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Morphodynamic Alterations and Scour Processes around Bridge Openings: A Case Study of Selected Bridges on the Sodo-Konso Highway, Ethiopia

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Abstract

Numerous bridges in southern Ethiopia are greatly affected by morphodynamic changes in the alluvial channels caused by hydraulic responses to flow depth, velocity, shear stress and longitudinal slope. These bridges are vital for enabling traffic flows between communities in the region. In this study, morphodynamic alterations around bridge openings were conducted using the hydraulic flow parameters based on field and laboratory investigations conducted in selected bridge sites between the Sodo and Konso highway routes.The morphodynamic analysis of 1984 to 2021, 1,276 Landsat images of 5 selected scour susceptible bridge sites have been analyzed using RivMap toolbox in MATLAB after rapid assessment of the channel stability of 15 bridges based on the field observation. The 38 years of channel geomorphological changes showed that lateral widening of the alluvial valley was dominant at the selected bridge sites. The widening of the channel worsened the contraction, increased the potential for local scour, and raised flow velocity caused by the narrow bridge opening. Results from the HEC RAS (Hydrologic Engineering Center River Analysis System) showed that three of the studied bridges—Kulfo, Alge, and Wajifo had a low risk of scour, while the Sile and Sego bridges faced the most severe scour risks. In particular, Sego Bridge was highly vulnerable during floods with 50, 100, and 500-year return periods due to the extreme narrowing of the valley at the bridge location and ongoing lateral widening of the upstream floodplain channel over time. This suggests that Sego Bridge requires a new relief culvert or other countermeasures to safely manage extreme flooding. Thus, design and analysis of the bridge structures in the lower alluvial reaches of the rivers require a thorough investigation of the geomorphology and provision of adequate openings for the potential floodplain widening.

Keywords: *bridge scour, morphodynamic, HEC RAS, contraction scour, local scour*

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1. INTRDUCTION

Spatial and temporal morphodynamics of the alluvial river channel lateral migration is a widely documented concept in many studies (Li et al., 2017; Boothroyd et al., 2020; Li et al., 2020). Rapid lateral widening highly threatens riparian land property and hydraulic structures near the reach (Boothroyd et al., 2020). Natural and human-induced factors for channel geomorphic changes were reported in several case studies (Beyene et al., 2023). Some of the recent works revealed reach scale thalweg migration (Li et al., 2017), catchment scale multi-temporal annually resolved satellite images of active channel masking (Boothroyd et al., 2020), GIS-based channel platform analysis (Mandarino et al., 2019),watercourse constriction based morphological patterns (Oliveto & Marino, 2019) and in-stream sand mining influence based on morphodynamic alterations (Lade et al., 2019).

Understanding the evolution of the channel platform is essential for effective engineering planning, as it provides insights into long-term morphological changes, sediment transport patterns, and areas prone to erosion or deposition. This knowledge supports the design of resilient infrastructure and the mitigation of risks associated with channel instability.

Bridges are infrastructures used to connect two shores of the rivers to enhance traffic flow. However, these structures affect the natural water flow, and their stability is also impacted by the scouring (Liao et al., 2018). Scour depth prediction is a significant bridge design phenomenon (Chavan & Kumar, 2018). Experimental and numerical studies to estimate scour depth based on water surface, flow velocity, and bed shear stress are used to simulate 3D scour processes (Omara et al., 2019).

Studies on Nonuniform sand beds, pier groups, flood-season scour patterns, scour hole evolution, pier modifications, compound channel abutment scour, clear water scour, complex flow field scour, and eddy simulations (Chavan & Kumar, 2018; Zhou et al., 2020; (Tabarestani & Zarrati, 2016; Khan et al., 2017; (Poggi & Kudryavtseva, 2019; Farooq & Ghumman, 2019; Ghazvinei et al., 2016; Guillermo et al., 2013; Ettema et al., 2017 ; Kirkil et al., 2009) , monitoring of temporal and spatial evolution of scour hole around bridge shows that the focus of the most cases was attempting to determine the scour depth at particular condition.

Numerous studies have been carried out on river reach morphodynamics (Church, 2006; Lade et al., 2019; Boothroyd et al., 2020). In other words, most of the bridge scour analysis-related works revealed that experimental pier and abutment scour depth determination to evaluate counter-measurement protection mechanisms (Kumcu et al., 2014; Xiong et al., 2017). The lateral migration of the channel through time induced a significant change in the flow direction (angle of attack), velocity, and bed shear stress (Omara et al., 2019). Actual field-based channel evolution geomorphologic analysis-related scour determination research work is very scanty. Scouring around bridge foundations was the most significant contributing factor to bridge failures. The scour failures tended to occur without prior warning and led to fatalities and economic loss (Wang et al., 2017).

Degradation or/and aggradation of the river bed and bank materials as well as contraction and local scour conditions were critical factors of the service life of the bridge. Reasonable and prudent hydraulic analysis of a bridge design required an assessment of the proposed bridge's vulnerability to potential scour. The hydraulic performance of the existing bridges depended on the estimation, monitoring, and countermeasures (Wang et al., 2017) related to counterbalance flow complications occurring due to the construction of the structure. Identifying and modeling of these effects would sophisticate the maintenance and operation of the bridge, including probable repair, reconstruction, and potential liability. Bridge failure could be caused by foundation, structural, and hydraulic failures, but the majority of bridge failures were due to hydraulic conditions. Pier scour was the major possible cause of hydraulic failures (Farooq & Ghumman, 2019) of a bridge, particularly in alluvial channels where the riverbed and banks were under continuous modification. Local scour could be a complicated phenomenon owing to three-dimensional flow separation on the upstream side of the bridge pier and sediment load transport (Tabarestani & Zarrati, 2016). Lots of research works have been done on this topic to derive the relationship between the maximum depths of scour, and understand the mechanism of local scour and its control. Therefore, a large amount of research work is available on the topic of bridge scour and its protection. However, only a few studies are available so far on the flow field around the bridge elements.
Because of the hazard and economic hardships posed by a rapid bridge collapse, special considerations should be given to select appropriate flood magnitudes for use in the analysis. The inherent complexities of stream stability, further complicated by highway stream crossings,

required a multilevel solution procedure. The evaluation of a highway stream crossing or encroachment should begin with a qualitative assessment of stream stability(FHWA, 2009). This might involve the application of geomorphic concepts to identify potential problems and alternative solutions. This analysis should be followed by quantitative analysis using basic hydrologic, hydraulic, and sediment transport engineering concepts. Such analysis could include an evaluation of flood history, channel hydraulic conditions, and basic sediment transport analysis such as evaluation of catchment area sediment yield, incipient motion analysis, and scour calculations. This analysis would be adequate for many locations if the problems and the relationships between different factors affecting stability were adequately explained. Otherwise, a more complex quantitative analysis based on detailed mathematical modeling and/or physical hydraulic models should be considered.

