et al. (2019) data driven models (such as machine learning) have proven to be even better than the physical, conceptual models in flood forecasting studies. Artificial Neural Network (ANN), Neuro-fuzzy, Support Vector Machine (SVM), Support Vector Regression (SVR), were reported to be the most machine learning algorithms widely used with ANN at their head (the best). They were reported to be suitable for the prediction of both the short-term and long-term flood forecasting. New techniques such as hybridization with other methods (soft computing techniques, numerical methods, physical methods) when applied to the machine learning methods, could allow a better improvement of the results (Mosavi et al. 2018).

Luchetta and Manetti (2003) compared a fuzzy-logic-based algorithm for hydrologic forecasting to an ANN model and showed that the fuzzy approach outperformed the ANNs. Liong et al. (2000) predicted daily river water levels in the Buriganga River, in Bangladesh by using a fuzzy logic model in which the upstream water levels were the inputs.

The table 5 represents a summary of different countries with the hydrological models implemented for flood issues with their characteristics.

Table 5: Summary of hydrological models used for flood forecasting in Africa

Countries	Models name	Models characteristics	Inputs	Remarks	References
Nigeria	HEC-HMS	Conceptual semi-distributed model	Temperature, Rainfall, Discharge	satisfactory results were obtained	Tefera (2015)
Ghana	WRF-Hydro	Conceptual Physical model	Rainfall, Temperature, Evapotranspiration, Land use	satisfactory results were obtained	Ansah et al., 2020
Morocco	HEC-HMS	Conceptual semi-distributed	Rainfall, Evapotranspiration, Discharge	satisfactory results were obtained	(Aqnouy et al.,2018)
Mali	MIKE-BASIN	Conceptual Physical model	Rainfall, Evapotranspiration	satisfactory results were obtained	(Danish Hydraulic Institue 2003)
Senegal	SWAT	Conceptual semi-distributed	Rainfall. Evapotranspiration, Land use	satisfactory results were obtained	(Neitsch et al. 2005)
Rwanda	HBV	Conceptual Lumped	Rainfall, Evapotranspiration, Discharge	satisfactory results were obtained	Assoumpta and Aja (2021)
Togo	LISFLOOD	Conceptual physical	Rainfall, Evapotranspiration, Discharge, Land use	satisfactory results were obtained	Komi et al., 2017
Kenya	CREST	Conceptual physical	Rainfall, Evapotranspiration, discharge, land use	satisfactory results were obtained	Hoedjes et al. (2014)
Egypt	ARIMA	Machine learning	Rainfall, evapotranspiration,	satisfactory results	(2006)

				were obtained	
South Africa	TOPKAPI	Conceptual Physical	Rainfall, Evapotranspiration, discharge, land use	satisfactory results were obtained	Vischel et al. (2008)

In Africa, it is difficult to get information related to flood forecasting system implemented for the most of the flood institutions in the region. According to Thiemig et al. (2010) most of the flood forecasting already implemented in Africa are obsolete and need to be improved. Moreover, it is well to recognize that the flood forecasting has improved nowadays because of the improvement of the rainfall forecast. The lead time, which can go beyond 15 days, has also improved with the rainfall forecast improvement. However, in Africa, lot of works have to be done especially in West Africa where the data resources are scarce.

4.2.Discussion

Hydrological modeling for flood forecasting is of upmost importance for early warning system and to decision makers. This review of literature reveals that Africans have started to be interested into the mitigation of flood events by the implementation of flood forecasting models. Africa is the third continent after Asia and Europe the most negatively affected by flood events causing important damages such as losses of life and enormous economic damages (EM-DAT,2015).

Despite the recognized importance, the flood topic has not received enough attention it deserves especially in Africa (Haile et al. 2016). HEC-HMS (Hydrological Engineering Center, 2009), HBV (Hydrologiska Byråns Vattenbalansavdelning, Lindström et al. (1997)), MIKE BASIN (Danish Hydraulic Institue 2003), GeoFSM (Artan et al. 2007b), SWAT (Neitsch et al. 2005) are the widely models used by many African institutions for the flood forecasting issues (Thiemig et al. 2011). SWAT was used in Senegal, Egypt and Tanzania respectively by the University of Cheick Anta DIOP, the Water resources institution and the Dar es Salam University. The HEC-HMS is applied in Burundi, Egypt, Ethiopia with a lead-time varying from 12h for small catchments to 3 days, it has been used in Nigeria (Tefera 2015). HBV was used in Zou basin in Benin to evaluate water resources and flood hazard (Hounkpe and Diekkruger 2018).

Africa is at an early stage of flood adaptation through hydrological modeling. This is why there are not so many hydrological models implemented and applied in West Africa regions. In West Africa, to the best of authors ability, the models widely used for flood forecasting issues are HEC-HMS, HBV, WRF-Hydro and SWAT. They have the ability to easily simulate the observed discharge. Also, the required input data are not too much for the model calibration. The computation time of the model is not very important. The fact that these models have been used in Africa can let us hope that their usefulness in every West Africa catchment. One of the main problem scientists are facing is the data collection issue. The weaknesses of HBV as well HEC-HMS can be the inability to model the physical aspect of the catchment. Because of that, the model cannot reproduce exactly certain reality aspects of the basin.

One of the challenges in flood forecasting domain in Africa is the difficulty to have access to the information. The majority of the implemented early warning system are already obsolete and need to be revised (Thiemig et al. 2015).

Urgent solution has to be found and implemented for the welfare of Population. Nowadays, there were numerous methods and models developed and used for flood forecasting around the world; however, it should be noted that flood forecasting requires a good understanding of both meteorological and hydrological conditions of the particular country or region (WMO, 2011). As numerical weather prediction models continue to improve, operational centers are increasingly using their meteorological output to drive hydrological models, creating hydro meteorological systems capable of forecasting river flow and flood events at much longer lead times than has previously been possible. Furthermore, developments in, for example, modelling capabilities, data, and resources in recent years have made it possible to produce global scale of flood forecasting systems. The main challenges African People are facing, are the financing for such kind of researches as well as the motivation and ambitious of the decision makers to take this issue seriously into account. The data required to carry out such kind of works are scarce in the region, making the study difficult to be undertaken. With the climate change, it will be more logical to go for flood prediction and implement hydrological models for the flood mitigation in advance rather than waiting for the catastrophe to happen and starts the mitigation aspect.

Several flood forecasting models are available and some already implemented in some countries. There are different from their structures, their required data, their outputs. If the physical models provide reliable results with a high accuracy, however, it required an important quantity of data with a high computation cost. That aspect makes its use difficult and restricted by just a few quantities of researchers. However, the conceptual models are more suitable in West Africa regions because of the less number of input data.

4.3.Partial conclusion

Flood events not only are occurring frequently and with a high intensity causing important losses of life and economic damages. In Africa particularly, the increasing occurrences and intensity of flood events in several countries and with very weak means of mitigation and adaptation is noticed. The focus should be put on the flood forecasting models in Africa, in order to reduce considerably the damages. Also, the various flood-prone areas, occupied by the population for settlements should be evacuated. Structural methods against flood (such as construction of levees, flood control reservoirs and river training work) have showed their limits, they have failed in the majority of the cases in preventing floods leading to enormous damages. Therefore, the researches should be oriented in the flood forecasting. Data collection, scarcity and inaccuracy are issues that need to be solved. Decisions makers have to be conscious of these facts and find solutions to data collection difficulties.

African countries are affected by the impact but in comparison with the developed countries, the impact is low as well as the occurrences, economic damages issues. Asian continent comes first followed by the Europe and then Africa. However, this has not to mislead Africans because even one death is too much. Due to the weak means to fight against flood, lot of damages in terms of losses of life and economic damages are noticed in Africa during flood events. The developed countries are in advance upon Africa because of their various means of protection against flood events, one of the important and useful solution is the flood forecasting systems implemented in several European and Asian countries, whereas in Africa, so much have to be done in that aspect.

CHAPTER 5 TRENDS IN FLOOD EVENTS IN BAMAKO AND ITS RELATIONSHIP WITH EXTREME RAINFALL BASED ON HISTORICAL FLOOD INFORMATION AND RAINFALL TIME SERIES.

This chapter describes the relationship between extreme rainfall and flood events occurrences in Mali especially in Bamako. Flood events are among the natural catastrophes which occur the most frequently. So many losses are linked to these catastrophes. The purpose of this study is to find out the trend evolution of floods in the past and the threshold value above which flood may occur in Bamako city. To do so, RClimDex package in R software has been used to get the extreme rainfall indices.

5.1.Change point analysis and homogeneity test

Presented in Table 6is the summary of homogeneity and stationarity tests, the calculated values are below the reference value of 1.96. Therefore, the null hypothesis is accepted for the independence and the Rang or normality test which implies that the time series are stationary. All these tests confirm the stationarity of the time series and verify the null hypothesis at 5% significance level. According to Lee & Heghinian test, the probability to have a break is equal to 0.219 in 2018. And finally, the procedure of segmentation of Hubert gives a significance level of the test of Scheffe at 1% which is considered as adequate.

Table 6: Summary of homogeneity and stationarity tests

TESTS	At 90%	95%	99%
PETTITT	Accepted	Accepted	Accepted
BUISHAND	Accepted	Accepted	Accepted
LEE & HEGHINIAN	Breakpoint in 2018, with a probability of break of 0.22 in 2018.		
AUTOCORRELATION-RANG	the calculated values are below the reference value of 1.96. Therefore, the null hypothesis is accepted for the independence and the Rang or normality test which means that the time series is stationary		

5.2.Station and gridded precipitation comparison

Figure 15 shows the comparison between CHIRPS and station rainfall data at Bamako. The daily and monthly scale data show a good correlation and unimodal pattern with the peak that appears in August for both CHIRPS and Station. The PBIAS value at monthly is 20% which is in an acceptable range according to (Cohen Liechti et al., 2012). The statistical comparison based on the Nash & Sutcliffe, Correlation Coefficient as well as the Mean Bias Error are shown in Table 7. The acceptable bias values range between -25% to 25% (Cohen Liechti et al., 2012). Satisfactory values were obtained from these statistical analysis' tests.

Table 7: Statistical comparison between CHRIPS and Station rainfall at Bamako

Statistical indicators	Daily	Monthly
Mean Bias Error	-0.20	-0.20
NSE	0.73	0.98
Correlation coefficient	0.73	0.99

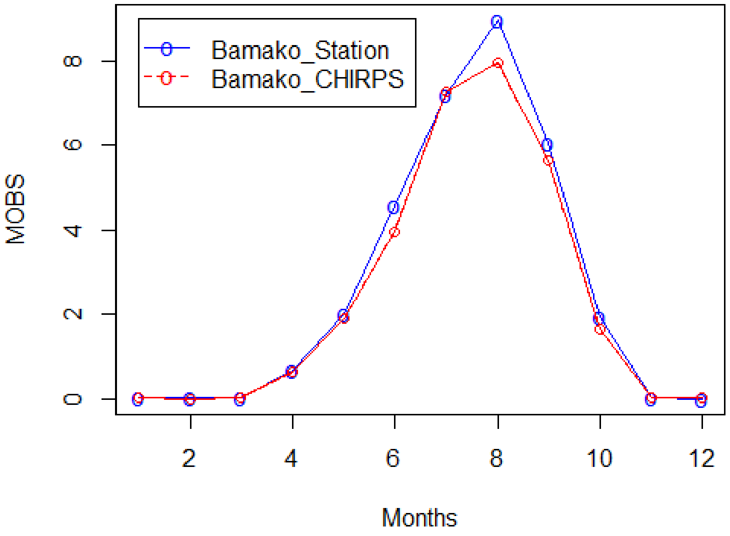

Figure 15: Bamako station and CHIRPS Rainfall comparison

All extreme rainfall indices have shown an upward trend for the study period 1982-2019 except the CWD (Fig.16). The rainfall RX1-DAY, RX5DAY, PRCPTOT have all presented an increasing trend from 1982 to 2019 (Fig.17;18;19;20) except the CWD that has shown a downward trend from 1982 to 2019 (Fig. 16). This confirms the studies done by Larbi et al., (2018) in the Vea catchment of Ghana during the period 2016-2018. However, according to the study by Tazen et al., (2019) in Burkina Faso, only RX1DAY, RX5DAY and R99PTOT showed an upward trend while the rest of the rainfall extreme indices showed a downward trend during the period of 1961-2015.

Table 8: Modified Mann Kendall test and Sen's slope statistics

Indices	P-Values	Z values	Sen's slope	Tau	S	Var(S)
RX1DAY	0.247	1.15	0.22	0.13	93	6327
RX5DAY	0.56	0.57	0.15	0.06	47	6327
CWD	0.36	-0.89	0	-0.10	-71	6077.66
PRCPTOT	0.006	2.74	4.88	0.31	219	6327
R99P	0.05	1.93	0	0.2	146	5628

