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Hydrologic Modelling for Flood Threshold and Hazard Prediction in the Black Volta River Basin, West Africa

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Abstract

The Black Volta River Basin (BVRB) is one of the flood-prone subbasins in the West African subregion experiencing frequent and severe flood-related disasters in recent times. Flood prediction systems embedded with hydrological models are important non-structural measures for effective flood management. This study adopted a Hydrological Modeling approach using Hydrological Engineering Center's Hydrological Modeling System (HEC-HMS) software to simulate flood events within the BVRB. The future average frequency of occurrence of flood events in terms of peak flows was simulated using the calibrated and validated model and Intensity-Duration-Frequency (IDF) curves for the basin. This was followed by the application of a rating curve to obtain floodwater levels corresponding to the predicted peak discharges and subsequently, a flood hazard classification ranging from moderate, high, and very high severity levels in terms of peak flow and water levels.

The Nash–Sutcliffe model efficiency (NSE) coefficient results of > 0.70 for both calibration and validation indicate the model's good performance in the basin. The model application for flood threshold prediction and hazard classification in terms of peak flows and flood water levels in the basin particularly at the Chache station reveals that a severe flood of magnitude (flood water level ≥ 8 m and equivalent discharge ≥ 1935 m³/s) is likely to be experienced in the basin for a rainfall event of at least 25-year return period. Moderate flooding is likely to be experienced for at least a 5-year return period rainfall event (7.0 m $\leq$ flood water level < 7.5 m and 1365 m³/s $\leq$ peak flow < 1635 m³/s) in the study area. The outcomes of this study help to better understand the hydrological response and flood characterization due to extreme rainfall events for flood monitoring purposes in the BVRB.

Keywords: Flood threshold and Hazard Prediction, HEC-HMS, Black Volta River Basin, Rating Curve

1.0 Introduction

It is globally recognized that floods are the most common natural disasters, leading to the largest loss of human life, broad devastation, and impact on social and economic development in both rural and urban areas [13]. Flood disasters account for roughly a third of all deaths, injuries, and property damage caused by natural disasters [47]. Floods and flood-related disasters claim the lives of about 20,000 people each year, leaving people homeless and affecting at least 20 million people throughout the world [42].

The BVRB shared by four West African countries namely Mali, Burkina Faso, Ghana and Ivory Coast has been affected by flooding events almost every year between August and September causing damage to life and property [26]. According to [19], thousands of hectares of farmland and properties in the BVRB have been destroyed by several severe floods between 1991 and 2018. Flood fatalities in the BVRB have increased within the last two decades according to [28]. In September 2007, the BVRB, along with other sub-basins of the Volta River system in Ghana, was hit by severe rainfall causing streams and dams to overflow leading to one of the worst floods the region has ever experienced [7]. The government of Ghana declared the region a disaster zone in September 2007 due to the severity of the flood [33]. Again in 2009, the region experienced torrential rains which led to flooding that caused damage to properties, livestock, and destruction of habitat [7]. In 2010 also, floods devastated 55 villages, displacing around 700,000 people, 3234 buildings collapsed, 23,588 acres of agricultural land were lost and 1109 domestic animals, including cattle, goats, sheep, and poultry, were destroyed [3]. The most recent devastating flood event occurred between August and September 2018, when long-duration heavy downpour caused severe flooding in the region causing about seven (7) deaths and displacement of about 100,000 people, wreaking havoc on farms, roads, and infrastructure, including bridges and cutting off many towns according to the National Disaster Management Organization ((NADMO). This increasing trend of flood events therefore suggest that the development of a flood prediction system is considered vital for effective flood risk management in the BVRB.

Flood prediction is about the estimation of future average frequency of occurrence of flood events requiring rainfall patterns, catchment characteristics, and river hydrographs as key input variables. It aims to give advance notification of discharges or water levels that are high enough to compromise the safety of properties and activities at a single or multiple sites in flood plains. Flood

prediction has become necessary as an adaptation strategy to limit the damaging effects of floods. Precise and reliable flood prediction is required to create appropriate flood risk management strategies, mitigate flood hazards, evacuate people from flood-prone areas, and manage environmental and water resource systems [12].

Hydrological models have been regarded as one of the effective flood prediction techniques and has been used effectively in various regions around the world for flood forecasting [35, 38, 40, 45, 46, 47]. Hydrologic models allow the prediction of changes in the hydrologic response of a basin, as a result of various changes in basin practices, as well as a thorough understanding of the hydrological parameters that influence the basin's hydrological response [24].

Depending on the purpose of modeling and availability of monitoring data, hydrological modelling approach can be described as event-based or continuous models [44]. Event-based models are developed to simulate individual rainfall-runoff events, with their focus being infiltration and surface runoff [14], while ignoring the effects of hydrologic processes such as evapotranspiration, interception, depression storage as well as the interaction between the aquifer and the streams. Event-based models calculate total runoff volume, runoff depth, peak discharges, and peak discharge time. Continuous models are suitable for water availability studies for a watershed. It considers a time series of rainfall, which could include more than one storm event [35]. In the continuous simulation process, both dry and wet conditions of the basin over that long time period are used to develop hydrological models [17].

Hydrological models have also been divided into three categories based on the process description, these are; lumped, distributed, and semi-distributed models [4, 11, 14, 27, 30, 44]. Lumped model parameters do not vary spatially within the basin, basin response is only evaluated at the outlet, without explicitly accounting for the response of individual sub-basins [18]. Distributed models account for spatial variability in processes, inputs, boundary conditions, and basin characteristics [35]. This model type necessitates a large amount of data which are often unavailable [14]. However, the governing physical processes, are meticulously modeled, and when properly applied, can provide the highest degree of accuracy [18]. Semi-distributed (simplified distributed) models allow parameters to vary in space by dividing the basin into smaller sub-basins. The primary advantage of these models is that their structure is more physically based than that of lumped

models, and they require less input data than fully distributed models [4]. Examples are; HEC-HMS [22], SWAT [8], and HBV [10].

Previous studies conducted in the BVRB have applied different hydrologic models such as HBV-IWS model, SWAT model and WetSpass-M model among others, to study the hydrologic response of the basin with the exception of HEC-HMS. However, the outcome of these studies is lacks information required to addresses the issue of the increasing flood events experienced in the basin. For example, [4], used SWAT model to assess rainfall variability impacts along with changes in land use and land cover on streamflow in the BVRB. The results of the study suggested that, SWAT modeling performed well in the area. [1] used the WetSpass model, which can simulate spatially distributed recharge, surface runoff, and evapotranspiration for seasonally averaged conditions to simulate runoff in the BVRB. The study's findings revealed that the model performed well and that, small changes in rainfall could result in large changes in surface runoff in the area. [6] investigated how well the Soil and Water Assessment Tool (SWAT) model can be used to predict surface runoff flows in the BVRB. The study recorded poor model performance and concluded that, uncertainties in the model's conceptual framework, as well as a high frequency of missing data gaps, resulted in poor model performance.

HEC-HMS model has been tested and calibrated to simulate and forecast peak flows. For example, [48] used IDF curves to create design storms in the Zhudong river basin in China to simulate peak flows for various reoccurrence intervals and concluded HEC-HMS is applicable for forecasting peak flows in the region. [20] also developed a hydrological model using HEC-HMS for the Bukit Merah basin in Malaysia and used predicted future rainfall data to forecast peak flows of forecasted floods in the region. The HEC-HMS model has been used to model rainfall-runoff processes in various basins in various African countries as well such as; Ethiopia [18], Morocco [29], Rwanda [31], and Kenya [25] among others. In each of these studies, the model proved suitable for simulation of the hydrologic processes and peak flows of various events.

In the West African sub-region, not much research has been done using the HEC-HMS model for rainfall-runoff modeling. However, a few studies revealed the applicability of the HEC-HMS model to simulate flood events within the region. [41] used the HEC-HMS model to simulate peak flows for wadi Ressoul in the El Berda watershed, northeast of Algeria. The model calibration and validation of the aforementioned study gave good results and the study concluded that the HEC-

HMS model is suitable for hydrological modeling in the West African sub-region and a data-scarce catchment.

To address the gaps in the previous studies while opening up the discussions of hydrological modelling applications and flood prediction techniques in the BVRB, this study adopted an Event-based Hydrological Modeling approach using HEC-HMS software to simulate Hydro-Meteorological processes and flood events in the BVRB. The model is then applied for flood prediction in terms of peak flows using IDF curves and flood water levels using a rating curve followed by flood hazard classification in the BVRB. The outcomes of this study will largely contribute to gaining a better understanding of the hydrological response of the basin for flood monitoring purposes. Additionally, it will also provide a scientific basis for adequate decision-making in the management, control, and mitigation of floods and flood-related hazards in the BVRB.

