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RIVER MODELING FOR FLOOD INUNDATION MAP PREDICTIONS USING 2D-HEC-RAS HYDRAULIC MODELING WITH INTEGRATION OF GIS

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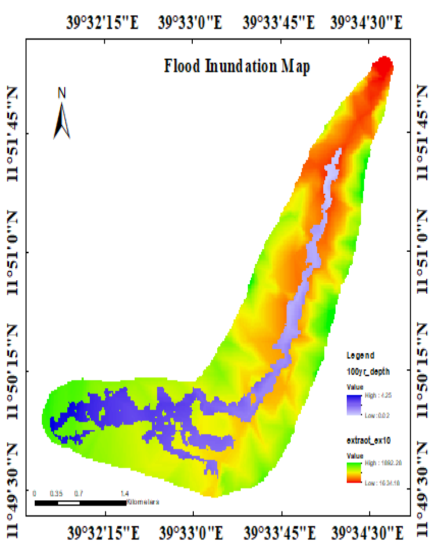
Graphical abstract



Abstract

Floods are natural disasters which if occurred produce damage to property and human life. The study of floods is important for protection of properties and human life risk. This study focuses on flooding characteristics in the flood plain of Tikurwha river catchment using two-dimensional (2D) hydrodynamic modeling. The flood inundation map of the flood prone areas is carried out using HEC-RAS 2D models with incorporation of Arc-GIS tools. Hence, using the magnitude of the flood at 2, 10, 50- and 100-year return period with a respective value of 72, 98.69, 123 and 135 (m3/s). The output of flood hazard inundation maps are carried out in 2D HEC-RAS Mapper in which the flood area at a respective return period's flood magnitude are 75 ha, 102 ha, 108 ha, and 122 ha respectively. Based on the obtained flood inundation area, the economic impact of the flood at the specified return periods are estimated as 1791.99, 2436.89, 2589.45, and 2914.861 quintals of crop production were damaged due to flooding at respective return periods of 2, 10, 50 and 100 years.

Keywords: Inundation map, HEC-RAS, Crop damage, Tikurwha, Flood damage

1.0 INTRODUCTION

In our planet, natural disasters are obviously happening problems which affect living standard of mankind[1]. Among these, floods are the ones which occur naturally and damage humans' life as well as resources frequently[2]. In recent years, there have been a number of significant riverine floods in the rest of the world, which resulted in haunting loss of life, enormous material damage and thousands of subsists have been lost[3]

Ethiopia has faced such problems from 1980 to 2010, 86 natural tragedies were recorded and it resulted loss of 313,486 human lives, 57,382,354 people were overstated and results an economic damage of US$31.7million[4]. In August 2006, overflow of the Dechatu River killed more than 300 people in Dire Dawa, displaced more than thousands and triggered extensive destruction to homes and marketplaces[5].

The Amhara National Regional State is one of the most undulated and severely affected areas in the country by disasters and famine[6]. These deep-rooted man-made and nature triggered shocks have been affecting the livelihoods of rural households. North Wollo, Gubalafto Wereda is situated in the northern part of the country geographically located at 39.45– 39.58E longitude and 11.72 – 11.87N latitude which has faced frequent flooding disasters. The watershed of Tikurwha River falls to Awash Basin which is steep, rugged and mountainous and exposed to flash floods. The season from July to September is the long rainy in which most of the flood disaster is happenning. Flash floods are the greatest hazards coming from tropical cyclones and severe storms. Flash floods cause loss of life, damage to property, and encourage the spread of diseases. Flooding as a result of high intensity of rainfall has

occurred in most part of Ethiopia. In 27 June 2008, floods in Gubalafto affected the property of 18 owners and approximately 591,665.75 Ethiopian Birr were lost. In 23rd - 24th August 2010, 2298 people were exposed to flood disaster. During this year 33 households have been displaced and a total of 600 hectares of cultivated land has been damaged and due to these disasters, a total of 21,144,000 Ethiopian Birr were accounted as loss. The downstream part of Tikurwha catchment is one of the flood prone areas by flash floods in Gubalalafto floodplains. Even though flooding is a frequent series problem observed in Tikurwha River, it is not yet studied for its impact on society.
Therefore, the purpose of this research was to model the flow process and produce the flood map of the flood prone areas of the study catchment.