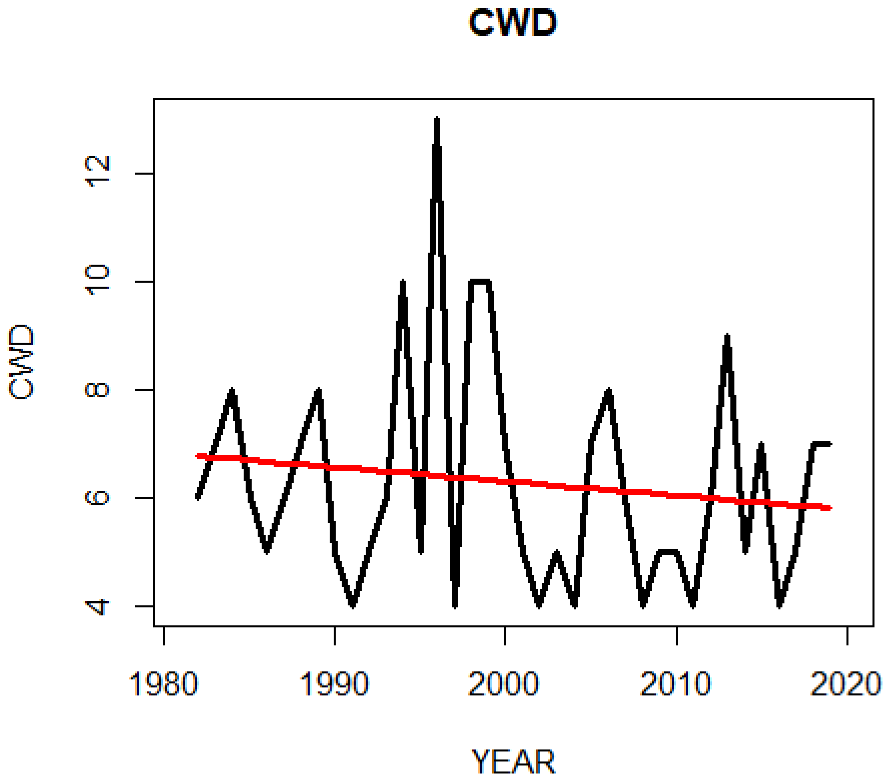

Figure 16: Extreme rainfall indices CWD

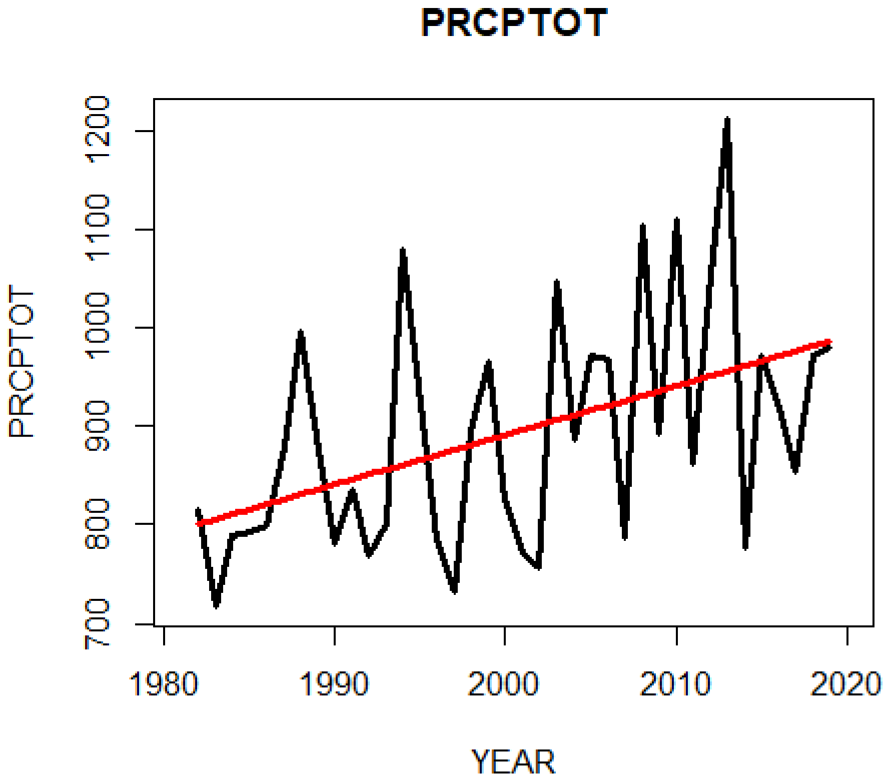

Figure 17: Extreme rainfall indices PRCPTOT

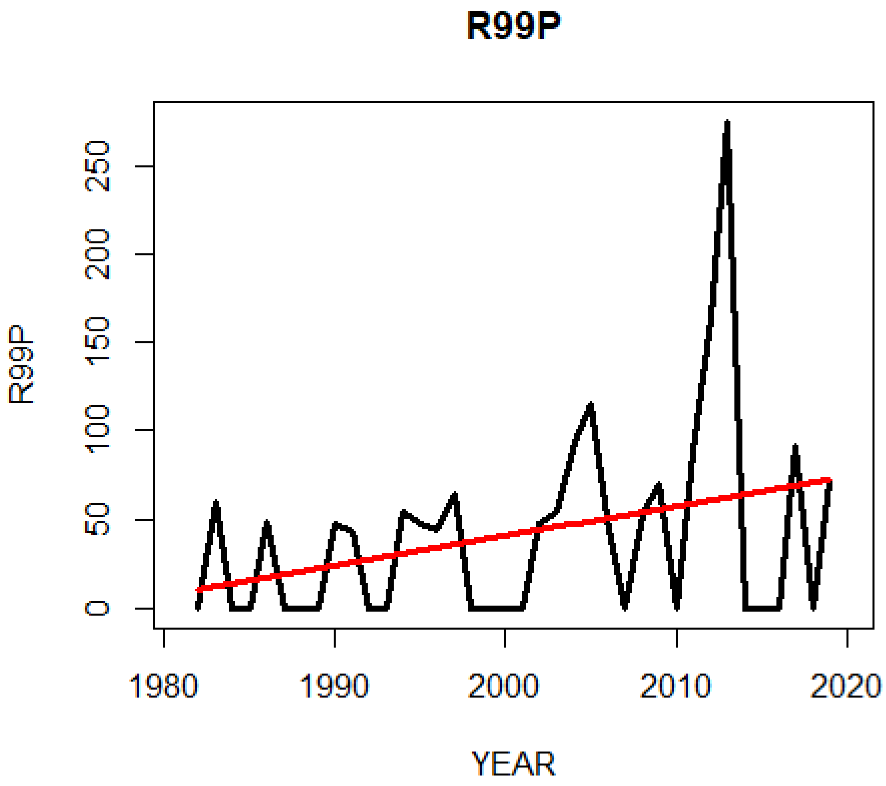

Figure 18: Extreme rainfall indices R99P

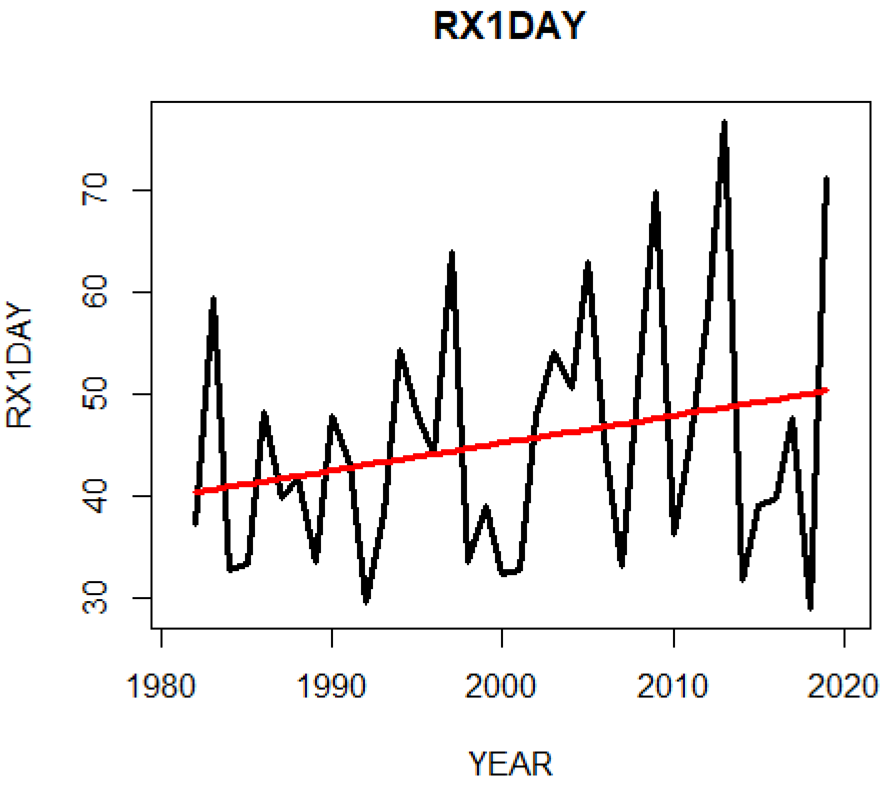

Figure 19: Extreme rainfall indices RX1Day

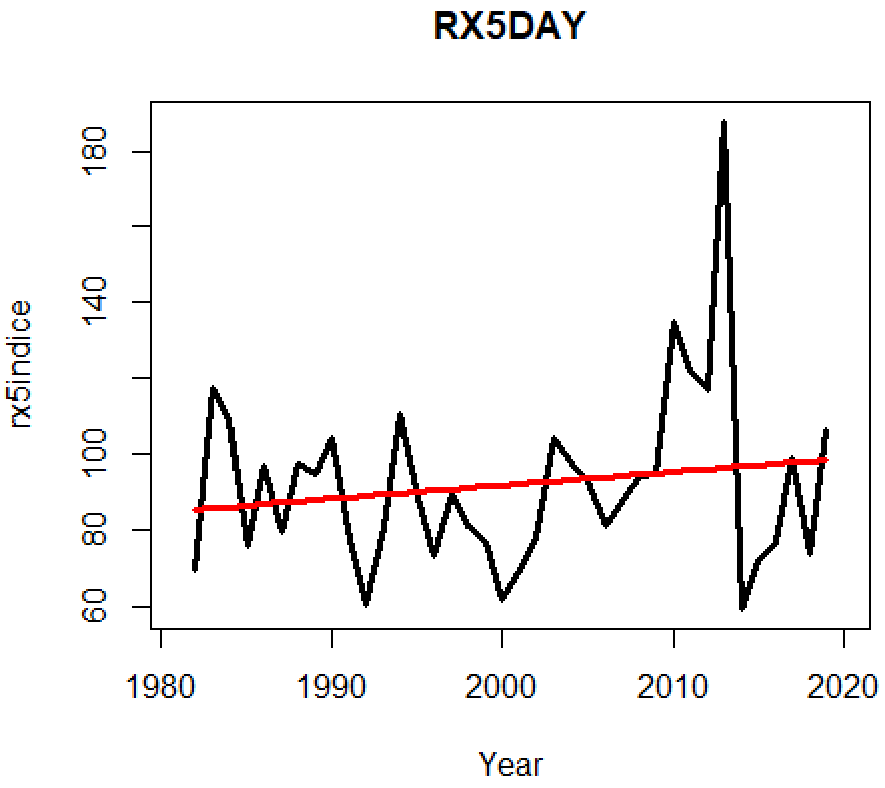

Figure 20: Extreme rainfall indice RX5Day

5.3.Historical Flood events in Bamako

Figure 21 represents the historical flood events occurring in Bamako since 1988 which has been provided by the National Directorate of the Civil Protection and EM-DAT. Since it is a new directorate, the historical data provided by the civil protection service extends from 2013 to 2019, the remaining is obtained on the EM-DAT website. It consists of number of victims; 2013 and 2019 appears to be the years with a great number of victims and deaths (Fig.21). These years correspond to the years with extreme rainfall over some West African countries which may create flash flood in some countries such as in Benin and Mali (Yabi et *al.*, 2012; Muller et *al.*, 2020).

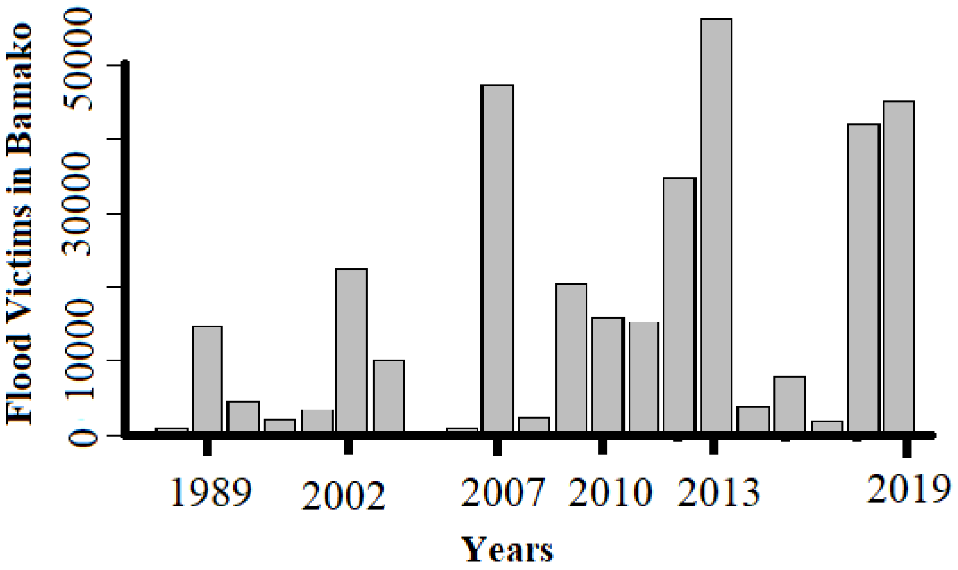

Figure 21: Historical flood information in Bamako related to flood victims

5.4.Return period for maximum daily rainfall

The standardized annual maximum index of daily rainfall is shown on Fig. 22. The index of the years 1983, 1997, 2005, 2009, 2013 and 2019 are greater than the unit and they correspond to the years with intense rainfall where most of floods were recorded. Particularly, 2013 corresponds to the year with an intense flood in Bamako. By comparing the two other extreme rainfall indices (annual maximum consecutive 5-days rainfall RX5Day and annual number of extremely wet days with rainfall greater than 99th percentile of rainfall), it is found that these indices impact on flood occurrences with similar characteristic like RX1Day (Fig. 19). However, 2013 remains the year with the highest intense rainfall. 2010, 1994, 2005 are the other years presenting a higher value of rainfall. The characteristics of CWD (Fig.16) is different from the other indexes. This is understandable since from 1982 to 2019, the rainfall occurrence and intensity have changed. The CWD (the consecutive wet days) shows that it was intense during the period 1990 to 2000 than the period from 2000 to 2019. However, the intensity of rainfall during the years from 2000 to 2019 was very higher explaining why the occurrence of flood events is more important from 2000 to 2019 than the year from 1982 to 2000. The occurrence of flood can also be explained by change in land use and soil characteristics. With more houses, soil destruction or trees cutting, the soil becomes more impervious not able to infiltrate rain water. Most part of the water coming from the rainfall is automatically running off on the surface causing the flood.

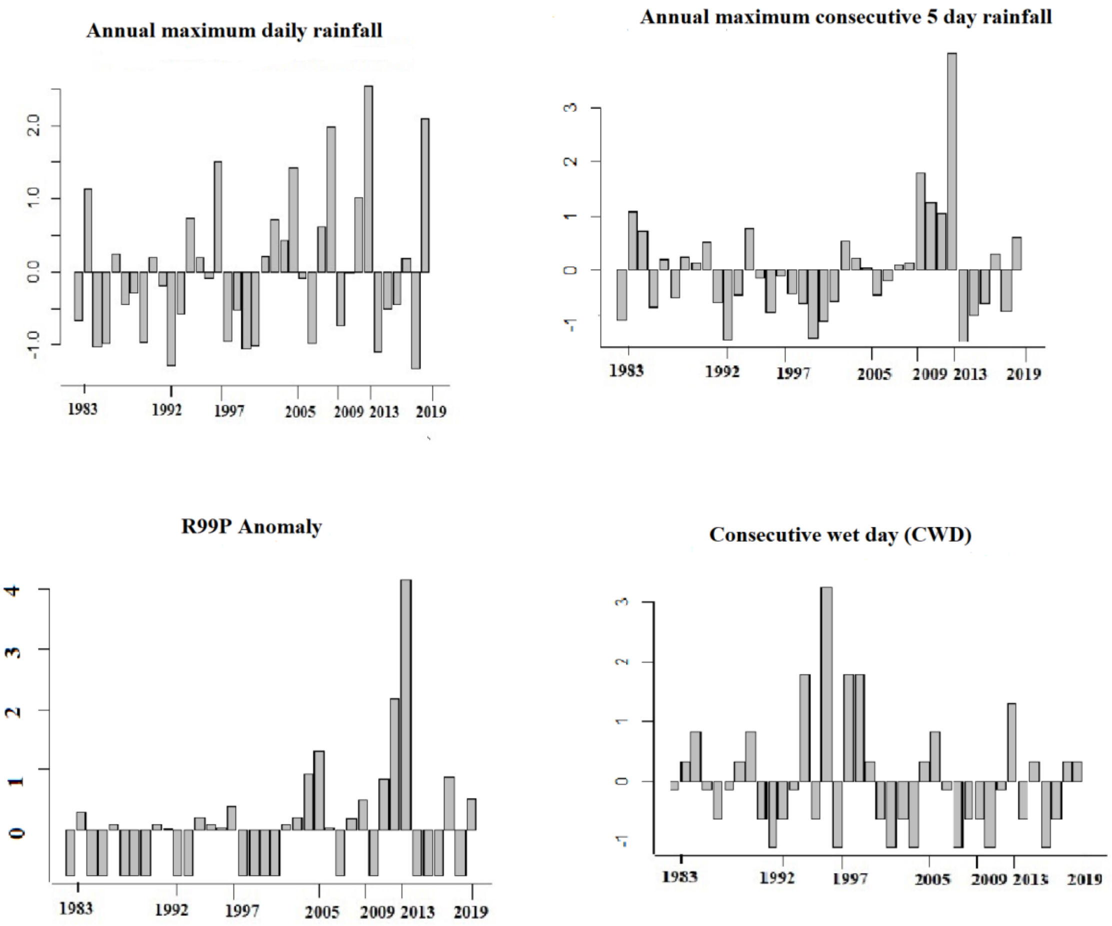

Figure 22: Extreme rainfall anomaly (RX1Day, RX5Day, R99P, CWD)

Three statistical methods (Gumbel, GEV, Log-Pearson type III) were retained for the analysis of the return period. Table 9 shows the comparison between Gumbel, GEV, and Log-Pearson (LP) distribution based on AIC and BIC criteria. The Chi-square test used to choose the best distribution for the return period estimation indicated the Gumbel distribution as the best with the lowest AIC and BIC values (Table 9). Presented in Figure 23 are the results for the return period of quantiles associated with the annual maximal daily rainfall at Bamako. Most of the floods which occurred in Bamako are in the range of normal (Return period T ≤ 5 with =54.4mm) to severe abnormal (Return period 10<T<50, between 61.4mm to 77.2mm). The values of annual maximum daily rainfall corresponding to the return periods of 5, 10, 50, and 100 years are respectively 79.8, 94.9, 137.9 and 161.1 mm.

Table 9: Comparison of the Gumbel, GEV, Log-Pearson (LP) distribution based on AIC and BIC criteria

Model	Parameters numbers	XT	P(Mi)	P(Mi)x	BIC	AIC
Gumbel	2	83.924	33.33	76.13	297.671	294.396

LP type III	3	84.903	33.33	15.88	300.805	295.893
GEV	3	81.640	33.33	7.99	302.179	297.266

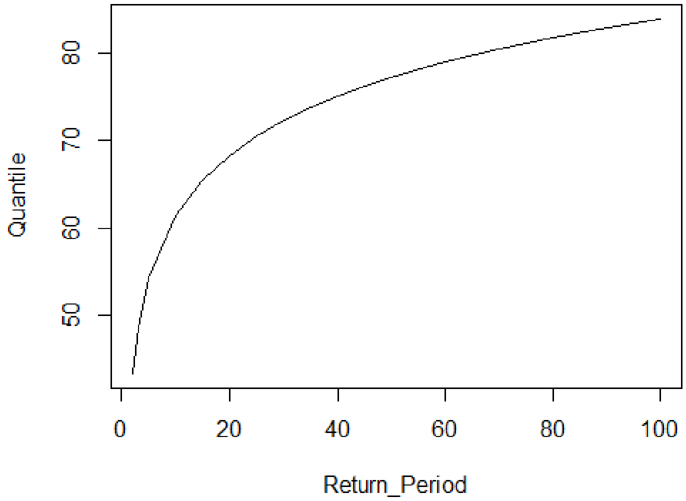

Figure 23: Return period of quantile associated with the annual maximal daily rainfall at Bamako

5.5.Relationship between extreme rainfall and flood events

The relationship between extreme rainfall and flood is derived by the calculation of the return period of Gumbel. It was noticed that most of the floods occurring in Bamako are classified in the range of normal to severely abnormal with a return period T≤5 and 10<T<50 respectively. Tables 10 and 11 represent the annual maximal rainfall (RX1Day) values and the return period with its attributed classes respectively. The comparison of both tables shows that the annual maximal rainfall is ranged between the return period (T) of 5 to 50 which are classified between the normal (return period T≤5) to severely abnormal (return period 10<T<50). In other words, the rainfall events in RX1DAY responsible for flood ranges from 44 mm to 76 mm. This range of values is in the class of normal (return period T≤5) to severely abnormal (return period 10<T<50) (Tables 4 and 10). The presented results clearly show that the rainfall responsible for the flood in Bamako, ranges between the normal and severely abnormal class of return period (return period 50≤T<100).