2.0 Materials and methods

2.1 Study Area

The BVRB is a trans-national river system that stretches from North to South through Mali, Burkina Faso, Ghana and Côte d'Ivoire, and from Burkina Faso, Côte d'Ivoire and Ghana from West to East (Fig. 1). The basin lies between Latitude 7° 00' 00" N and 14° 30' 00" N and Longitude 5° 30' 00" W and 1° 30' 00" W, and covers an estimated area of about 149,000 km². The BVRB accounts for about 38% of the Volta basin system. The basin's topography is considered relatively steep with a maximum elevation in the headwaters of approximately 784 m and minimum elevation at its confluence of approximately 75 m.

The basin has a variable spatial and temporal rainfall pattern. The upstream and downstream portions of the basin experience unimodal and bimodal rainfall patterns respectively [34]. The basin falls within the Sahel, Sudan, and Guinea Savanna climatic zones [39]. Rainfall increases from 400 mm/year in the north to 1500 mm/year in the south, with an average of 1000 mm/year in the northern parts and 1400 mm/year in the south [39]. However, over 80% of the yearly total rainfall is in July, August, and September [37]. During the harmattan period from November to April, the basin experiences little or no rainfall. The basin experiences a mean annual temperature of about 27°C, which varies spatially from north to south [37]. For most of the year, mean monthly potential evapotranspiration exceeds mean monthly rainfall across the entire basin [4].

The major land use activity in the basin is agriculture [37]. Cassava, yam, maize, beans, sorghum, rice, millet, and groundnuts are among the major food crops, while vegetables that are grown include cabbage, tomatoes, lettuce, and okra. The main three types in the area include the baobab, shear nut, dawa-dawa, and neem trees. These trees have long taproots and can survive the harsh dry season conditions [1, 2].

2.2 Data

2.2.1 Observed Hydro-meteorological data

The observed hydro-meteorological data used for this study are the mean daily time series of rainfall and streamflow obtained from the Ghana Meteorological Agency and the Hydrological Services Department, Ghana respectively. The rainfall data serve as the main input data while the observed stream flow data is required for the calibration and validation of the model. A total number of 23 meteorological stations and 4 hydrologic-stations were identified in the BVRB (Fig. 1). An overview of the obtained data types, resolution and the sources are provided in Table 1.

2.2.4 Digital elevation model

The Digital Elevation Model (DEM) at 30 m x 30m resolution obtained from Shuttle Radar Topography Mission (SRTM) was corrected for sinks. The DEM is required for the delineation and determination of the hydrological parameters of the BVRB which serve as input in the HEC-HMS model.

2.2.3 Soil types

The Soil types map (Fig. 3a) and its properties were obtained from the Council for Scientific and Industrial Research, Ghana, soil database and the United Nation's Food and Agriculture (FAO) soil database. In all, five soil types were identified in the study area with Luvisols covering over 65 % of the BVRB. The rest of the soil types are Gleysols, Acrisols, Arenosols and Cambisols.

2.2.2 Land use/land cover (LULC) types

The BVRB land use/land cover (LULC) map was obtained from the hybrid classification of the Enhanced Thematic Mapper (ETM+) Landsat image. LULC information is vital for water resources analysis and especially for modeling hydrological processes. The BVRB land use map together with the soil map is used for the creation of Curve Number (CN) which is a key input

parameter for the loss method of the hydrological model. In all, Five (5) land use/cover classes were identified in the study area (Fig. 3b).

2.3 Methodology

The methods and techniques used to develop the event-based hydrologic model for the BVRB study includes geospatial preprocessing, basin and reach parameterization, and meteorologic model development. Fig. 2 shows the flowchart of the methodology for the hydrological model development and calibration process.

2.3.1 Geospatial Pre-Processing

The watershed delineation and drainage network were developed using the Geospatial Hydrologic Modeling Extension (HEC - GeoHMS) software an extension to ArcGIS. The major spatial input data was the Digital Elecation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM). HEC - GeoHMS is used to generate the physical parameters of the basin such as drainage area, stream lengths, basin slopes, etc. From these physical parameters, initial estimates of unit hydrograph parameters, time of concentration (T_c) and Curve Number (CN), were developed for each sub-basin. Reach routing parameters, such as reach slope and length, were also extracted from the DEM and imported into the HEC-HMS model.

2.3.2 HEC-HMS Model Development

HEC-HMS simulates hydrologic processes through the development of a basin and meteorologic model. The basin and meteorologic model work together to define the rainfall-runoff processes within the watershed.

The meteorologic model provides precipitation in the form of rain or snow as input to the basin model and also dictates evapotranspiration processes within the watershed. The Black Volta Basin was evaluated using the inverse distance meteorologic model within HEC-HMS. The inverse distance method applies observed precipitation data at gauges throughout the watershed based on the distance between the meteorologic station and the centroid node of each subbasin.

The basin characteristics including soil loss, hydrograph transformation, baseflow, and river reach routing provide a hydrologic representation of the modeled basin (Fig. 4). The basin model uses the loss method to calculate precipitation lost to storage and precipitation infiltrating into the soils in the watershed and the subsequent amount of excess precipitation. Excess precipitation is routed

to the subbasin outlet as overland flow using a unit hydrograph transform (Soil Conservation Services (SCS) Unit Hydrograph) method. Precipitation infiltrating into the soil is routed to the subbasin outlet using the recession baseflow method. Overland flow and baseflow are combined at each subbasin outlet before entering the reach network. As the combined flow is routed down through the river reach network of the basin, flow is aggregated from additional subbasins and routing reaches in hydrologic order (Hydrologic Engineering Center, 2000)[22].

The development of an event-based HEC-HMS hydrological model for the Black Volta Basin for flood prediction employed the selection of methods with data availability, model type and widely used recommendation into consideration. The SCS Curve Number method was used to represent the soil loss characteristics within the basin. The SCS Unit Hydrograph method was used to represent hydrograph transformation. The Muskingum Cunge method was used for the reach routing modeling of the basin rivers and recession method was used to represent the baseflow characteristics of the basin.

2.3.2.1 SCS Curve Number (CN) method

The SCS Curve Number (CN) method was chosen for simulating precipitation loss due to infiltration. The method includes three parameters: Initial Abstraction (I_a), Curve Number (CN) and percent imperviousness. Initial abstraction is estimated as the soil storage capacity in millimeters prior to the storm event simulation and is related to the antecedent conditions of the basin. The SCS CN method estimates the excess precipitation using the function as shown in Equation 1,2 and 3 [22].

$$P_e = \frac{(P - I_a)^2}{(P - I_a + S)} \quad (1)$$

$$I_a = 0.2 * S \quad (2)$$

$$S = \frac{25400}{CN} - 254 \quad (3)$$

Where P_e = accumulated excess precipitation at time t , P = depth of accumulated rainfall at time t , I_a = initial abstraction, and S = potential maximum retention.

The curve numbers range from roughly 30, indicating that the soil and land use have very high infiltration rates and 100 which acts as water where all precipitation becomes runoff [36].

The CN layer was created in GIS using the soil map as well as the land use and land cover map (LULC). For the CN layer preparation, the soil layer was split into distinct hydrological groups, such as A, B, C, and D, and interpreted in GIS. After using GIS to create a CN map, it was discovered that the CN ranges from a maximum of 90 to a minimum of 78 at different locations (Fig. 3c). Using the equation 4, the final CN for the sub-basins is computed.

$$CN = \frac{\sum A_i CN_i}{\sum A_i} \quad (4)$$

The impervious area for each sub-basin was estimated by converting the obtained land use data to a percent impervious grid. Using the sub-basin delineation and the percent impervious grid, the “Zonal Statistics” tool in ArcGIS was used to extract overall percent imperviousness for each sub-basin.

2.3.2.2 SCS Unit Hydrograph method

The SCS unit hydrograph method representing the transform model that simulate the direct runoff of the excess precipitation on the basin [43] requires the Lag Time (T_{lag}) as the main input parameter for this method (Equation 5). It is computed for each watershed as a function of the time of concentration (T_c) from the center of mass of excess rainfall to the hydrograph peak as;

$$T_{lag} = 0.6T_c \quad (5)$$

Time of concentration (T_c) indicates the length of time necessary for surface flow to move from the subbasin divide to the outlet. T_c was calculated using the TR-55 method for calculating travel times from the hydrological distant point in each sub-basin, which is related to the longest flow path, derived for each sub-basin using HEC-GeoHMS.

2.3.2.3 Muskingum-Cunge Reach routing method

The BVRB consists of river reaches with varying shapes, slopes and floodplain storage capacity. In an effort to represent the range of river reaches found throughout the watershed, the Muskingum-Cunge routing method was used. The Muskingum-Cunge routing approach estimates the translation and attenuation of flood hydrographs over the reach using physically-based characteristics such as length, slope, Manning's n-values, and cross-sectional geometry [23].

Routing reach lengths and slopes were derived directly from the geo-processing and watershed delineation using HEC-GeoHMS while the width of each reach of the river network was obtained

with the help of satellite images (eg. Google Earth tool) and field measurements. Manning's roughness coefficient number for the riverbeds was chosen based on field observations and research. The routing model is used to simulate flow from the upstream parts of a basin to the downstream or basin's outlet [32].

