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Assessment and Upgrading of Local Scour Depth Estimation Equation for Bridge Piers in Kombolcha-Weldia Highway, Ethiopia

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Abstract

Frequent erosion caused by turbulent river flow has significantly affected bridge stability along the Kombolcha-Weldia highway in Ethiopia's Amhara region. This has led to erosion of foundation over the years. To tackle this issue, six established scour depth estimation equations—Colorado State University (CSU), Bruisers, Jain and Fischer, Froehlich, HEC-18/Muller, and Laursen's empirical equation—were assessed for their accuracy in predicting bridge pier scour depths. A detailed field study was conducted. This included topographic surveys, evaluations of pier alignment and shape, riverbed material sampling, and direct measurements of scour depth at five selected bridges. Peak flood discharge was calculated using the Rational Method for catchments under 50 ha and the Soil Conservation Service (SCS) unit hydrograph method for larger catchments. Total scour depth was determined by examining three main components: long-term degradation, contraction scour, and local scour. Key variables such as pier width, shape, and flow alignment were found to significantly influence scour magnitude. The predicted scour depths from the selected formulas were compared with field-measured values. The analysis showed that the equations from Jain and Fischer, Laursen, and Froehlich provided more accurate estimates of scour depth than the others. Among these, the Jain and Fischer equation was recognized as the most suitable for predicting local scour in both sand-bed and gravel-bed rivers within the study area. Based on these findings, it is recommended to prioritize the Jain and Fischer equation for estimating scour depth in similar hydrological and geomorphic conditions. This approach will help improve the assessment and mitigation of bridge foundation risks in the region.

Keywords: Bridge Pier Scour; Design return period; Jain and Fischer equation; Kombolcha-Weldia; Scour depth estimation.

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1. INTRODUCTION

Flowing water at high velocities increases the risk of bridge foundation scour, due to its erosive capacity to excavate and transport sediment from the stream bed and banks (Ebrahimi et al., 2018). Scouring rate varies from material to material. The erosion resistance of soil or rocks is a primary controlling factor in how quickly it is transported by flowing water (Annandale, 2000). Granular soils are rapidly eroded by flowing water due to their non-cohesive character whereas cohesive, cemented, and compacted soils are more resistant to scouring effect (Sheppard et al., 2014). Under constant flow conditions, scour reaches to its maximum depth (Wang, 2010); in sand and gravel bed materials in a short span of time; cohesive bed materials in some days; glacial tills, sand stones and shale in few months; limestone in years and dense granites extends to some centuries (Temesgen et al., 2015). Scour occurs due to high velocity of river flow (Sarlak and Tigrek, 2011) and becomes more aggravated by debris when rock boulders, gravel and silt are carried away by river current (Yanmaz and Çalamak, 2016, Ebtehaj et al., 2017). When scour becomes severe, foundation materials existing below the pier footing may become prone to erosion (Kothyari, 2007) leaving the structure unsupported leading to collapse (Ghazvinei et al., 2012; Zaid et al., 2019).

Research in Ethiopia has not been extensively conducted to find bridge failure due to scouring. In recent years, initiation has been taken up by bridge management systems in order to prevent such disasters. As a result, measures have been proposed to rehabilitate and redesign the damaged bridges (Girma, 2018). According to Ethiopian Road Authority (ERA) 2013, 445 road and highway bridges in northern, north-eastern and eastern parts of Amhara region and some parts of Afar region were inspected. Thus, it was found that 112 bridges were under bad to worse conditions due to scouring. A number of scour depth estimation equations have been in practice by technocrats (Vonkeman and Basson, 2018). Once flow velocity in the channel reaches the piers, sediments in the vicinity of the piers start moving followed by initialization of scouring (Shukri, 2017). Though several equations are developed and implemented for numerous bridge designs in the world, modifications to the existing equations are imminent and further improvement of the equations is anticipated. In this research, six scour equations using field data were selected for comparison for scour depth determination. Owing to the empirical nature of the equations (Kafi and Alam 1995; Ghani and Nalluri 1996; Yahaya and Ghani 1999; Yahaya et al., 2002, Ebtehaj et al., 2016) unanimous decision cannot be taken up to find the superlative equation among the existing equations since rate and type of scouring varies from one to the other (Gilja and Mari, 2018).

A significant gap exists in the detailed performance evaluation of scour depth prediction equations in Ethiopia. This study aims to address this gap by comparing six key scour depth equations. To ensure strong validation, predicted scour depths from each equation were compared by field measurements collected from bridge sites throughout Ethiopia.

2. MATERIAL AND METHODS

2.1 Study Area

The study area encompasses the Kombolcha to Weldia roadway. This route crosses many rivers, depressions, and gullies (Figure 1). It moves through hilly and uneven land where rivers have high runoff rates and face scouring issues especially downstream at bridges and other structures. Land use and land cover (LULC) in the area mainly includes gently sloping farmland and thinly vegetated grasslands. The catchment has erosion-prone alluvial deposits which heighten the risk of scouring.