Problems associated with aggradation can be particularly hazardous, especially in areas with limited freeboard. In such cases, increased flood risks such as more frequent overtopping may pose threats to upstream properties and public safety. Therefore, when aggradation is anticipated, it is important to assess these potential consequences. In addition, aggradation in a stream may serve to moderate potential scour depths (FHWA, 2012).

The highway from Sodo to Konso is a part of socio-economically significant main federal transport route to the South Ethiopia. There are multiple bridges designed to cross perennial and non-perennial river valleys. In some of the rivers, more than one bridge structures were constructed (three adjacent bridges on the Sile River) within a short distance apart from the existing one due to the failure of the former crossing. As witnessed from the failure of the existing bridges, hydraulic failure seems to be dominant. It needs to be analyzed to identify and mitigate this effect for maintenance and possible adjustments of the conditions for the new design. This study will focus on investigating morphodynamic alterations around bridge openings and openings in the process of scouring under the influence of hydraulic flow parameters for the selected bridges. The specific aims of the present study are to (1) investigate the contraction scour potential; (2) identify the major hydraulic factors for the failure of bridges; and (3) evaluate the remedial alternatives for the scour problem.

In this study, the subsequent section is structured as materials and methods (rapid assessment of channel stability, morphodynamic analysis by using RIVMAP tools in google earth engine, and hydraulic and geotechnical laboratory test, and run HEC-RAS software to plot scour prism) results on alluvial channel migration pre-entire reach and commutative migration rate per annual, discusses the implications of contraction and local scouring of abutment and pier and proposes mitigation strategies with a final conclusion(key findings and recommendations for future research).

2. MATERIALS AND METHODOLOGY

2.1 Description of the study

The highway from Sodo to Konso is located in the South Ethiopia regional state as shown in Figure 1.

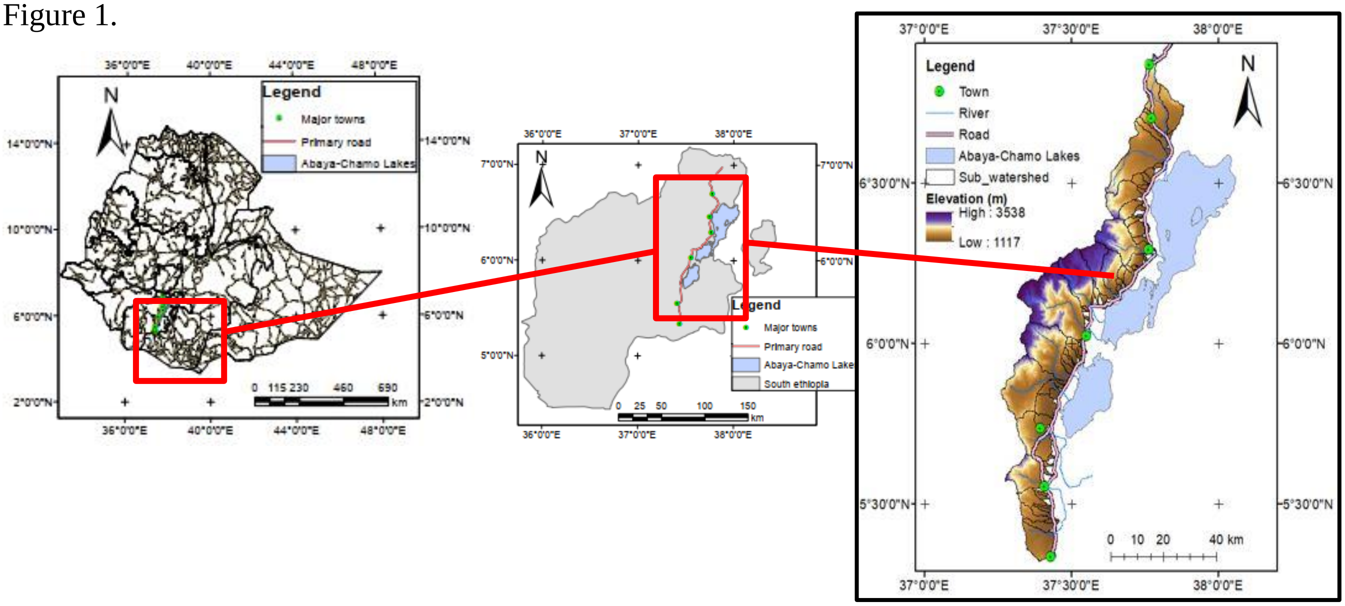

Figure 1. Location of the study area

2.2 The Nature of Rivers

Rivers crossing this highway route are located in the Rift Valley Lakes basin with perennial and ephemeral characteristics. Most of the bridges were constructed across the lower reaches of the ephemeral stream valleys and encountered continuous upstream land use changes and human interactions which can result in long-term degradation or aggradation and lateral widening of the valley.