The Muskingum equation relates the relationship between the reach storage and discharge as the flood propagates through the reach. The basic parameters in the Muskingum–Cunge equation that are incorporated by National Resources Conservation System (NRCS) are X and K and are given as:

$$X = \frac{1}{2} \left(1 - \frac{Q}{BS_o c \Delta x} \right) \quad (6)$$

where, X = weighting factor, non-dimensional, Q = reference flow from the inflow hydrograph (m³/s), B = bottom width of flow area or average width (m), c = flood wave celerity (m/sec), Δx = length of routing (m), S_o = bed slope of the channel (dimensionless) and

$$K = \frac{\Delta x}{c} \quad (7)$$

2.3.2.4 Recession Baseflow Method

For event-based hydrological modeling, the base flow component does not play a significant role in the runoff generated. However, the recession baseflow method was applied in this study for model calibration purposes. The recession base flow method was chosen because of its simplicity and is intended to mimic the typical behavior seen in watersheds when channel flow declines exponentially following an event [15]. The recession baseflow method consists of three parameters: initial base flow, recession constant, and threshold ratio [22]. It is estimated thus;

$$Q_t = Q_0 k^t \quad (8)$$

Where Q_0 = initial baseflow (at time zero); and k = an exponential decay constant.

Initial baseflow describes the initial baseflow for each sub-basin. During calibration, initial baseflow was calibrated to observed data for each simulation. The recession constant parameter determines the slope of the baseflow hydrograph's receding limb.

2.3.3 Model Performance Evaluation

The Objective functions are statistical criteria used to determine the performance of a model [17]. In this study, objective functions used to access the model accuracy are the Nash-Sutcliffe efficiency measure (NSE), Percentage bias (δ_b), Percent Difference in Runoff Volume (V_R), and the Percent Difference in Peak Discharge (Q_P). These objective functions are commonly used to access the performance of rainfall-runoff models [9, 15, 16, 21, 41, 43].

$$NSE = 1 - \frac{\sum(Q_n^{sim} - Q_n^{obs})^2}{\sum(Q_n^{obs} - \bar{Q}_n^{obs})^2} \quad (9)$$

Where, Q_n^{sim} and Q_n^{obs} are the simulated and observed discharges at time step n, respectively. $\bar{Q}_n^{obs}$ is the average observed flow.

$$\delta_b = \left| \frac{\sum_{i=1}^n (Q_n^{sim} - Q_n^{obs})^2}{\sum_{i=1}^n Q_n^{obs}} \right| \times 100\% \quad (10)$$

Where, Q_n^{sim} and Q_n^{obs} are the simulated and observed discharges at time step n, respectively.

$$V_R = \frac{V_R^{sim} - V_R^{obs}}{V_R^{obs}} \times 100 \quad (11)$$

Where V_R^{sim} and V_R^{obs} are the simulated and observed total runoff volume, respectively.

$$Q_P = \frac{Q_P^{sim} - Q_P^{obs}}{Q_P^{obs}} \times 100 \quad (12)$$

Where Q_P^{sim} and Q_P^{obs} are simulated and observed peak discharges, respectively.

2.3.4 Model Calibration and Validation

Event based models only require data at the event scale, hence prominent flood events within the periods of 1996 to 2010 were selected for calibration and validation of the model. The floods of 1996, 1999, 2007, and 2010 were some of the largest flood events in the streamflow record of the BVRB. Hence, the selection of events of 1996 and 2007 floods for calibration, and 1999 and 2010 for validation (Table 2). Availability and completeness of rainfall and stream monitoring data for

the selected flood events are other factors that were considered in selecting the flood events for use in calibration and validation.

The model calibration and validation were carried out based on simulated and observed discharge at the gauging stations of Chache, Bui, and Bamboi. The goal was to get the simulated discharge data to match the observed discharge data in terms of peak value, curve shape, and time of peak while keeping parameter changes within a reasonable range. The model parameters were initially calibrated manually after which it was subjected to the HEC-HMS model's automatic calibration methods. The Automatic calibration method uses an iterative process to minimize the objective function, to achieve agreement between simulated and observed discharge flow data. Optimization trials, which is, the selections for the objective function, search method, and basin model parameters to be adjusted in order to find an optimal model to improve the results of the calibration.

2.3.5 Sensitivity Analysis

Sensitivity analysis is the evaluation of model input parameters to estimate model stability and the effects of the input parameters on the output of the model [5]. Parameters such as curve number, initial abstraction, impervious layer percentage, and lag time were adjusted in the range of $\pm 20\%$ with 5% intervals to analyze the sensitivity of the calibration parameters.

2.3.6 Model Application

The calibrated and validated hydrological model of the BVRB was applied for the forecasting of floods in terms of peak flows and water levels using the obtained Intensity-Duration-Frequency (IDF) curves and rating curve (Equation 13) for selected stations within the basin.

2.3.6.1 Forecasting Peak flows using IDF curves

The forecasting of flood using calibrated hydrological model was carried with the Intensity-Duration-Frequency (IDF) curves as the main input rainfall data in the model. The IDF curves show the intensity of rainfalls for various rainfall durations expressed in return periods. Fig. 7 (A, B and C) shows the IDF curves obtained from GMet for selected stations within the basin.

Rainfall depths were calculated from the IDF curves corresponding to 5-year, 10-year, 15-year, 20-year, 25-year, 50-year, 75 and 100-year return periods (Table 6) and used as inputs into the

calibrated HEC-HMS model to simulate peak flows using the frequency storm method of the meteorological model.

2.3.6.2 Flood Water Levels determination using Rating Curve

Rating curve establishes the relationship between flood water levels (H) and discharges (Q) at a river station and are very useful because they allow estimating discharge flows using water level records and vice versa in a hydrometric station. In this study, the available rating curve (Equation 13) at the Chache gauge station on the BVRB obtained from the Hydrologic Service Authority (HSA) of Ghana was used as the means of determining the flood water levels corresponding to the forecasted peak flows for each return period simulated using the IDF curves.

$$Q = K(h + a)^p \quad (13)$$

where Q is the discharge, h is the stage (Water level [m]), a = -0.3965, is the stage at zero flow (datum correction) and K = 13.4109 and p = 2.4503 are constants.

2.3.6.3 Flood Hazard Classification

Flood hazard describes the flood condition that harm people. This condition can be classified into different levels of severity based on flood characteristics such as flood water level, flood velocity, flood warning time, flood extent etc for specific return period. In this study, flood hazard has been classified base on flood water levels into five (5) level of severity of inundation namely; normal level, warning level, moderate, high and very high. The normal level here is defined as the water level at the banks of the river at the Chache station.

3.0 Results and Discussion

3.1 Basin Parameter Optimization

Table 4 is the summary results of the optimized sub-basin parameters of BVRB during calibration process. During optimization, initial basin parameter values are automatically adjusted to give a good agreement between simulated and observed discharge values. The Initial discharge, ratio to peak and recession constant values for the recession baseflow method were adjusted, the curve numbers and initial abstraction values for the loss method were adjusted. For the transform method, the lag time was the only adjusted parameter, whereas the initial and maximum storage

for the canopy method was adjusted and the manning's coefficient was adjusted for the reach routing. These adjustments were done for each sub-basin within the catchment. The optimized parameter values were used for model validation. Tables 4a and 4b shows the initial values assigned to various basin parameters and their corresponding optimized values (after optimization) used for the model validation.

3.2 Model Calibration

The flood events of September 1996 and 2007 were calibrated based on the general shape of the hydrographs, runoff volume, and peak flow values. The peak flow, which corresponds to the maximum downstream flooding, is the most significant feature of the hydrograph when assessing a flood event. Data for flood events on all the hydrologic gauge stations (Chache, Bui, and Bamboi) were only available in daily averages and not hourly averages; therefore, this distorts the Nash-Sutcliffe efficiency for these events. However, the results of the hydrologic model showed a sound fit between the simulation and the observation after optimization, and the model works well across a range of events. Table 3 shows a general performance rating for the three recommended statistics. Even though the model tended to overestimate the runoff before optimization, the shape of the hydrograph and time of peaks matches suitably as shown in Fig. 5a to Fig. 5e.

The sensitivity analysis revealed that the curve number, initial abstraction, and lag time were found to be the most sensitive, less sensitive, and least sensitive model parameters, respectively.

The modeling results of peak discharge, total volume, and their relative errors in comparison to observed data, the Nash Sutcliffe Efficiency, and Root mean Square error values during calibration are shown in Table 5. The Percent difference in runoff volume ranges between 6.7%, which is considered to be very good, and 23.9%, which is considered satisfactory based on the general performance rating (Table 3). The percent difference in peak discharge obtained ranges between -0.2% considered as very good and 24.8%, which is considered as satisfactory. The NSE ranges from 0.789 (at Bamboi in September 2007) to 0.919 (at Chache in September 1996). This indicated a very good agreement between the observed and simulated runoff based on the performance rating (Table 3). The percentage bias gave unsatisfactory performances except for the September 2007 event at Bui with a percentage bias of 6.70%, which is considered good. Fig. 5a to Fig. 5e shows the observed and simulated hydrographs for the various stations for the calibration period. Overall, the model performs well with good agreement between simulated and observed values.