Table 10: Annual maximal rainfall with its corresponding return period and attributed classes

Years	Annual maximal rainfall	Return period	Attributed classes
1983	59.38	5≤T<10	Abnormal
1986	48.25	T<5	Normal
1990	47.78	T<5	Normal
1991	43.07	T<5	Normal
1994	54.3	T<5	Normal

1995	47.81	T<5	Normal
1996	44.18	T<5	Normal
1997	63.92	10≤T<50	Severely abnormal
2002	47.87	T<5	Normal
2003	54.12	T<5	Normal
2004	50.61	T<5	Normal
2005	62.87	10≤T<50	Severely abnormal
2006	44.19	T<5	Normal
2008	52.95	T<5	Normal
2009	69.82	10≤T<50	Severely abnormal
2011	45.05	T<5	Normal
2012	57.95	5≤T<10	Abnormal
2013	76.61	10≤T<50	Severely abnormal
2017	47.6	T<5	Normal

Table 11: Return period of the annual maximal rainfall with its correspondent quantile

Return period	5	10	15	20	30	40	50	80	100
Quantile	54.2	61.4	65.5	68.3	72.3	75.1	77.2	81.8	83.9

Years with R99P extreme values greater than 47mm coincide most of time with the years in which floods occurred in Bamako (which are 1994, 1997, 2005, 2009, 2010, 2013, 2019). The year with the highest rainfall is 2013 which is then considered as the year of an intense flooding event (Fig.24). The values of annual maximum daily rainfall corresponding to the return period of 5, 10, 20, 50, 100 years, are respectively: 54.2, 61.2, 68.3, 77.2, 83.9. A total of twenty floods were recorded from 1982 to 2019. Eight occurred in the period between 1982 and 2000 with one classified as abnormal and another one as severely abnormal and the remaining six in the normal class; twelve floods happened in the period between 2000 and 2019 where four are classified severely abnormal, one in the class of abnormal and the remaining seven in the normal class.

Therefore, 58% of floods that occurred in Bamako are due to normal rainfall while 33,3% are caused by severely abnormal rainfall.

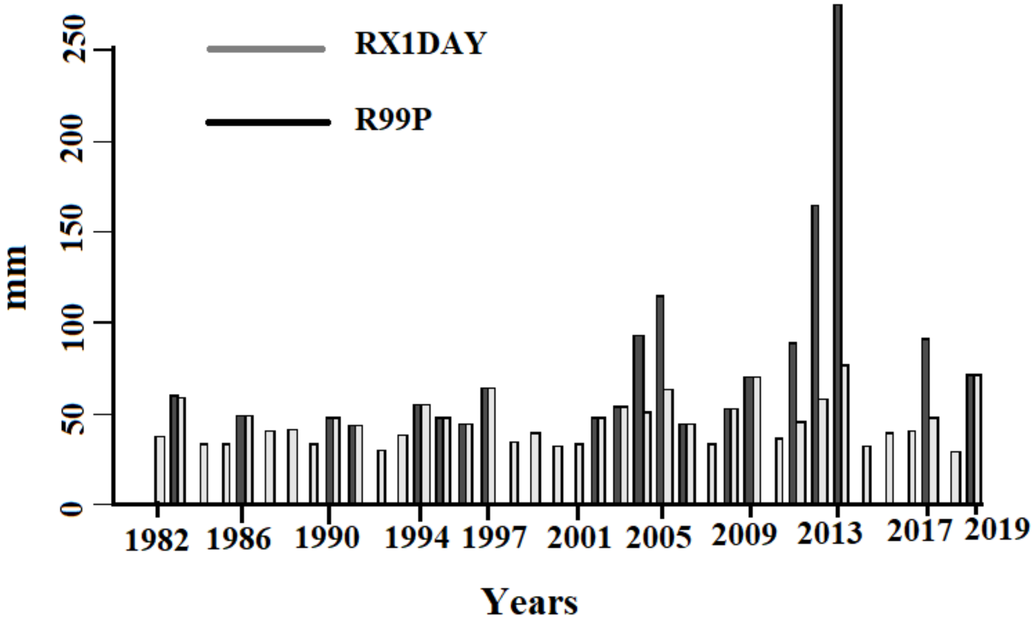

Figure 24: RX1Day and R99P extreme rainfall comparison

5.6.Discussion

This study presented the relationship between extreme rainfall and urban flash flood. The extreme rainfall indices computed showed an upward trend for the study period 1982–2019. The historical data has been collected from both National Directorate of Civil Protection and the EM-DAT website. The aim was to analyze the historical flood events occurring in the past in Bamako and to compare with the extreme rainfall indices data (RX1Day). There are some authors (Sarr and Camara, 2017) who found out that the Sahel region is experiencing a decreasing trend in rainfall. This could mean that the decreasing rainfall is not comparable to the extreme rainfall. While rainfall is decreasing in the Sahel region, the region is experiencing extreme rainfall occurrences, and increasing flood events. This finding is in conformity with the study done in Ghana at the Vea catchment by Larbi et al. (2018), and also the study carried out by (Sarr and Camara, 2017) who found out an increase in extreme rainfall and its consequences such as floods in the Sahel region. However, the study of Tazen et al. (2019) contrast the findings of this study who found out that the extreme rainfall indices (RX1 day, RX 5 day, R99p, RCPTOT) presented a downward trend in Burkina Faso. For the current study, it appears that the years where flood occurred in Bamako correspond with the years of heavy rainfall, meaning that the flash flood is mostly related to the extreme rainfall. For instance, the years 2013, 2019 appeared to be the years of flood in the historical graph, at the same time, these years correspond to the years of a heavy rainfall in the

RX1day indices This corroborates the relationship between extreme rainfall and flash flood occurrence. This is in the line with other studies done for examples in Egypt and Bangladesh by Nashwan et al. (2019) and Sarfaraz et al., (2019) respectively who found out that the flash flood is extremely related to extreme rainfall. The analysis of return period allowed for investigations into the type of rainfall responsible for the flash floods. The rainfall responsible for flood events in Bamako is ranged between the return period $T < 5$ and $10 < T < 50$, which is respectively classified in the normal to severely abnormal classes. This means that the rainfall responsible for flash flood in Bamako is far from being exceptional (return period $T < 100$). The last decade of the study period 1982–2019 presents a higher number of flood events than the first decade. This may be explained either by the development of impervious areas during the last decade and by the increasing extreme rainfall events or both. Similar results were obtained by Tazen et al. (2019) in Burkina Faso, where a normal rainfall induced a flash flood. In that case, the main responsible factor might be the land use changes. The increasing impervious areas not allowing the rainwater to infiltrate, leads to rainfall running off on the surface, thus causing a flash flood. Several methods are being developed nowadays in order to get better response against flood issues. One of these methods is low impacts development (LID). LID aims at putting in place a method that manages stormwater runoff and increasing infiltration in order to reduce surface runoff. Green roofs, rain garden, retention systems and porous pavements are some of the LID's natural structures developed to attenuate flood events impacts (Pour et al., 2020). Ahmed et al. (2017) stated that LIDs proved its effectiveness considerably by reducing peaks and water runoff volumes. It is a very cost-effective and is a climate resilient and suitable for urban development which plan to be sustainable. It is worth mentioning that this kind of study being rare in the Mali contributes to enhance the knowledge in flood issue and help the policy makers in their decisions related to floods. The threshold above which the flood could occur is well known in the study. This is very important in order to mitigate and to adapt to the flood damages. The main limitation of this study was the scarcity and lack of long-term data. Given that the changes in land use play an important role in the occurrence of flood, it is obvious that in the future, a study based on the land use changes has to be taken into consideration in order to highlight the implication of the land use changes in the occurrence of the flash flood in the study area. This increase in floods may be explained by either the small increase in the amount of precipitation from 1982 to 2019 or by the increase of the bare soil due to urbanization. Similar conclusions were drawn in the study of flood events done in Ouagadougou where there has been an increase in flood numbers from 1961 to 2015 and the rainfall responsible (Tazen et al., 2018).

5.7.Partial conclusion

It was noted that the value beyond which the flood may occur in Bamako town is 47mm, value obtained through the comparison between the extreme rainfall indices of RX1-DAY and R99P with the different dates where floods were recorded in Bamako. Years 2013, 2009, 2019, 2005,1997, 1983 were recorded as the years where the floods were intense accompanied by enormous damages. 2013 was recorded as the year of intense flood with 77mm of precipitation as annual maximal daily rainfall located in the severely abnormal class. The evidence is that the floods that occurred in Bamako from 1982 to 2019 are far from being exceptional, which means that the flood is not caused by an exceptional rainfall. Another remark is that the number of floods from 1982 to 2019 has increased. Eight floods in the periods of 1982 to 2000 and twelve floods from 2000 to 2019.

CHAPTER 6 CALIBRATION AND VALIDATION OF HYDROLOGICAL MODELS HBV AND HEC-HMS FOR THE FLOOD FORECASTING SYSTEM PURPOSE

This chapter focuses on the calibration and validation of the two hydrological models that are used in this study by the observed historical rainfall data in the study area. Calibration and validation details of both models are well explained in the section 1. The sections 2 and 3 are based on the water balance and peak flow discharge respectively. The discussion and partial conclusion are contained in sections 4 and 5.

6.1.Hydrological modeling calibration and validation

HEC-HMS model was used for the purpose of flood forecasting in the Upper Niger River Basin, Koulikoro catchment. The study area, delineated by ArcGIS, is used as an input for the HEC-HMS model providing the catchment characteristics for the remaining of the hydrological modeling. Lumped HEC-HMS version was used for this study. For that option, the five sub-basins created during the preprocessing were merged to have one single sub-basin area as the catchment of the whole study area (Fig.25).

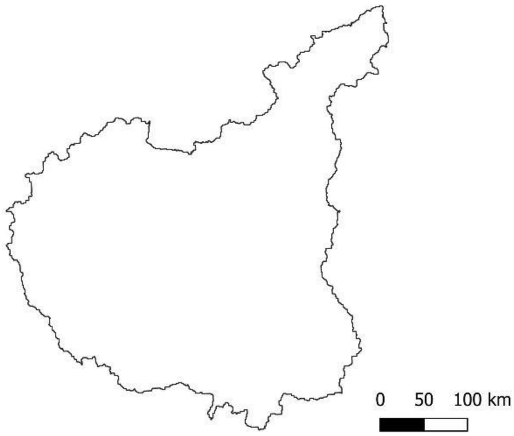

Figure 25: Sub-basin merged to one single basin

The study period ranges from 1991 to 2000. The data has been split into two parts: from1991 to 1995 for the calibration and the remaining from 1996 to 2000 for the validation. The model gave satisfactory results for both calibration and validation with NASH value of 0.80 and 0.70 respectively (Fig.26; 27). Four main parameters were used for this calibration process: Curve Number, Canopy, SCS Unit Hydrograph and Simple Surface.

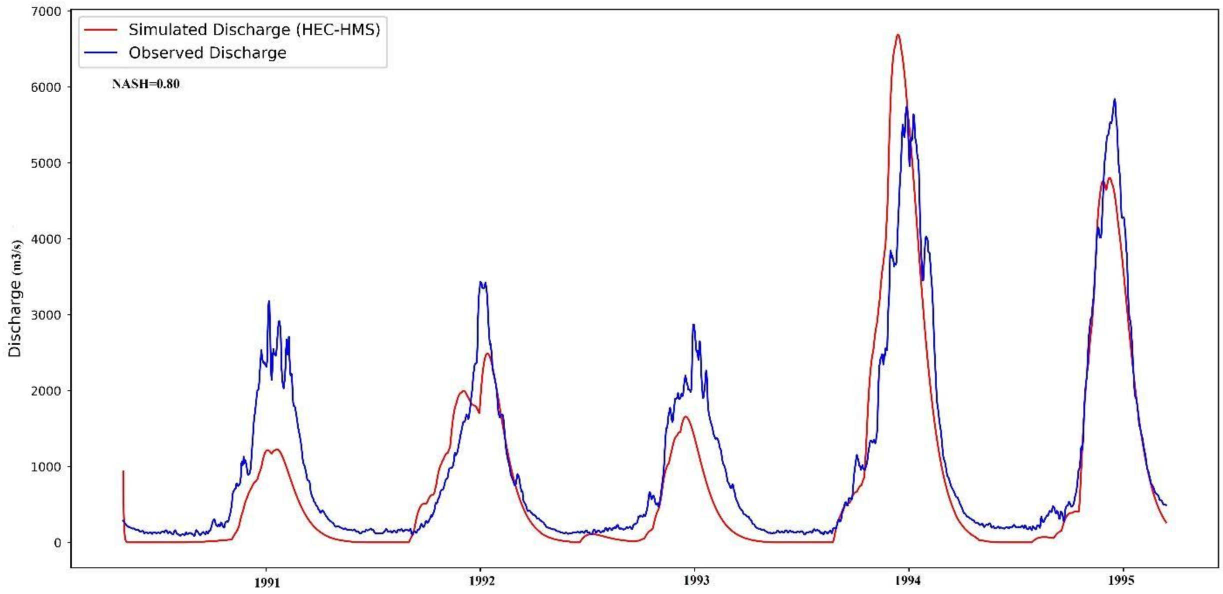

Figure 26: HEC_HMS Calibration 1991-1995

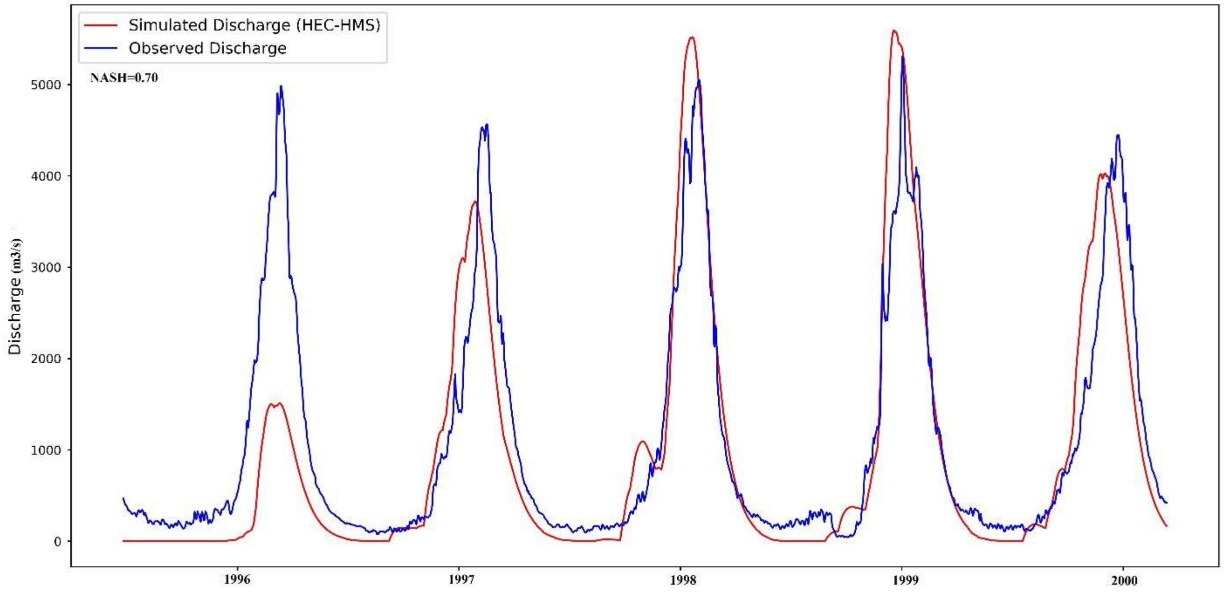

Figure 27: HEC-HMS Validation 1996-2000

HBV lumped model was used in order to simulate the flood events that occurred in the Koulikoro catchment during the study period 1991-2000. After preprocessing the data using ArcGis for the area map as well as the calculation of average rainfall and evapotranspiration through Thiessen polygon method, the data were computed inside the model. The time series data were divided into two parts. The first starts from 1991 to 1995. It has been used to set up the model and calibrate it. The remaining data were used for the validation 1996-2000. The main parameters calibrated for this study are: the soil moisture routine composed of FC, LP, BETA, the response routine containing the PERC, UZL, K0, K1, K3 and the last parameter which is Routing routine MAXBAS. The HBV model simulates well the discharge for the calibration period 1991-1995 with a NASH value of 0.90 (Fig.28). The HBV model is suitable and capable to simulate flood event and then can be used for the flood forecasting analysis in this area in Africa. HBV model, despite its easiness to be used, seems to not be widely applied in Africa region for the flood mitigation. Very few literatures exist on it. This can confirm the novelty of this work that confirms the usefulness of the model applicability and suitability to be used in the African regions.

During the validation, the HBV model simulates well the discharge for the period of 1996-2000. The value of NASH-Sutcliffe coefficient is 0.92 (Fig.29).

