HYDROLOGICAL AND HYDRAULICS INVESTIGATION FOR THE DESIGN OF BRIDGE ACROSS AJOWA RIVER AT WUCHALE TOWN AMHARA REGION SOUTH WOLLO ETHIOPIA

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ABSTRACT

Bridges are constructed across the river to create way from one end to another end. The purpose of this study is to carry out hydrological analysis of the rivers, streams and flood paths which intersect with the proposed bridge, to estimate their different return floods magnitudes in order to size the openings of the proposed bridges. During the study the following tasks have been carried out analysis and interpretation of different topographic maps, soils map, satellite imagery and DEM (Digital Elevation Model) data collection of data and analysis for un-gauged rivers and streams, estimation of flood magnitudes by applying different rainfall-runoff models, Sizing of bridges, Provide designs type, size, and location of bridge Assess scour potential at bridge locations. The flood magnitudes at the bridge site are the function of geomorphology, geology, rainfall; soil and land use or land cover within the catchments of the rivers and streams crossing the road.

Keywords: River, Bridge, Rainfall, Soil, Flood.

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1. INTRODUCTION

As we know most of the bridges are very costly structures, spending millions of monies, but most of the bridges does not last longer life. If hydrological investigations are not properly

carried out bridge can fail due to such reasons [1]. In hydrology and hydraulics, the discharge is the volume of rate of water flow through a given cross-sectional area. It includes any suspended solids, dissolved chemicals and biologic material in addition to the water itself. The catchment of a river area a certain location is determined by the surface area of all land which drains toward the river from above that point. The river's discharge at that location depends on the rainfall intensity of the catchment area and the inflow and outflow of groundwater to or from the area of river, stream modifications such as rivers and irrigation diversions [2]. As a result of flooding, it is important for the flood management department to prevent the effects of flood by employing flood mitigation measures like infrastructure development and river trainings. River floods carried by storms are major devastations and had caused damages structures worth billions during a flood [3]. Design of flood magnitudes are required for the design of bridges openings, drainage of air ports, and construction of flood walls and levees. The damages due to the devastating floods can be minimized by various flood control measures [4]. HEC-RAS is equipped to model a network of channels, a single river reach. It is made easy in order to model some complex flow conditions by using the HEC-RAS one-dimensional approach. It is able to modeling subcritical, supercritical and mixed flow regime along with the effects of bridges, culverts, weirs, and structures. It is costly and difficult to do constant measurement of the rivers flow in normal situation and in flood risk situations [5]. The river system often consists of a main river and several small tributaries. The Slope of main rivers is often smaller than tributaries. Storm brings strong rainfall in short period, which causes floods surge in a short period. Most of the large amount of debris with floods is blocking near span make bridge failure. Hydrological and hydraulics investigations of the bridges should be carried out within a bridge community in a certain rain catchment area [6]. HEC-RAS (Hydrologic Engineering Centre- River Analysis System) is numerical analysis and design software it gives the details of flood profiles. The software is easily available and it has precise calibration accuracy also [7]. Using a computational model has many advantages e.g. Calculating flood elevations with an accuracy written and documented programs is a scientific and analytical technique [8].

2. STUDY AREA

The proposed Ajowa bridge project is found in South Wollo, of the Amhara Regional State. The proposed bridge connects main Wuchale town with Robit keble. The proposed ajowa river bridge control points like ajowa River.

3. OBJECTVES

- Rainfall analysis and determination of different return period flood magnitudes for the rivers, streams and flood paths crossing the Ajowa bridge project.
- Identification of different sections of the bridge project exhibiting unstable hydrological conditions (e.g. Erosion) and the causes of such instability, and the proposal of appropriate mitigation measures.
- Determination of appropriate sizes of waterway opening for the various watercourses as a major hydrological parameter in determining a suitable category of conduit in each case, i.e. bridge.

4. METHODOLOGY AND APPROCH

HEC-RAS Software the Hydrologic Engineering Center River Analysis System (HEC-RAS) is a program developed by the US Army Corps of Engineers. The HEC-RAS is numerical software for hydrology calculations. It is widely used in one-dimensional water surface profile

calculations in case of steady and unsteady river flow regimes. In addition, it contains components for one-dimensional sediment transport numerical analysis [9]. There are various recognized methods and approaches for hydrologic or hydraulic design of drainage facilities.