2.0 METHODOLOGY

2.1 Description of the Study Area

This paper has been carried out in Amhara National Regional State of central Ethiopia Located in north Wollo zone in Gubalafto floodplains at Tikurwha River. It is 530 km far from the capital city Addis Ababa of Ethiopia. The geographic boundary of the study area is situated between 39.45°– 39.58°E longitude and 11.72° – 11.87°N latitude with an elevation varies from 1631 to 3802 m above mean sea level. The study area is shown in Figure 1.

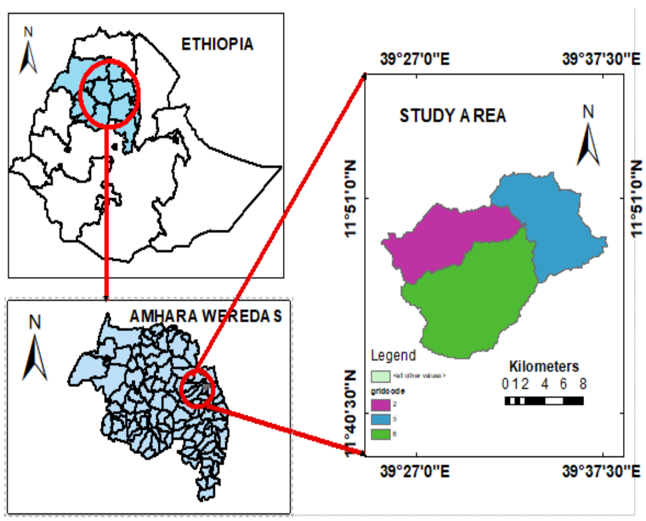


Figure 1 Location map of the study area

In this study, the flood inundation maps are obtained by 2D-HEC-RAS modeling. The watershed is delineated with Arc Hydro extension tools in ArcGIS by using 30*30m DEM. To produce inundated extents the flood magnitude at 2, 10, 50 and 100 years return periods were input to the 2D-hydraulic model. The general methodology framework of the research is as outlined in Figure 2.

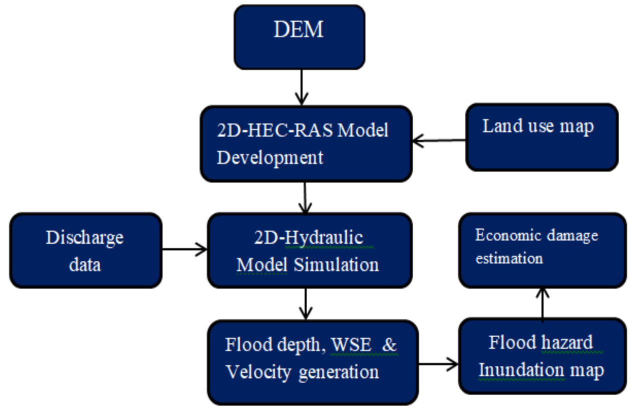


Figure 2 Research framework

2.2 Hydraulic model development

HEC-RAS is a tool developed for analyzing hydraulics of river system [7]. The main input of HEC-RAS for performing hydraulic analysis is geometric data and flow data[8]. These basic geometric data include physical feature of the river i.e., channel length, banks, flood banks and cross-sections of the river. HEC-RAS has capability of performing one-dimensional and two-dimensional hydraulic calculations for water surface profile computation[9]. 1D model may underestimate frictional losses, inundation extents and fail to capture flood dynamics[10]. Two dimensional modeling is relatively new function in HEC-RAS released in 2014[11] and has better estimate flows in topographically complex floodplains[12]. In this paper, two-dimensional steady flow analyses is performed for Tikurwha River and the result is used to generate flood inundation of the study area. The 2D hydraulic model consists of 2D computational mesh representing the underlying topography by connected cells/elements mesh construction and features[11]. Each mesh is built up by interconnected cells that may vary in size and shape and makes 2D geometry[8]. But the main issue with 2D modeling is the often large computation times each cell in computational mesh makes up a control volume for which the water surface elevation and flow across the faces is to be solved using the diffusive wave simplification equation[13].