3.3 Model Validation

The flood events of September 1999 and 2010 were used for model validation. The optimized parameters from the calibration stage were used to simulate flood events for 1999 and 2010 in the study area. Table 6 shows the results of validation listing the peak discharge, total volume, and relative errors concerning observed data, as well as the Nash–Sutcliffe Efficiency (NSE).

The peak discharge of all the events was slightly overestimated except for the September 1999 event at Bui station, which was underestimated. The percent difference in peak discharge ranges from -51% to 19.1%. The total volume was underestimated for all events except for September 1999 at Chache, which was slightly overestimated. The percent difference in runoff volume ranges from -23.3% to 5.9%. Considering the Nash–Sutcliffe Efficiency (NSE) criteria, satisfactory to good results were obtained between the observed and simulated values with NSE values ranging from 0.505 to 0.965. Fig. 6a to Fig. 6e shows the observed and simulated hydrographs for the various stations for the validation periods. The total simulation results of the events chosen for validation suggest that the HEC-HMS model has the potential to perform well in predicting peak flows and runoff volume in the BVRB using SCS-Curve Number and SCS Unit hydrograph methods. Good hydrological model calibration and validation findings show that it is possible to simulate discharge along the BVRB in Ghana even with insufficient input data, using a semi-distributed model.

3.4 Prediction of Flood Threshold Peak Flows and Water levels

The Calibrated model was used to simulate peak runoffs using the design storms developed from the IDF curves (Fig. 7a to Fig. 7c). Table 7 shows the simulated peak runoff at the selected gauge stations; Chache, Bui, and Bamboi stations with their corresponding return periods. The only available rating curve (Equation 11) at Chache station was then applied to estimate the corresponding flood water levels at Chache station in the BVRB as shown in Table 8. The 3 – dimensional (3D) relationship of the flood threshold peak flow and water level corresponding to return period at Chache station is illustrated in Fig. 8.

A 5-year return period of rainfall in the basin recorded a peak discharge of 1568.8 m³/s, 3251.7 m³/s, and 5488.9 m³/s at Chache, Bui, and Bamboi discharge stations respectively. The 15-year return period simulation gave a peak discharge of 1833.7 m³/s. Comparing this peak flow value to the observed peak discharge of 1811.0 m³/s at Chache station during the September 1999 flood

event, it is reasonable to infer that the rainfall event that caused the flood was a 15-year return period rainfall.

Similarly, the simulation of the 15-year return period of rainfall gave a peak discharge of 4149.8 m³/s at Bui station, this value is similar to the observed peak discharge of 4100.0 m³/s recorded at the station during the September 2007 flood event. Hence, it is reasonable to suggest that the rainfall event, which caused the flooding event, was a 15-year return period rainfall. The simulation for a 10-year return period of rainfall at Bamboi station produced a peak flow of 6436.2 m³/s, which is close to the reported peak discharge of 6158.9 m³/s during the September 2007 flood event. It could be inferred that a 10-year return period of rainfall led to the September 2007 flood at Bamboi. In addition, the 50-year return period of rainfall gave a peak discharge of 8652.2 m³/s. This value is close to the observed peak discharge of 8680.2 m³/s recorded at the station for the September 2010 flooding event. It is, therefore, reasonable to suggest that the September 2010 flooding at the Bamboi Station event was caused by a 50-year return period of rainfall.

The deductions made from the simulated peak flows with corresponding return period compared with the observed peak flows of flooding events at the selected stations in the basin shows the model capability to be used as a predictive tool for floods. In the situation of inadequate data to help classify a flooding event in the basin as caused by a given return period, the application of the model to simulate the peak flow for the corresponding rainfall event can help classify a flood event in terms of return period using IDF curves developed for the basin. Such classification helps in the risk management of floods in the basin.

3.5 Flood Hazard Classification

The result of the flood hazard classification is shown in Table 9. It can be observed from Fig.9 and Fig. 10 that a rainfall event of return period greater or equal to 25 years (i.e. flood water level $\geq$ 8m corresponding to discharge $\geq$ 1935 m³/s) is likely results in very high severe flooding at the cache station. A high severity level of flooding is likely to occur for a rainfall of return period ranging between 10 years to 20 years (7.5 m $\leq$ flood water level $<$ 8 m and 1635 m³/s $\leq$ discharge $<$ 1935 m³/s). The occurrence of a moderately severe flooding in the basin is possible for a rainfall event of return period greater or equal to 5-year (7.0 m $\leq$ flood water level $<$ 7.5 m and 1365 m³/s $\leq$ discharge $<$ 1635 m³/s). The forecasted water level at Chache station for the return periods are

all above the warning level of 6.5m and the normal level of 6m (ie. river bank water level). Hence, inundations are likely to occur when flows exceed warning level of 1130 m³/s at the station.

This information is important for flood disaster management organization and other stakeholders such as the Hydrological Service department (HSD) of Ghana to be on flood warning alert when rainfall of such magnitude is expected to occur within a year especially in the raining season period as predicted by Ghana Meteorological Agency (GMet).

4.0 Conclusion

The event-based HEC-HMS model for the BVRB was capable of simulating peak flows and runoff volumes of flood events of 1996 and 2007 with an average NSE ranging between 0.789 to 0.919 during the calibration process. The validation process results for the 1999 and 2010 flood events recorded NSE values ranging between 0.505 - 0.965. Therefore, it is reasonable to conclude that the calibrated model has a good performance and is suitable for predicting peak flow and peak volumes in the BVRB in Ghana.

The model application of flood forecasting using the IDF curves simulated the peak flows corresponding to the return periods 5, 10, 15, 20, 25, 50, 75, and 100 years and compared with the observed peak flows of different flood events in the basin. Analysis of the results shows that the flood event in September 1999 at Chache with an observed peak flow of 1811.0 m³/s was reasonably equivalent to the simulated peak flow of 1860 m³/s resulting from the 15-year rainfall event. The September 2007 flood event at Bui station recorded an observed peak flow of 4100 m³/s and this can be equated to the simulated peak flow of 4149.8 m³/s resulting from the 15-year rainfall event. Again, the September 2007 flood event at Bamboi reported an observed peak flow record of 6158.9 m³/s which is close to the simulated peak flow of 6436.2 m³/s resulting from the 10-year rainfall event. The September 2010 flood event at Bamboi recorded a peak flow of 8680.2 m³/s which is close to the simulated peak flow of 8652.2 m³/s resulting from the 10-year rainfall event. This concludes that the event-based HEC-HMS model can be used as a flood forecasting tool and can also be used to classify a flood event in terms of their return period especially in an ungauged environment using IDF curves. This classification helps in the risk management of floods in the basin.

The flood hazard classification using the rating curve at Chache station in the BVRB resulted in flood hazard levels for different peak discharges and flood water levels ranging from moderate,

high and very high severity levels corresponding to different return periods of rainfall in the basin. The study reveals that at least a 25-year return period rainfall event (i.e., flood water level ≥ 8 m equivalent to discharge ≥ 1935 m³/s) is likely to cause severe flooding in the Basin, particularly at the Chache station. Moderate flooding is likely to be experienced for at least a 5-year return period rainfall event in the study area.

The application of the flood hazard classification to the flood event in September 1999 at Chache, in the basin shows that the flood event with the recorded peak flow of 1811,0 m³/s inferred to have resulted from a 15-year return period of rainfall event can be classified as a high severe flooding with flood water level ranging between 7.5m to 8m (ie. $7.5 \text{ m} \leq \text{flood water level} < 8 \text{ m}$).

Although outcomes of this research will offer essential information for flood management in the BVRB, there were key uncertainties associated with the study; the spatial and temporal HEC-HMS input data, methods for accounting for the hydrologic processes in the basin model, and inadequate rating curves and lack of updated IDF curves at some gauge stations. This implies that additional research is needed to enhance the results with respect to the above uncertainties by using other methods in the HEC-HMS basin model, high resolution spatial and temporal input data, and developing new rating curves at various stations and the application of a hydraulic modelling (eg. HEC-RAS) to validate the flood water levels in the BVRB.

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Author contributions

Felicia Yeboah: Model simulations, validation, writing – original Draft.

Edward Kofi Ackom: Conceptualization, methodology; software simulation assistance; review and editing.

Sandow Mark Yidana: Supervision, formal analysis, data curation; methodology, review and editing, funding acquisition.

Alfred Awotwe: Review and editing

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Data Availability:

The data that support the findings of this study are available from the corresponding author upon reasonable request and with permission of Ghana Meteorological Agency (GMet) and Hydrological Service Authority (HSA) of Ghana.

Code Availability: Not applicable.

Declarations

Ethics Approval: The author declares no ethical violation during the preparation of this manuscript.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests: The authors declare no competing interests.

