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Extreme Weather and Flood Forecasting and Modelling for Eastern Tana Sub Basin, Upper Blue Nile Basin, Ethiopia

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Abstract

River flood is a natural disaster that occurs each year in the Fogera floodplain causing enormous damage to the human life and property. Overflow of Ribb and Gummara rivers and backwater effects from Lake Tana has affected and displaced thousands of people since 2006. Heavy rainfall for a number of days in the upper stream part of the catchment caused the river to spill and to inundate the floodplain. Three models were used for this research; the numerical weather prediction model (WRF), physical based semi distributed hydrological model SWAT) and the LISFLOOD_FP 1D2D flood inundation hydrodynamic model to forecast the extreme weather, flood and flood modeling. Daily rainfall, maximum and minimum temperature for the forecasted period ranges from 0 to 95.8mm, 18 to 28oc and 9 to 18oc, respectively. The maximum forecasted flow at Ribb and Gummara rivers were to be 141m3/s and 185 m3/s, respectively. The flood extent of the forecasted period is 32km2; depth ranges 0.01 to 3.5m; and velocity ranges from 0 to 2. 375 m/s. This technique was shown to be an effective way of flood forecasting and modeling. Integrating Rainfall Runoff model with hydrodynamic model provides thus good alternative for forecasting and modeling.

Keywords*:* SWAT, LISFLOOD, WRF, Extreme weather, forecasting and modeling.

1. INTRODUCTION

The earth`s climate will hit developing countries like Ethiopia first and the hardest because their economic are strongly dependent on crude forms of natural resources and their economic structure is less flexible to adjust to such drastic changes (Bryan et al., 2009). In Ethiopia floods are common and have been occurring throughout the country with varying time and magnitude. Flood disasters are caused by rivers overflow or burst their banks and inundate to downstream flood plain land; particularly large scale flooding (riverine flooding) in the country is common in the low land flat parts due to high intensity of rainfall from highland parts (Deressa et al., 2009).

Weather-related disasters are increasing in intensity and are expected to increase with climate change (Parry, 2007). Approximately 70% of all disasters occurring in the world are related to hydro-meteorological events (Barrientosa and Swainc, 2014). Death and destruction due to flooding continue to be all too common phenomena throughout the world; and affecting millions of people annually which is about a third of all natural disasters throughout the world and are responsible for more than half of the fatalities (Berz, 2000).

As recently as 2006, flooding occurred in almost all parts of the country and devastate the entire country of which Lake Tana remains one of these areas regularly inundated. In spite of the recurrent flood problem, the existing disaster management mechanism is primarily focused on strengthening rescue and relief arrangements during and after flood disasters. Little work has been done in scientific context on minimizing the incidence and extent of flood damage; but need to forecast the extreme weather as well as extreme weather related disasters.

Hence, it's essential to forecast and model the occurrence of extreme weather related disasters to secure human life and property. Therefore, the objectives of this study were to forecast extreme weather and runoff, flood level, velocity and depth, and evaluate the applicability of integrating WRF-SWAT-LISFLOOD_FP models to forecast flooding in fogera floodplain, Easter Tana sub basin.

2. MATERIALS AND METHODS

2.1 Study area description

The study was conducted in the upper Blue Nile part of Ethiopia in Amahara Region, South Gondar Zone. Geographically the area is located between 10°57′and 12°47′N and 36°38′and 38°14′E (Figure 1). It has an aerial extent of about 4174.33km^2 drained by Ribb and Gummara Rivers; which is nearly 600 km away from Addis Ababa. It's characterized by different geographic futures like flood plain, high mountainous land with cold weather (Guna Mountain), Plateau, and rivers. The basins topography ranges from 1783m near to Lake Tana up to 4089m above mean see level on Guna Mountain. The climate is tropical highland monsoon where the seasonal rainfall distribution is controlled by the movement of the inter-tropical convergence zone and moist air from the Atlantic and Indian Ocean in the summer (June-September) (Kebede et al., 2006). The seasonal distribution of rainfall is controlled by the northward and southward movement of the inter-tropical convergence zone (ITCZ). Moist air masses are driven from the Atlantic and Indian Oceans during summer (June–September). During the rest of the year the ITCZ shifts southwards and dry conditions persists in the region between October and May.

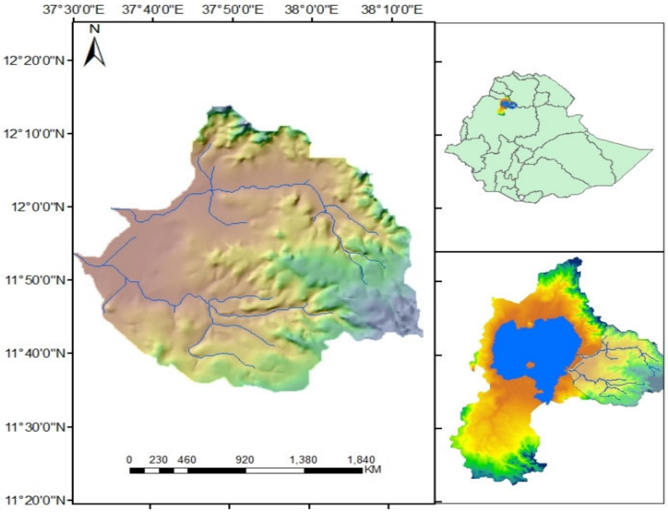


Figure 1: Location of study area:

2.2 The data set

Time series daily rainfall and temperature data for the selected stations from 1951-2012 were obtained from National Meteorological Agency of Ethiopia (NMA). The other variables evapotranspiration, solar radiation, wind speed and relative humidity, were simulated from SWAT weather Generator. Similarly, daily stream flow data series of Ribb and Gumara rivers for the years of 1973 to 2009 were obtained from Ethiopian ministry of water Irrigation and Energy.