2.3 Diffusive Wave Approximation

If gravity and friction are assumed to be the dominating forces acting on the control volume, the momentum equation can be simplified to the so-called diffusive wave approximation of the momentum equation[14]. The following derivation follows the HEC-RAS Hydraulic Reference Manual [15]. In the diffusive wave approximation of the momentum equation, the acceleration terms as well as the eddy viscosity and coriolis terms are neglected, and the momentum balance is written as a balance between gravitation and bottom friction forces[16]. The momentum equation can now be written as

$$g\nabla H = -c_f V \tag{1}$$

Where V is the flow velocity in vector form V=(u,v). If the bottom friction is evaluated using the Manning formula, equation 1 can be rewritten as:

$$V = \frac{(R(H))^{2/3}}{n}\frac{\nabla H}{|\nabla H|^{1/2}} \tag{2}$$

Where R (H) is the hydraulic radius at the water surface elevation H, r is the differential operator, and n is the Manning friction coefficient. Inserting equation into the continuity equation and writing in vector form gives:

$$\frac{\partial H}{\partial t} + \nabla.\beta\nabla H + q = 0 \quad (3)$$

Where:

$$\beta = \frac{(R(H))^{2/3}}{n} \quad (4)$$

Using the diffusive wave approximation of the shallow water equations the governing equations for 2-dimensional flow (2D continuity equation and 2D momentum equation) are thus simplified to equation (4).

The diffusive wave approximation leads to shorter computation time and may reduce model instability[17]. It may be used to describe varying flow in moderate to steep reaches. However, flow separation, eddies as well as momentum transfer cannot be modeled [18].

Manning's roughness coefficient of the surface affects the characteristics of runoff with respect to the hydrologic cycle[20]. The roughness of the surface retards the flow. For overland flow increased roughness delays the runoff and increase the potential for infiltration. Reduced velocities associated with increased roughness should also decrease the amount of erosion. To get meaningful inundation depth and flow velocity scenario in the study area by many factors and its selection in natural channels depends heavily on engineering experience and engineering judgment on Pictures of channels and flood plains (Ethiopian Roads Authority Drainage Design Manual, 2013) for which the Manning's 'n' has been recommended. The "n" values for upper Tikurwha River are assigned based on ERA recommendation for different channels of flood plains.

3.0 RESULTS AND DISCUSSION

3.1 Flood Inundation Map Outputs

The flood inundation maps generated using the 2D HecRAS model are presented in Figure 3. The magnitudes of hectarage and their flow rates are shown in Table 1. All crops and other properties in this area are damaged and clearly under risk even in the two-year return period flood. As the farm land holdings are around 1.5ha per farmer, the inundated land affects about 50 farmers for the lowest 2 years return period and more than 90 farmers in the 100 years return period flood. This is significant for the rural families of the study area. Four inundation maps of the 2, 10, 50 and 100 years of return periods are presented in Fig 3 to show the coverage and visualization difference among these return periods.

Table 1: Flood magnitude and corresponding inundation areas

Return periods (Yrs)	2	10	50	100
Flow (m3/s)	72	98.69	123	135
Inundation area (ha)	75	102	108	122