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Figures

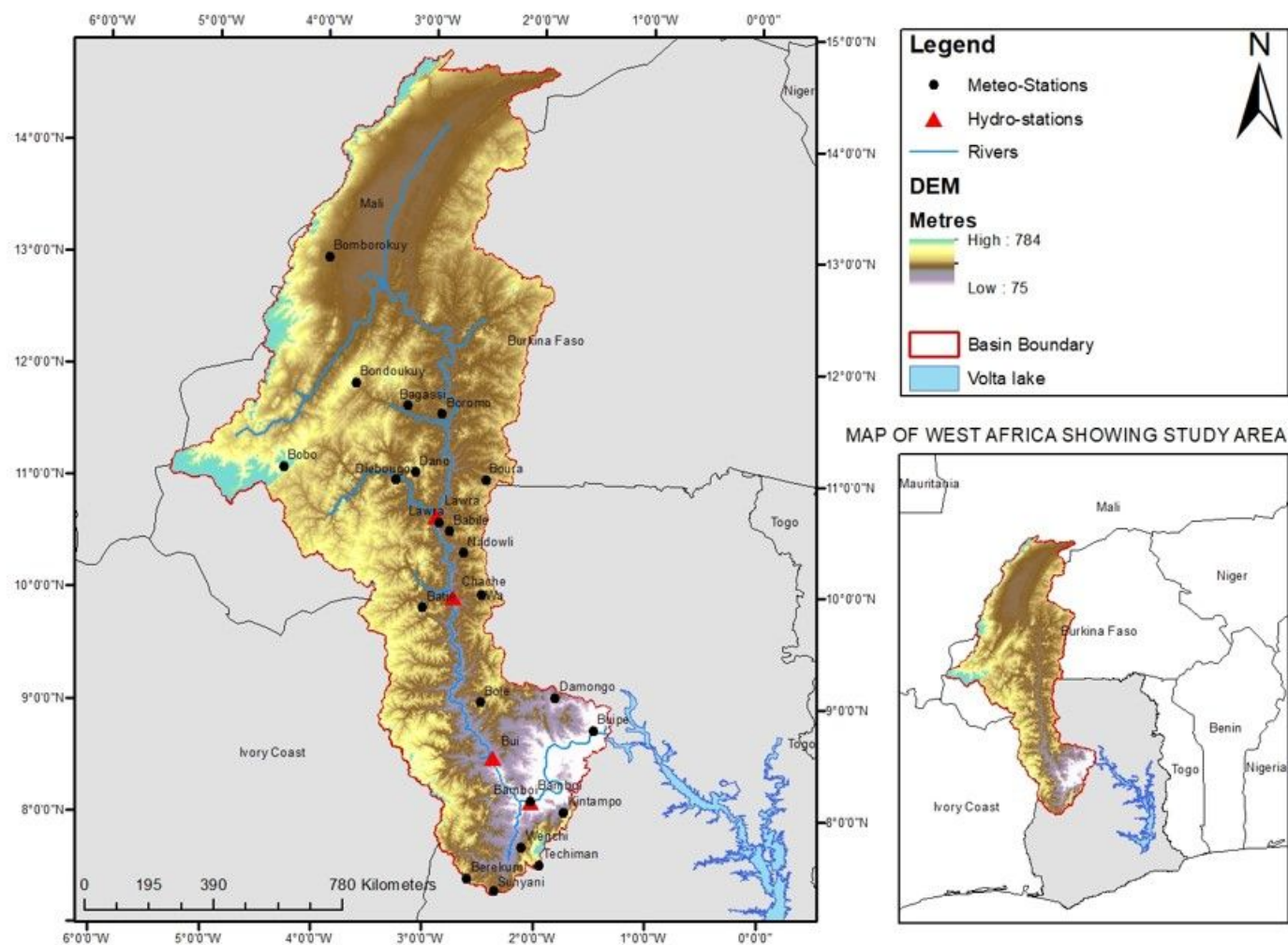


Figure 1

Map of study area showing location.