- Modified Rational Method (MRM)
- Soil Conservation Service (SCS) graphical Method

Detailed Hydrological investigations are carried out for all the bridge structures with careful analysis of Digital Elevation Model (DEM 30*30) resolution, available maps and field investigations. Catchment areas, rainfall, runoff duration intensity relationships, catchment run-off characteristics and channel slopes or discharge characteristics, for each catchment area has been calculated.

4.1. The Rational Method

The Rational Method is the most accurate for calculating the design storm peak run-off for area up to 50ha (0.5km²). The Method can be employed to small rural catchment area if they do not exceed 0.5km². The consequences of using the Rational Method to larger catchment is to produce an over calculate of discharge.

The rational formula is expressed as:

$$Q = 0.278C I A$$

Where,

Q = Maximum rate of runoff in m³/s

C = Runoff coefficient representing a ratio of runoff to rainfall

I = Rainfall intensity for a duration equal to the time of concentration and for design return period in mm/hour.

A = Catchment area tributary to the design location in km²

4.1.1. Runoff Coefficient (C)

Values shown in Table 3 are stipulated in ERADDM for determination of C (for non-urban catchments), depending on terrain type and hydrologic soil grouping.

Table 1 Runoff Coefficients, C Value (Adopted from ERA, 2013 and FHWA manual)

Factor		Description	Runoff coefficient
Cs	Average slope of catchment	<3.5% Flat	0.05
		3.5% - 10% Soft to moderate	0.10
		10% - 25% Rolling	0.15
		25%-45% Hilly	0.2
		>45% Mountainous	0.25
Cp	Permeability of Soil	Well drained soil e.g. sand and gravel	0.10
		Fair drained soil e.g sand and gravel with fines	1.15
		Poorly drained soil e.g silt	0.25
		Impervious soil e.g clay, organic silts and clay	0.50
		Water-logged black cotton soil rock	0.40
Cv	Vegetation	Dense first/thick bush	0.05
		Sparse forest/dense grass	0.10
		Grassland/scrub	0.15
		Cultivation	0.20
		Space grassland	0.25
		Barren	0.30
C = Cs + Cp + Cv			

4.3.2. Rainfall Intensity (I)

ERADDM divides the country into different rainfall zones and for each gives Intensity - Duration - Frequency IDF curves, Project IDF curve has been used of ERA regional IDF curve and adopted for this particular project of region C.

4.3.3. Time of Concentration (T_c)

The rainfall intensity used in the rational method is determined from the time of concentration (T_c). T_c is defined as the time required for surface runoff water to flow hydraulically from the remotest point of the catchment to the point of exit.

$$T_c = 0.0147 * L^{1.155} H^{-0.385} \text{ (Kirpich /SCS Equation)}$$

Where

T_c = Time of concentration in minutes

L = Maximum length of flow in meter

H = Elevation difference between the most remote and outlet in meter

4.3.4. Frequency Factor

As per ERADDM, the frequency factor is used to magnify the less frequent storms, i.e. storms with recurrence interval greater than 10year.

Table 2 (ERADDM) Frequency Factors for Rational Formula

Recurrence Interval (years)	C _f
5	1.0
10	1.0
25	1.1
50	1.2
100	1.25

4.2. Soil Conservation Service (SCS) method

This method is developed by the U. S. Soil Conservation Service for estimation rates of run-off and required same basic data as the Rational Method. The SCS approach, however, is more sophisticated in that it considered also the time distribution of the rainfall intensity, the initial rainfall intensity losses to interception and depression storage, and an infiltration rate is decreases during the course of storm. With the SCS method, the direct run-off can be estimated for any storm, either real or fabricated, by subtracting infiltration and other losses from the rainfall to obtain the precipitation excess.

4.2.1. Catchment Area

The catchments area can be estimated from topographic maps and field surveys. For large catchment areas it can be necessary to divide the area into sub-catchment areas to account for major land use changes, obtain analysis results at different points within the catchment area, or locate storm water drainage structures and assess their effects on the flood flows. A field inspection of existing or proposed drainage systems has been made to estimate if the natural drainage divides has been changed.

4.2.2. Rainfall

The SCS method is based on a one-day storm event which is a Type-II-time distribution. The Type-II storm distribution is a typical time distribution which SCS has prepared from rainfall data records. It is useful for interior rather than coastal regions and will be appropriate to Ethiopia. To utilize this distribution, it is necessary for the user to obtain the one-day rainfall values for the frequency of the design storm required.