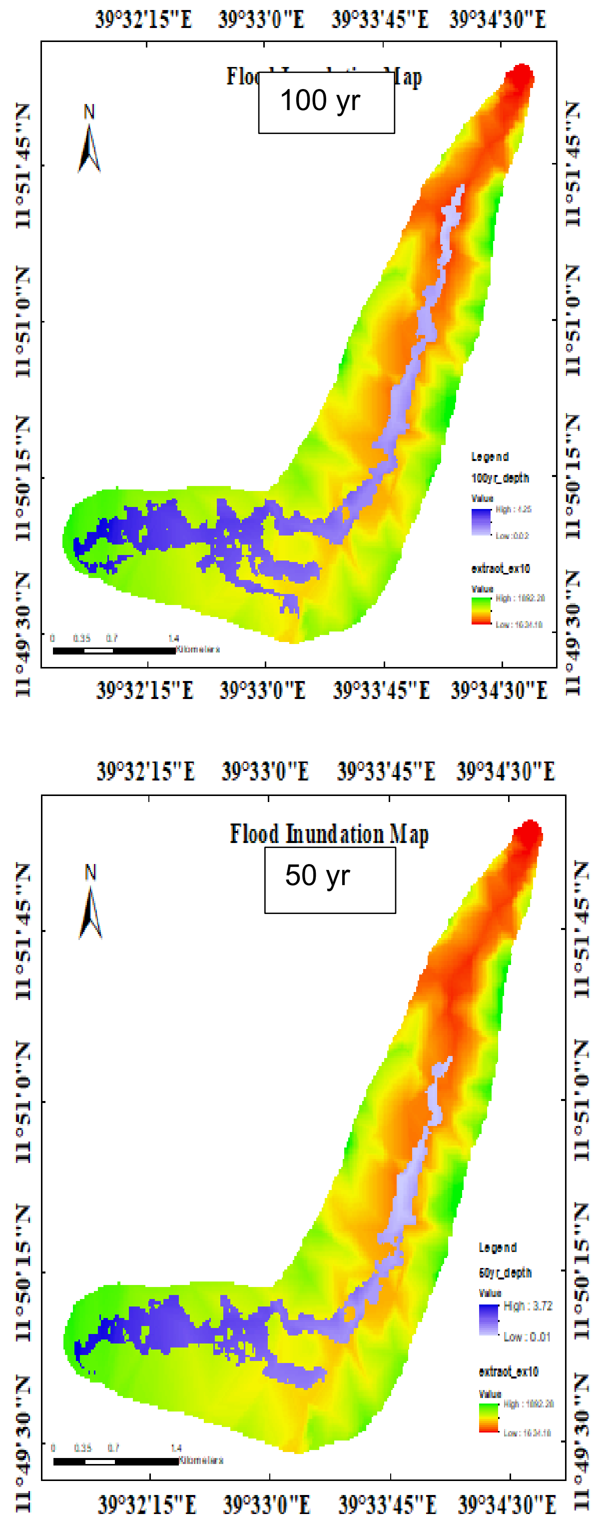


Figure -3A Flood inundation maps of Tikurwha River for 100, 50 return periods

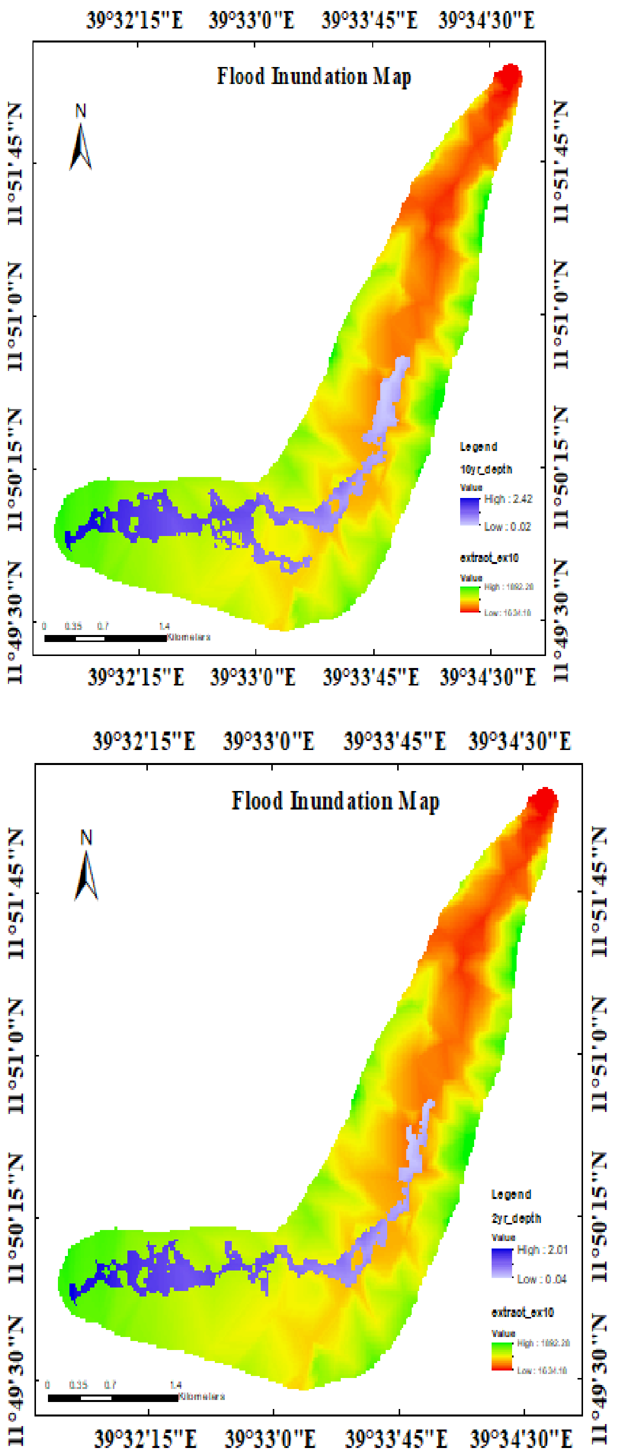


Figure -3B Flood inundation maps of Tikurwha River for 10 and 2 return periods

The flood velocity profile is another parameter which is generated and presented in Figure 4. Higher velocities of up to 5m/s flood are observed for the 100-year return period which is quite big for the area to inundate the crops and households of the nearby areas. The 2-year return period flood also produces close to 3m/s and it is high velocity.