Spatial resolution of 30x30m land use image was downloaded from landsat8 OPL sensor with 169 Path and 52 Row for 01/02/2014 and reclassified using supervised maximum likelihood land use classification method using GIS integrating with Google earth. Also soil data was extracted from Blue Nile Basin soil data (Soill90) obtained from ministry of water irrigation and energy of Ethiopia. River cross section data of Ribb and Gummara Rivers and Survey data for Fogera flood Plain were obtained from Tana Sub Basin Office (TaSBO) which is collected by MoWIE. The rivers width was obtained by digitizing from a satellite ESRi high resolution world imagery base map of resolution 1m and better of resolutions (15cm and 60 cm) on ArcGIS map window.

2.3 Extreme Weather forecasting

Extreme weather has been forecasted for the entire period of August 20-Sepet10, 2006 using a numerical weather prediction WRF model. To forecast the extreme weather nested three domains [Ethiopia (45km), Northern part (15km), and fogera (5km)] resolution were selected by assuming 1 degree ~111km around equator. The model handled three domains at the same nest level (no overlapping nests), and/or three nest levels (telescoping). The nesting ratio for the WRF-ARW is 3 and the grid spacing of a nest was 1/3 of its parent.

The initial and lateral boundary meteorological and terrestrial gridded data which used to run the WRF-ARW model has been downloaded from Global Forecasting System (GFS) which was produced by the National Centers for Environmental Prediction (NCEP) and it is updated for every six hours. The Real-data was interpolated to run the NWP using WRF Pre-processing System (WPS). The WRF Model (ARW dynamical cores) was initialized numerical integration programs for real data processing. The output of the model WRF_ARW was processed on WRF-post processing and visualized using Grid Analysis and Display System (GRADS). The output of the WRF model, weather data, was processed for input of SWAT model. From the output of the model few parameter was selected and used as SWAT model impute.

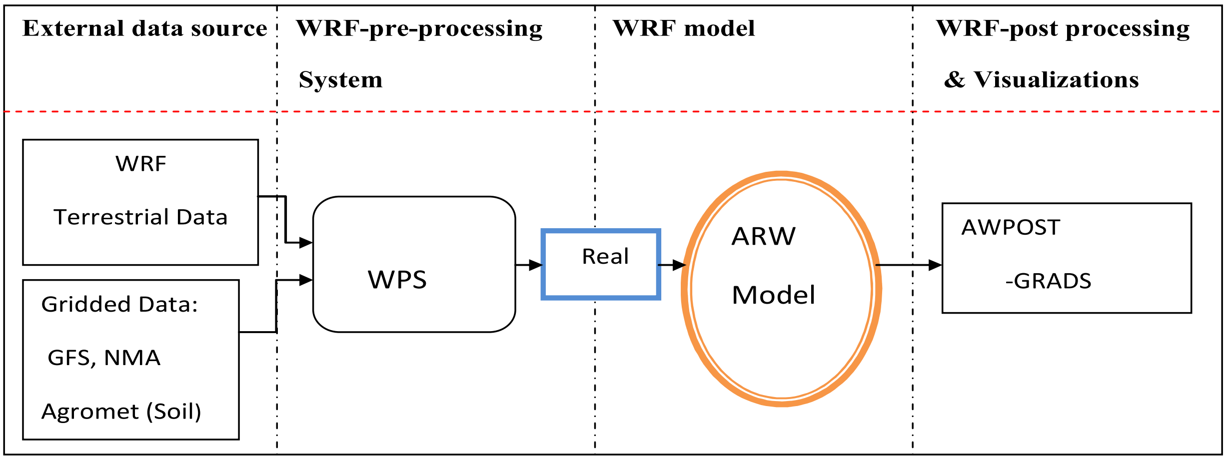


Figure 2: Approach of WRF-ARW numerical weather forecasting model

2.4 Runoff forecasting

A conceptual, physically-based, continuous SWAT model was employed to simulate stream flow. The forecasted weather data using WRF_AWR were used as input for SWAT model to forecast stream flow. Before forecasting, the model was calibrated and validated using observed flow data. From the available data, 2 years (1994-1996) for warm-up, 9 years (1996-2004) for calibration and 5 years (2005-2009) were used for validation. Model calibration was performed using the Sequential Uncertainty Fitting _version 2 (SUFI-2) interface of SWAT-CUP. SWAT-CUP is a separate calibration and uncertainty program developed by Abbaspour et al. (2004). It is a commonly used procedure for calibration and uncertainty analysis. (Setegn et al., 2008), and (Yang et al., 2008) compared different procedures and found SUFI-2 is better that gives good results even at smallest number of runs as compared to other procedures.