2.3 Reach Type and Morphology River

The bridge structures on the Sodo to Konso highway are mostly constructed in the alluvial reaches of the rivers, predominantly characterized by the erosion and deposition of the bed and banks. However, these conditions are seldom consistent due to year-to-year weather-dependent fluctuations. The long-term variations are credible due to the impacts of land use changes and human interventions. The bed and banks of these alluvial reaches are composed of sediment transported by the river through time. That means, the channel is not confined to the rock bed but flanked by the flood plain of small and/or undefined banks (Lagasse et al., 2001). In the dry season, clear water scour conditions are predominant, resulting in insignificant morphological changes due to the ephemeral nature of most streams. However, live bed and bank scour happens reasonably during high flow times. The alluvial reaches with these erosion-prone banks are significantly sensitive to the flow variations and/or complications happening due to the effects of the bridges constructed across the valleys.

2.4 Data collection

2.4.1 Primary data collection

Field observations were made to collect soil samples from the selected bridge sites, and field measurements with important parameters were taken in the first phase (November and December 2021), in the second phase (February and March 2022), and in the third phase (April and June 2022). Reconnaissance observation of the bridge site was a preliminary important aspect of the geomorphic study to assess whether the bridge is susceptible to scour failure or not. Primary evaluation of the selection of the bridges was based on the checklist prepared according to the HEC 20 manual. Field observations and measurements of the valley width, GPS elevations (above mean sea level), opening width, pier diameter, valley shape, bedforms, sediment characteristics, drift accumulation, flood marks, flow behavior, channel classification, obstructions, erosion activity, and riparian vegetation were evaluated according to the guidelines of rapid assessment of channel stability (Lagasse et al., 2001)**.** Bed soil samples were taken in wet and dry seasons

(November 2021 and February 2022) to handle the effect of the armoring layer on the sample homogeneity. Sample of the bed soils were dug from the upstream zone of flow contraction and downstream zone of flow expansion as well as the bed of the bridge site in which the flow is constricted. The sample depth varied form 0.5m in some pit sites to 1m in most pit sites at the Wajifo, Alge, and Kulfo bridges to account for relatively undisturbed subsurface bed layer. Hence the top coarser armor bed layer was assumed to be disturbed during high floods. In case of Sile and Sego bridge sites, the particle distribution through pit depth was uniform and the surface of thin sand armor layer was less than 0.3m for most pits.

2.4.2 Secondary data Collection

2.4.2.1 Satellite Image Data

Landsat 5, Landsat 7, and Landsat 8 satellite images of 30x30m resolution from the USGS archive were used for 38 years from 1984 to 2021 as shown in Table 1 below owing to its availability for a long time as compared to other higher resolution imagery to perform geomorphological analysis.

Table 1. Landsat image collections used for ROI

№o	Satellite	Image collection	Date	No of images
1	Landsat 5	LANDSAT/LT05/C02/T1_L2	12/04/1984 to 30/12/2001	537
2	Landsat 7	LANDSAT/LE07/C02/T1_L2	01/01/2002 to 31/12/2012	384
3	Landsat 8	LANDSAT/LC08/C01/T1_TOA	01/01/2013 to 08/11/2021	355

2.4.2.2 Rainfall Data

Some rivers in this route have gauging stations and meteorological stations nearby. However, most of the bridges located at the ungagged catchments rainfall data were used from EMI as shown in Table 2 below.

Table 2. Rainfall data

No	Station Name	Year	Percentage missed (%)	Bridge site used
1	Mirab abaya	1976 – 2016	8.34	Alge and Wajifo
2	Arba Minch	1976 – 2016	7.85	Kulfo
3	Gato	1976 – 2016	2.83	Sile and Sego

2.5 Methodology

2.5.1 General Conceptual Framework

The general methodological framework of the study is shown in the Figure 2 below.

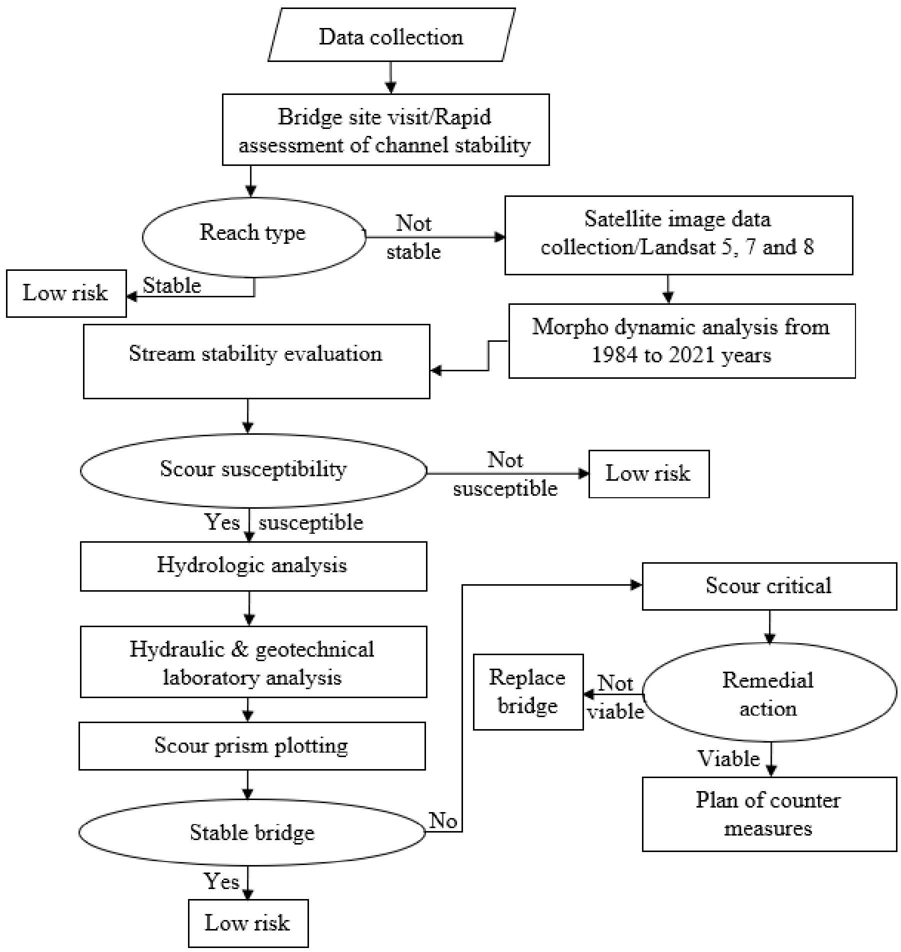

Figure 2. Conceptual framework of the study

2.5.2 Selection Based on Field Observation

There are more than 15 bridges over the stream valleys crossing the Sodo to Konso highway as listed in Table 3 below. Some of these valleys are more actively adjusting their beds and banks frequently during the bridge's useful life operation. The selection was conducted according to assessment of the channel stability (Lagasse et al., 2001). Evaluation criteria were used to determine whether a bridge is low risk or susceptible to scour, based on a standardized checklist.