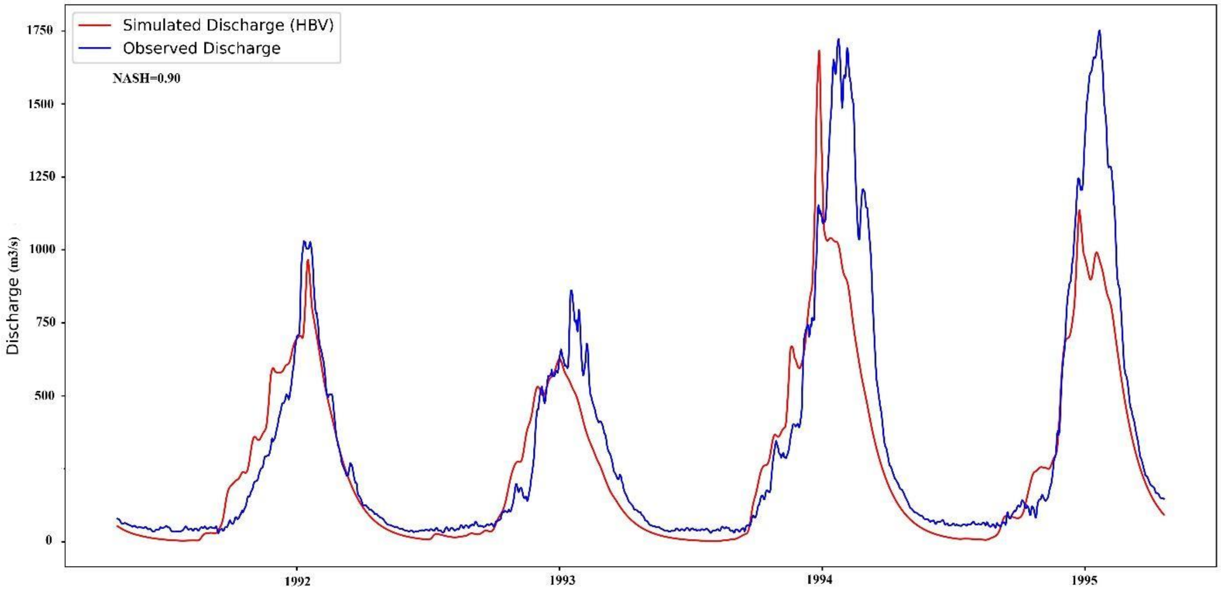

Figure 28: HBV Calibration

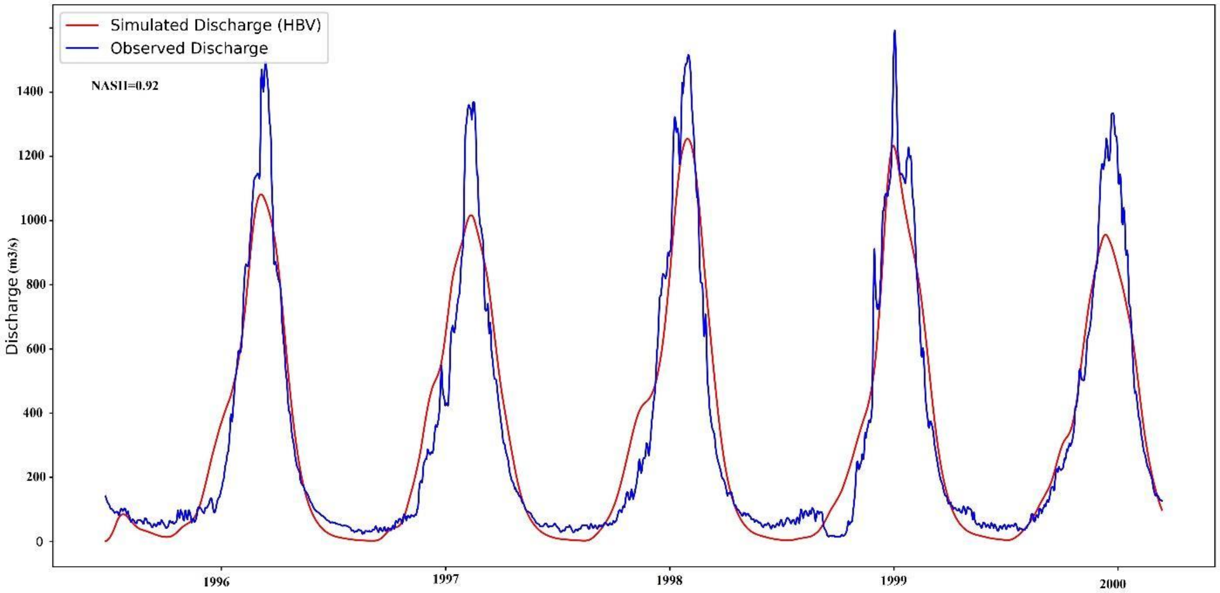

Figure 29: HBV Validation

6.2.Water balance

The Niger River Basin is known to be in an area where the climate is very hot. From Guinea to Mali, the flow decreases as well as the rainfall. Three main water balance components (rainfall, evapotranspiration and discharge) are selected during this study by the two models (HEC-HMS and HBV). Both of the models simulated well the water balance components, however the amount of evapotranspiration is very high both in the calibration and validation, the remaining of water is running on the surface. Just less than 1% of the rainfall is infiltrating under the ground to recharge the aquifer. For HEC-HMS model, 60.62% of the rainfall is evaporated and just 39.24% run off over the land and less than 2% infiltrated for the calibration period. For the validation, 75.37% of rainfall evaporated, 24.64% run off over on the surface and less than 1% infiltrated. (Table12).

Table 12: Water balance

Rainfall	Rainfall	ETR	Q	Storage
Calibration HEC-HMS 1991-1995	2486.8 (100%)	1507.8 (60.62%)	976.1 (39.24%)	-1%
Validation HEC-HMS 1996-2000	2550.2 (100%)	1922.1 (75.37%)	628.4 (24.64%)	1%

6.3.Peak discharge

The objective for using the models are to see their ability to simulate the discharge along with its peak if any. In Mali, floods occurred in 1994 and the dry year started from 2000. Both of the models simulated well the high discharge, and the different peaks values noticed in 1994 and 1998, 1999 correspond to the years of flood in Mali especially in Bamako.

The ability of the models to well simulate the high discharge allows them to be considered as models that can deal with floods issues.

6.3.Discussion

The catastrophes caused by the flood impact can be mitigated through the implementation of certain methods. One of the strategies is the employment of a flood estimation system using hydrological rainfall-runoff models (Devi et al., 2019; Gao et al., 2017; Knebl et. al., 2005) the conceptual and physical-based models enhance the understanding of hydrological process and flood occurrences. Recently, flood forecasting application is becoming more and more important because it can provide lead time for the people to take immediate or emergency response before the occurrence of flood, and then reduce the impacts of flood (Hamidon et al., 2020). The performance of these hydrological models are however limited to the spatial and temporal accuracy of rainfall input (Arnauld et al., 2002; Pechlivanidis et al., 2017).

Several rainfall-runoff models are available nowadays in order to get better response in flood forecasting. These models allow to predict peak discharge, river flow volume of a catchment using the rainfall input data as well other data such as the evapotranspiration and the observed discharge data. One of this widely used model is the HEC-HMS model. Nowadays, the advance of GIS and its association with hydrological model lead to better results in the flood forecasting analysis. The catchment characteristics based on the digital elevation data is well estimated through the usefulness of the GIS in rainfall-runoff model. The HEC-HMS is used for the discharge simulation representing the catchment response to the rainfall input data (Knebl et. al., 2005). The model will simulate rainfall-runoff and routing process in natural or controlled watershed. It shall predict flow, stage, and timing for giving rainfall input into the basin.

Etche (2019) in his Master thesis, defended on 02/09/2019 in Cote d'Ivoire, used the hydrological model HEC-HMS for the flood inundation modeling in the Gourou watershed in Cote d'Ivoire. He presented the ability of the HEC-HMS to model fairly well the peak discharges. Tefera (2015) has used the hydrological model HEC-HMS in his master thesis in order to evaluate the flood forecasting in the Benue basin in Nigeria. The model has been integrated with GIS through HEC-GeoHMS. The model performance was satisfactory with NASH=0.5 for the calibration period and very good during the validation for some years of validation and poor for other years. Again, Oleyiblo et al., (2010) studied the performance applicability and capability of the model HEC-HMS to perform the flood forecasting in China. The model has been well calibrated and validated with an acceptable statistical value 0.9 for the coefficient of determination and was able to predict the flood. Ramly et al., (2016) studied the flood estimating for smart control operation through HEC-HMC in Kuala Lumpur. The results show promising performance regarding the use of radar rainfall, and there was an acceptable percent error in the peak discharge simulation. The main inputs of the HEC-HMS comprise the characteristics of the catchment, infiltration loss method, transform method, base flow method and meteorological data. While, the main outcomes consist of the hydrographs, peak of the discharge, flow volume. The outcomes of the HEC-HMS can be used for designing structural measures for river flood mitigation (Ramly et al., 2016).

It is the lumped hydrological model of HBV that is used for this study. The fact that it uses very few amount of data and its easiness to be computed make it very common useful model for the hydrological scientists. Grillakis et al., (2010) studied the application of HBV hydrological model in a flash flood case in Slovenia. The results were satisfactory with good values of Nash ranged between 0.82 and 0.96. Kobold et al., (2006) carried out a study based on the use of HBV hydrological model for flash flood forecasting in Slovenia. The results obtained were good with Nash and Sutcliffe efficiency criterion.

This study aimed at implementing a hydrological rainfall-runoff model in the study area for the flood issues. HEC-HMS and HBV models were used for this study in Upper Niger River Basin area in Mali. Both of the models gave satisfactory results during the calibration and validation respectively 0.90 and 0.71 for the HBV model and 0.80 and 0.70 for the HEC-HMS model. For the best of our knowledge, any study regarding the hydrological modelling based on flood events was carried out in the Upper Niger River Basin particularly in the Malian part of the Niger basin.

Ramly et al. (2019) used the HEC-HMS model in flood forecasting study in the Malasia, Klang River Basin. They obtained good results with 0.86 Nash value. In China, Haibo et al. (2018) carried out a flood forecasting study using the HEC-HMS hydrological model in the Huan river in Xiaogan city. The results obtained were satisfactory with 0.92 as model efficiency value. In Canada, Manitoba (Bhuiyan et al., 2017) performed a flood forecasting study for both continued and events simulation in the Sturgeon Creek watershed. The result obtained, showed that the suitability of the model to simulate both the events and continued well. Oleyiblo et al. (2010) in Misai and Wan'an catchment in China performed a study regarding the flood forecasting issue. According to these authors, all of the model efficiencies (coefficient of determination and coefficients of agreement) were above 0.92 meaning that the model HEC-HMS is suitable to simulate the flood forecasting events in this catchment in China. Also in Africa, even if it is not frequent HEC-HMS has been used in some countries for the flood issues. Tefera (2015) and Etche (2019) used HEC-HMS model for the flood forecasting purpose in Nigeria and Cote d'Ivoire respectively. Both of them obtained good results and the HEC-HMS model simulated the flood events.

If Tefera's study in 2015 has been carried out in the Nigeria part of the Niger River Basin, this current study in the Upper Niger River Basin in Mali is in the same line. As in Nigeria and Cote d'Ivoire, satisfactory results 0.80 and 0.70 respectively for the calibration and validation were obtained. This proves the efficiency and suitability of the model for Africa continent and especially the study region.

Moreover, regarding the water balance, 60.62% of the rainfall are evaporated and just 39.24% are flowing on the surface and less than 1% are infiltrated during the calibration. For the validation, 75.37% of rainfall are evaporated, 24.64% are flowing on the surface and less than 1% are infiltrated when using HEC-HMS model. These results showed that the majority of the rainfall is lost by evaporation (more than the half) the remaining is flowing on the surface leading to a probable flood, very few quantity of precipitation is infiltrated generally less than 2% for the period between 1990 to 2000. This can be due to the climate of the region, very hot and also the quality of the soil not allowing water to infiltrate. This finding is in the same line of the study done by Mahe and Paturel (2009) about the Sahel annual rainfall variability and runoff increase of Sahelian rivers. They stated that the increase of temperature over West Africa during the end of the 20th century induced of Potential Evapotranspiration. However, the joint effect of climate change and human activities on land cover over more than three decades is responsible for an increase of the runoff coefficient of the West African Sahelian rivers since 1970s, despite the rainfall shortage during the same period. For that raison, the fresh water can be a serious problem in the future in that region. Because very few of water are infiltrated, more than 85% are evaporated and 10% are flowing on the surface due to the soil degradation and the remaining is infiltrated. This means that the groundwater is not well recharged.

It is important to precise that the effect of the Selingue dam was not considered during the modeling process. Selingue dam is located in a tributary of Niger River Basin called Sankarani.

It has an impact of the main Niger River Basin in Koulikoro because most of the time, the release of water induces an increase of water in the River Basin. Selingue dam allows to regulate the hydrology of the Niger River especially in Koulikoro. It can contribute to allow water to flow during the dry period in the basin. During the rainfall season, the extreme rainfall coincides sometime with the release of water from the dam which can lead to a flood. During the modelling process, the Selingue dam has not been taking into account. This is important to acknowledge knowing the importance of the dam in the region. The purpose of the hydrological modelling was to analyse only the discharge functioning as well as the probable flood occurrences in the region without the implication of any dam. The impact of the dam for the flood is weak however, its importance is huge when regulate the hydrology in the region especially during the dry period. For this study, it has been decided to model the hydrology of the basin without taking into account the dam influence.

6.4.Partial conclusion

This study aims at implementing a rainfall-runoff model in the Upper Niger River Basin in Mali, Koulikoro watershed, for the purpose of flood forecasting issue, water balance characterization and peak flow simulation. The models HEC-HMS and the HBV are used for this study. The HEC-HMS and HBV models are the mostly models used in Africa because of their easiness uses, computation time and input data required for its running.

The hydrology of the area showed that more than 60% of water are evaporated and 30% are flowing on the surface, the remaining less than 2% are infiltrated. This may highlight the issue of fresh water availability in the coming years.

The peak discharge was simulated by both of the models. Also, the years of flood 1994, 1998, 1999 are the years presenting the peak discharges. Both of the models are suitable for the use of flood concerns in the region. This is an adding value in the concept of flood adaptation in the region. Because for the best of our knowledge, any flood adaptation study through hydrological modeling implementation in the area has been carried out. This study confirms the efficiency, suitability and capability of the Lumped HBV-and HEC-HMS models to simulate the flood discharge in the UNRB area in Mali for the flood forecasting adaptation purposes.

CHAPTER 7 FLOOD FORECASTING SYSTEM IMPLEMENTED THROUGH HBV AND HEC-HMS MODELS IN KOULIKORO WATERSHED

This chapter deals with the hydrological flood forecasting modeling aspect. Based on the simulated flood and discharge results from HBV and HEC-HMS, modelling flood in the study area was achieved.

The hydrological modeling results are included in section 1. The discussion as well as the partial conclusion are summarized in sections 2 and 3 respectively.

7.1.Hydrological modeling

The data has been split into two parts. The first from 1993 to 1998 used for the calibration and the second one from 1999 to 2013 for the validation. Both the calibration and validation have been well reproduced by HBV model with good values of model efficiency values. Since the rainfall is forecasted according to the lead-time of 24h-ahead, 48h-ahead, 72h-ahead and 96h-ahead, the plots of each of these lead-times are done. Satisfactory results and values of NASH as well as the coefficient of determination are obtained from both the calibration and validation. NASH values for the calibration of the 24h, 48h, 72h, 96h are respectively 0.59;0.89;0.83;0.83 (Fig.30; 31; 32; 33). Regarding the validation of 24h, 48h, 72h, 96h, the NASH values are respectively 0.71; 0.84; 0.83; 0.86 (Fig. 34;35;36;37).

Regarding the flood forecasting processed by HEC-HMS model, good values of NASH are obtained. The same length and type of data has been used when using the HEC-HMS model like during the modeling process with HBV model. Curve number, SCS Unit Hydrograph, Simple Canopy, Simple Surface are the various parameters used to calibrate the model. The most important parameters are the curve number with the peak of the simulated discharge and the SCS Unit hydrograph which impact both on the shape of the graph. The model efficiency NASH values during this calibration for the 24h, 48h, 72h and 96h forecasted rainfall are respectively 0.74, 0.76, 0.71 and 0.62 (Fig.38; 39; 40; 41). For the validation the NASH values are respectively 0.82; 0.84; 0.77 and 0.76 for respectively 24h, 48h, 72h and 96h (Fig.42,43,44,45).

Except the figures 30 and 31 respectively the calibration of 24h-ahead and 48h-ahead of HBV hydrological model, the remaining of the figures are in the Annexes section.