The performance of model was evaluated using dimensionless Nash-Sutcliffe efficiency (NS) (Nash and Sutcliffe 1970) and coefficient of determination (R^2). The dimensionless Nash-Sutcliffe efficiency measures normalized magnitude of the residual variance relative to measured flow variance. The value of NS ranges from $-\infty$ to 1, while the value 1 for NS indicates the perfect fit from the 1:1 line. NS values less than zero indicate unsatisfactory performance. Table 1 shows the mathematical representations of this techniques and recommended range of performance for the SWAT model. Coefficient of determination (R^2) was used to measure the level of correlation among model variables, and to measure mean differences of water balance components using different station densities. Coefficient of determination is the square of the correlation between observed and simulated that measures how much measured value variation is explained in the simulation (Krause et al., 2005). It ranges between 0 and 1. The value 1 indicates that the variation of the simulation is equal to the variation of the observed time series.

2.5 Flood modeling and forecasting

Among the most widely used hydraulic models LISFLOOD model is selected for this research. LISFLOOD is a distributed, raster- based; combination rainfall-runoff and hydrodynamic model embedded in a dynamic GIS environment (De Roo et al., 2000, de Roo et al., 2003, De Roo, 1999), and has been developed for the simulation of hydrological processes and floods in European drainage basins. It is a flexible tool which is capable of simulating hydrological processes on a wide range of spatial and temporal scales, maintaining high resolution even when simulating large catchment areas.

The LISFLOOD-FP, one of the modules of LISFLOOD, includes a number of numerical schemes (solvers) which simulate the propagation of flood waves along channels and across floodplains using the shallow water equations. The choice of numerical scheme is depend on the characteristics of the system has to be modeled, requirements of time for execution and type of data available. The momentum and continuity equations for the 1D full shallow water equations have given below (equations (5) and (6) respectively):

$$\frac{\partial Qx}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x{}^2}{A}\right) + gA\frac{\partial(h+z)}{\partial x} + \frac{gQ_x{}^2 n^2}{R^{4/3}A} = 0 \qquad (5)$$

$$\frac{\partial A}{\partial x} + \frac{\partial Qx}{\partial x} = 0 \qquad (6)$$

where Qx is volumetric flow rate in the x Cartesian direction, A is the cross sectional area of flow, h is the water depth, z is the bed elevation, g is gravity, n is the Manning's coefficient of friction, R is the hydraulic radius, t is time and x is the distance in the x Cartesian direction.

2.5.1 Floodplain flow solvers: LISFLOOD Roe

The "Roe" solver includes all of the terms in the full shallow water equations (Trigg et al., 2009) was selected for this research. The method has based on the Godunov approach and uses an approximate Riemann solver by Roe based on the TRENT model presented in Villanueva and Wright (2006). The explicit descritisation is first order in space on a raster grid. It solves the full shallow water equations with a shock-capturing scheme. LISFLOOD-Roe uses a point wise friction based on the Manning´s equation, while the domain boundary/internal boundary (wall) uses the ghost cell approach. The stability of this approach has approximated by the Courant–Friedrichs–Levy (CFL) condition for shallow water models.

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial(h_t + z)}{\partial x} + \frac{gQ^t n^2}{R^{4/3}A} = 0 \qquad (7)$$

Where Q is discharge, t is time, A is cross section area g is gravitational constant, ht is water free surface height, z = bed elevation, n is Manning's coefficient and R = Hydraulic Radius.

2.5.2 Channel flow solvers

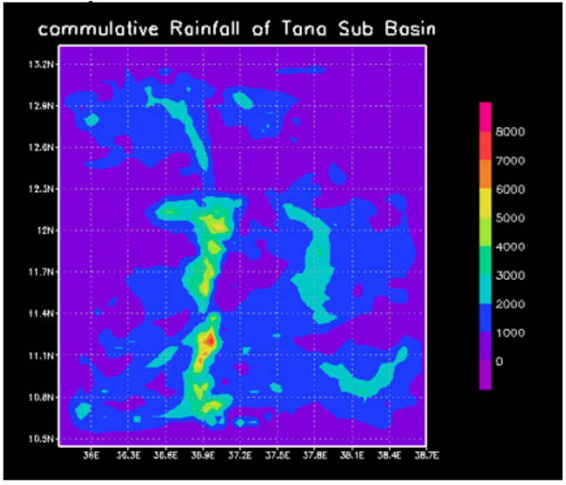
The "diffusive" channel flow solver has selected for this research uses the 1D diffusive wave equations and it includes the water slope term, which is able to predict backwater effects. Using the 1D-channel solvers, once channel water depth reaches bank full height, water has routed onto adjacent floodplain cells has distributed as per the chosen floodplain solver. There is no transfer of momentum between the channel and floodplain, only mass. The 1D diffusive solvers assume that the in-channel flow component can be represented using a diffusive 1D wave equation with the channel geometry simplified to a rectangle. The 1D diffusive channel flow solver assumes that the channel to be wide and shallow, so the wetted perimeter is approximated by the channel width such that the lateral friction is neglected.

3. Result and Discussion

3.1 Extreme Weather forecasting

The extreme weather for the study area has forecasted using a numerical weather prediction model WRF-ARW from 20August-10Sept 2006. The weather parameters have forecasted at a six- hour time step and converted to daily for SWAT model input. Air temperature, wind speed at two meter, solar radiation, relative humidity, precipitation, geopotential height, sea surface temperature and Surface temperature were among the outputs of the WRF model. Precipitation and temperature of the output parameters have selected for SWAT model input to forecast the flood. The result in figure 3 shows that Eastern Tana Sub basin has subjected to intense and heavy rains during the selected period. The developments of intensive weather events that invade Eastern Tana sub basin during 20 Aug- 7 Sept 2006, have characterized by "exceptional and extremely heavy rainfall," which affected almost all part of the Eastern Tana Sub Basin.