Table 3. Scour susceptible bridge evaluation based on field observations

№o	Bridge name	Pier width (m)	No. of span	Pier type	Valley width (m)	Scour evaluation	Remark
1	Hamessa		3	Round nose	46.4	Low risk	Rocky stable bed and banks
2	Wajifo		4	Circular	63.4	Scour susceptible	Upstream right bank as well as middle span bed degradation & improperly placed upstream small gabion check dam
3	Welo		1		20	Low risk	Small catchment
4	Keme		3	Circular	45	Low risk	Small catchment
5	Alge /Shafe		2	Circular	33	Scour susceptible	Aggradation (drift accumulation) in the left span and degradation in the right bank (abutment scour)
6	Baso		3	Circular	60	Low risk	Relatively stable bed & banks
7	Hare		2	Round nose	30.5	Low risk	Upstream right bank degradation (small extent)
8	Kulfo (upper)		3	Circular	48	Scour susceptible	Bed degradation in the middle span & right abutment
9	Kulfo (lower)		5	Circular	60	Low risk	Bed aggradation
10	Sile		2	Circular	40	Scour susceptible	Upstream meander, loose banks and existing bridges
11	Sego /Elgo		1		14	Scour susceptible	Degradation in the upstream banks/upstream braided stream and abutment scour
12	Wozeka		5	Round nose	100	Low risk	Bed aggradation
13	Gato		3	Circular	60	Low risk	Relatively stable stream

14	Bayde		4	Round nose	82	Low risk	Relatively stable stream
15	Kayle		4	Round nose	80	Low risk	Stable but there is human interference (bed sand mining)

2.5.3 Morphodynamic Analysis

Alluvial morphodynamic awareness is important for engineering decisions regarding the analysis of new and existing hydraulic structures. Unlike geomorphologists and geologists, engineers are concerned with changes in river morphology relatively for a short period of 10 to 20 to 50 upto 100 years(R.J.Grade, 2006). Based on the field observations and scour susceptibility, five bridges namely Wajifo, Alge, Kulfo, Sile, and Sego were selected for analysis. The banks and beds of these bridge sites were relatively unstable as compared to other bridge sites as shown in Figure 3: (a) Wajifo bridge site with improper upstream gabion check dam (b) Alge bridge with channel migration to the right bank (c) Kulfo bridge with bed scour at the middle span (d) and (e), Slie bridges new and existing respectively with bank and bed scour (f) Sego bridge with left bank scour and flow obstruction due to the existing bridge abutment.