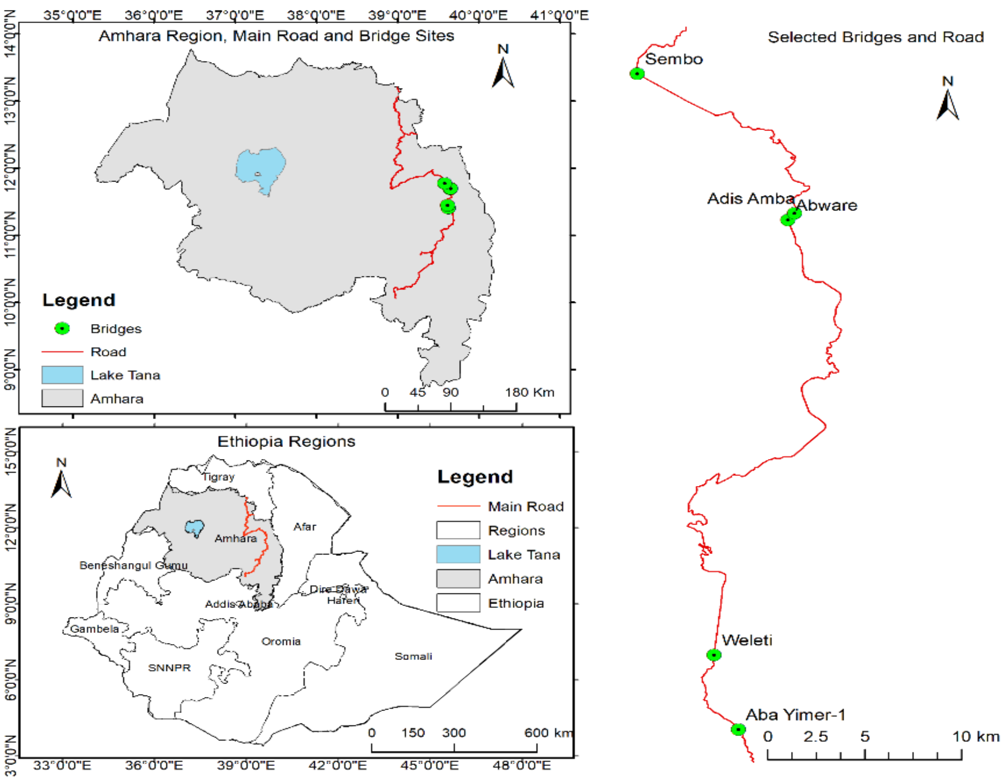


Figure 1. Location of scoured bridges in the study area

2.2 Salient Features of Selected Bridges

The main road runs from Kombolcha to Weldia, passing through mountainous and rolling land. For this reason, scouring problems have been common along this stretch of road. Five bridges from Haik to Weldia were chosen because these areas were prone to bridge scour failures. As shown in Figure 2, the catchment areas of these bridges had poorly vegetated grass and cultivated land with gentle slopes, such as at Adis Amba, and the stream beds were sandy. This contributed to high runoff and scouring issues at the downstream outlets of the bridges. In addition, social need, budget consideration and scour condition of the sites were the criteria to select road segment. . Field data were collected from the five existing bridges of this road segment. The construction history and design data were obtained from the regional Roads Authority and the Kombolcha District Road Construction Office. Table 1 presents the key features of the selected bridges and their scouring conditions, including information on location, bridge type, and length.

Figure 2. Photo of the selected five bridges under this study

Table 1: Location of selected bridges and some salient features of bridges

Sl. No.	Bridge Name	Northing	Easting	Altitude (m) a.m.s.l	Bridge Type	Bridge Length (m)	Bridge Condition
1	Aba Yimer-1	1260648	568497	1699.06	RC Slab Culvert	6	Under scouring
2	Weleti	1265266	567254	1548.17	RC Box Culvert	10	Under scouring
3	Abware	1292272	570938	1642.36	RC Deck Girder	16	Under scouring
4	Sembo	1301342	563305	1884.03	RC Slab Culvert	8	Under scouring
5	Adis Amba	1292697	571268	1637.77	RC Deck Girder	64	Under scouring

2.3 Morphology of the River

The morphology of the rivers primarily affected scouring at bridge foundations, influenced by the underlying geology, climate, and vegetation. Field analysis confirmed that all five rivers had alluvial bed and bank materials, making them very sensitive to erosion. The rivers had specific characteristics. The Aba Yimer River changed from a wide, shallow channel upstream to a narrow, deeper section downstream with mixed alluvial and rocky banks. The Weleti River carried coarse sediments along banks of alluvium and silt-clay. The Abware River, being a seasonal channel, had a sand bed prone to erosion and confined to deep gorges. The Adis Amba River flowed through an area with grass-covered alluvial banks. Lastly, the Sembo River had a gravel bed and moved boulders with banks supported by short bushes and no ongoing sand mining. The consistent presence of erodible alluvial materials indicated a high potential for scouring at any hydraulic structure built across these rivers.