The forecasted rainfall of the selected station has obtained from the WRF output gridded data. Unfortunately, the selected stations point has no the same coordinate with girded point. Hence, the forecasted rainfall for the station points has obtained from the neighboring gridded points using regression method. The cumulative of forecasted rainfall is similar with the cumulative of the observed (Figure3). The forecasted daily rainfall for the forecasted period ranges from 0 to 95.8mm. A very intense and heavy rain has occurred during 25th of the days almost all over the entire sub basin.



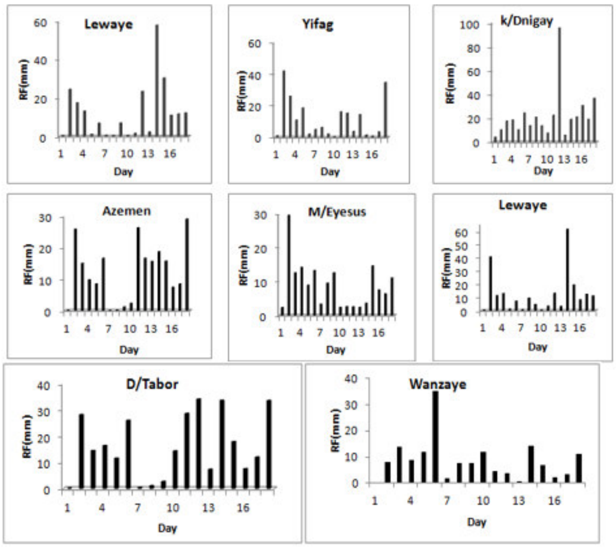


Figure 3: The figure shows the spatial distribution of Forecasted rainfall over the study area from 20Aug-10 Sept 2006

Similarly, the forecasted temperature for the station points has obtained from the neighboring gridded points using regression method. As can be seen Figure 4, the spatial variation of average temperature over the Tana Sub basin. The maximum forecasted air temperature for the selected period of the entire sub basin ranges from 18°c to 28°c; and minimum temperature ranges from 9 °c to 18 °c. Generally, the WRF model has well forecasted the maximum and minimum temperature compared with the observed data for the sub basin.

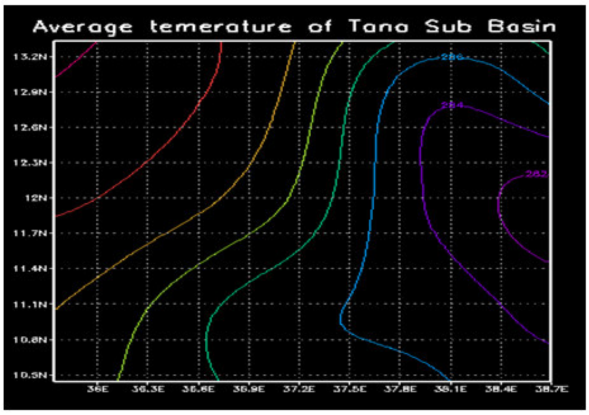
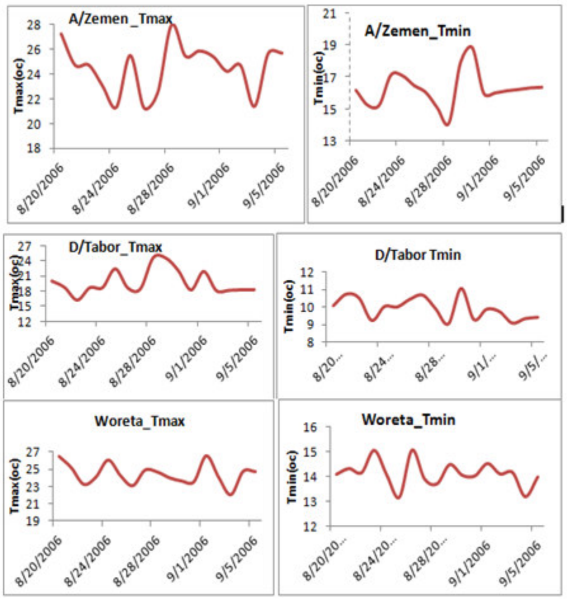


Figure 4: The figure shows the spatial distribution of Forecasted temperature over the study area from 20Aug-10 Sept 2006



The calibration and validation of the model was a key factor in reducing the uncertainty and increasing confidence in its predicative abilities, which makes the application an effective model. Information on the sensitivity analysis, calibration and validation of multivariable SWAT models was provided to assist watershed modelers in developing their models to achieve their watershed management goals (White and Chaubey, 2005). SWAT simulation has executed for the 1994-2009 period by providing two-years for an initialization period. Calibration of SWAT has performed for 1994 - 2004, while 2005 - 2009 have used as the validation years.

The goodness of fit of the model is evaluated using coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE)]. It has found that the model has strong predictive capability as shown table1. Statistical model efficiency criteria fulfilled the requirement of R2 > 0.6 and NSE > 0.5 which is recommended by SWAT developer (Santhi et al., 2001). This showed the model parameters represent the processes occurring in the watershed to the best of their ability given available data and can used to predict watershed response for various outputs.