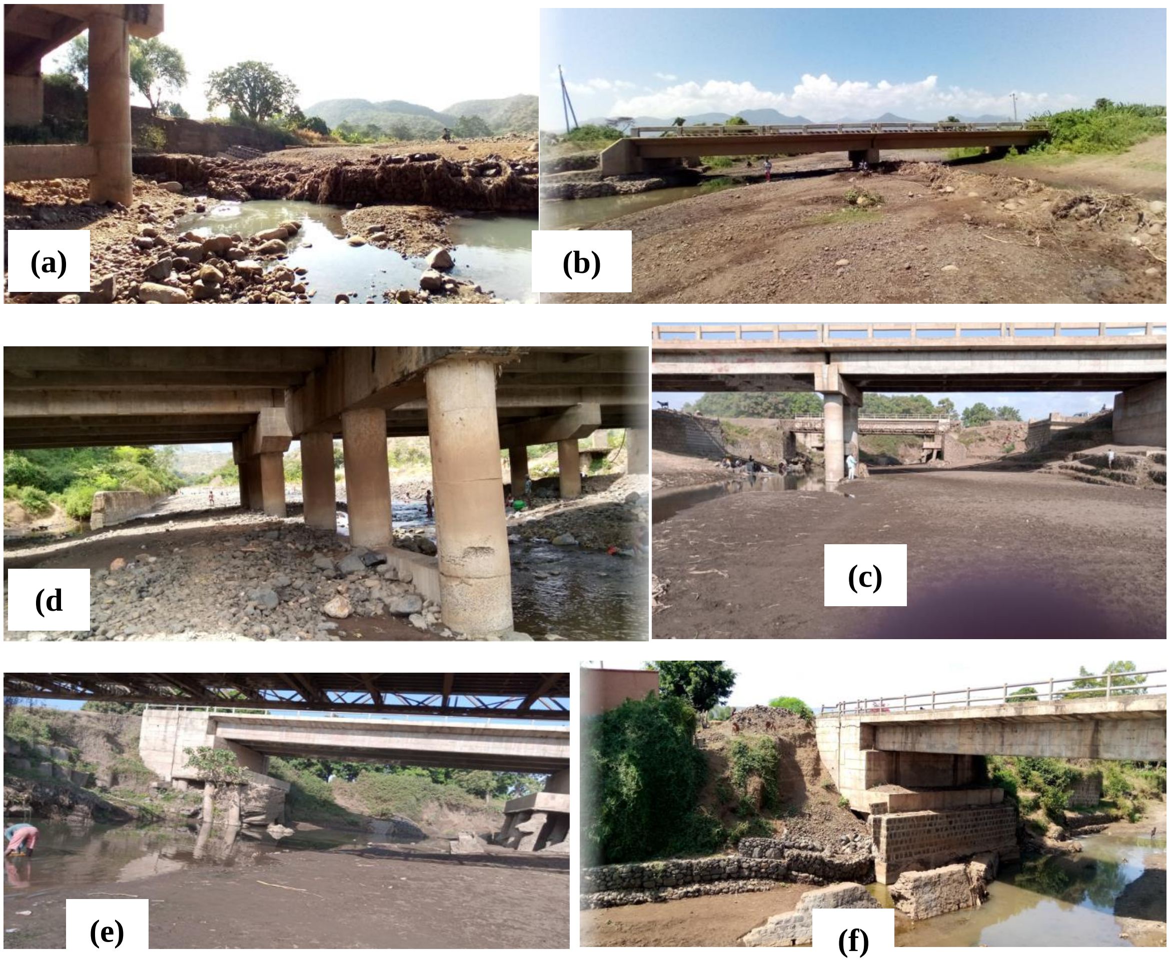

Figure 3. Scour susceptible bridges site photos

2.5.4 Landsat Image Analyses

The cloud-based computing platform Google Earth Engine (GEE) was used to analyze large geospatial datasets (Gorelick et al., 2017). In this study, GEE was used for active channels as a mask for Landsat images. The procedures were executed on this semi-automated platform for image collections from 1984 to 2021 on the annual basis of the ROI. Rectangular ROI for the river reach with a defined and visible flow channel near the bridge site was selected for each bridge. These areas were 20.25, 21.25, 23.54, 24, and 32.62 km2 for the Sego, Sile, Kulfo, Alge and Wajifo rivers, respectively. According to (Boothroyd et al., 2020)**,** the first yearly image collections were filtered, then cloud masking (Foga et al., 2017) was applied for shadows of clouds and annual images were composited using a median reducer to aggregate the cloud-masked images.

Annual composite images were used to manage incomplete images of ROI in path 169 & rows 055 to 056 and to overcome cloud-obscured scenes by cloud masking or SLC-off stripes in Landsat 7(Schwenk et al., 2017). Active channel classification was applied based on spectral indices MNDWI (Equation 3.1), NDVI (Equation 3.2) , and EVI (Equation 3.3) thresholds (Zou et al., 2018). The active channel mask output of the grayscale image for MNDWI ≥ -0.4, NDVI ≤ 0.2 thresholds (Boothroyd et al., 2020) , and EVI < 0.1 to remove mixed pixels of vegetation and water (Zou et al., 2018) were computed. Finally, the GeoTIFF image of the active channel was exported to Google Drive.

$$\text{MNDWI} = (\text{Green - SWIR})/(\text{Green} + \text{SWIR})$$

$$\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$$

$$\text{EVI} = 2.5 * [(\text{NIR} - \text{Red})/(\text{NIR} + 6 * \text{Red - } 7.5 * \text{Blue} + 1)]$$

Where: MNDWI – Modified normalized difference water index

NDVI – Normalized difference vegetation index

EVI – Enhanced vegetation index

NIR – Near infra-red

SWIR – Short wave infra-red

Band designation:

(a) B1, B2, B3, B4, and B5 are blue, green, red, NIR, and SWIR respectively for Landsat5 & Landsat7.

(b) B2, B3, B4, B5, and B6 are blue, green, red, NIR, and SWIR respectively for Landsat8

Figure 4 shows the GEE procedure applied to the ROI of Alge River reach comprising 7.5 km length and 3.2 km width (a) the raw Landsat images of each year were smashed together for temporal compositing after cloud masking (b) classification of active channel (c) NDVI (d) active channel with NDVI background.