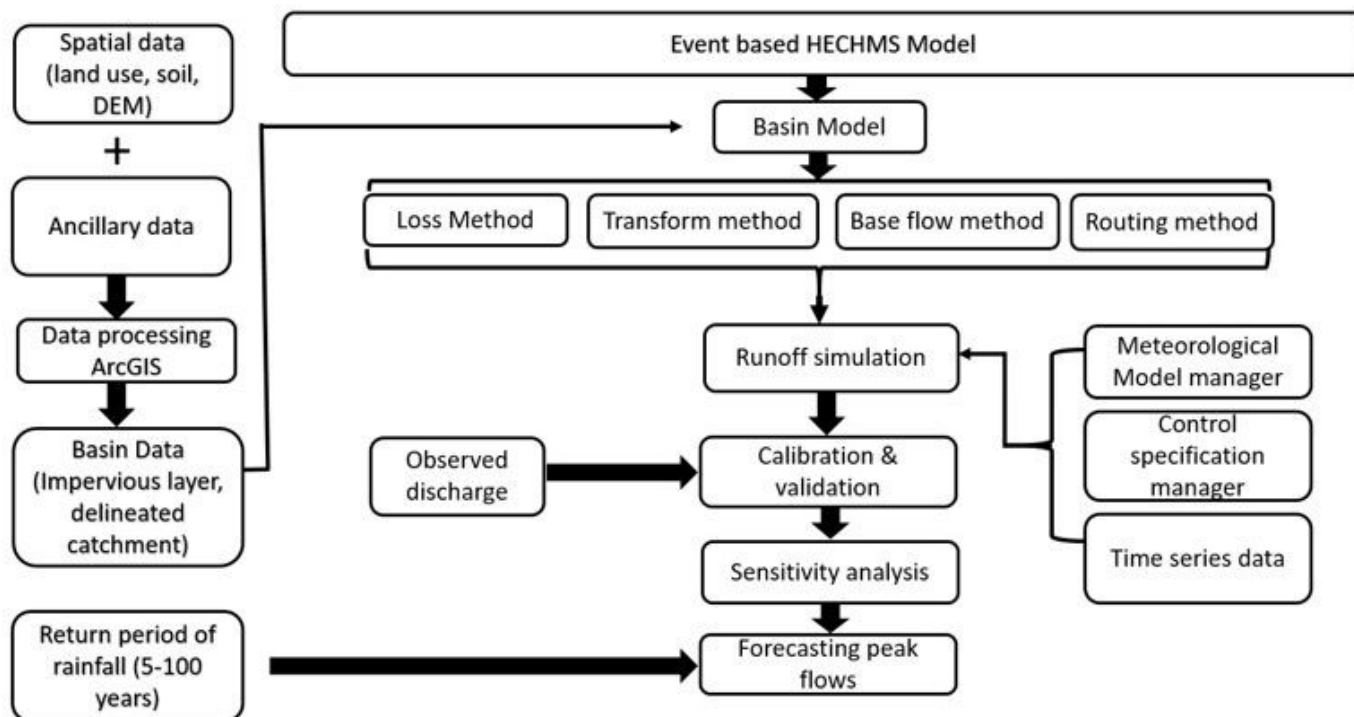


Figure 2

Flowchart for Hydrological Model Development

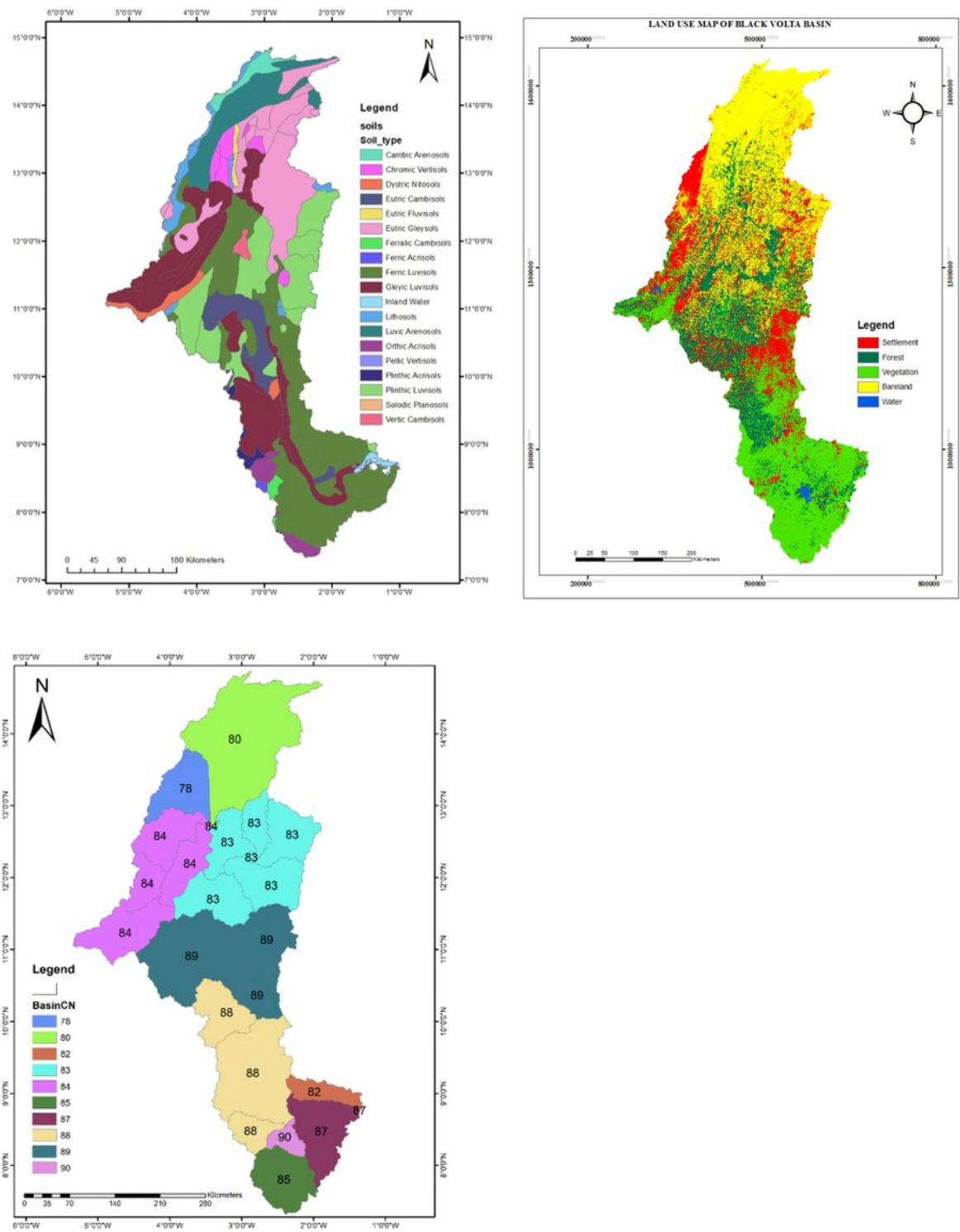


Figure 3

- a: Soil map of the BVRB
- b: Landuse/cover (LULC) map of the BVRB
- c: Curve Number (CN) map of the BVRB

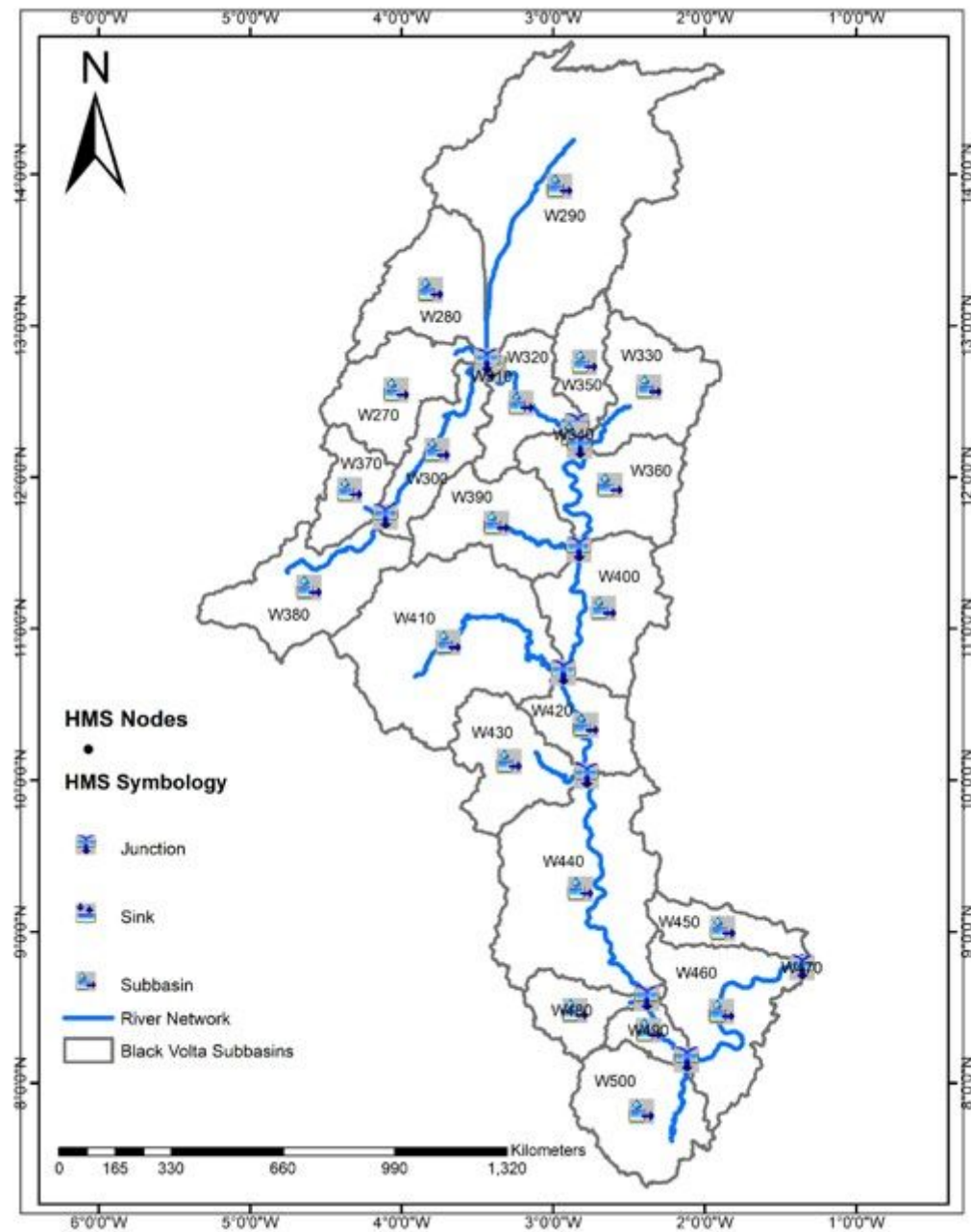


Figure 4

Delineated Subbasin and River Network of BVRB

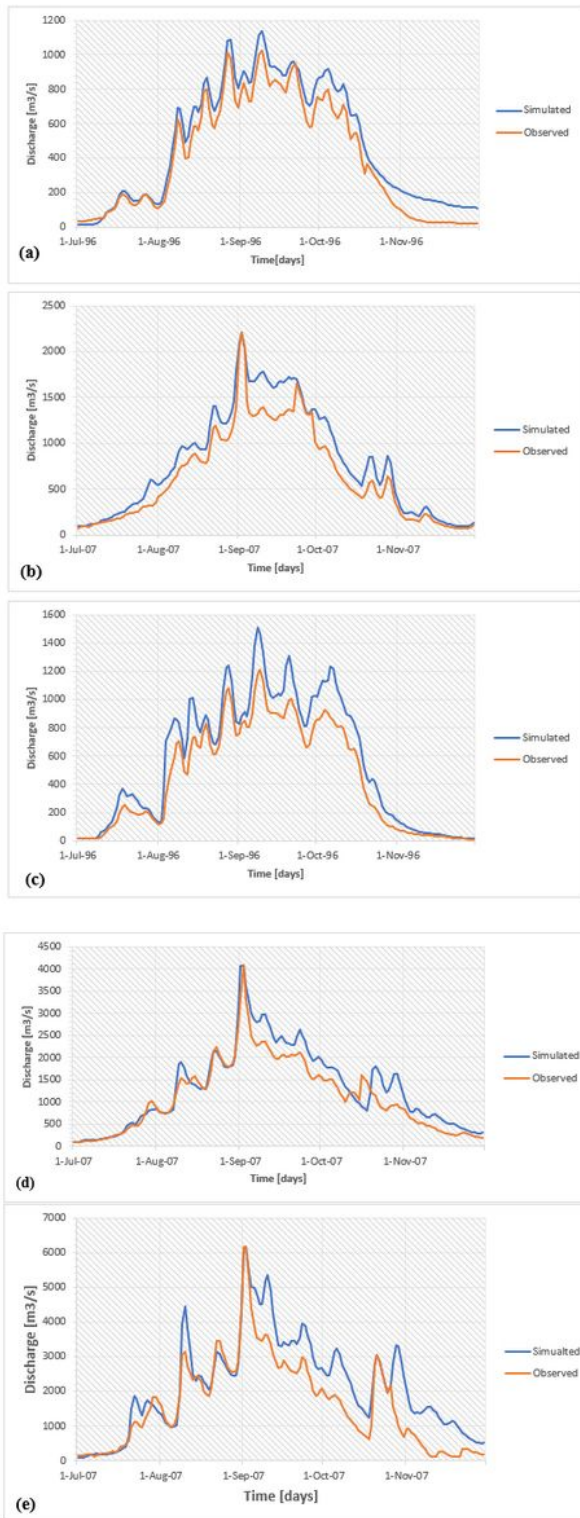


Figure 5

Simulated and observed hydrographs under calibration process (a) Chache, 1996 Event (b) Chache, 2007 event (c) Bui, 1996 Event (d) Bui, 2007 Event, (e) Bamboi, 2007 Event