Model calibration is done to compare the flow obtained from the simulation and observation at the selected hydrological station on a daily basis. The model calibration method considers every sub-basin located in the upper selected point. Then, in order to obtain the closest simulated flow to the observed value at the selected point, Automatic SWAT-CUP calibration was applied to find the suitable value for parameters of outlet sub-basin. The model output variance is expressed as the variance in model performance measurements such as coefficient of determination (R2) and Nash-Sutcliffe efficiency (NSE)]. The R^2 and NSE were used in this study; the calibration results obtained from selected points are shown in Fig. 24. The calibrated results for the main river at Ribb station, calibrated for the period 1994-2004, gave NSE and R^2 about 0.72 and 0.73, respectively with high uncertainty p_ factor of 0.34 and of r_0.48. This is due to the model over estimate the peak discharge during summer. Similarly, the calibrated results for the Gummara river at Gummara station, calibrated for the period 1994-2004, gave NSE and R2 about 0.75 and 0.77, respectively with low uncertainty p_ factor of 0.74 and of r_0.46 as can be seen the Fig.5 and Fig.6; there is a good agreement between simulated and observed flows.

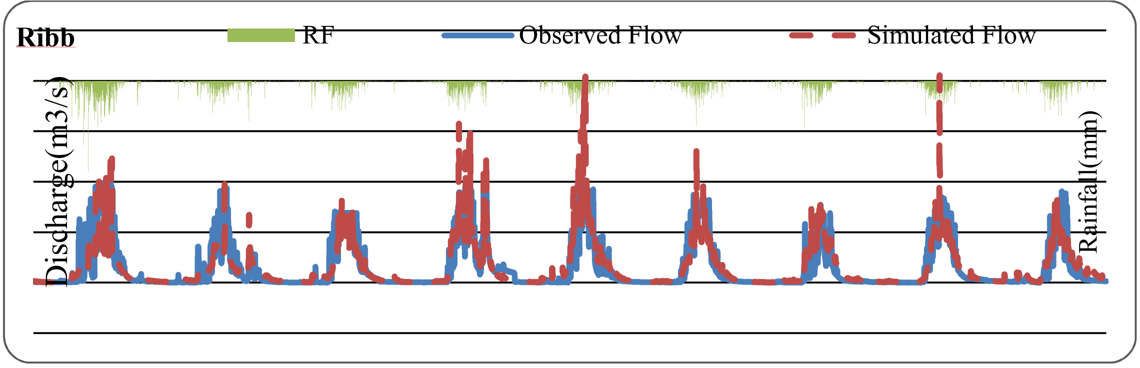


Fig. 5 the calibration results at Ribb station for the period 1994-2004, gave NSE and R^2 about 0.72 and 0.73 respectively and the model is in good agreement.

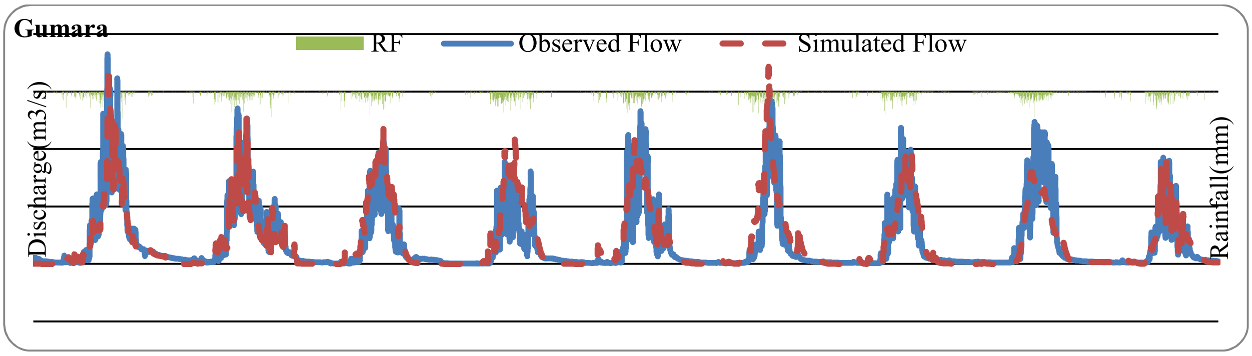


Fig. 6 the calibration result at Gummara station for the period 1994-2004, gave NSE and R^2 about 0.75 and 0.77 respectively and the model is in good agreement better than at Ribb.

The two statistical model performance measures used in calibration procedure were also used in validating processes. It was found that the model has strong predictive capability with NSE of 0.73 and R2 of 0.74 for Gummara River; and NSE of 0.68 and R2 of 0.76 for Ribb River.