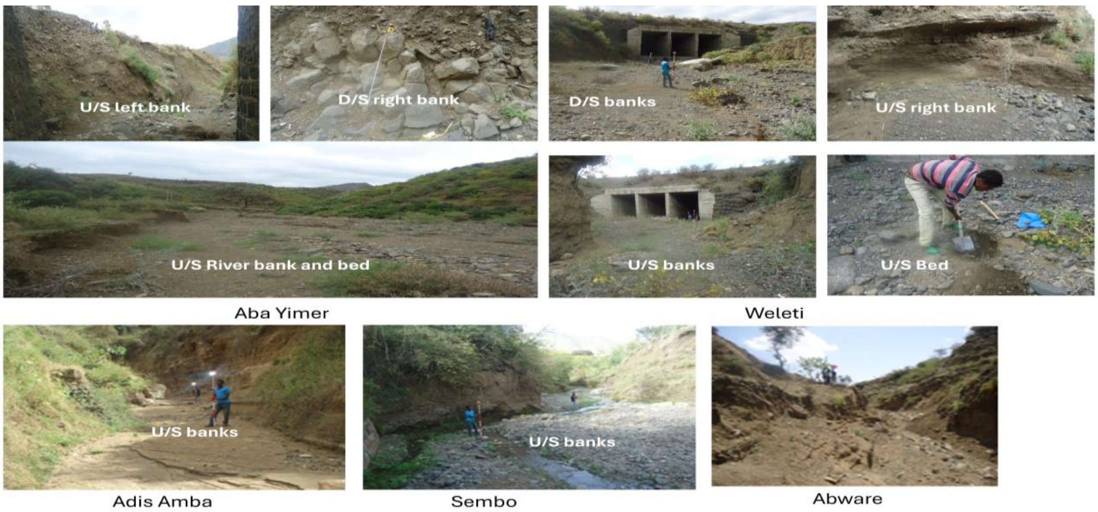


Figure 3. Morphological characteristics of Rivers for selected bridges

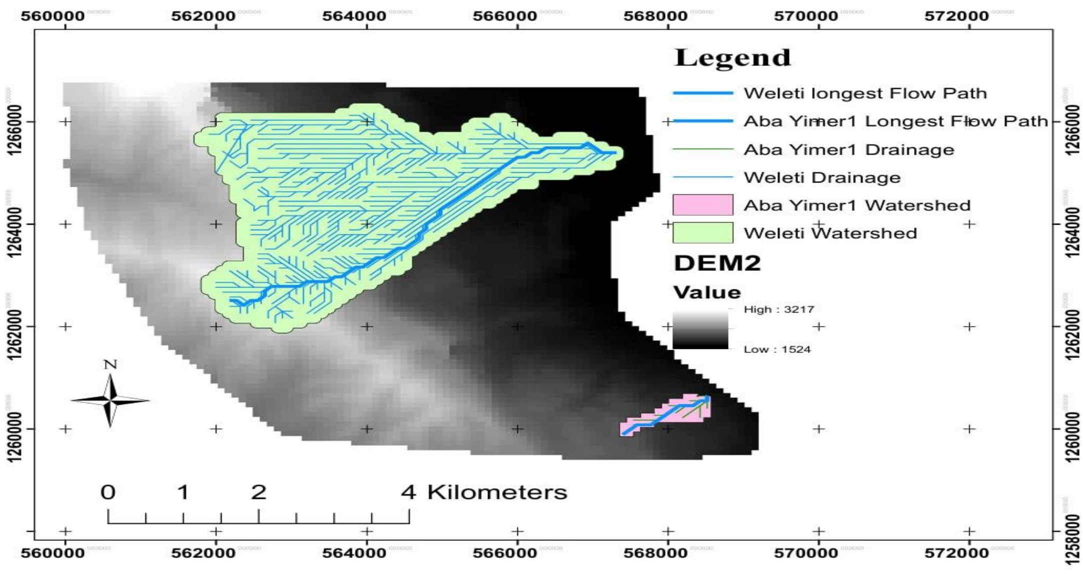
2.4 Data Collection

2.4.1. Meteorological and Stream Flow Data

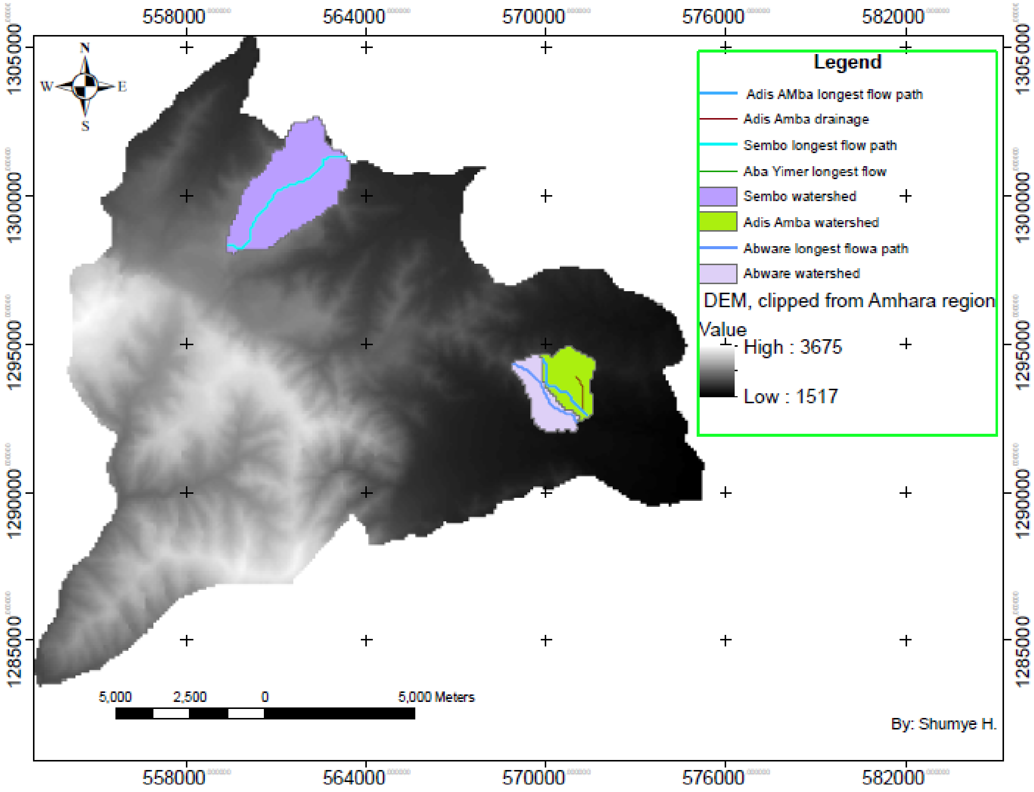
The primary data collected during fieldwork included scour depth, river cross section, stage-discharge measurements, riverbed and bank materials, and topographic surveys of the study area.. Secondary data such as hydrologic and design information for each selected bridge were gathered from various organizations. For instance, design cross section data were obtained from the Ethiopia Roads Authority Kombolcha District Office. This data was crucial for comparing with the current measured cross sections of the selected bridges. Maximum 24-hour rainfall data from 1954 to 1989 was collected from three rain gauge stations: Haik, Sirinka, and Weldia. These stations were chosen based on their proximity to the selected bridges, the quality of the recorded data, and data availability. Since the rivers had no gauging stations, peak discharge was estimated using the rainfall-runoff relationship.

2.4.2. Topographic maps

The topographic map of the study area was extracted from the Digital Elevation Model (DEM) of the Amhara region, having a resolution of 30m x 30m. The integration of regional raster, shapefile, and field survey data enabled the systematic classification of soil types, land use, land cover (LULC), and other catchment characteristics. The catchment parameters were estimated accurately with the Arc Hydro extension tool in Arc GIS environment. The LULC and soil map were obtained from the Ministry of Water and Energy. The physical characteristics of the watershed were extracted from the DEM (Figure 4).



(a)



(b)

Figure 4: (a) Catchment boundary of Aba Yimer-1 and Weleti Bridges (b) Catchment boundary of Abware, Adis Amba and Sembo Bridges

2.4.3. Surveying Data

Detailed primary surveying data was collected for cross sections and slopes of rivers both downstream and upstream of the bridges and up to 130m-400m distance river center using total station. The slope of the riverbed (the riverbed profile) was generated using this data.

2.4.4. Riverbed Materials Data

Samples were collected from all five bridge locations, with two to three samples taken from the bed materials on the riverbed. This aimed to analyze the grain size distribution using sieve analysis after a physical inspection. Sample collections were done along the river course because this method provided a better grain size distribution in a uniform pattern. Based on the type and characteristics of the materials, samples were collected from a depth of 60 cm to 75 cm from the sandy riverbeds at Abware and Adis Amba. Samples were taken from the gravel river course at Aba Yimer-1 and Sembo at a depth of 75 cm to 100 cm. The collected materials were then mixed thoroughly and transported for laboratory analysis.

2.5 Methods

2.5.1 Scour Depth Estimation Equations

In this study, we selected six scour depth estimation equations for evaluation. These equations included: CSU, Bruisers, Jain and Fischer, Froehlich, HEC-18/Muller, and Laursen. We chose them because of their effectiveness in previous studies, current use in Ethiopia, and suitability for the selected stream characteristics.

Table 2: Summary of selected equations and their key features

Equations	Key features	Common use
CSU	Empirical, including correction factors	Standard in U.S design
Bruisers	Based on lab data for cylindrical piers	Experimental validation
Jain and Fischer	Includes sediment and flow intensity	Advanced modeling
Froehlich	Includes for pier shape and angle	Shape is sensitive design
HEC-18/Muller	Widely accepted	Regulatory compliance
Laursen	Oldest empirical model	Historical comparison

The selected equations are presented as follows.

1. Colorado State University (CSU) Equation (Richardson et al.,1975)

$$\frac{d_{se}}{b} = 2k_1 k_2 k_3 \left(\frac{b}{y}\right)^{0.65} F_r^{\ 0.43} \tag{1}$$

Where, d_{se} is the maximum scour depth in equilibrium condition, b is the pier width, y is flow depth, K_1 is a shape factor, K_2 is the alignment factor, K_3 is the correction factor for bed forms and F_r is Froude's number

2. Bruisers et al. (1977) Equation

$$\frac{d_{se}}{b} = 2\left(2\frac{U}{U_c} - 1\right) tanh\left(\frac{h}{b}\right) K_s k_\theta \tag{2}$$

$$U_c = 31.08\theta^{1/2} h^{1/6} d_{50}^{\ 1/3} \tag{3}$$

Where d_{se} is the maximum scour depth in equilibrium condition, b is the pier width, U is the approaching flow velocity, U_c is the critical velocity for sediment motion in SI units, θ is the Shields mobility parameter, h is the approaching flow depth, K_s the pier shape factor and K_θ the pier alignment factor (Breusers et al., 1977).

3. Jain and Fischer (1979) Equation

$d_{se} = 1.84b\left(\frac{h}{b}\right)^{0.3} F_{rc}{}^{0.25}$, valid for F_r-F_{rc}<0. (4)

$d_{se} = 2.0b\left(\frac{h}{b}\right)^{0.5} (F_r - F_{rc})^{0.25}$, valid for F_r-F_{rc}> 0.2 in live-bed conditions (5)

Where, $Fr = \frac{U}{(gh)^{0.5}}$ and $F_{rc} = \frac{U_c}{(gh)^{0.5}}$ (6)

For this study, for 0<Fr-Frc<0.2, the largest value which was obtained from the above two equations has been taken.