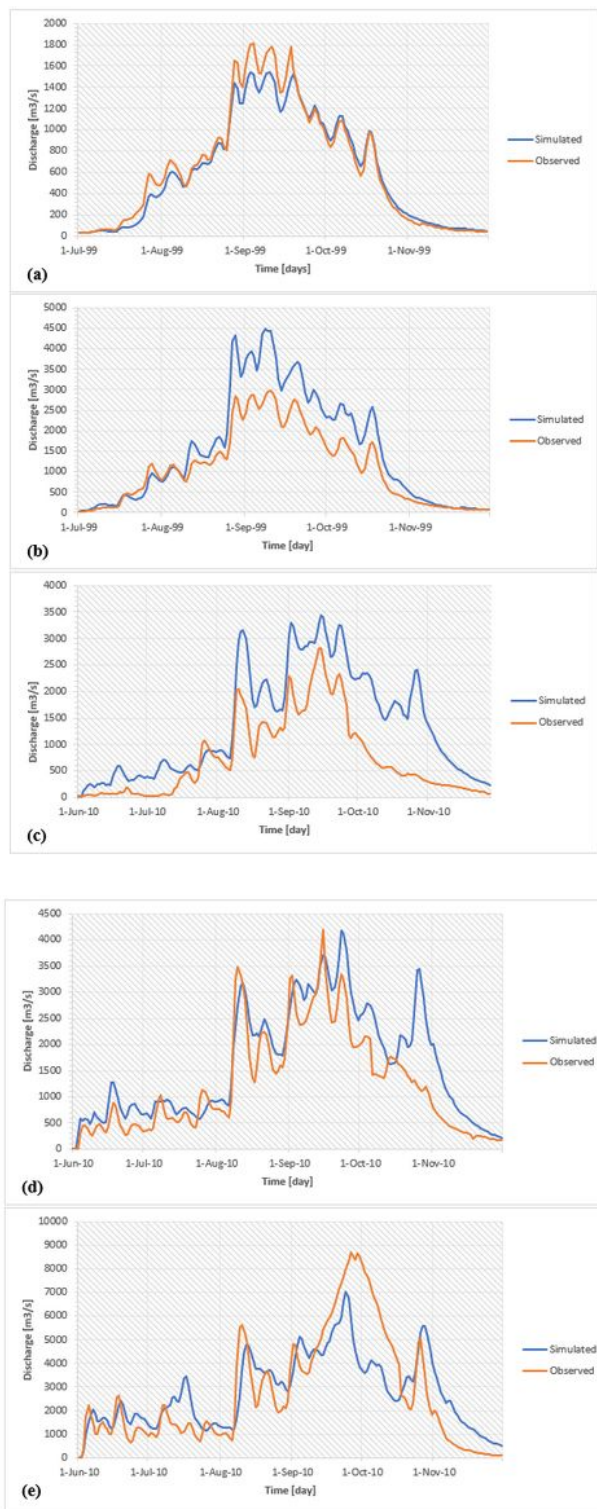


Figure 6

Simulated and observed hydrographs under Validation process (a) Chache, 1999 Event (b) Bui, 1999 Event (c) Chache, 2010 Event, (d) Bui, 2010 Event (e) Bamboi, 2010 Event

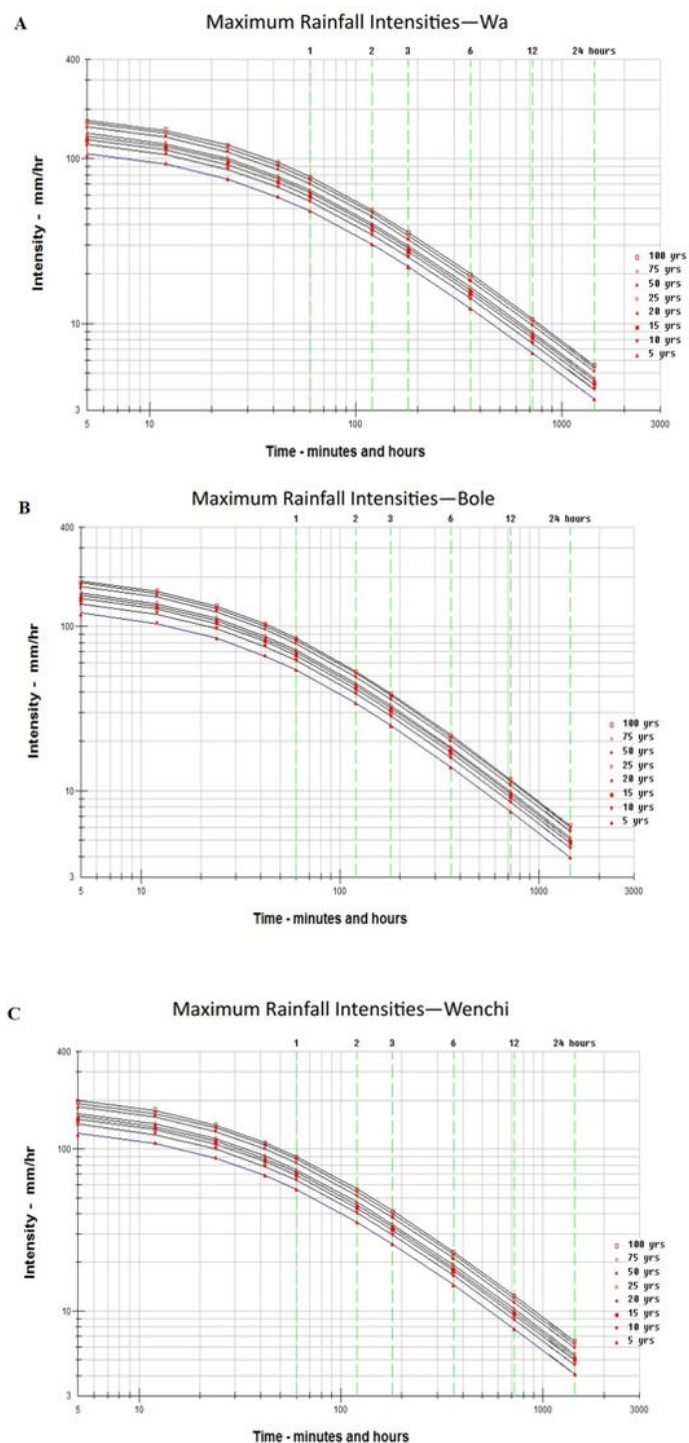


Figure 7

Intensity-Duration-Frequency (IDF) curves (a) Wa station, (b) Bole Station (c) Wenchi station (Source: Updated 1974 IDF curve for Ghana by J.B Dankwa, GMet 2016)