4.2.3. Rainfall Runoff equation

The relationship between accumulated rainfall and accumulated run-off is derived by SCS from experimental plots for various hydrologic and vegetative cover conditions. Data for land treatment measures, such as contouring and terracing, from experimental catchment area was included. The equation was developed mainly for small catchment areas for which daily rainfall and catchment area data are primarily available. It was developed from recorded storm data that includes total value of rainfall in a calendar day but not its distribution with respect to time. The SCS run-off equation for estimating direct run-off from one-day storm rainfall.

The equation is:
$$Q = \frac{(P-Ia)^2}{(P-Ia)+S}$$

Where:

Q = accumulated direct runoff in mm

P = accumulated rainfall (potential maximum run-off) in mm

Ia = initial abstraction including surface storage, interception and infiltration prior to runoff in mm

S = potential maximum retention in mm

The relationship between Ia and S was developed from experimental catchment area data. It removes the necessity for estimating Ia for common usage.

The empirical relationship used in the SCS runoff equation is:

$$Ia = 0.2 * S$$

Substituting $0.2 * S$ for Ia, the SCS rainfall-runoff equation becomes:

$$Q = \frac{(P - 0.2 * S)^2}{(P + 0.8 * S)}$$

S is related to the soil and cover conditions of the catchment area through the CN.

CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{25400}{CN - 254}$$

4.2.4. Run-off Factors

Run-off is rainfall excess the value by which rainfall exceeds the ability of the land to infiltrate or retain rainwater. The principal physical catchment area characteristics affecting the relationship between rainfall and runoff are land use, land treatment, soil types, and land slope.

5. RESULTS AND DISCUSSION

5.1. HEC-RAS (Hydraulic Engineering Center-River Analysis System) Analysis Result

The main objective of the HEC-RAS (Hydraulic Engineering Center-River Analysis System) program is quite simple to compute water surface elevations at all locations of interest for either a given set of flow data or by routing hydrographs through the system.

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Figure 1 XYZ Perspective of Ajowa River

Figure 2 Water surface profile of Ajowa river

5.2. Bridge Design Criteria

The following are the criteria related to the hydraulics analysis for the sufficiency of the bridge. Simple spread sheet and HEC-RAS software has been used for the analysis.

Design Floods: The purposes of the evaluation of backwater, clearance, and overtopping, design floods have been determined.

Backwater: Backwater increases over existing condition up to 0.5 m during the passage of the 100year flood. Furthermore, backwater shall not significantly increase flood damage to property up-stream of the crossing.

Clearance: The minimum clearance conforming to the requirements of the Bridge Design manual will be provided between the design approach, water surface elevation and the low chord of the bridge to allow passage debris. Clearance will be according to ERA's Bridge Design Manual whose values are as stated below table.

Table 3 Free board recommendation ERA 2013

Discharge, Q (m ³ /s)	Freeboard (m)
0 – 3.0	0.3
3.0 -30	0.6
30 -300	0.9
> 300.0	1.2

5.3. Hydrologic and Hydraulics Investigations

Following are the preliminary investigations, site visit has been carried out for hydrologic and hydraulics investigations of streams and major rivers at Ajowa. In this regard, the location of rivers is identified physically, channel measurement and hydraulic condition of the rivers has been also observed and noted. Thus, it is confirmed that all of the rivers are seasonal. Moreover, site Hydrologic and hydraulic data has been collected; the river characteristics and their locations are studied. The summary of recommended hydrologic and hydraulic analysis is given in the table below table.

Table 4 Summary of hydrology/ hydraulics of Bridges

S.No	Station	50 yr. Peak Discharge Q (m ³ /s)	100 yr. Peak Discharge Q (m ³ /s)	Recommended size		Remark
				Span(m)	Height(m)	
1		264.016	294.209	38	3.7	Geometrically detected

Table 5 Ajowa River Bridge design flood using USSCS (United States Soil Conservation Service)

Return period (years)	qu (Unit peak discharge) m ³ /s/km ² /mm	Catchment Area (km ²)	Q depth of runoff (mm)	qp =qu*A*Q
25	0.10848	32.251	66.949	234.24
50	0.10848	32.251	75.460	264.016
100	0.10848	32.251	84.090	294.209

Table 6 Ajowa River bridge catchment soil

S.No	Item	Area (sq.km)	Percentage %	Hydrological soil group
1	Eutric cambisols	1.387	4.30	B
2	Eutric Regosols	2.34	7.26	A
3	Eutric leptosols	28.524	88.44	D
Total		32.251	100.00	