4. Froehlich (1988) Equation (Landers and Mueller,1996)

$d_{se} = 0.32\varphi Fr^{0.2}\left(\frac{b_e}{b}\right)^{0.62}\left(\frac{h}{b}\right)^{0.46}\left(\frac{b}{d_{50}}\right)^{0.08} + b$ (7)

Where be(feet) is the width of the bridge pier projected orthogonally to the approach flow, φ (dimensionless coefficient based on the shape of the pier nose), d50 the median grain size (feet), b (feet) is pier width and Fr (Dimensionless) is the Froude Number directly upstream from the pier. The value of ϕ is different for different pier shape, ϕ = 1.3 for square nosed-piers, ϕ = 1.0 for round-nosed piers, ϕ = 0.7 for sharp-nosed piers.

5. HEC-18/ Mueller Equation

$\frac{d_{se}}{b} = 2k_1k_2k_3k_4k_w\left(\frac{b}{h}\right)^{0.35}(Fr)^{0.43}$

(8)

$K_w = 1.0\left(\frac{h}{b}\right)^{0.13}(Fr_1)^{0.25}$ For V/Vc>1 (9)

$K_w = 2.58\left(\frac{h}{b}\right)^{0.34}(Fr_1)^{0.65}$ For V/Vc<1

(10)

Where K_1, K_2, K_3, K_4 and K_w are correction factors accounting for pier nose shape, flow angle of attack, presence of bed forms, bed armoring and wide piers in shallow flows, respectively (Richardson and Davis, 2001).

6. Laursen (1960) Equation

$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}}\left(\frac{W_1}{W_2}\right)^{K_1}$

(11)

Where, y_2 is the average depth in the contracted section, y_1 is the average depth in the upstream main channel, Q_2 is the discharge through the contracted section, Q_1 is the discharge in the approach main channel, W_1 is the width of the main channel, W_2 is the width of the contracted section and the exponent K_1 is an empirical constant. Laursen (1956 and 1958) also developed an empirical formula to determine local scour around bridge piers that is given as follows.

$$D = 1.5B^{0.7}H^{0.3} \quad (12)$$

Where, D is scour depth measured from ambient bed elevation, in feet, B is width of the pier, in feet; and H is flow depth, in feet.

2.5.2 Hydrologic and Hydraulic Analysis

2.5.2.1 Hydrologic Analysis

Data Quality Test

Rainfall and flow data quality test was done prior to using for different analysis. Then, the data were checked for variance.

Design Discharge Estimation

Rational and SCS methods were used for this study. The Rational method is the best choice for estimating the design discharge (peak runoff) for areas up to 50 ha, while the SCS method is suitable for larger agricultural areas. The equation used by the Rational method is as follows (Chow et. Al.,1988; Haan et.al.,1994; Mays,2010).

$$Q = 0.00278\ CA \quad (13)$$

Where Q represents the design peak discharge (m^3sec-1); C is the runoff coefficient; I is rainfall intensity in mm/h for the design return period, over a duration equal to the "time of concentration" for the catchment, and A is the catchment area tributary to the design location in hectares.

The SCS method was developed by the US Soil Conservation Service. This method combines rainfall intensities with catchment parameters and uses a standard unit hydrograph to determine the distribution time of the runoff. The SCS method relies on the basic principles of the rainfall-runoff relationship, expressed in Eq. 14 (USDA,1972).

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \quad (14)$$

Here, P is the maximum runoff potential (mm); Q is the actual runoff (mm); I_a is the initial abstraction (mm), and S is the maximum runoff potential difference. For this study, $I_a = 0.2S$ was used.

The runoff curve number (CN), soil type, land use, and antecedent soil moisture (infiltration rate) are important factors to consider with the SCS method. They significantly affect the runoff potential from a catchment. These values were taken from standard tables based on the catchment characteristics. The runoff (in volumetric units) calculated using the SCS method was then converted into design discharge by dividing the runoff volume by the time of concentration (Tc). To find T_c of the five river bridges catchment outlets, we used Kirpich's time of concentration formula (Kirpich,1940) given as:

$$Tc = \sum 0.948 \left\{ \left(\frac{{L_1}^3}{H_1}\right)^{0.385} + \left(\frac{{L_2}^3}{H_2}\right)^{0.385} + \cdots + \left(\frac{{L_n}^3}{H_n}\right)^{0.385} \right\} \quad (15)$$

Where Tc = time of concentration (hr.), L = length of overland flow (m) and H = elevation difference (m)

Return Period

In the present study, a 100-year return period for two bridges (Abware and Adis Amba) and a 50-year return period were applied for three culvert bridge structures (Aba Yimer-1, Sembo and Weleti). This ensures that the bridge can handle the flood event without significant damage or failure.

2.5.2.2 Hydraulic Analysis

For hydraulic and scour analysis, we surveyed river cross-sections and longitudinal profiles to gather key parameters such as flow area, wetted perimeter, hydraulic radius, and slope. We calculated roughness coefficients using Manning's equation. Additionally, we identified the mean grain size (D_{50}) of the bed material as a crucial input for scour calculations. The sampling protocol involved dividing the riverbed near each bridge into segments of similar material. We collected 2-3 sub-samples from each segment, mixed them, and tagged them for laboratory analysis. We took samples from various locations across the channel width to ensure horizontal representation while vertical variation was insignificant to determine the average grain size. We adjusted sampling depths based on the expected bed material. For the sandy Abware and Adis Amba rivers, we dug shallower pits (60–75 cm). For the anticipated gravel-bed rivers of

Aba Yimer-1, Weleti, and Sembo, we excavated deeper pits (75–100 cm), adjusting the exact depth based on our observations during the excavation.

The general conceptual framework of this study is depicted in Figure 5.