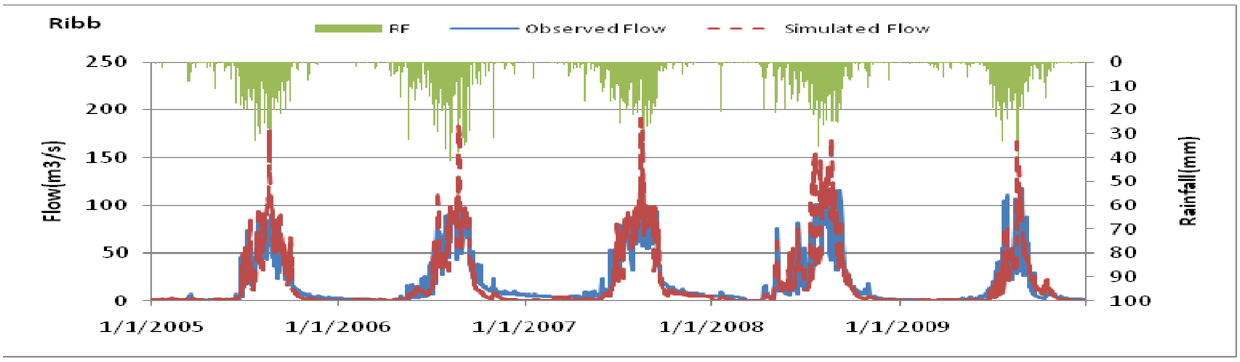


Fig. 7 the validation result at Ribb station for the period 2005-2009, gave NSE and R^2 about 0.68 and 0.76 respectively and the model is in good agreement.

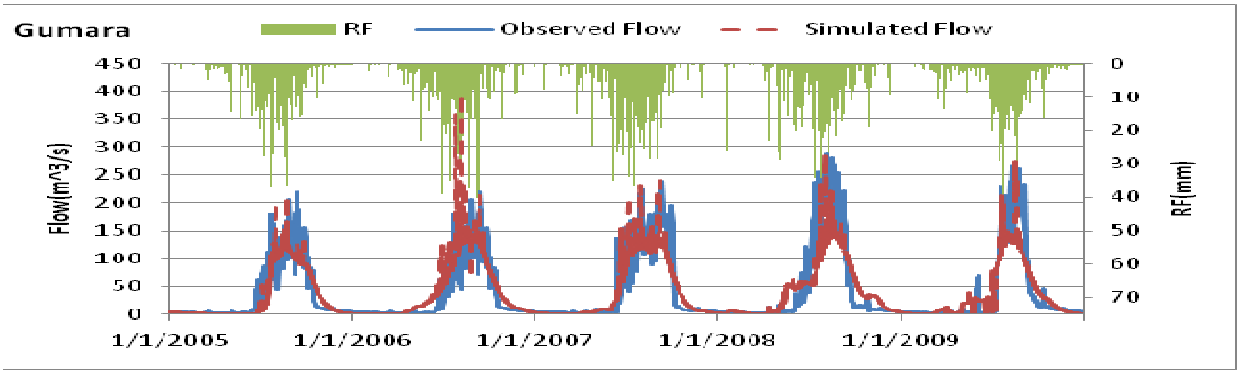


Fig. 8 the validation result at Gummara station for the period 2005-2009, gave NSE and R^2 about 0.73 and 0.74 respectively and the model is in good agreement.

3.2.2Flow Forecasting

The forecasted weather data using NWP-WRF model has used as input for SWAT model. The simulated value has considered as forecasted flow. It has also found that the simulated flow rate using NWP_WRF data was lower than the observations for both watersheds for consecutive five days from 27 Aug – 1 Sept 2006. This was because the rainfall from the NWP-WRF model was lower than the measured rainfall. In Summary, the simulated flow rates for the rivers using data from NWP-WRF were higher than the observations flow at Ribb River and lower than at Gummara River. The maximum forecasted flow at Ribb was 141cms but the maximum observed flow was 93cms. Similarly, for Gummara, the maximum forecasted and observed flow was 185cms but the maximum observed flow was 206cms.