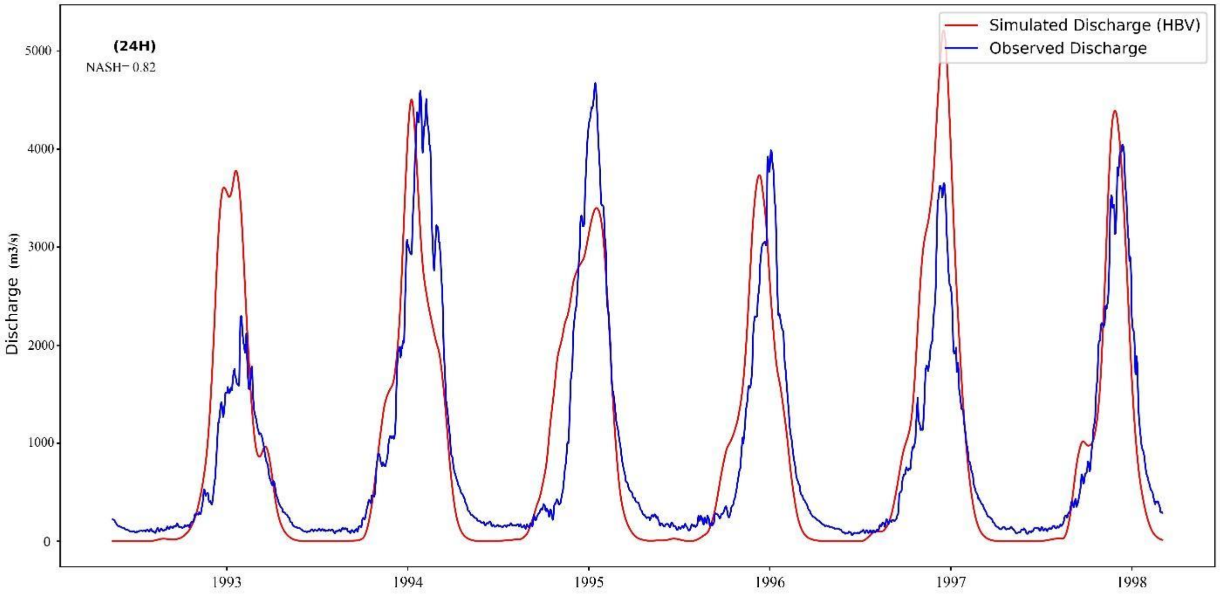

Figure 30: HBV-24H Calibration

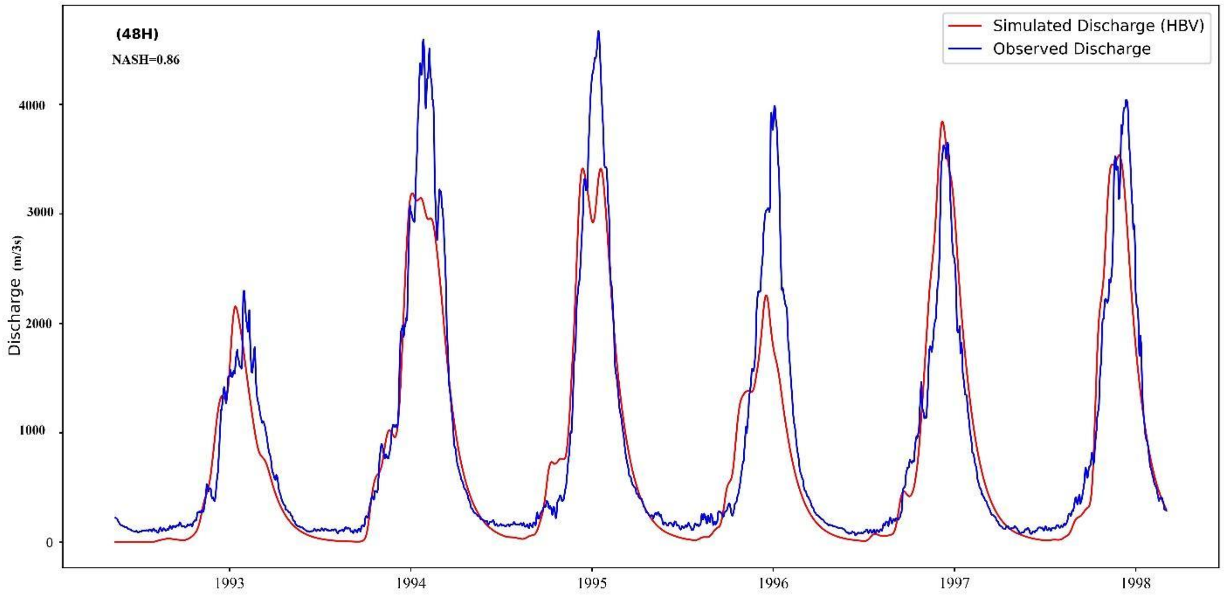

Figure 31: HBV_48H Calibration

These results are summarized into the table 13.

Table 13: Summary of model parameters values

Models	Parameters	NASH
HBV	FC 50 LP 0.99 BETA 0.1 KO 0.04 K1 0.001 K2 0.01 MAXBAS 25	Calibration 24h: 0.59 48h: 0.89 72h: 0.83 96h: 0.83 Validation 24h: 0.71 48h: 0.84 72h: 0.83 96h: 0.86
HEC-HMS	Simple Canopy 80 Simple Surface 80 Curve Number 6 SCS Unit Hydrograph 30000	Calibration 24h: 0.74 48h: 0.76 72h: 0.71 96h: 0.62 Validation 24h: 0.82 48h: 0.84

		72h: 0.77 96h: 0.76

7.2.NCEP center and model efficiency determination through PoD and FAR

The probability of detection (or the hit rate HR) and the false alarm rate FAR are essential and necessary for the analysis of any forecasted rainfall for any flood forecasting study. It allows to know the probability of occurrence of the forecasted rainfall. The PoD or HR is only based on the occurred events after being predicted. So it takes into account only the occurred events. In contrary to the PoD, the FAR only considers the events that did not occur after being predicted to occur. These two parameters are important and should have to be used together. They need to be associated each other in order to put light on the quality of the forecasted rainfall. A table of contingency (Tables 14; 15) is made based on the various events such as: the success events, the false alarm rate, the missed events, the correct rejection events.

Table 14 Contingency table

Predicted events	**Observed events**		
	YES	NO	Total Marginal
YES	SUCESS	FALSE ALARM	OCCURED
NO	MISSED	REJECTION	NON OCCURED
Total Marginal	OCCURED	NO OCCURED	TOTAL

Table 15: PoD and FAR calculation formula

Predicted events	Observed events		
	YES	NO	Total Marginal
YES	A	*B*	*A+B*
NO	*C*	*D*	*C+D*
Total marginal	*A+C*	*B+D*	*A+B+C+D=N*

Same comparison is made for the various output discharge data of the hydrological models HBV and HEC-HMS. Firstly, a threshold value of 3600 m3/s is settled to be the value above which flood may occur in the Upper Niger River. Various contingency tables (16; 17; 18; 19; 20; 21; 22;23) are made regarding to the output discharge data from hydrological model HBV and HEC-HMS.

Table 16 HEC-HMS 24H-ahead discharge

HEC-HMS 24H-AHEAD			
Predicted events	Observed events		
	YES	NO	Total marginal
YES	1994, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2005, 2006		
NO	1995, 2003, 2004	1993	
Total marginal	13	1	14

Table 17 HEC-HMS 48H-ahead discharge

HEC-HMS-48H-AHEAD			
Predicted events	Observed events		
	YES	NO	Total marginal
YES	1996, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006	1993	
NO	1994, 1995, 1997, 1998		
Total marginal	13	1	14

Table 18 HEC-HMS 72h_ahead discharge

HEC-HMS-72H-AHEAD			
Predicted events	Observed events		
	YES	NO	
YES	1996, 1999, 2000, 2001, 2002, 2003,	1993	Total marginal

	2004, 2005, 2006		
NO	1994, 1995, 1997, 1998		
Total marginal	13	1	14

Table 19 HEC-HMS 96h-ahead discharge

HEC-HMS 96H-ahead			
Predicted events	Observed events		
	YES	NO	Total marginal
YES	1994, 1996, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006		
NO	1995, 1997, 1998	1993	
Total marginal	13	1	14

Table 20 HBV-24h ahead discharge

HBV-24h ahead			
Predicted events	Observed events		
	YES	NO	Total marginal
YES	1994, 1996, 1999, 2001, 2002, 2003, 2004, 2005, 2006		
NO	2000, 2003	1993	
Total Marginal	13	1	14

Table 21 HBV 48h-ahead discharge

HBV 48h_ahead			
Predicted events	Observed events		
	YES	NO	Total Marginal
YES	1994, 1995, 1996, 1997, 1998, 1999, 2006		
NO	2000, 2001, 2002, 2003, 2004, 2005	1993	
Total marginal	13	1	14

Table 22 HBV 72h_head discharge

HBV 72h-ahead			
Predicted events	Observed events		
	YES	NO	Total marginal
YES	1994, 1997, 2005, 2006		
NO	1995, 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2004	1993	
Total marginal	13	1	14

Table 23 HBV 96h_ahead discharge

HBV 96h_ahead			
Predicted events	Observed events		
	YES	NO	Total marginal
YES	1994, 1995, 1996, 1999, 2002, 2003, 2005, 2006		
NO	1997, 1998, 2000, 2001, 2004	1993	
Total marginal	13	1	14

The NCEP center is used to download the forecasted rainfall of 24h-ahead, 48h-ahead, 72h-ahead and 96h-ahead. In order to evaluate the model, the contingency table (Table 24) has been generated. The purpose of this table is to see whether the model over or under-estimates the observed rainfall. To do so, the indices probability of detection PoD (or hit rate) and the false alarm rate FAR have been calculated (Table 24). Since they have to be used together to be meaningful, the calculation of PoD over FAR (PoD/FAR) is done. The more the value is greater than 1 the more the PoD is superior to the false alarm and the model is meaningful. Other indices (Critical Success Indices, CSI) that taking into account both the PoD and FAR are used. The more the value is higher the more meaningful is the model. From all of these points, it is noticed that the NCEP over-estimated the observed rainfall. The PoD/FAR decreases with the lead-time from 24h-ahead to 96h-ahead. The values of PoD/FAR are 1.9 and 1.2 respectively for the 24h-ahead and 48h-ahead; and 1.05 for both 72h-ahead and 96h-ahead. The more the forecast lead-time is large the bad will be the model rainfall estimation. However, this over-estimation did not have any major consequence in term of model during the calibration and validation processes.

The NCEP is used to get the forecasted rainfall data of 24h, 48h, 72h and 96h-ahead. After the calibration and validation process of the model using NCEP data, the next step is to evaluate the model NCEP whether it is meaningful or not. For that analysis, the observed rainfall data has been compared to the NCEP data. it appears that the NCEP over-estimates the observed rainfall data also the more the lead-time is the bad will be the rainfall (Table 24).

Two indices PoD and FAR allowing to evaluate the NCEP model are used. The aim is to see whether more success prediction (PoD) or false alarm rate (FAR) will be obtained. The results are in the table 24. It is noticed that from 24h-ahead to 96h-ahead, the value of PoD over FAR (PoD/FAR) decreases which means that the NCEP model is less reliablel if the lead-time increases.

The threshold value of rainfall above which flood may occur is determined (70.47mm) based on quantile calculation. If both the predicted and observed rainfall are above this value (70.47mm), it means that the model has well predicted, it is a “SUCCESS”. If the predicted rainfall over-estimates the observed one, the model has made a “FALSE ALARM”. It is a “MISSED” if the observed rainfall is higher than the predicted one. Finally, when both predicted and observed are below the threshold it is “CORRECT REJECTION”.

Table 24: Contingency table for the rainfall accuracy calculation

YEAR	OBSERVED	24H_ahead	48H_ahead	72H_ahead	96H_ahead
1993	50.28	68	59.5	76.8	39.7
1994	95.40	69	72.5	125.4	72.2
1995	77.83	99.2	113	111	104
1996	64.20	107	95.7	101	109
1997	81.61	63.3	105.3	108.7	93.9
1998	82.32	88.4	52.5	49.1	54.3
1999	73.60	69.1	57	55.6	51.3

2000	66.15	65.4	63.8	61.8	52.5
2001	31.25	58.1	55.6	49	45.6
2002	22.81	56.4	49.3	68.7	58.2
2003	29.81	88.8	71.7	80.1	79.05
2004	35.72	44.7	77.5	58.5	78.6
2005	39.46	80.6	58.4	86.1	55.5
2006	22.85	67.7	62	78.8	96.2
33%= 36.80 66%=70.47					

Calculation of PoD and FAR for the rainfall forecasted

$$PoD_{\mathbf{24h}} = \frac{4}{4+1} = 0.8 \qquad FAR_{\mathbf{24h}} = \frac{3}{3+4} = 0.42$$

$$PoD_{\mathbf{48h}} = \frac{3}{3+2} = 0.6 \qquad FAR_{\mathbf{48h}} = \frac{3}{3+3} = 0.5$$

$$PoD_{\mathbf{72h}} = \frac{3}{3+2} = 0.6 \qquad FAR_{\mathbf{72h}} = \frac{4}{4+3} = 0.57$$

$$PoD_{\mathbf{96h}} = \frac{3}{3+2} = 0.6 \qquad FAR_{\mathbf{96h}} = \frac{4}{4+3} = 0.57$$

Table 25 PoD FAR and CSI indices calculation for the forecasted rainfall

FORECASTED RAINFALL	**POD**	**FAR**	**POD/FAR**	**CSI**
24H	**0.8**	**0.42**	**1.9**	**0.5**
48H	**0.6**	**0.5**	**1.2**	**0.4**
72h	**0.6**	**0.57**	**1.05**	**0.33**
96h	**0.6**	**0.57**	**1.05**	**0.33**

These indices have been applied to the discharge data available from the hydrological models HBV and HEC-HMS during calibration and validation. The aim was to analyze the discharge data and whether the percentage of PoD is beyond or below the FAR one.

The contingency tables (Tables 26; 27) are made for the discharge data of both HBV and HEC-HMS models. It is important to notice that any false alarm rate has been detected. This fact puts more trust on the usefulness of the NCEP center data to be used to provide forecast rainfall for such kind of study. The combination of all these results allows to accept NCEP as an acceptable model to get the forecasted rainfall.

Calculation of PoD and FAR HEC-HMS

$$PoD_{\mathbf{24h}} = \frac{10}{10+3} = 0.73 \qquad FAR_{\mathbf{24h}} = \frac{0}{0+10} = 0$$

$$PoD_{\mathbf{48h}} = \frac{9}{9+4} = 0.69 \qquad FAR_{\mathbf{48h}} = \frac{0}{0+9} = 0$$

$\text{PoD}_{72h} = \frac{10}{10+3} = 0.73$ $\text{FAR}_{72h} = \frac{0}{0+10} = 0$

$\text{PoD}_{96h} = \frac{10}{10+3} = 0.73$ $\text{FAR}_{96h} = \frac{0}{0+10} = 0$

PoD and FAR of HBV models

$\text{PoD}_{24h} = \frac{11}{11+2} = 0.84$ $\text{FAR}_{24h} = \frac{1}{1+11} = 0.08$

$\text{PoD}_{48h} = \frac{7}{7+6} = 0.54$ $\text{FAR}_{48h} = \frac{0}{0+7} = 0$

$\text{PoD}_{72h} = \frac{4}{4+9} = 0.31$ $\text{FAR}_{72h} = \frac{0}{0+4} = 0$

$\text{PoD}_{96h} = \frac{8}{8+5} = 0.62$ $\text{FAR}_{96h} = \frac{0}{0+8} = 0$

Table 26 PoD and FAR and CSI indices calculation for the HBV discharge

DISCHARGE_HEC-HMS	POD	FAR	POD/FAR	CSI
24H	0.73	0	-	0.73
48H	0.69	0	-	0.69
72h	0.73	0	-	0.73
96h	0.73	0	-	0.73

Table 27 PoD and FAR and CSI indices calculation for the HEC-HMS discharge

DISCHARGE_HBV	POD	FAR	POD/FAR	CSI
24H	0.84	0.08	10.5	0.78
48H	0.54	0	-	0.54
72h	0.31	0	-	0.31
96h	0.62	0	-	0.62

7.3.Discussion

Flood forecasting has become an important issue in West Africa region. Despite the high catastrophic level of this scourge, the concept of non-structural methods through flood forecasting is not well known in West Africa. This work was based on forecasting the flood events through the calibration and validation of two hydrological models HBV and HEC-HMS. Forecasted rainfall of four (4) days ahead (24h, 48h, 72h, 96h-ahead) of NCEP center was used from the Copernicus website. According to Bennett et al. (2014) the impacts of flood can be reduced by implementing preventive measures Medium range weather forecasts produce rainfall forecasts up to 15 days in advance. However, forecast performance may deteriorate with the increase of the lead time (Bennett et al, 2014). The data has been directly used by the model without any bias correction process. However, the models, already calibrated using the observed rainfall data, have been calibrated and validated again with the NCEP forecasted rainfall data for this flood forecasting analysis. Both the models (HBV, HEC-HMS) calibrated the observed discharge with good values of model efficiency. Also, they both simulated well the peak values of the observed discharge which correspond to the period of flood events in the region. Similar results were found in the study of Artan et al. (2007). They found the usefulness of the remote sensing data in flood forecasting. The little number of parameters of these two models makes them easy to calibrate. Yawson et al. (2015) point it out that the increasing number of models parameters or the model complexity does not necessary improve the model performance. Abdo et al. (2012) stress on the importance of the reliable flood prediction with a reasonable lead time in Blue Nile River in Sudan. Many damages such as losses of life, economic damages could be avoided with an accurate and well flood forecasting implemented in the area. Thiemig et al. (2010) performed an ensemble flood forecasting study in Africa especially un Juba-Shabelle river basin. They achieved an early warning systems for large to medium-size river basins with lead time of 10 days, LISFLOOD was the hydrological model used. Despite the applicability of the model in Europe, it has been said that the same methodology can be applied in Africa.