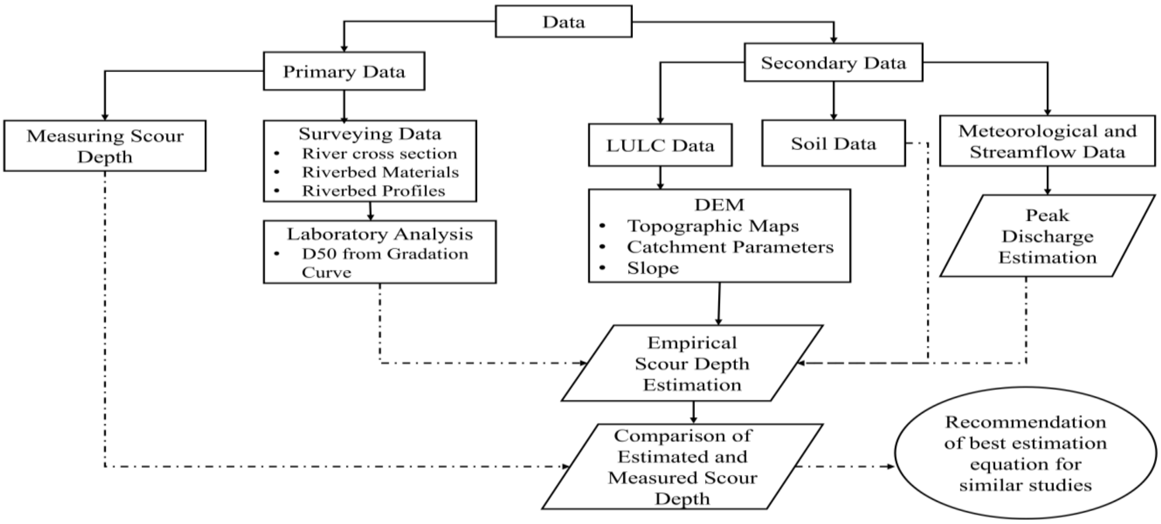


Figure 5. Conceptual framework of the present study

3. RESULTS AND DISCUSSION

3.1 Results of Hydrologic Analysis

The estimation of peak flood discharge was based on catchment area. The study used the Rational Method for areas smaller than 50 ha. For larger areas, it employed SCS Unit Hydrograph method. In this study, the Abware and Adis Amba bridges were analyzed with the Rational Method while the other bridges were assessed using the SCS method.

The hydrological parameters for Aba Yimer-1, shown in Table 3, include a time of concentration (T_c) of 0.14 hours, indicating a very quick runoff response. This is backed by a runoff coefficient (C) of 0.82, which is typical for a highly impervious catchment. A summary of the catchment parameters for each bridge site is available in Table 3.

Table 3: Catchment parameter and design peak discharge results for each bridge

Sl. No.	Bridge Name	Catchment area (ha)	CN-II	CN-III	C	T_c (hr)	Design discharge (m^3s^{-1})	Method
1	Aba Yimer-1	47.98	77.76	89.62	0.82	0.14	30.24	Rational
2	Weleti	1173.91	70.71	85.43	0.64	0.71	32.2	SCS
3	Abware	256.36	77.67	89.60	0.64	0.33	4.81	SCS
4	Adis Amba	255.72	81.47	91.88	0.77	0.31	7.62	SCS
5	Sembo	1031.54	80.10	89.98	0.75	0.45	8.1	SCS

3.2 Results of Hydraulic Analysis

3.2.1. Manning's roughness Coefficient

Considering the riverbed and bank materials in the study area, along with the roughness coefficient from the Ethiopian Road Authority (ERA) manual 2022, we estimated the roughness values (n). In this study, we used n = 0.04 for the cross sections of Aba Yimer, Weleti, and Sembo rivers while n = 0.03 was used for the cross sections of Abware and Adis Amba rivers.

3.2.2. River Cross-section and Riverbed Profile Parameters

Using the coordinates of lateral distance, ground elevation and river center data, the river cross sections and riverbed profiles were generated to determine the hydraulic parameters such as flow area, wetted perimeter, hydraulic radius, and the bed slope (Figure 6). The riverbed slope of the selected bridges depicted steepest slope in each riverbed profile along the river breadth (Figure 7). From the stage discharge curves (Figure 8), the approaching flow depth of each river for the return periods was determined as follows:

Aba Yimer-1: y_{50} = 0.61m for Q_{P50} = 30.24 m^3s^{-1}

Weleti River: y_{50} = 0.82 m for Q_{P50} = 32.2 m^3s^{-1}

Abware River: y_{100} = 0.55m for Q_{P100} = 4.81 m^3s^{-1}

Adis Amba River: y_{100} = 1.02 m for Q_{P100} = 7.62 m^3s^{-1}

Sembo River: y_{50} = 0.54 m for Q_{P50} = 8.10 m^3s^{-1}

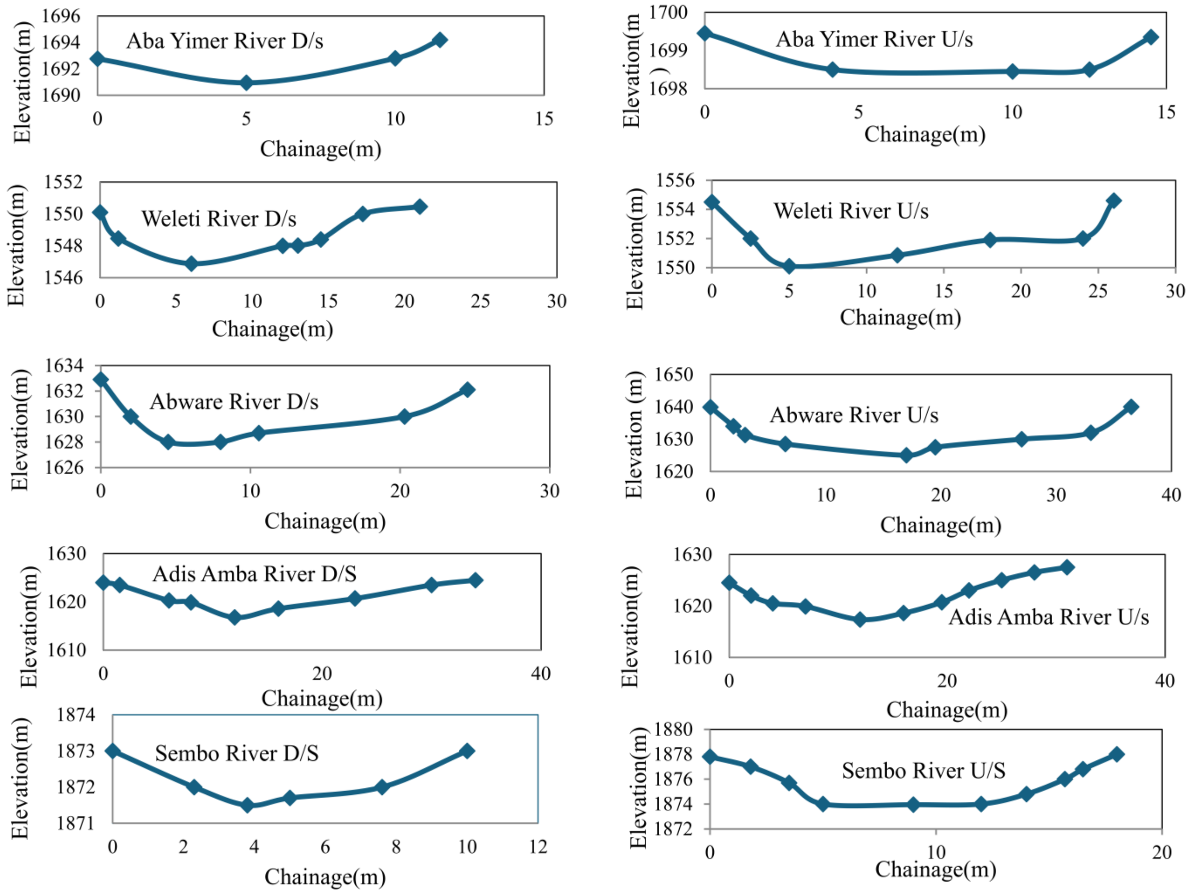


Figure 6. U/s and D/s River Cross Sections (from left bank to the right bank)