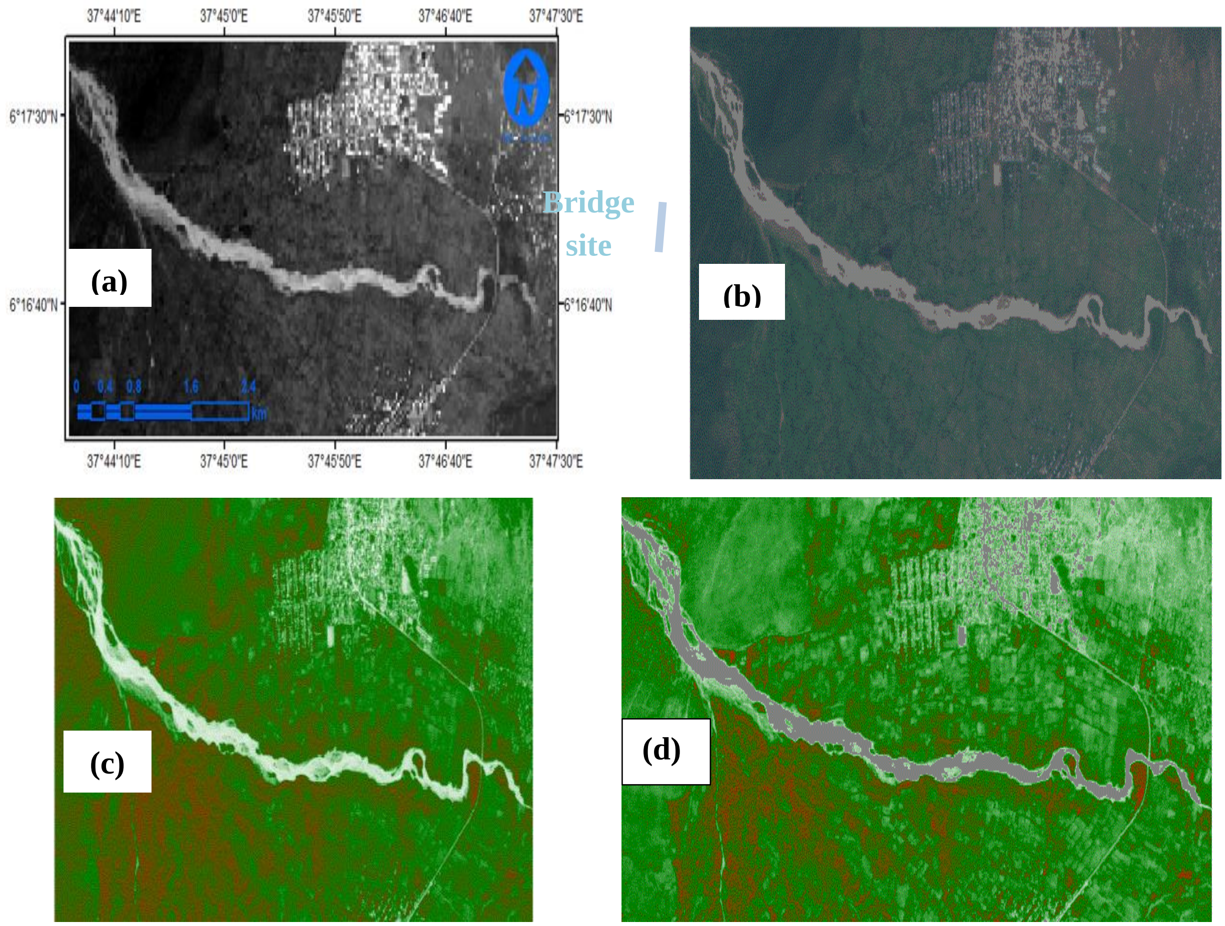

Figure 1. Alge River reaches active channel classification

2.5.5 HEC RAS model setup

In this study, HEC RAS 6.4.1 model was used to hydraulic analysis of river channels. It comprises hydraulic analysis components, data processing, reporting and storage facilities to analyze steady flow computations, unsteady flow simulation, sediment transport, and water quality analysis. Additionally, the model requires inputs such as river geometric data, floodplain elevation and length, channel cross section data, Manning's roughness coefficient, boundary conditions and flow data to provide rating curves, water surface profiles, EGL (Energy Grade Line), velocity, flow area, slope, elevation and stream flow visualization (USACE, 2016).

Hydro-meteorological data, spatial data, field measurements and design documents were used to fulfill the model data requirements. For the selected bridge sites, TIN was developed from 12.5x12.5m DEM from ALOS PALSAR, USGS with the help of HEC-GeoRAS to extract stream length, cross sectional data and over bank floodplain conditions. Cross sectional locations were selected based on the perpendicular crossing to the channel center line (Gary W. *et al,* 2021) in a manner that it should not cross each other.

Bridge cross sectional data were collected from field observation, measurements and/or design documents. In case of Kulfo and Wajifo, design documents were used to get dimensions of piers, abutments, span length, lower and upper chord elevations but for the Alge, Sile and Sego bridges these parameters were measured from field by using Tap meter and GPS. The important dimensions for scour analysis in HEC RAS input were shown in the Table 4 below.

Table 4. Selected bridge cross sections

No	Bridge name	Pier width (m)	Abutment type	Elevation (m)	
				High chord	Low chord
1	Wajifo	1.2	Sloping 1:10 (H: V)	1217	1215.05
2	Alge	0.73	Vertical	1199.24	1198.49
3	Kulfo	1.02	Vertical	1229.8	1228.52
4	Sile	1.21	Vertical	1110.72	1109.52
5	Sego	No pier	Vertical	1117.13	1116.13

3. RESULTS AND DISCUSSION

3.1 Active channel migration

The focused ROI for Sego, Sile, Kulfo, Alge and Wajifo rivers using RivMap toolbox centerline analysis (Schwenk et al., 2017) was applied to 38 years from 1984 to 2021centerlines from the annually resolved active channel masks (Figure 5) show that the morphdynamic change of each river reach.