Flood forecasting study requests some demands. The first point is to calibrate the hydrological model with the observed data, after downloading the forecasted rainfall that will be used as input to forge the hydrological model already calibrated. The model used to download the rainfall has to be analyzed whether it is good or not and to see if it provides more false alarm rate or not. The NCEP center used to provide the forecast rainfall over-estimates the observed rainfall data. Nevertheless, this did not have any huge consequence during calibration. It has been noticed that the more important the lead-time is, the less reliable will be the forecasted rainfall. From 24h-ahead rainfall data to 96h-ahead the quality deteriorates. Also same analyses have been noticed for the discharges output data, any FAR is detected for this data. The NCEP can be used as a reliable source to get the forecasted rainfall data for the flood forecasting study in the Upper Niger River Basin. However, it is important to notice that, one of the difficulty encountered during this analysis is the short length of the observed rainfall data. The data availability is very complicated. But at least the available one were satisfactorily used to perform this study.

7.4.Partial conclusion

The flood events are part of the catastrophic events that killed and destroyed lot of life and materials. It is major water-related disasters that affect millions of people and resulting in thousands of mortalities and billion dollar losses globally every year. The aim of this work is to find out a solution allowing to mitigate the impacts of these flood events. The non-structural methods, the most usually applicable is chosen. Forecasted rainfall of 4 days ahead is downloaded from NCEP center through Copernicus website. The hindcast rainfall data ranges from 1993 to 2013. After a first calibration of the model using the observed data, the models are calibrated again by the NCEP hindscat data and validated. The calibration data range from 1993 to 1998, for the validation, the data range from 1999 to 2013. Two hydrological models HBV and HEC-HMS are used for the hydrological modeling aspect. Both of them satisfactory calibrated well the model. The observed discharge is well simulated, especially the peaks which correspond to the flood years.

These result findings are important for forecasting of the coming floods. The coming floods can be known in advance what can allow the population to be award in advance and take necessary actions to avoid or mitigate the effect of floods.

CHAPTER 8: GENERAL CONCLUSION, SUGGESTIONS AND PERSPECTIVES

8.1.General conclusion

The general focus of this work was the reduction of flood risk through the assessment of flood forecasting system.

To attain this humble goal, the flood forecasting and warning system was the major issue to address. High impact factor journals indexed under Scopus, Web of Sciences etc… were used to carry out a review of flood forecasting system already implemented in West Africa region. It turned out that in Africa, the flood forecasting system is at the early developmental stage. Moreover, despite the fact that Africa is frequently hit by this catastrophic event, most of the already flood forecasting system implemented are not functional and need to be improved. Another issue that makes the work complicated is the non-availability or sharing of transboundary data. The flood forecasting system is very important and since its implementation, the number of flood victims has reduced considerably. It is more reliable than the structural methods (levee, reservoir bank, dyke etc…) that cannot predict any coming floods; worst the structural methods can even mislead people letting them build in the flooding area. Asia is the continent that suffered the most from frequent occurrence of flood. Africa comes third after Europe. However, because of the weak way to handle flood issues, Africa seems to be the continent the most negatively impacted by those climatic catastrophes. This is the reason why more care should be turned on the flood forecasting in Africa in order to mitigate the flood events.

The second part of this work addressed the urban flash flood and extreme rainfall event trends analysis in Bamako. The aim of this work was to analyze the flood events occurrence in the city of Bamako-Mali, to find out the main cause leading to this occurrence as well as its historical trends from 1982 to 2019. In order to achieve this objective, precipitation, temperature and flood events information are used. RClimDex, a R software package is used to get the extreme rainfall indices such as RX1 day, RX5 days, R99PCPTOT, PRCPTOT, CWD. The RClimdex software requires as input data the rainfall as well as the temperature data. All these indices showed an increasing trend except the CWD. The decreasing trend of consecutive wet day explain the type of warm climate over the cold one. Modified Mann-kendall test, previously done, confirms the non-stationarity of the times series. The historical flood events, occurred in Bamako, seem to have a link with the extreme rainfall indices (R99TOT), because the years of flood events correspond to the years where the maximum value of rainfall is observed in R99PCTOT. Also, from the 1982 to 2019 flood events frequencies and occurrences display a positive trend like the extreme rainfall indices for the same period, leading to the conclusion that they may have a link especially when it is known that the rainfall does not show any positive trend. The threshold value of rainfall above which flood may occur has been said to be equal to 47mm per day. One of the important findings is that the rainfall responsible for the flood is between the classes of abnormal and severely abnormal. This means that the rainfall responsible for the flood events in Bamako is far from being exceptional. If the flood in the capital of Mali Republic is not due to an exceptional rainfall, it means that other causes should be linked to the extreme rainfall. Mainly, the non-maintenance of the gutters and most often the blockage of the river banks as well as the land use changes could constitute the main reasons contributor of floods in the capital city Bamako. This hypothesis is confirmed by a study carried out by Aich et al. 2016. They stated that there is a high sensitivity of the Sahelian and Sudanian regions of the Niger River Basin to climatic and land use changes. In order to mitigate these flood events by the mean of non-structural methods, the third part of this work is put in place.

The third part of this work focuses on flood forecasting through two hydrological models HBV and HEC-HMS. Both of these models use as input data, the rainfall, temperatures discharge and evapotranspiration. It consisted in calibrating and validating both models. In fact, the first step of flood forecasting system was to calibrate and validate the hydrological models. Both models have simulated the observed discharge with a good value of NASH. The few number of model parameters makes easier the calibration processes. The peak discharge representing the flood events are well simulated.

The fourth part is in fact the continuity of the third one. It is based on the recalibration and revalidation of the rainfall from the NCEP center (24h-ahead, 48h-ahead, 72h-ahead, 96h-ahead). The aim is to observed the possibility and ability of the two models to simulate historical flood events through the four (4) ahead NCEP precipitation. The observed discharge is well calibrated and validated with good values of model efficiency for the all 4 ahead precipitation hindcast data. These findings prove the ability the NCEP data to be used in our study area. Another step was the evaluation of the NCEP center in order to see if the probability of the rainfall occurrence provided by this center is higher. For that, PoD and FAR and well as CSI indices were calculated to determine the percentage of "SUCCESS" or "FALSE ALARM RATE" as well as for the predicted rainfall from NCEP than the simulated discharge from the HBV and HEC-HMS models. The results showed good value of PoD over FAR for the NCEP rainfall even if it has over-estimated the observed rainfall data, also any false alarm has been detected for the simulated discharge which put the stress on the NCEP model accuracy to be used for such kind of study in UNRB area.

8.2.Suggestions

Three major purposes can justify the use of the dams. Firstly, the dams are used to satisfy the supply of drinking and irrigation water, secondly they allow to regulate flow system in order to better manage drought and flood periods in a river and lastly, dams are used to generate energy.

Dams, by providing a flood control and a stable water supply, show their ability to improve the quality of our lives. However, when these dams are not well maintained, they may collapse, leading to a catastrophic damage (Boulange et al., 2021).

According to Boulange et al (2021), population growth as well the climate change will be the reasons of the flood risk increase in the world in the future. The role of dams has been neglected for a long time in flood control probably due to the lack of the data.

Dams are regulating half of planet's major rivers, and only 23% of rivers in the world are not under dam influence (Boulange et al., 2021). 9,1 and 15.3 million per year are the number of people affected by flood at the end of 21 first century respectively for the representative concentration pathway (RCP) 2.6 and 6.0 not considering the dams (Boulange et al. 2021). When dams are considering, the number of people exposed to the floods reduce considerably by 20.6% and 12.6% respectively for the RCP 2.6 and 6.0. The use of dams is important to control flood considerably. However, this dam should have to be well controlled.

Selingue dam built in 1982, is located on Sankarani tributary 60 km from Niger River and 150 km from Bamako the Capital of Mali. It plays several roles such as hydropower generation, irrigation. Selingue dam is very important in flood controlling aspect in the downstream, Koulikoro area, in the UNRB.

When analyzing the discharge of Koulikoro before and after the dam implementation, the influence of the dam seems obvious. However, the influence of Selingue dam in the maximum discharge seems to not be very important in the Niger River in contrary to the low water level.

When comparing the stations of Banankoro located in the upstream area and the station of Koulikoro, it appears that the discharge at Koulikoro in a period of low water level is more important than the one in Banankoro. That is to show the importance of the dam to support the period of low water level. If the dam did not exist, the discharge at Koulikoro will not be so different from the one at Banankoro. This is very important for the dam because it allows the Niger River to continue flowing during the drought period. That is one of the importance of dam implementation, the regulation of the streamflow.

Dam management against flood

Dams have the ability to improve the quality of our lives and protect life property by providing a stable water supply and flood control. However, dams could also cause severe disasters at downstream area if they collapse. This is why dam management should be considered with more precaution. Constructing reservoirs where the excess water can be stored allows a regulated temporal distribution of streamflow and help to alleviate the flood problems. Water storage reservoir is the basic component of water management. When dam is implemented, the flood occurrences depend on the operation of the dam.

Three scenario of dam operation will be carried out and presented in order to see the impact of each of these scenario on the flood events in the downstream area.

Scenario 1: Keeping the water in the dam's reservoir to the highest level

We assume that in order to achieve the highest water level in the dam's reservoir, no action is taken. The water level will change at the end of the flood. And consequently, at the end of flood period, we have as result a 1.75m decrease of water level in the reservoir and a creation of flood downstream. The energy was produced also in order to cover the demand.

Scenario 2: When a great rainfall is predicted, water level is dropped down to avoid flood.

In this scenario, an alternative water management plan is presented, keeping the turbines of hydropower plant switched on for 24 h before the rainfall starts, in order to manage a controlled water level decrease. The cost of this management is that a quantity of water is used to produce energy at non-peak hours of the day when the price of energy is low. Additionally, the bottom outlet will be also used for certain hours, so that the level of water in the dam's reservoir does not reach the critical height for opening the spillway's floodgates. The main objective is to avoid the water level in the reservoir to reach the highest allowing level when the floodgate must open, because in such a case, a flood maybe occurred downstream and additionally considerable water loss will happen.

When evaluating the current dam management, we realize that not only the flood did not happen in the downstream area, but also the quantity of water stored in the reservoir can allow to generate sufficient energy. For sure, this system of dam management is far better the best one because the flood is avoided in the downstream and enough water is stored allowing to generate electricity.

Scenario 3: The weather forecast of a great rainfall is not confirmed

In this scenario, the water management is linked to the fact that the weather forecast of rainfall in 24h will be confirmed. Unfortunately, the weather forecasts are not confirmed and the rainfall does not happen. In the reservoir, 24h before the expected rainfall, the operator started to lower the level of water. The result of this scenario is awful for the country located in the upstream. Because the flood will be avoided of course but the water loss is too much and can cause loss of energy production. For such kind of inconvenient, the countries located in the downstream where the flood has been avoided, should contribute to pay for compensation of the upstream country.

It is possible sometimes to produce electricity and at the same time avoid flood in the downstream. However, if it is about to make a choice between producing an electricity and avoid the area against floods, it will be fair to protect the area by avoiding the flood. Because the energy profit of one hundred and thousand Euros energy profit can provoke the flood and destruction of two hundred million of Euros.

The best management of Selingue dam can allow to avoid flood in the downstream area. This best management has to be linked to the NCEP forecast rainfall data, the flood forecast system. Selingue dam workers and flood forecasting system should work together to share the information. For instance, if an extreme rainfall is predicted to occur in 48h, urgent measure should be taken to at least open dam gates and spill water for the dam to store sufficient quantity of the extreme rainwater predicted to occur. For that specific case, not only the flood will be avoided in the downstream but also the energy would be produced.

8.3. Perspectives

This work was based on flood risk reduction through the evaluation of flood forecasting system with hydrological models.

Several results were obtained. Among them firstly the emergency of some African countries to implement flood forecasting system because few flood forecasting systems exist in Africa. Also it has been established that the extreme rainfall events only are not responsible for the floods occurring in Bamako. Lastly the hydrological models HBV and HEC-HMS were able to be calibrated and validated using the observed data, and in the same direction NCEP satellite rainfall data has been used as input data to forge the hydrological models already calibrated. This NCEP data appears to be acceptable and can be used for the future similar study as a satellite forecasted rainfall to be used for the flood forecasting purpose.

a. After all these points, it is well to notice that the work is not yet done and some points have been highlighted to be studied in the future. The extreme rainfall may not cause the flood itself only but when considering the consecutive rainfall day such as (three consecutive rainfall day, five consecutive rainfall day or seven consecutive rainfall day), this can be one of the causes leading to flood. So it has to be considered for the next studies.
b. This study was based on the flood forecasting assessment through the hydrological models. The next study should consider the dissemination of the flood information to the population called “the Early Warning System”.

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https://cds.climate.copernicus.eu/cdsapp#!/dataset/seasonaloriginalsinglelevels?tab=form.

ANNEXES: Papers Publication and Figures of calibration and validation for the NCEP rainfall data through HBV and HEC-HMW hydrological models

Annexe 1: Publication papers

Fofana, M., Adounkpe J., Larbi, I., Hounkpe J., Djan'na, K., Toure A., Bocar, H., Sam-Quarcoo, D.; Andrew, M.L (2022). Urban flash flood and extreme rainfall events trend analysis in Bamako, Mali. *Environ. Chall. 2022*, *6*, 100449. DOI: https://doi.org/10.1016/j.envc.2022.100449

Fofana, M., Adounkpe, J. , Dotse, S. , Bokar, H. , Limantol, A. , Hounkpe, J. , Larbi, I. and Toure, A. (2023) Flood Forecasting and Warning System: A Survey of Models and Their Applications in West Africa. *American Journal of Climate Change*, **12**, 1-20. DOI: 10.4236/ajcc.2023.121001

Annexe 2: Figures of calibration and validation for the NCEP rainfall data (24h, 48h, 72h and 96h-ahead) through HBV and HEC-HMW hydrological models.