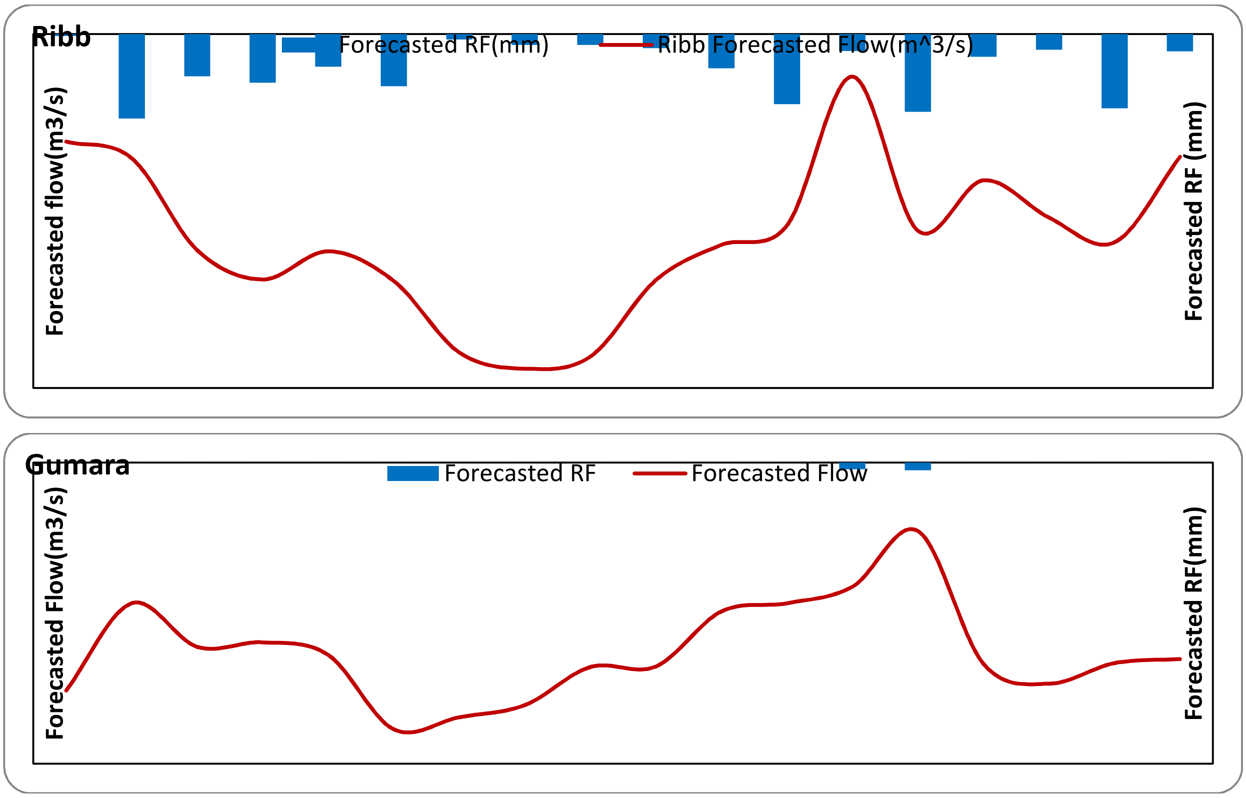


Fig. 9: Forecasted flood over Gummara and Ribb Gauges

3.3 Flood Modeling

Both upstream and downstream boundary conditions have given for the diffusive channel solver. The upstream boundary is the forecasted flow rate at gauging site of Ribb and Gummara rivers; and the downstream boundary condition is the Lake Tana water level. The advantage of the diffusive channel solver over Kinematic solver is that the tributaries have handled automatically by LISFLOOD-FP. To simulate a dynamic flood wave both upstream and downstream time varying boundary condition (QVAR and HVAR) have used.

The forecasted flood extent for the design period 20 Aug – 10 Sept 2006 has computed by integrating the hydrology model (SWAT) and a hydrodynamics model (LISFLOOD). The output from SWAT that is a hydrograph used as upper boundary for LISFLOOD model and the Lake level interims of elevation used as lower boundary. Therefore, the LISFLOOD computes the flood extent on accounts of the boundary conditions, the rivers width, and river cross – Section and Manning's friction coefficient.

The flood extent obtained from LISFLOOD_FP has processed on GIS environment. The extent of flood for the forecasted period is 329 Km^2. The flood depth ranges from 0.01 to 3.5m and the maximum depth is at the rivers. The flood velocity for the forecasted period ranges from 0 to 2.375 m/s. The model has not accounted the rainfall over the flood plain and the small rivers those are not tributary of the main rivers (Ribb and Gummara) Fig.10. This might be under estimate the flood extent.