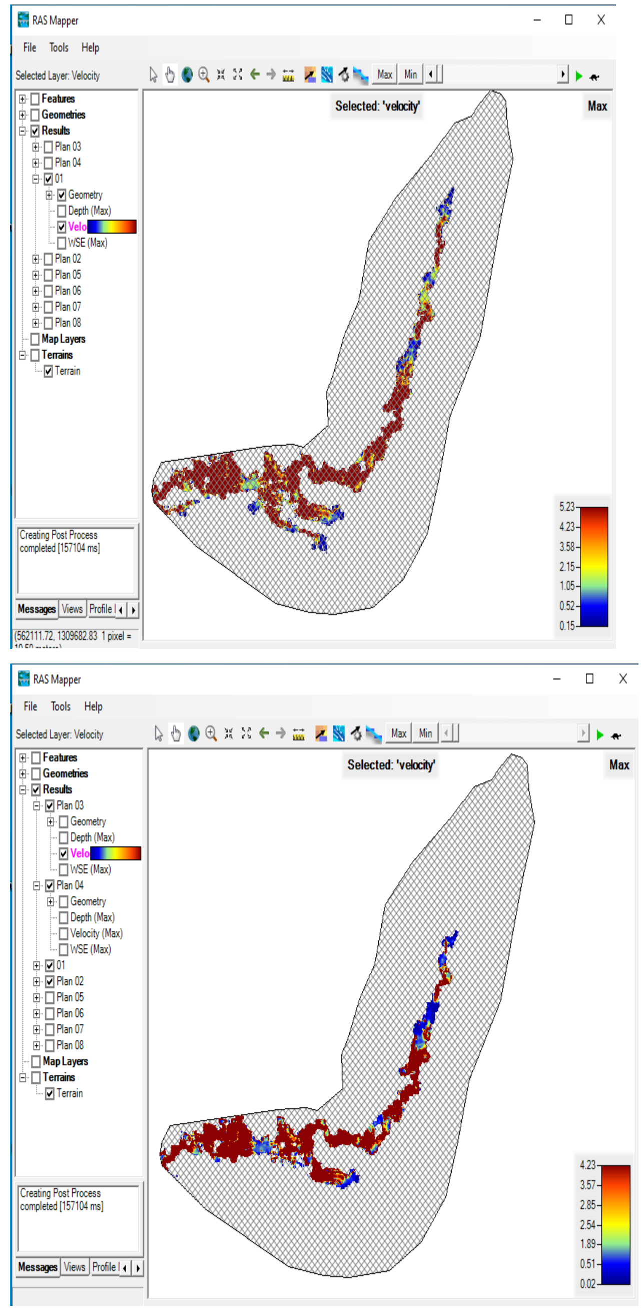


Figure-4A Flood velocity profile of the river at 100, 50 years return period

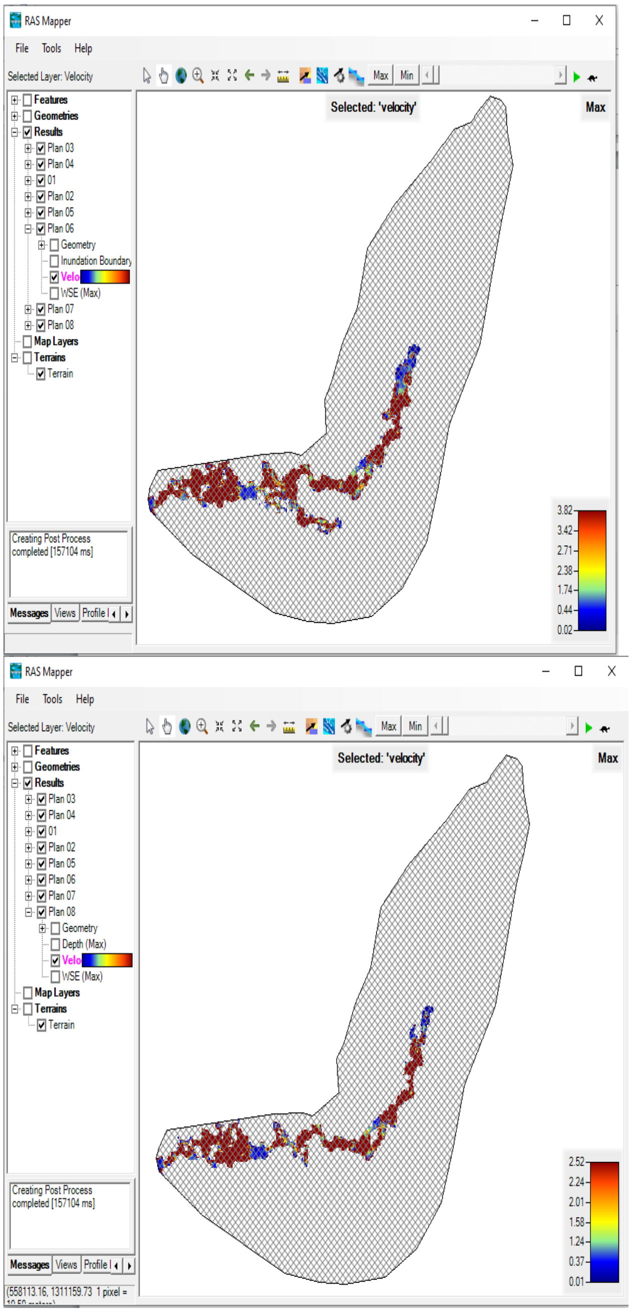


Figure-4-B Flood velocity profile of the river at 10 and 2 years return period

The water surface profiles are also presented for the four return periods in Figure 5. This surface profile is actual position of the water in terms of elevation relative to the ground. The water surface elevation can reach up to 1846.7masl.