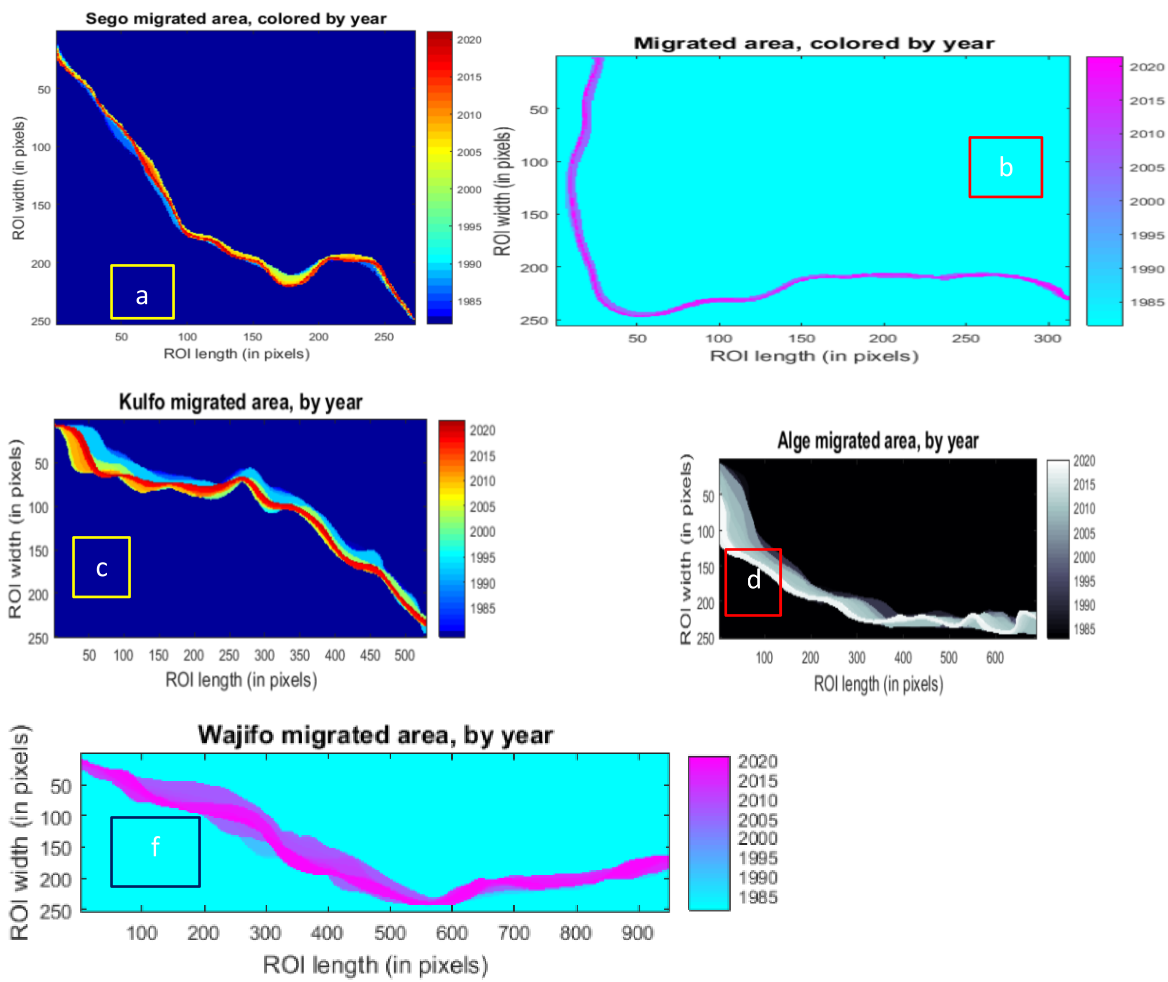

Figure 5. Center line migration rate (marked areas are bridge sites)

The cumulative center line migration area of 38 years was 0.0052, 0.0065, 0.04, 0.117, and 0.128 km^2 for Sego, Sile, Kulfo, Alge, and Wajifo bridge sites, respectively. This result shows that Alge and Wajifo bridge sites (reach near the bridge) encounter relatively unstable streams laterally. The channel migration rate, which is calculated from the ratio of the migrated area to the length of the center line, shows that the maximum migration rate of 20.45 m/year, which occurred in 2007 in Wajifo reach (Figure 6 (a) and 22.36 m/year occurred in 2011 in Alge reach (Figure 6 (c). The migration rate of Wajifo reach near the bridge site has become greater than the entire reach migration rate starting from the year 2013. As shown in Figure 6(b) and (d), the cumulative migrated area was also shown.

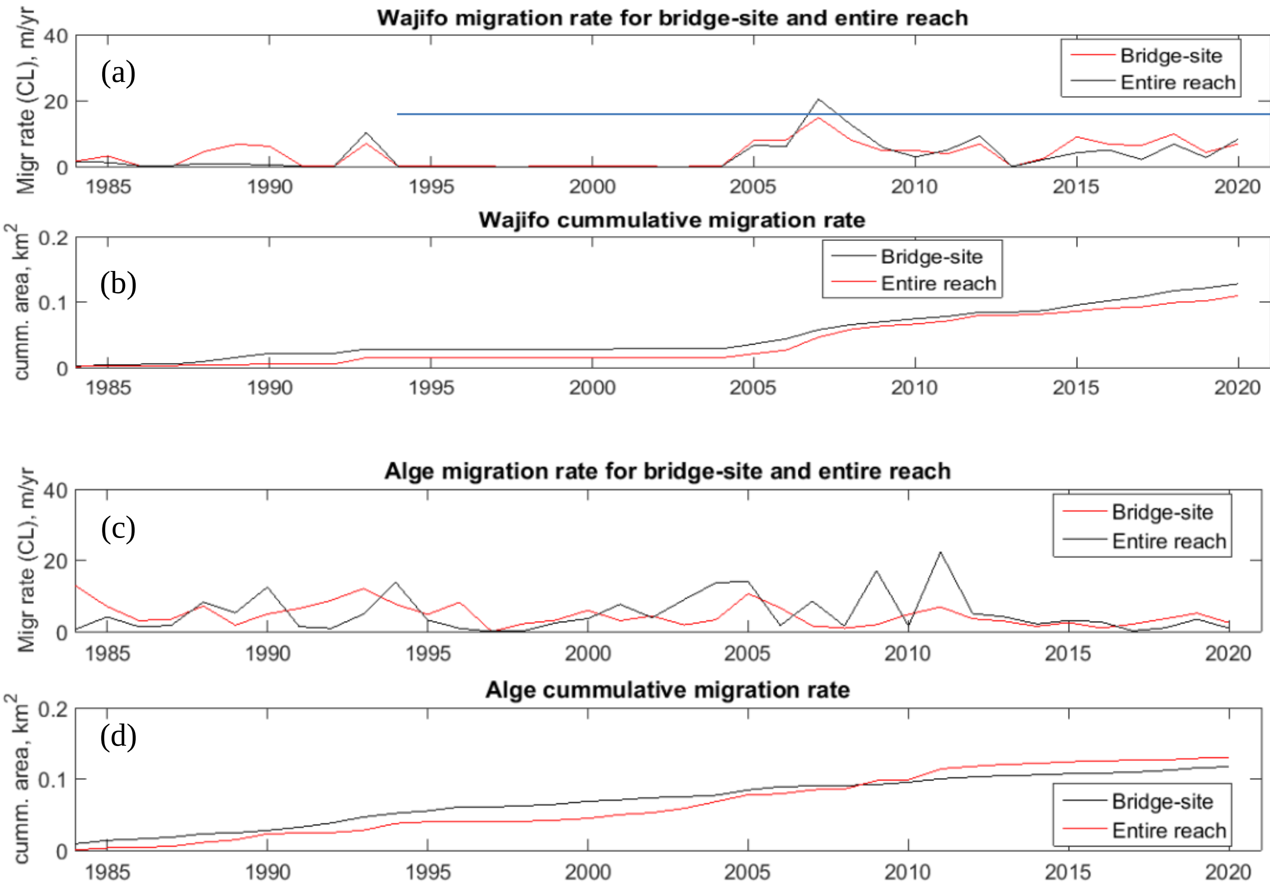

Figure 6. Wajifo and Alge migration rate including cumulative area

The maximum and average migration rates of the reach were plotted for the entire 38 years as shown in Figure 7 below. The result shows that Sego and Sile flow channels face relatively low center line lateral migration as compared to others. In the case of the Alge, Wajifo, and Kulfo rivers, the lateral shifting of the flow is relatively greater. The average migration rate near the Alge Bridge site is higher as compared to the rest of the selected sites.