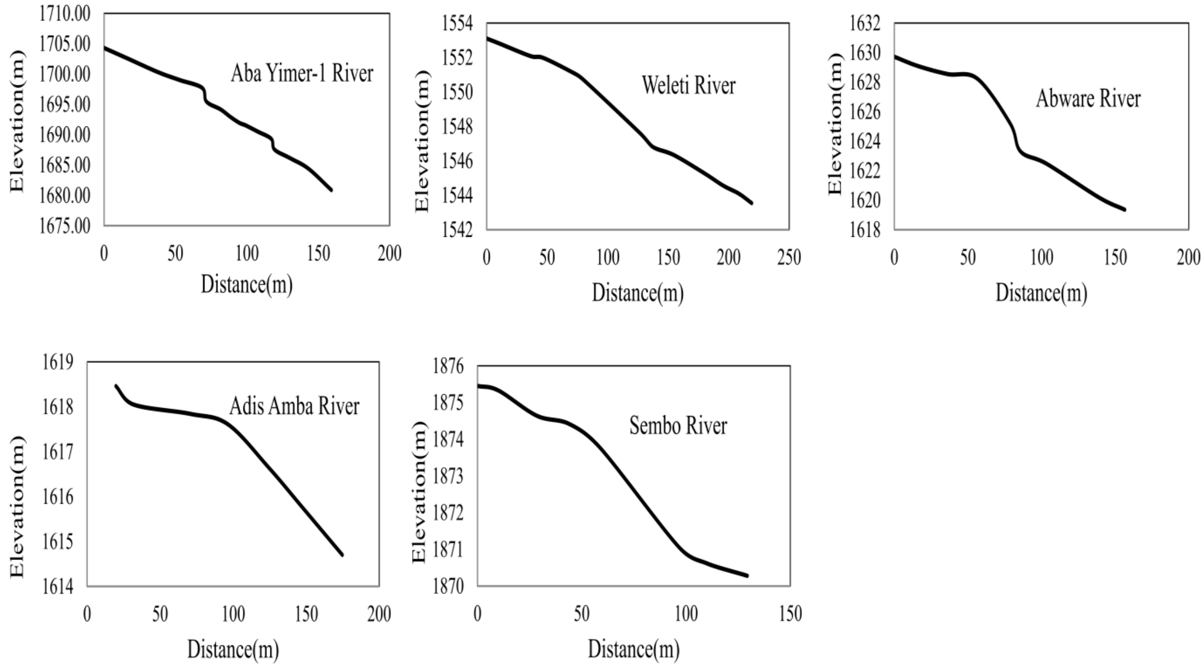


Figure 7. Riverbed profiles at each river

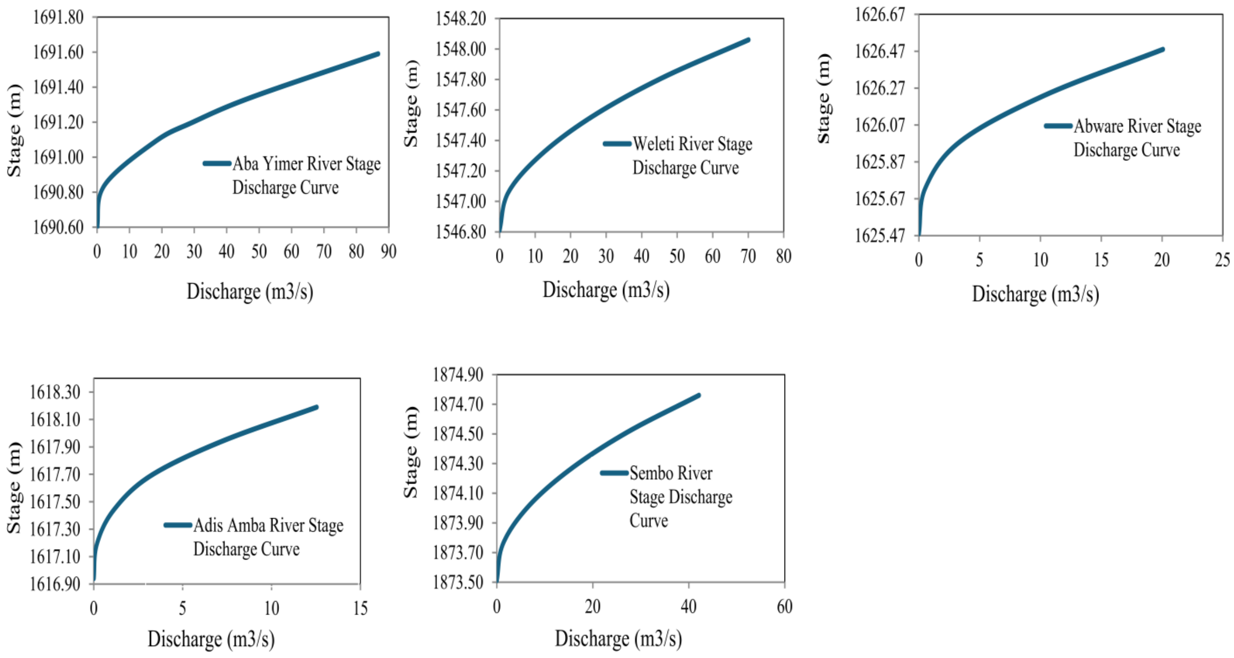


Figure 8. Stage Discharge Curve of the rivers

3.2.3. Laboratory Analysis of Average Grain Size

We developed a laboratory analysis of average grain size (gradation curve) based on the results from the percentage of finer and retained amounts at different sieves. We determined the average particle size, or D_{50} (mm), from the gradation curves of each riverbed material (Figure 9). The D_{50} size and bed material classification analysis was done in a laboratory and summarized in Table 4.

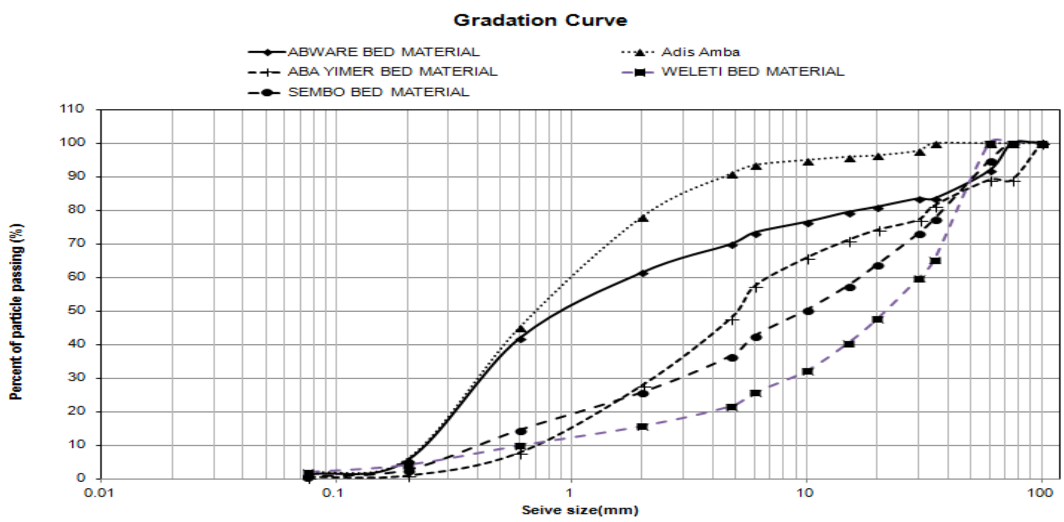


Figure 9. Gradation curves of the five rivers bed material

Table 4: D50 riverbed material classification

Sl. No.	Name of bridge	Median bed material diameter, D_{50} (mm)	Classification based on USCS
1	Aba Yimer	5	Gravel bed
2	Weleti	24	Gravel bed
3	Abware	0.91	Sand bed
4	Adis Amba	0.68	Sand bed
5	Sembo	9.1	Gravel bed