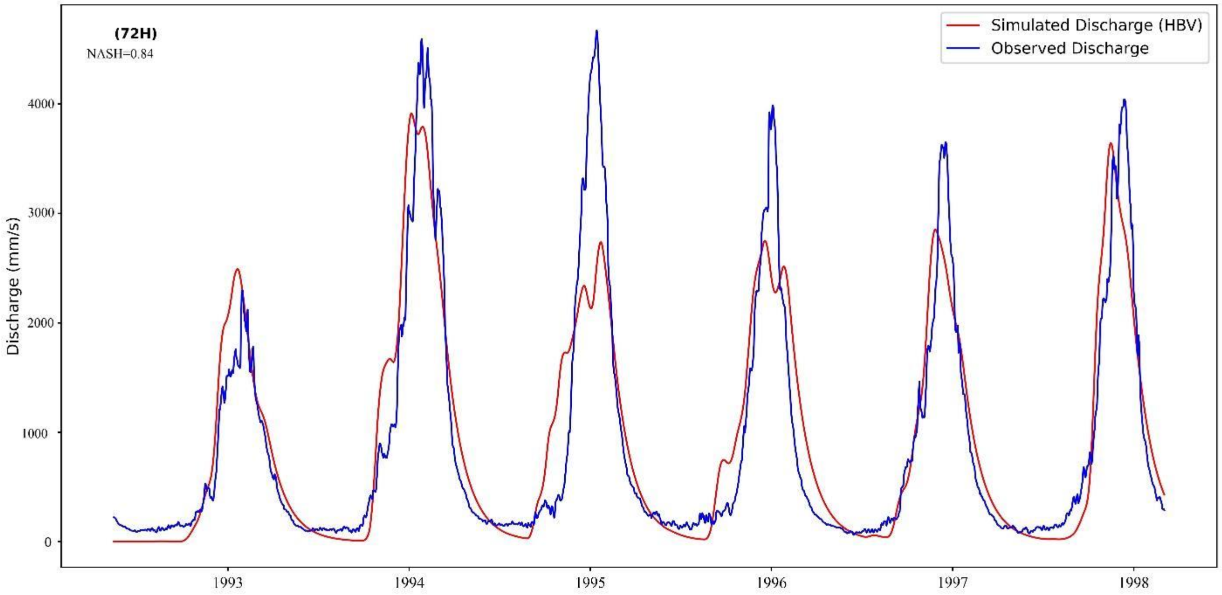

Figure 32: HBV-72h Calibration

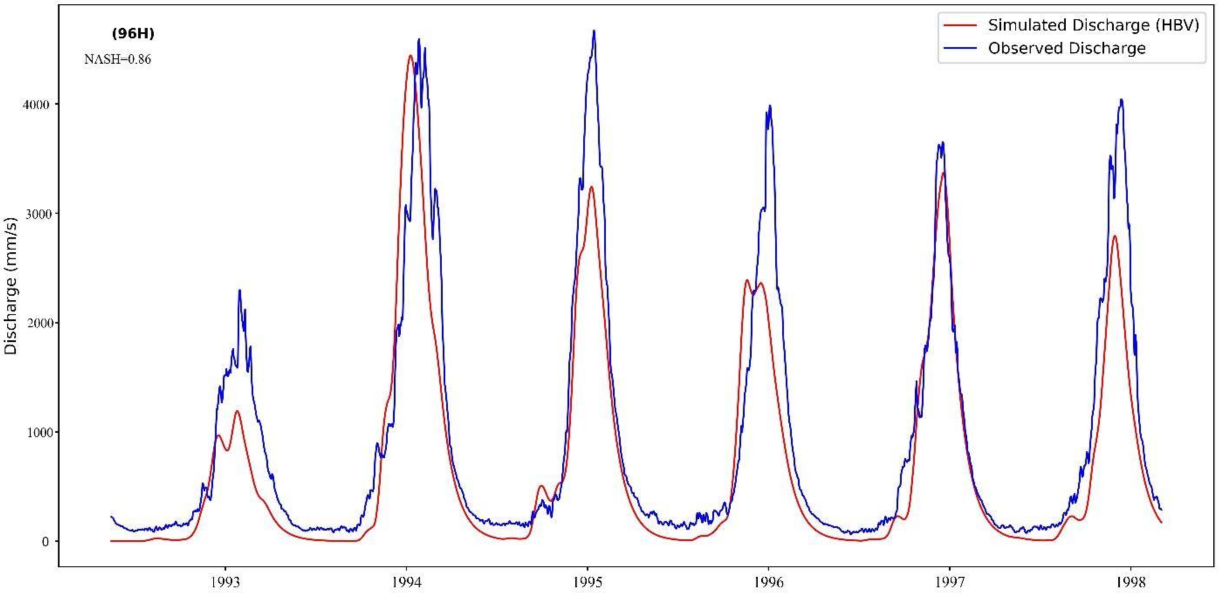

Figure 33: HBV 96h Calibration

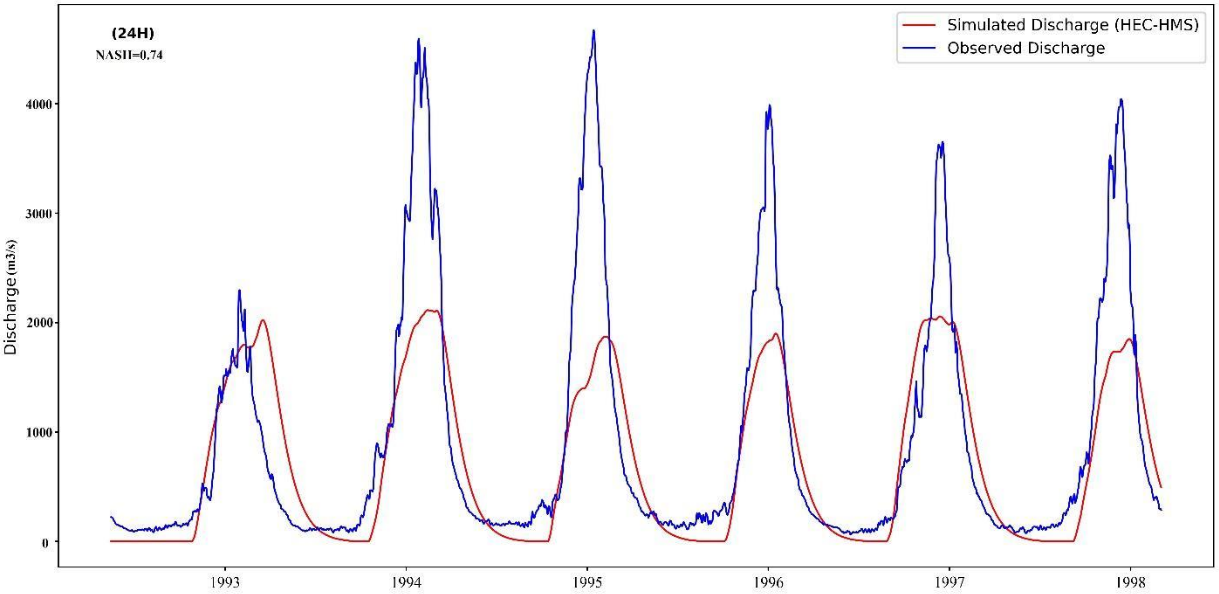

Figure 34: HEC-HMS 24h Calibration

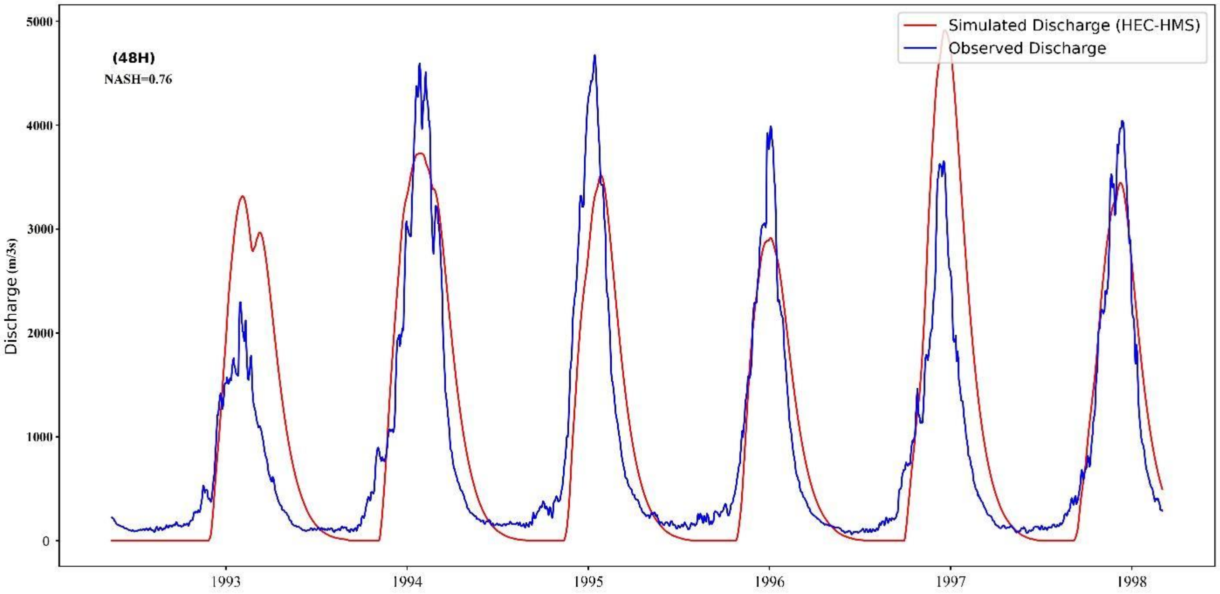

Figure 35: HEC-HMS 48h Calibration

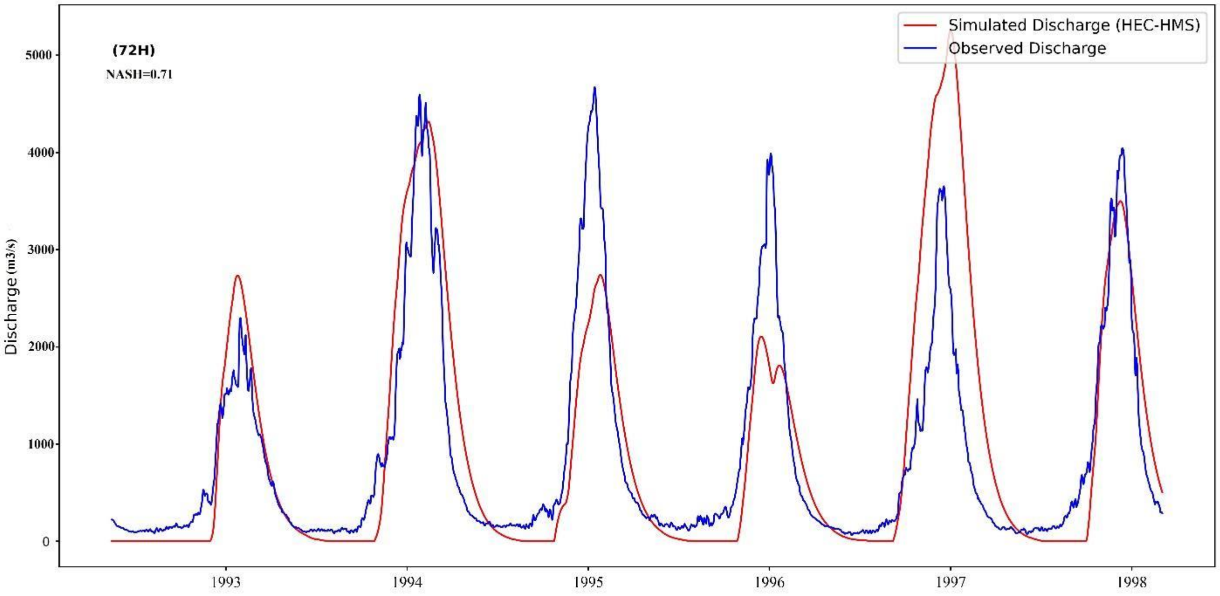

Figure 36: HEC-HMS 72h Calibration

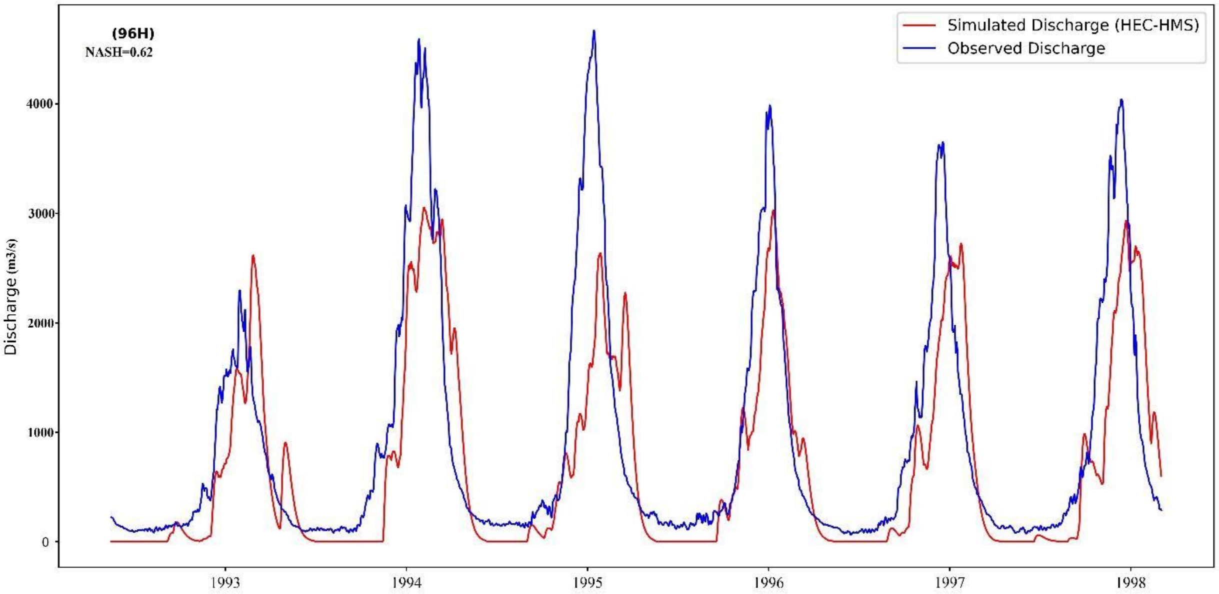

Figure 37: HEC-HMS 96h Calibration

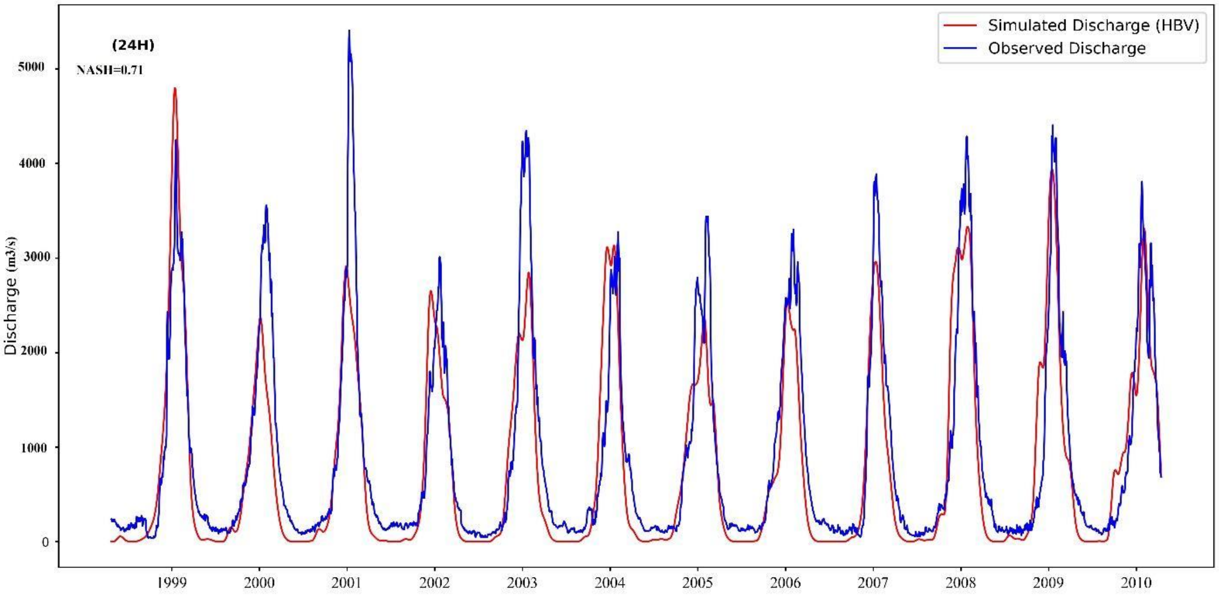

Figure 38: HBV 24h Validation

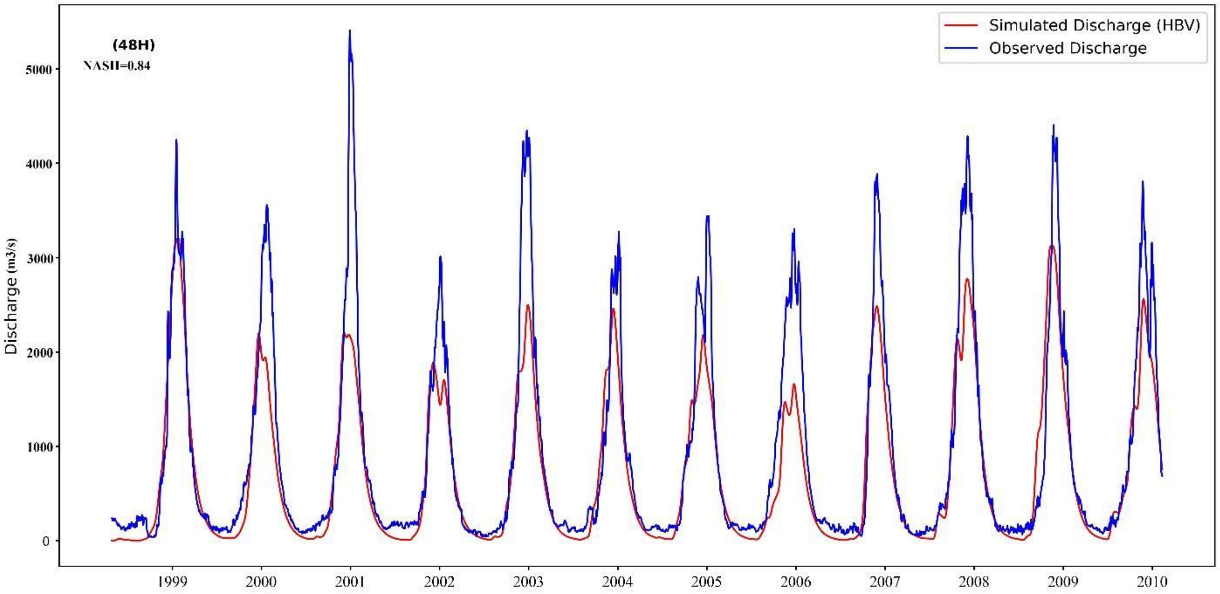

Figure 39: HBV 48h Validation

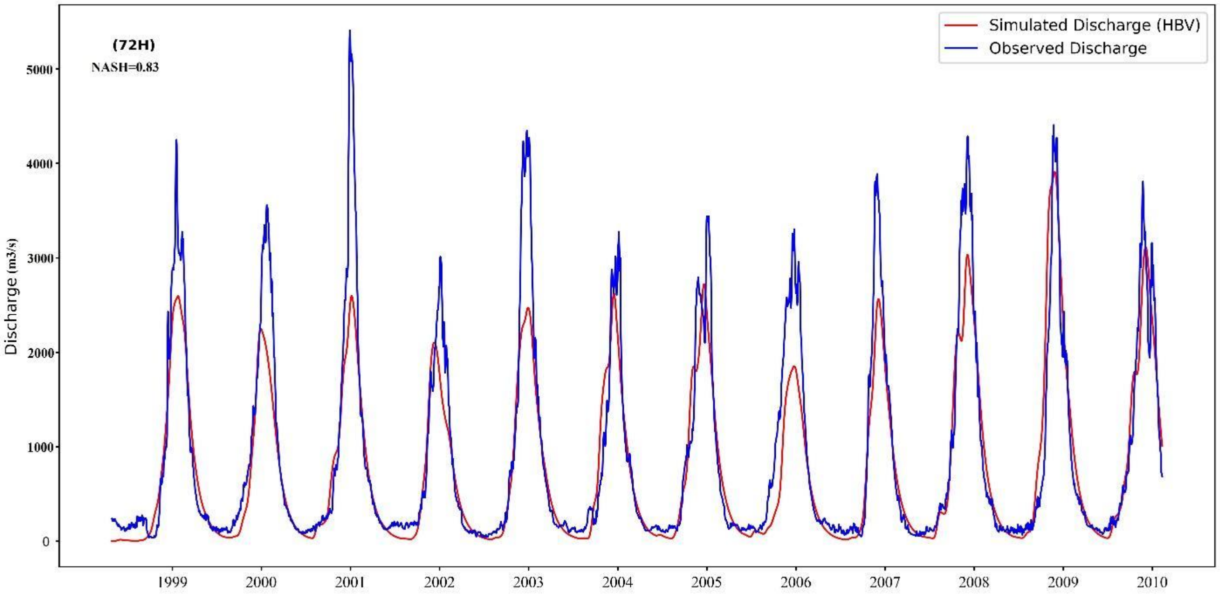

Figure 40: HBV 72h Validation

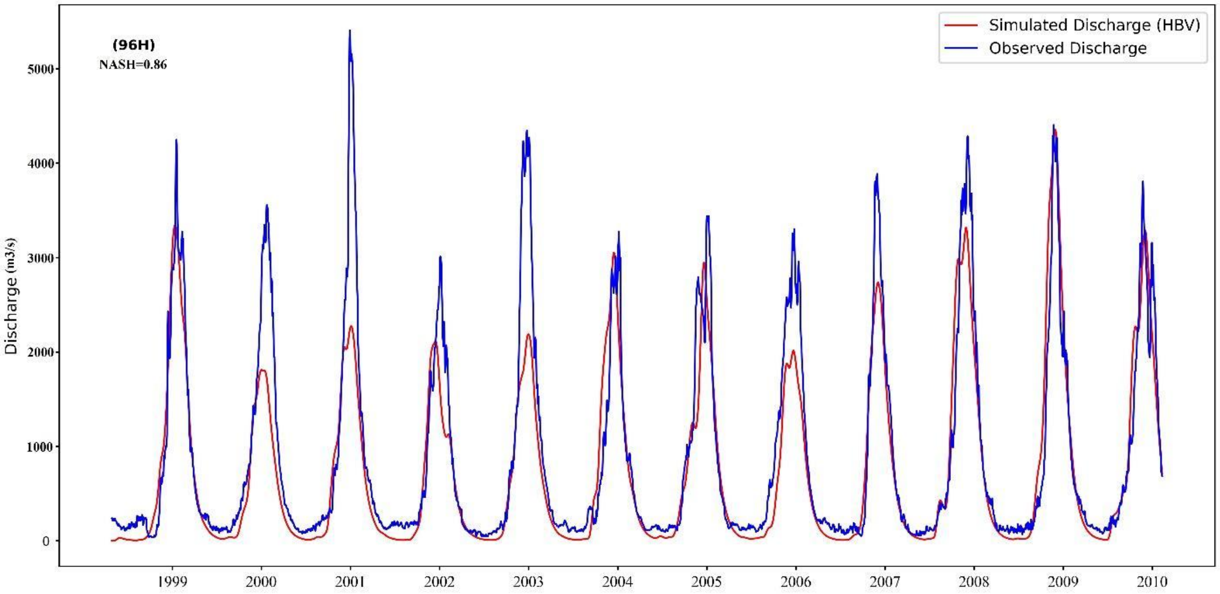

Figure 41: HBV 96h Validation

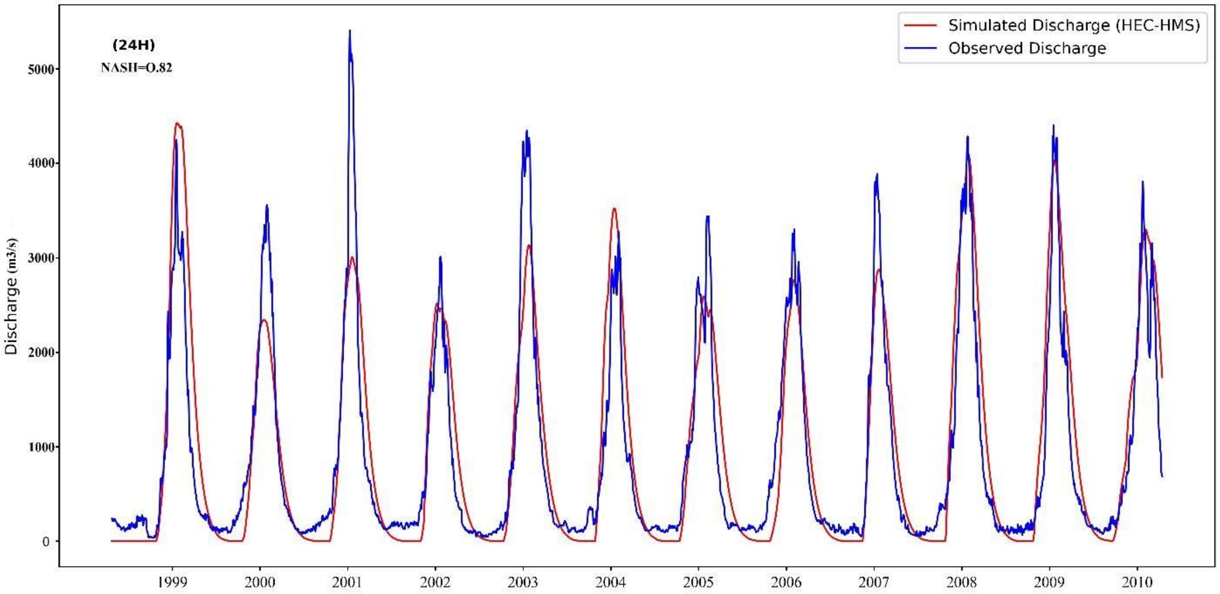

Figure 42: HEC-HMS 24h Validation

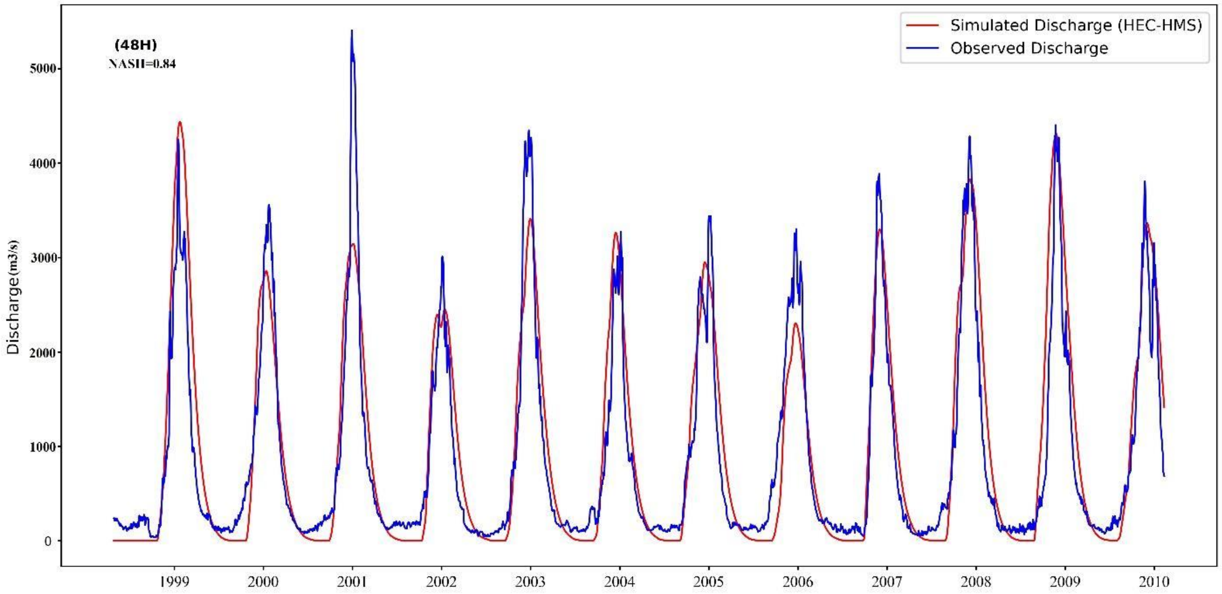

Figure 43: HEC-HMS 48h Validation

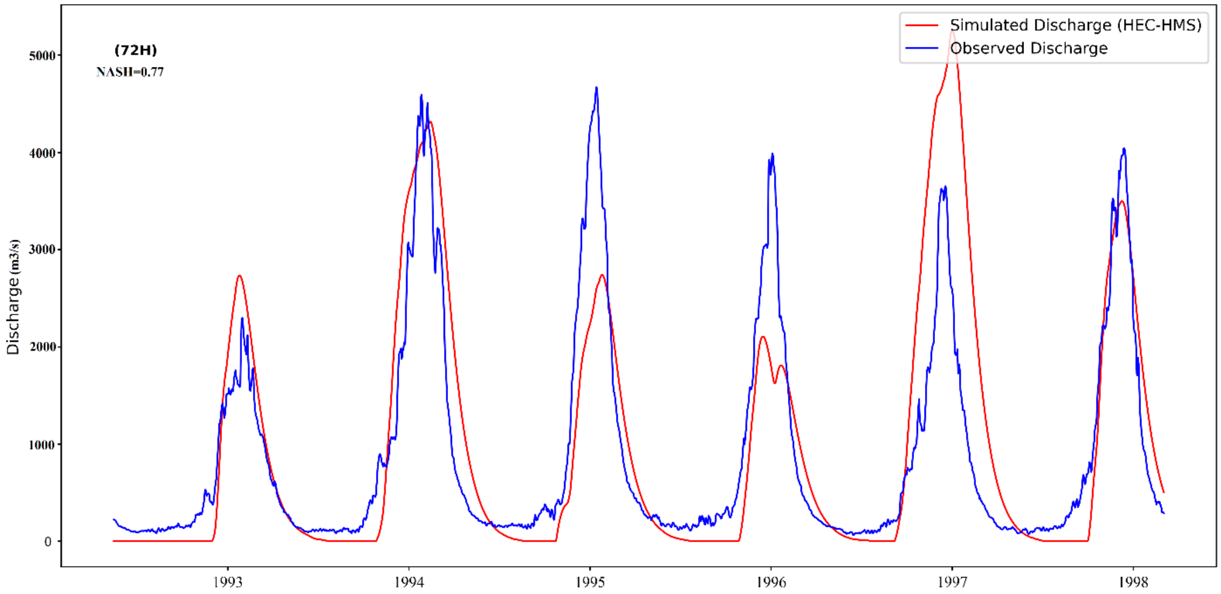

Figure 44: HEC-HMS 72h Validation

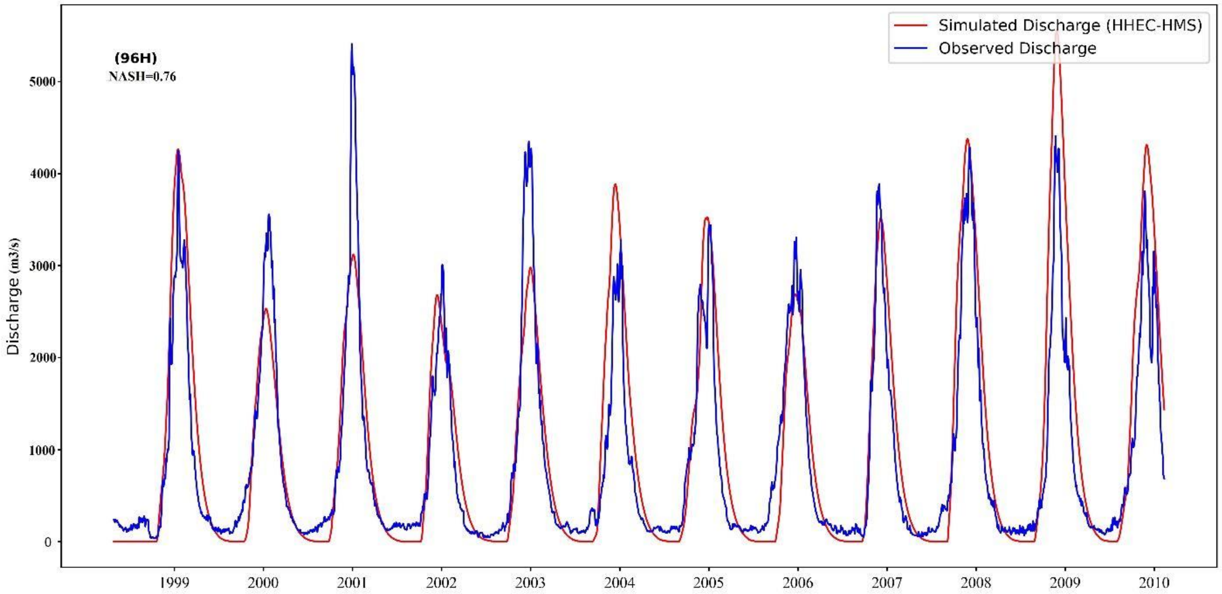

Figure 45: HEC-HMS 96h Validation

Mohamed FOFANA is born on October 1993 in Koulikoro, Mali.

He spent 9 years at the EDC Emile Delassus Camara primary school and 3 years at High school Lycee du Seminaire PieXII at Koulikoro. After his Baccalaureat obtained in 2010, he got a scholarship for Morocco where he spent 5 years of studies. He graduated his Bachelor degree on **“Fondamental Geology”** option *“Water and Soil*” at the University of Chouaib Doukkali, Faculty of Sciences in 2013. Two years after he got his Master degree on “Geosciences Applied to Energetic and Minerals Resources (G.A.E.M.R) in the domain of Geology again in 2015 at the University of Cadi Ayyad, Faculty of Sciences Semlalia, Marrakech, Morocco. August 2015 he came back home in Mali. He started teaching General Geology and Mineral resources courses at some Private Universities (such as Ahmed Baba Private University at Bamako and Applied Technologic’ Institute of Bamako from end 2015 to 2017. in 2017, Mohamed FOFANA succeeded to the National Public examination test (Concours de la Fonction Public) for high school teacher. Lycee Technique Public de Sevare at Mopti region, the Middle region of Mali is where Mohamed taught Geology since 2017 until he got WASCAL scholarship in 2019. He is now completing a PhD in climate change and water resources. Mohamed is calm, respectful, courageous and determined to succeed. Since there is a big gap in the domain of hydrology in Mali, He would like to contribute to reduce this gap allowing the coming generations to be well documented in the domain of hydrology in Mali. By doing so, he would like to contribute helping the population against any disaster related to climate change and water.

Abstract

This work was based on the issue of flood risk reduction through the implementation of flood forecasting system. Three main specific objectives are implemented in order to achieve this goal. First of all, an overview on flood forecasting system already implemented in Africa especially in West Africa is carried out. Secondly, the trends analysis of flood events as well as their relationship with extreme rainfall is performed in Bamako, the capital of the Republic of Mali. Thirdly, the flood forecasting