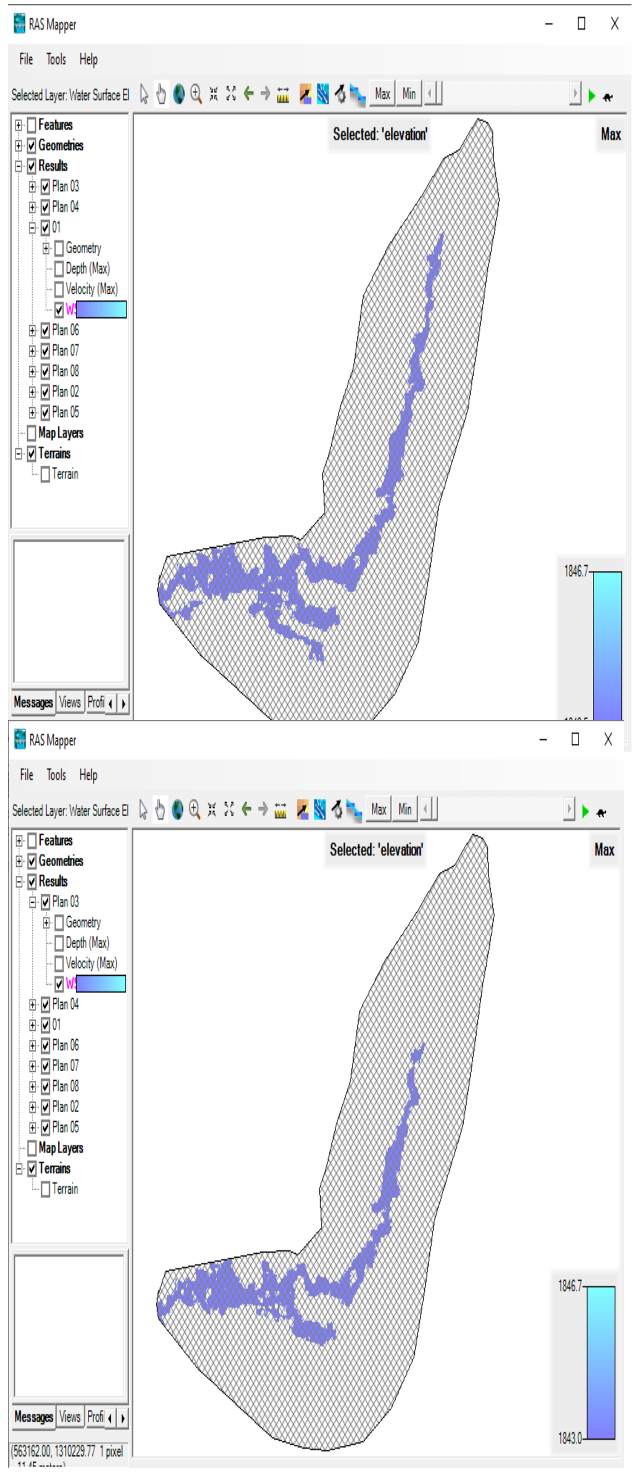


Figure-5A Water surface profile of the river at 100, 50 years return period respectively.