3.3 Scour Components and Bridge-Specific Observations

The total scour depth was assessed by considering three primary components: general scour, contraction scour, and local scour (Wang et al., 2019). In the present study, local scour was considered while other scour mechanisms were found negligible at the study locations. The key variables used in the scour analysis are summarized in Table 5. The correction factors K_1 (for pier nose shape) and K_2 (for flow attack angle) were obtained from ERA design manual, which provided standardized values for these coefficients based on various angles of attack (ranging from 0° to 30°) and different pier nose shapes (circular, rectangular, or sharp-nosed). These coefficients were essential for accurate local scour depth calculations as they accounted for the hydrodynamic effects of pier geometry and flow alignment. The recommended values of ERA manual were applied consistently across all bridge sites to maintain methodological uniformity in the scour predictions.

Table 5: Scour Variables Analysis

Sl. No	Name of the bridge	Shape of pier nose	Angle of attack (degrees)	K_1	Width normal to flow b (m)	Measured scour depth (m)	D_{50} (mm)	length L (m)	L/b	K_2
1	Aba Yimer	square	30	1.1	2.4	1.49	5	11.1	4.6	2
2	Weleti	square	0	1.1	0.6	1.12	24	32.56	54.3	1
3	Abware	square	0	1.1	2	4.89	0.91	9.7	4.9	1
4	Adis Amba	round	0	1	1.25	6.03	0.68	2.5	2.0	1
5	Sembo	square	0	1.1	3.5	2.15	9.1	9.7	2.8	1

All rivers in this study exhibited no aggradation but displayed significant downstream degradation. The degradation depth was calculated based on upstream river slope, design elevation, and current scour point elevation (Table 6). During high-flow conditions, the natural width of the rivers at the Aba Yimer-1, Weleti, Abware, and Adis Amba bridges exceeded the constructed waterway length designed for flood events. Except for Aba Yimer-1 Bridge, the other three bridges featured concrete beds along their longitudinal sections, preventing flow constriction and minimizing scour risk. The Sembo Bridge experienced constriction during peak floods, but its concrete floor at the contracted section mitigated scour effects. Field observations confirmed no significant contraction scour at any of the bridges studied. Instead, local scour was identified as a dominant contributor to total scour depth across all five bridges.

Scour depths were computed for 50 and 100-year return periods using multiple empirical formulas. A detailed result was provided in Tables 6-12. Additionally, Table 13 presents the average bridge scour depth for 50-year return period, comparing predictions from six different methods.

Table 6: Gradual degradation depth for different bridges

Sl. No..	Name of bridge	Slope	U/s elevation (m)	Distance (m)	Design elevation at point of scouring (m)	Current elevation at point of scouring (m)	Degradation depth (m)
1	Aba Yimer-1	0.153	1692.1	5	1691.3	1690.59	0.7
2	Weleti	0.066	1547.93	5	1547.6	1546.81	0.8
3	Abware	0.021	1630.37	5	1630.3	1625.48	4.8
4	Adis Amba	0.039	1622.97	5	1622.8	1616.94	5.8
5	Sembo	0.029	1875.66	5	1875.5	1873.51	2.0

Table 7: Local scour for design return period using CSU equation

Sl. No.	Name of bridge	K_1	K_2	K_3	b (m)	y(m)	$Q(m^3/s)$	$A(m^2)$	V(m/s)	F_r	d_{se} (m)
1	Aba Yimer-1	1.1	2	1	2.4	0.61	30.24	5.58	5.42	2.22	15.089
2	Weleti	1.1	1	1	0.6	0.82	32.2	8.08	3.99	1.41	2.08
3	Abware	1.1	1	1	2	0.55	4.81	1.58	3.04	1.31	5.71
4	Adis Amba	1	1	1	1.25	1.02	7.62	2.32	3.28	1.04	2.32
		1	1	1	1.25	0.84	4.12	1.46	2.82	0.98	2.57
5	Sembo	1.1	1	1	3.5	0.54	8.1	2.8	2.89	1.26	8.18
		1.1	1	1	3.5	0.37	3.86	1.55	2.49	1.3	10.64

Table 8: Local scour for design return period using Breusers equation

Sl. No	Bridge Name	D_{50} (m)	Θs (m)	H (m)	B (m)	Ks	Kθ	Uc (m/s)	U (m/s)	Tanh (h/b)	d_{se} (m)
1	Aba Yimer-1	0.0022	3.23E-02	0.61	2.4	1.1	2	0.945	5.42	0.25	27.51
2	Weleti	0.024	4.70E-02	0.82	0.6	1.1	1	1.88	3.99	0.88	3.75
3	Abware	0.0009	2.77E-02	0.55	2	1.1	1	0.454	3.04	0.27	14.7
4	Adis Amba	0.0007	3.13E-02	1.02	1.25	1	1	0.485	3.28	0.67	21.11
5	Sembo	0.0091	4.14E-02	0.54	3.5	1.1	1	1.191	2.89	0.15	4.55

Table 9: Local scour for design return period using Jain & Fischer live-bed equation

Sl. No.	Name of bridge	h(m)	b(m)	d_{50} (m)	u(m/s)	uc (m/s)	F_r	F_{rc}	F_r-F_{rc}	d_{se}(m)
1	Aba Yimer	0.61	2.4	0.0022	5.42	0.67	2.22	0.27	1.94	2.86
2	Weleti	0.82	0.6	0.024	3.99	1.88	1.41	0.66	0.74	1.30
3	Abware	0.55	2	0.00091	3.04	0.45	1.31	0.20	1.11	2.16
4	Adis Amba	1.02	1.25	0.00068	3.28	0.48	1.04	0.15	0.89	2.19
5	Sembo	0.54	3.5	0.0091	2.89	1.19	1.26	0.52	0.74	2.55