Table 7 Ajowa River bridge catchment land use

S.No	Item	Area (sq.km)	Percentage %	Land cover	Curve number
1	Agricultural	3.4245	10.62	Dominantly cultivated	80
2	Accacia bush land	5.2096	16.15	Agro pastoral	82
3	Barren/sparsely Vg	23.6169	73.23	Agro pastoral	94
Total		32.251			

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Table 8 Ajowa River Bridge Curve Number

Item	Area	CN	Product
Agricultural /Cropland	3.4245	80	273.96
Accacia bushland	5.2096	82	427.1872
Barren/Sparsely Veget	23.6169	94	2219.989
Total	32.251		2921.14
Average curve number		CN	90.58

Table 9 Ajowa Bridge Catchment Maximum Potential Retention (S)

25400	CN	254	
	90.58		
	280.4304	S	26.4

Table 10 Ajowa River Bridge Catchment Initial Abstraction (Ia)

Ia = 0.2*S	P*25	P*50	P*100	Ia/P*25	Ia/P*50	Ia/P*100
5.29	92.52	101.48	110.5	0.057135	0.052	0.048

Table 11 Ajowa River Bridge Direct runoff in mm depth, $Q=(P-0.25)2 \div ((P+0.8*S))$

Q*S	0.2*S	0.8*S	P*25	Q*25	P*50	Q*50	P*100	Q*100
26.43	5.286	21.144	92.52	66.949	101.48	75.460	110.5	84.0
	122.6244		7609.755		9253.269		11069.97	
			113.6644				131.6444	

Table 12 Ajowa Bridge Time Concentration for Over Land Flow

				C Values					
Length (km)	Min Elv	Max Elv	Slope= $H \div 1000 * L$	Barren/spar sely veg	Accacia bush land	Agricultu ral	CVL	S^0.5	Tc= $0.604(CvL \div S^{0.5})$
				23.6169	5.2096	3.4245			
6.678	1869.7	3011.1	0.1709	0.3	0.1700	0.2000	1.7923	0.4134	1.20
				7.08507	0.885632	0.6849			
						8.7			
				CV weight		0.18			

Table 13 Ajowa Bridge Time Concentration for Defined Water Course

Length (km)	Elevation 0.85L (m)	Elevation 0.1L(m)	$S_{av} = \frac{H_{0.85L} - H_{0.10L}}{(1000) * (0.75*L)}$	1000*Sav	$0.87*L^2$	$Tc = \frac{(0.87L^2 \div 1000 * S_{av})^{0.385}}$
5.61	2599.7	1945.8	0.1554	155.413	27.381	0.51
	4.7685	0.561				
	4768.5	561				
				Total Tc	Tc ₁ + Tc ₂	1.71

Table 14 Ajowa River Bridge Unit Peak Discharge

Logtc	c1*Logtc	(Logtc)^2	$C2*(Logtc)^2$	$Co+c1*Logtc+C2*(logtc)^2$	$qu = \alpha * 10^{C_0 + C_1 logtc + C_2 (logtc)^2}$
0.233	0.14342	0.0543683	-0.0089164	2.40089	0.10848
0.233	0.14342	0.0543683	-0.0089164	2.40089	0.10848
0.233	0.14342	0.0543683	-0.0089164	2.40089	0.10848

Table 15 Ajowa River Bridge Project Hydraulics

Dimensional computation for the given Design discharge for the given return period												
Bridge span	Average Channel slope (S)	Depth of flow (m)	Manning Roughness Coefficient (n)	Side slope H:V	Area (A)		Perimeter (p)		Hydraulic Radius R		Design Discharge Computation	
					Rectangular	Trapezoidal	Rectangular	Trapezoidal	Rectangular	Trapezoidal	Rectangular	Trapezoidal
38	0.2078	2.45	0.1	0.5	93.1	96.101	42.9	43.478	2.170	2.2103	711.37	713.41

Based on above investigations the proposed design of Ajowa river bridge details is as follows,

Depth of flow 2.45 m

Bridge span Length 38m

Free board 1.2 m

Total depth from river bed to bottom slab of the bridge 3.7m

6. CONCLUSION

- The Delineation of the catchment areas has been accomplished by using GIS Software from the Digital Elevation Models (DEM) of the Project area.
- Run-off or slope or discharge characteristics of the catchment area is determined.
- Location, capacity and type of drainage facilities required and Computation of water run-off quantities to be taken up by drainage structures are carried out using different acceptable calculation methodologies depending on the size of the catchment area and estimated run-off coefficient.
- The run-off coefficients are determined using available information and following field reconnaissance made by hydrologist.
- The bridge details such as depth of flow, length and free board is determined.

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