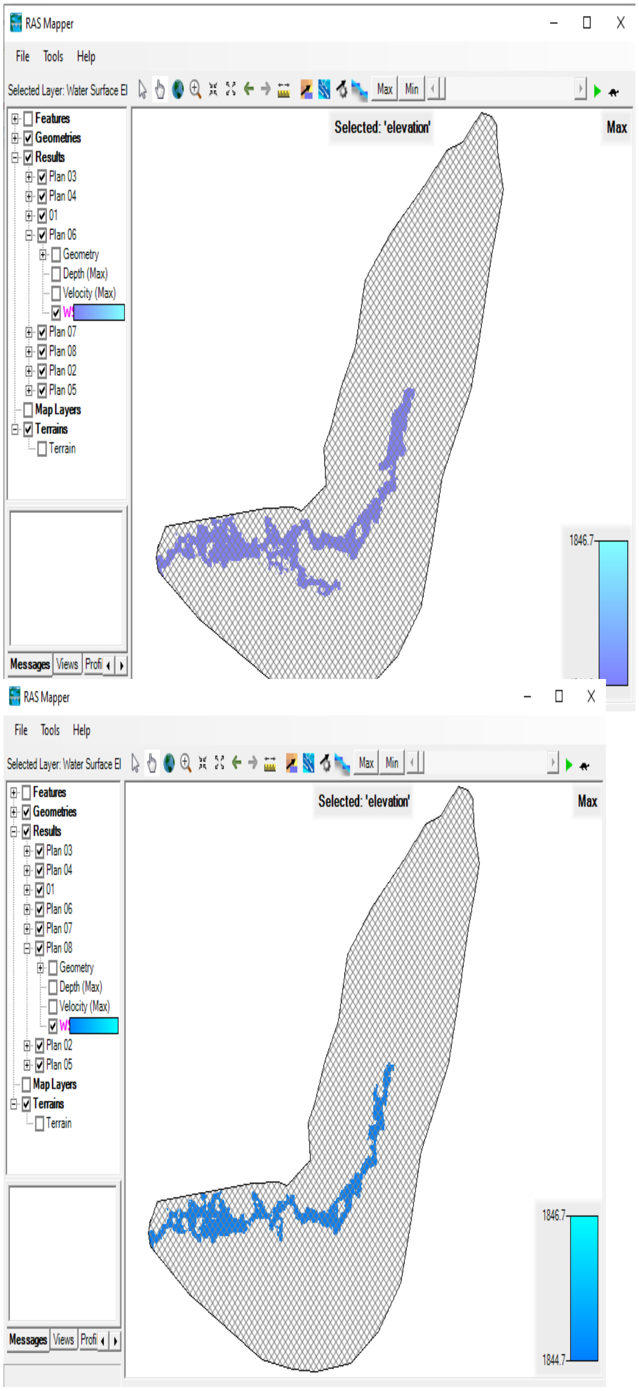


Figure-5B Water surface profile of the river at 10 and 2 years return period respectively.

3.2 Flood Hazard Results

The location and topography of the study area is highly undulated which makes the area vulnerable for flash floods and affects many cultivated lands at the downstream of Tikurwha river catchment. Consequently, the potential lands were exposed to flood disasters and leads to loss of different crop productions. In this research the total production damaged for the 2, 10, 50 and 100-year return periods of flood magnitudes are estimated and presented in Table 2.

Table 2: Estimated production losses with corresponding inundation areas

Crop type, crop grown in quintal per hectare and percent of coverage				Losses of crops in quintal at different year return periods With respective inundation area(ha)				
No	Crop type	Crop Quintal per hectare	% Coverage	Return Period	2	10	50	100
				Area(ha)	75	102	108	122
1	Teff	21	36.94		581.81	791.25	837.80	946.40
2	Sorghum	31.9	41.96		1003.8	1365.3	1446.6	1632.9
3	Wheat	16.52	11.1		137.53	187.04	198.04	223.71
4	Bean	15.28	6		68.76	93.51	99.01	111.85

The crop damage is calculated using the following formula:

Crop Loss = Average Crop Grown per hectare * % of Crop Coverage * Flood Inundated Area at different return periods. For instance: Crop Loss for Teff = 21*0.3694*75 = 581.81 quintal of Teff Loss for 2 years return period. Total crop loss of the four crops for the two-year return period is about 1791.99 quintals which is damaged every two years. Flood events with long return periods have small probability of occurrence but their magnitude and adverse effect on crop are very high. Flood with short return period occurs frequently and may result in repeated damage to crops relatively with less adverse effect.

Total crop loss for the 100-year return period is about 2914.86 quintals which is damaged in every 100 years. This is a big damage which is devastating the society at the study area.

3.0 CONCLUSION

In this paper, flood inundation map and the corresponding damage of the flood area is modeled with 2D unsteady flow analysis in HEC-RAS Mapper. The major tools used are Two-dimensional unsteady HEC-RAS model and ArcGIS for spatial data processing and HEC-GeoRAS for interfacing between HEC-RAS and ArcGIS. It is found out an agricultural area of 75 hectares and 122 hectares are inundated by the 2-years and 100 years return period floods respectively.

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