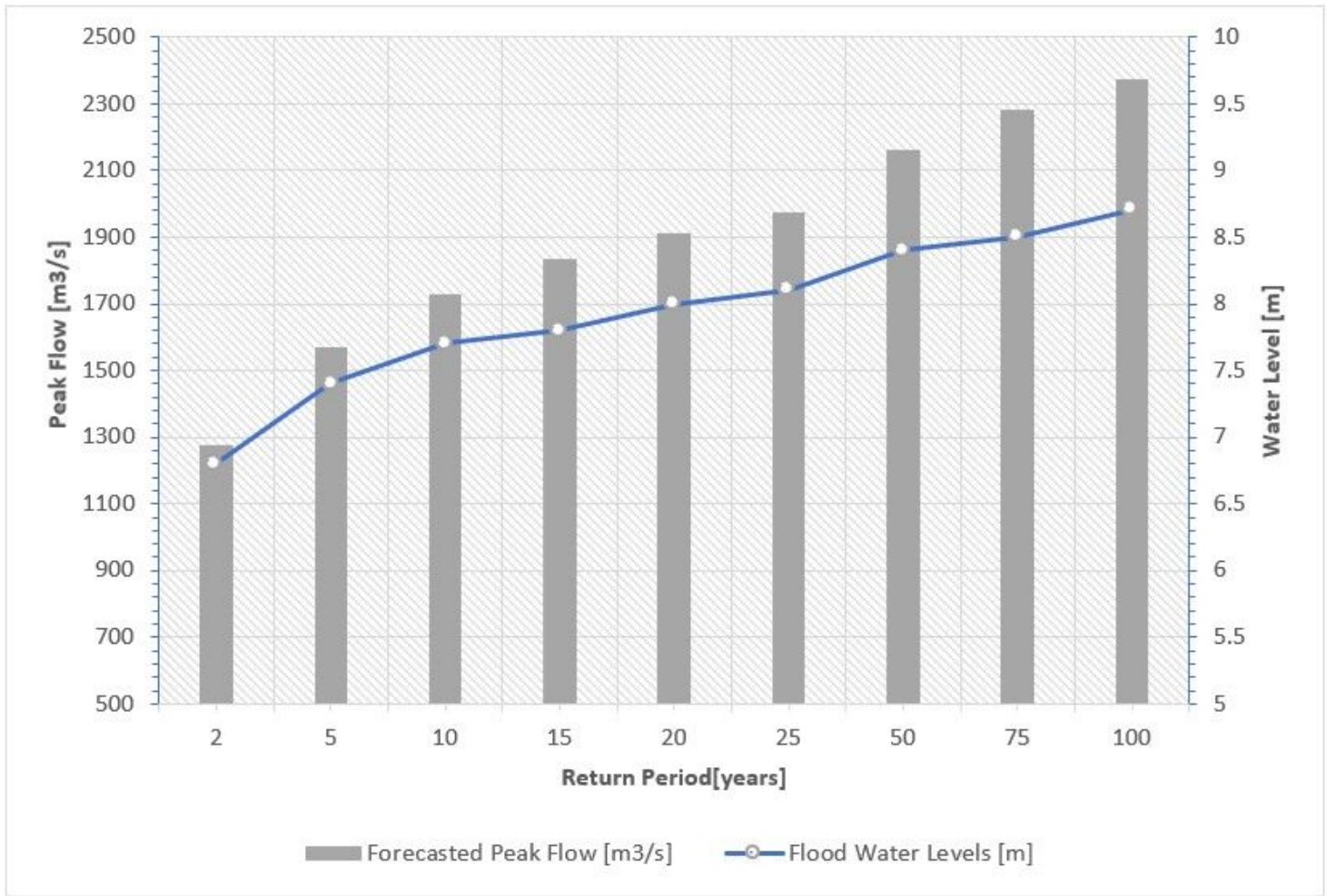


Figure 8

Peak Flow and Water Level Variation with Return Period @ Chache Station

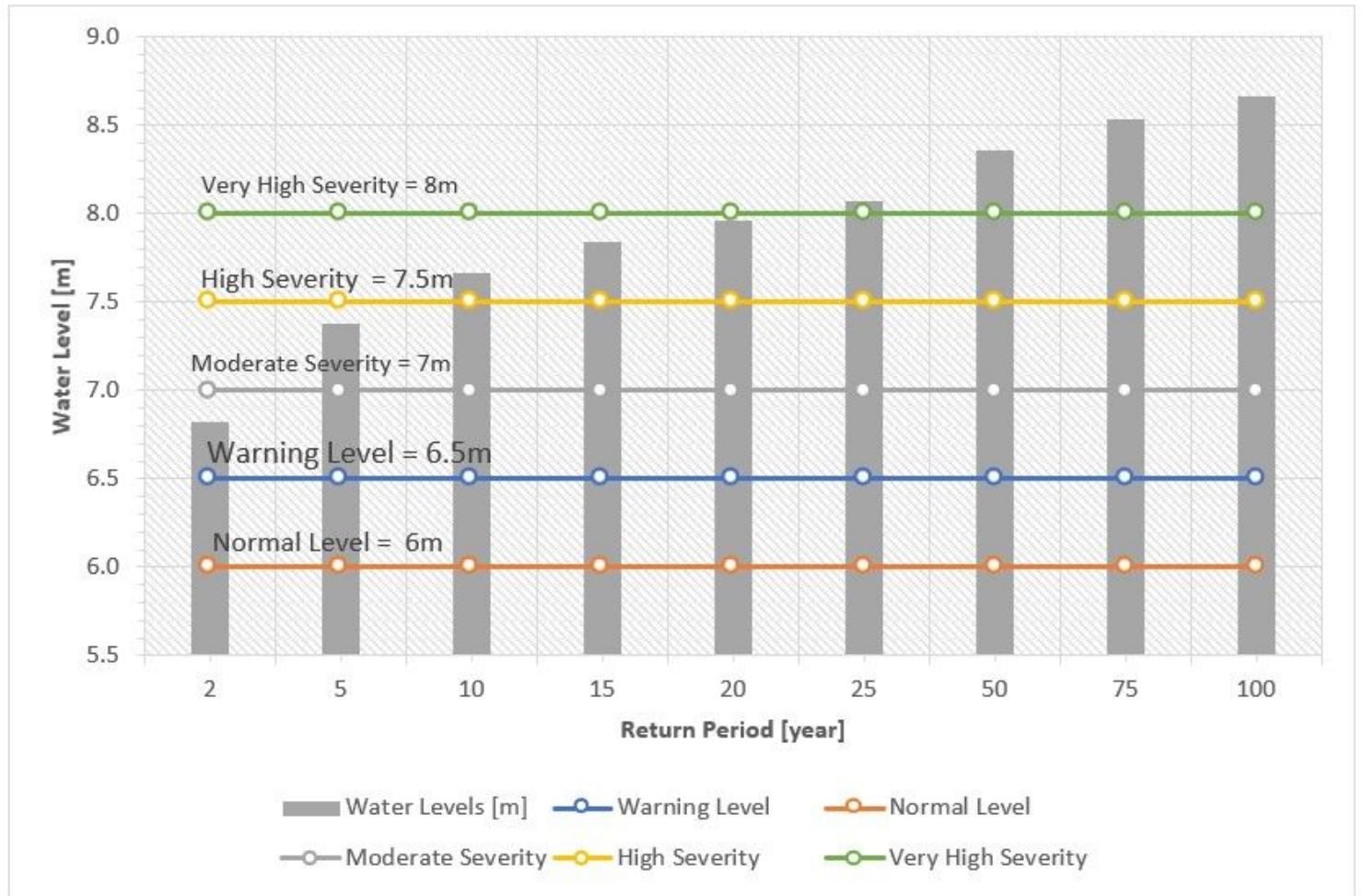


Figure 9

Flood Water level variation with Return period and flood severity levels @ Chache Station

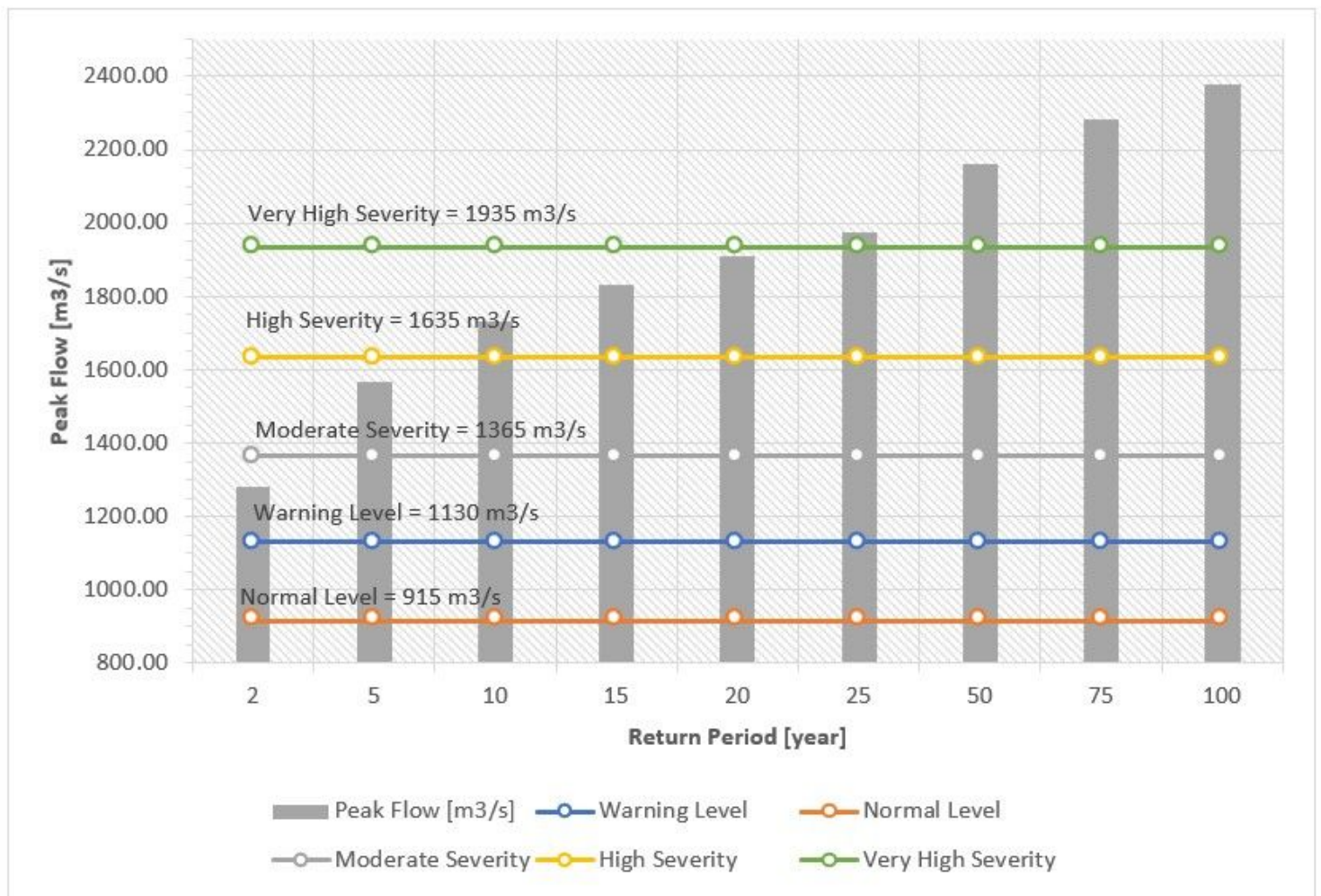


Figure 10

Peak Flow variation with Return period and flood severity levels @ Chache Station

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