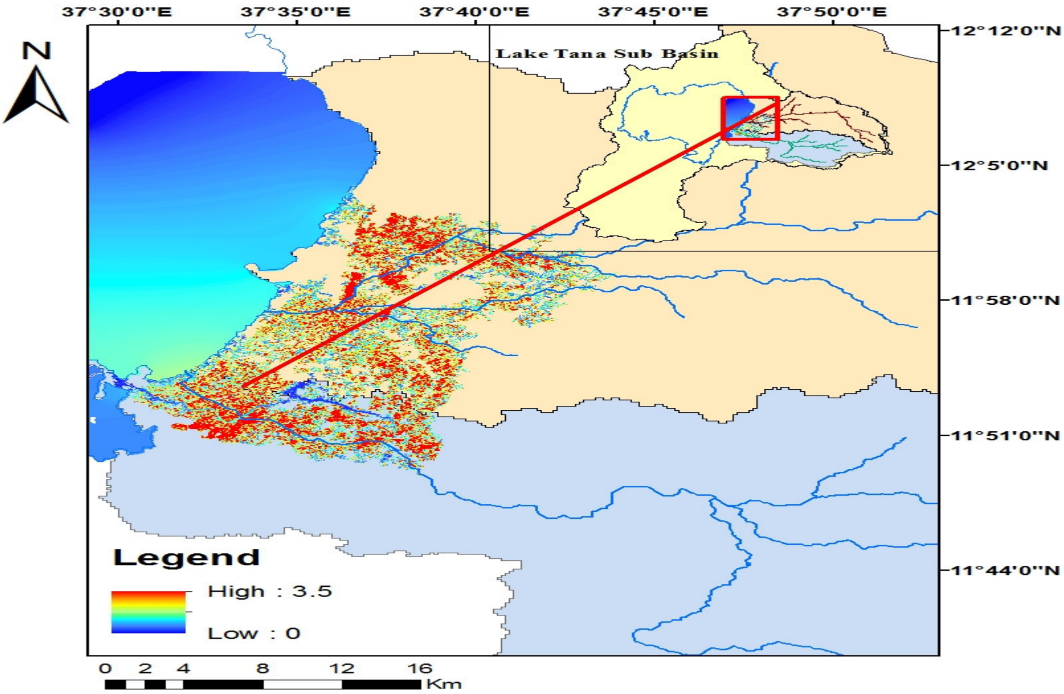


Fig. 2: Forecasted flood extent of Fogera flood plain for 20Aug-10 Sep 2006

3.4 Flood Model Verification

The goodness of fit between the created flood map from flood model and the flood map extracted from the satellite images has assessed by the measure of relative error (RE) and F-statistics (F). As shown the figure 12 indicates that the inundation area of the extracted flood images from the satellite is 259.7 Km^2 and predicted flood inundation area is 256.9 Km^2. The area of overlapping portion of the two flood inundations is 236.55 Km^2 with RE of 0.01 and F-statistics of 84.47%. This shows that the compared areas of the flood inundation are similar to each other but they are not geospatially similar. As can be seen figure 12 the satellite image shows more flooded area in the side of Ribb River but the forecasted flood area is more in the Gummara river side. This seems rescannable because the satellite image also accounts the logged water over the area due to rainfall and other tributaries. Near to the Ribb, river and center of the flood plain there are tributaries, which are causing flood.

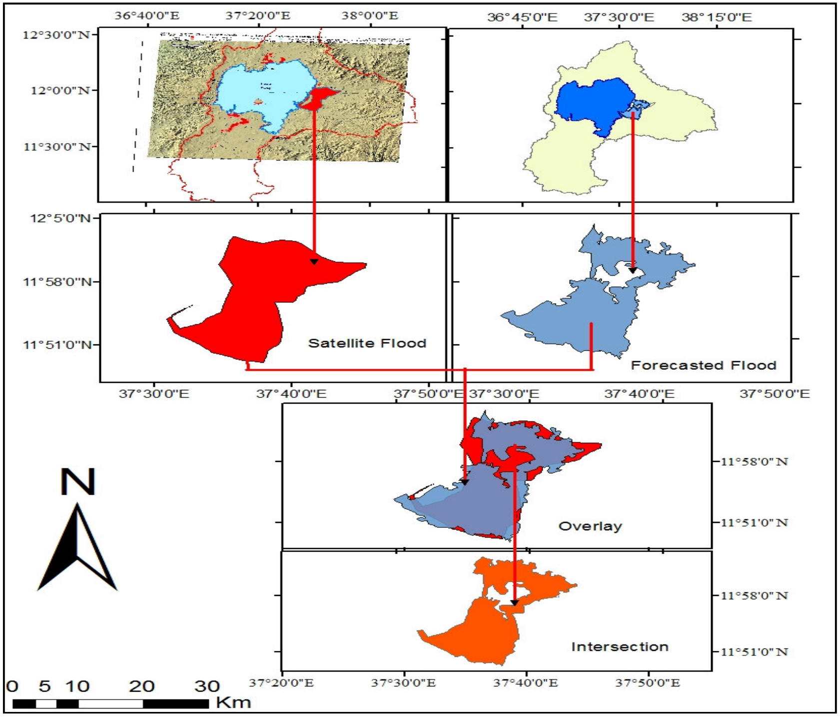


Fig. 12: Flood map from flood model and the flood map extracted from the satellite

The goodness of fit between the created flood map from flood model and the flood map extracted from the satellite images in table 2 shows that the model has well fitted.

Table 2: Measure of goodness of fit of the satellite image and forecasted flood extent

Year	RE	F
2006	0.011	84.47

Where

$$RE = \frac{|\mathrm{A_o} - \mathrm{A_p}|}{\mathrm{A_p}}$$

$$\mathrm{F} = \left(\frac{\mathrm{A_{op}}}{\mathrm{A_o} + \mathrm{A_p} - \mathrm{A_{op}}}\right) * 100$$

Ao indicates the inundation area of the extracted flood images from the satellite; Ap refers to the predicted flood inundation area; and Aop represents the intersection of Ao and Ap.

4. Conclusion

Flooding is the main challenge natural hazard in Eastern Tana sub Basin that affects human life and property badly. Thousands of people are displacing each year and the people in the area are always a misery due to flood. The Ethiopian government has taken an operation measure to control the impact of flood but the measure has abused by the farmers that they love the flood to get fertile soil.

The extreme weather over the study area is controlled by the movement of the inter-tropical convergence zone (ITCZ) position and orientation, monsoon trough, Low level jet (Somali Jet), Southern hemisphere high pressures, Southerly (cross equatorial) moisture flows, Strengthening frequency of Tropical Easterly Jet (TEJ), ENSO events and seasonal rainfall features Wet/dry summer (La Nina/El Nino).

Flooding has estimated by integrating three models (WRF_SWAT_LISFLOOD) and the approach that gave a good result. Even though the main source of flood was included in the flood model domain during flood modeling, few sources have left (the rainfall and the tributaries over the floodplain). This will a little bit underestimated the estimated flood.

The ongoing rapid land use change and expansion of agricultural area in this study area will have negative effects on the runoff properties. To attenuate the occurrence of flood on Fogera flood plain, a better land use management system is required, which can impede the unregulated conversion from one land use to another land use. To avoid future flood disasters, flood early warning and forecasting system, flood management and flood mitigation plans are need to be able to react quickly to areas affected by flooding. Flood monitoring system is required to assess, on a continuous basis, the areas affected by floods and to have emergency measures plan to reduce the damage of exceptional floods. Also, need to aware the community/ farmers about the effect of flood strongly to solve problems related to dyke breaking. Further investigations should consider on the possibility of flood forecasting and modeling with including other events in the area.

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