system is implemented in order to mitigate the coming floods in the study area. It allows to the population to take necessary advance against the floods, reducing considerably the flood impacts. Results showed that Africa is at the early stage of flood mitigation. Most of the flood forecasting systems in Africa are obsolete and need to be improved. Also the problem encountered in several institutions in Africa is the unwilling to share and the unavailability of the flood forecasting system information. HBV, HEC-HMS, SWAT, WRF-Hydro are the hydrological models the most used for the flood forecasting issues in Africa.From 1981 to 2019, the flood events historical trend in Bamako is increasing as well as the flood victims. RClimdex, which is a package of R, provides the extreme rainfall indices. These extreme rainfall indices (RX1 day, RX5 day, R99P, PRCPTOT, CWD) show the same trend increasing during the same period 1981 to 2019. Therefore, a strong relationship between flood occurrences and extreme rainfall is identified. Most of the years where floods occurred in Bamako correspond to the years of high rainfall value especially for the R99P. However, it has been observed that the rainfall responsible for flood in Bamako is 47mm, which is far from being exceptional. It is in the range of abnormal to severely abnormal classes. Meaning that there are other causes that should be added to the extreme rainfall to lead to flood events. Maintenance of gutters, building houses on the way of the river-bed in addition to the soil destruction, may be considered as the major causes to be linked to the extreme rainfall.

The flood forecasting system is implemented in the study area through two hydrological models HBV and HEC-HMS. Both of the models are well calibrated and validated with satisfactory model efficiency values for the four ahead NCEP rainfall data. Nash values are respectively 0.74, 0.76, 0.71, 0.62 for the 24h, 48h, 72h, and 96h ahead precipitation during the calibration and 0.82, 0.84, 0.77 and 0.76 during the validation for the HEC-HMS model respectively for the 24h, 48h, 72h and 96h ahead precipitation. For the HBV hydrological model, Nash values for the calibration are respectively 0.67, 0.86, 0.83, 0.80 for the 24h, 48h, 72h and 96h. During the validation, Nash values are 0.78, 0.78, 0.83, 0.80 for respectively 24h, 48h, 72h and 96h ahead precipitation. This interesting finding confirms the suitability of these models to be used for the flood forecasting system in the area and also it attests the suitability of the NCEP rainfall data to be used as the forecasted rainfall. This result may allow to the population to take necessary actions in advance against flood events and the impacts of flood will be reducing considerably. It may allow also to better manage Selingue dam located in the upstream of the outlet. Knowing the coming amount of rainfall, the decision makers of Selingue dam could know if and when it suits better to release flow from the dam.

Key words: (Flood forecasting system, extreme rainfall, hydrological models, Koulikoro watershed, Selingue dam)

PhD

Mohamed FOFANA

**FLOOD RISK REDUCTION THROUGH THE ASSESSMENT
OF FLOOD FORECASTING SYSTEM IN THE UPPER NIGER
RIVER BASIN IN MALI**

GRP/CCWR/INE