Table 10: Local scour for design return period using Froehlich design equation

Sl. No	Bridge name	Pier Shape	F_r	Ø	b (m)	be (m)	h (m)	d50 (m)	d_{se} (m)
1	Aba Yimer	square	2.22	1.3	0.67	0.20	0.05	0.016	8.042
2	Weleti	square	1.41	1.3	0.05	0.05	0.07	0.079	0.803
3	Abware	square	1.31	1.3	0.59	0.17	0.05	0.003	7.141
4	Adis Amba	Round	1.04	1	0.10	0.10	0.09	0.002	1.414
5	Sembo	square	1.26	1.3	0.83	0.29	0.04	0.03	10.036

Table 11: Local scour for design return period using HEC-18/Mueller equation

Sl. No.	Name of bridge	K_1	K_2	K_3	K_w	b(m)	h(m)	V (m/s)	F_r	d_{se} (m)
1	Aba Yimer	1.1	2	1.1	0.42	2.4	0.61	5.42	2.22	11.01
2	Weleti	1.1	1	1.1	1.36	0.6	0.82	3.99	1.41	2.51
3	Abware	1.1	1	1.1	0.28	2	0.55	3.04	1.31	4.27
4	Adis Amba	1	1	1.1	0.82	1.25	1.02	3.28	1.04	2.4
	Sembo	1.1	1	1.1	0.15	3.5	0.54	2.89	1.26	5.14

Table 12: Local scour for current age of each bridge and design return period using Lauren's equation

Sl. No.	Name of bridge	B (m)	H (m)	D (m)	D (m)
1	Aba Yimer	0.67	0.05	0.46	5.55
2	Weleti	0.05	0.07	0.08	0.99
		0.59	0.05	0.41	4.95
3	Abware	0.59	0.03	0.36	4.33
		0.10	0.07	0.12	1.66
5	Sembo	0.83	0.04	0.52	6.25

Table 13: Average bridge scour depth for return period of 50 years

Sl,No.	Name of bridge	CSU	Froehlich	Brueisers	HEC-18	Lauren	Jain & Fischer
1	Aba Yimer-1	15.09	8.04	27.51	11.01	5.55	2.86
2	Weleti	2.08	0.80	3.75	2.51	0.99	1.30
3	Abware	5.71	7.14	14.70	4.27	4.95	2.16
4	Adis Amba	2.32	1.41	21.11	2.40	1.76	2.19
5	Sembo	8.18	10.04	4.55	5.14	6.25	2.55

3.4 Comparison of Measured and Estimated Scour Depths

The evaluation of scour depth prediction equations was conducted by comparing computed scour depths with field-measured values at various bridge sites (Figure 6). A composite comparison further validated the performance of these equations. The analysis revealed that the Jain & Fischer equation outperformed others, providing the closest estimates for both gravel-bed and sand-bed rivers. Specifically, it yielded the most accurate scour predictions for two gravel-bed and one sand-bed river. Following Jain & Fischer (1979), Laursen's equation demonstrated reasonable accuracy, particularly for two sand-bed and two gravel-bed rivers. Meanwhile, Froehlich's equation performed well with smaller pier widths. normal to the flow. Moreover, it could produce the best-fit scour estimates for certain bridges with comparable pier dimensions.

The study indicated that most equations were highly sensitive to pier width and sediment grain size (D_{50}). However, the CSU and Laursen's equations were less influenced by these factors. Additionally, hydraulic parameters such as Manning's roughness coefficient (n), cross-sectional area of the river, and flow velocity were found to significantly affect scour depth magnitude. This suggests the importance of precise input data in scour modeling as variations in these parameters can lead to substantial discrepancies in scour predictions. Given these findings, Jain & Fischer's equation is recommended as the primary choice for local scour estimation in both gravel and sand-bed rivers. However, Laursen's and Froehlich's equations can serve as reliable alternatives, depending on site-specific conditions such as pier geometry and sediment characteristics. Engineers should exercise caution when selecting input parameters particularly pier width and grain size to ensure accurate scour depth predictions in bridge design. Though empirical scour equations provide useful estimates, their performance varies with hydraulic and structural conditions. A thorough understanding of parameter sensitivity is essential for optimizing scour depth calculations and ensuring the safety and stability of bridge foundations.

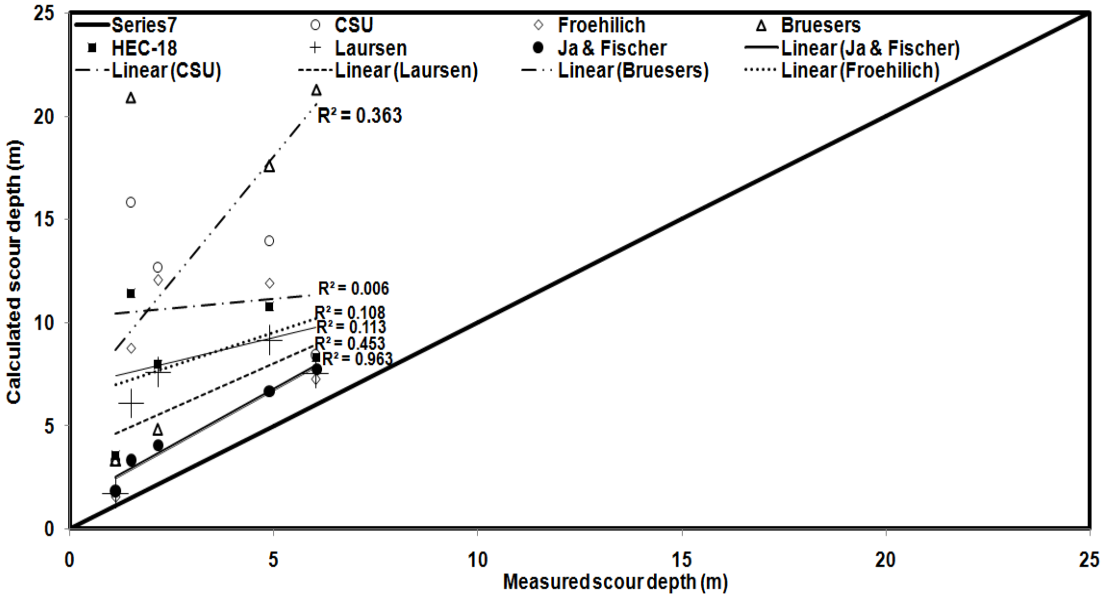


Figure 6. Performance comparison with regression equations

4. CONCLUSION

In this study, local scour depth estimation was considered using various empirical equations. Additionally, long-term degradation, contraction scour and local scour are estimated to calculate the total scour. Contraction scour hardly existed for all the selected bridge sites owing to sufficiently provided length of water way. Besides, there were no flow constrictions for all the selected bridges. Scour depth for selected bridges was measured and then the total scour was compared with the measured scour depths. From the comparative analysis, Jain & Fischer and Laursen & Froehlich equations estimated scour depth with better magnitudes in approaching the measured scour depths. Hence, bridge scour designers preferred to use Jain & Fischer equation to determine local scour as their leading choice for sand bed and gravel bed rivers. The scour variables such as pier width, shape, and alignment were found sensitive to scour magnitude and any changes to the magnitudes of these parameters significantly changes the value of scour depth. Hence, deciding and measuring these parameters should be done carefully while designing the equilibrium scour depth.

Conflict of Interest

The authors declared that no conflict of interest.

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