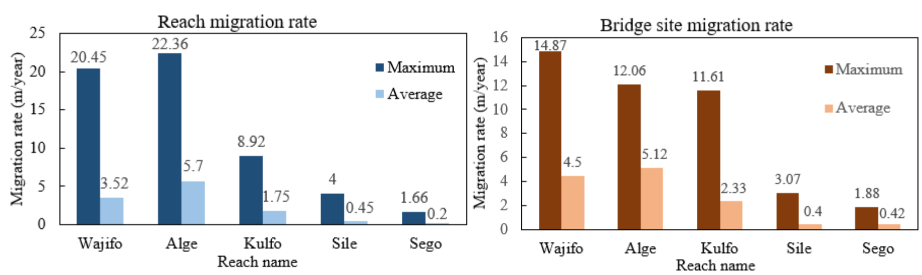

Figure 7. Maximum channel migration rates for river reach and near the bridge site

3.1.1 Contraction Scours at Selected Bridge Sites

Roughness coefficients were used in a range from 0.034 at Sile bridge site to 0.083 at Wajifo bridge site for the channel bed, as well as 0.10 Sego to 0.205 at Alge bridge site for the overbank floodplain.

The scour analysis has been conducted for a 50-year, 100-year, and 500-year flood event to evaluate the bridge foundation under a super-flood condition (USACE, 2016). The constriction of the valley due to the construction of the bridge aggravates the contraction scour potential with the incremental velocity induced by the rapidly varying flow at the crossing. Contraction scours in these reaches indicate how much bed material is already being transported from the upstream bridge zone of contraction. The result in Figure_8 below shows that the Sego Bridge faces relatively higher contraction scour depth for all flood events. This happened due to the extreme narrowing of the natural channel at the bridge site. Clear-water contraction scour occurs at the Sego bridge site, causing higher scour depth in the contracted section. This is due to the reason as documented(FHWA, 2012), the velocity, shear stress, and transport of sediment decrease in the upstream section of the bridge because of the rise in the backwater flux.

On this bridge site, the river banks near the bridge were narrowed by the gabion approach guide-banks projecting to the upstream channel and road embankments force the wide channel and over bank upstream flow to the main channel at the bridge (Figure 9). It is seen that the raising of the flow depth near the upstream face of the bridge is indirectly proportional to the bed slope of the channel, indicating narrowed natural flow (Figure_9 (a)). Kulfo and Wajifo bridges encounter smaller contraction scour depth due to the bridge spanning fully the entire floodplain for all events. In addition to this, Sile bridge contraction scour depth is relatively sensitive to the variation of the flow magnitude.

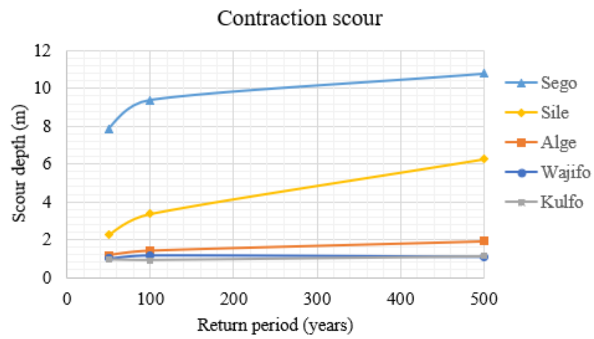

Figure 8. Contraction scour potential in the selected bridge sites

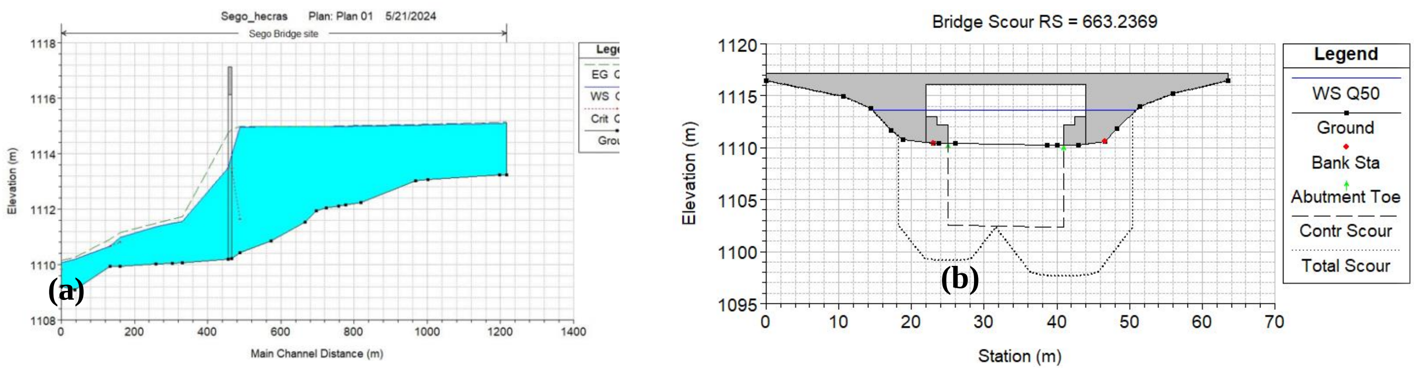

Figure 9. (a) Sego longitudinal flow profile (b) Scour prism

Regarding Sego Bridge, the channel width at the bridge site is about 20m, unlike the natural wide channel within the upstream distance to the bridge. This results in incremental contraction scour potential. The average approaching flow velocity at Sego, Alge, and Wajifo bridge sites are less than the scour critical velocities of the respective sites as shown in Figure_10 below, revealing clear-water scour. However, in Kulfo and Sile, the average approach velocity is greater than scour critical velocity resulting in live-bed contraction scour. It shows that there is appreciable bed material (sediment) movement in the approach section rather than on the bridge site of the Kulfo and Sile channels. (), the bed material transport in the uncontracted approach section is less than the carrying capacity of the flow in Alge, Sego, and Wajifo.

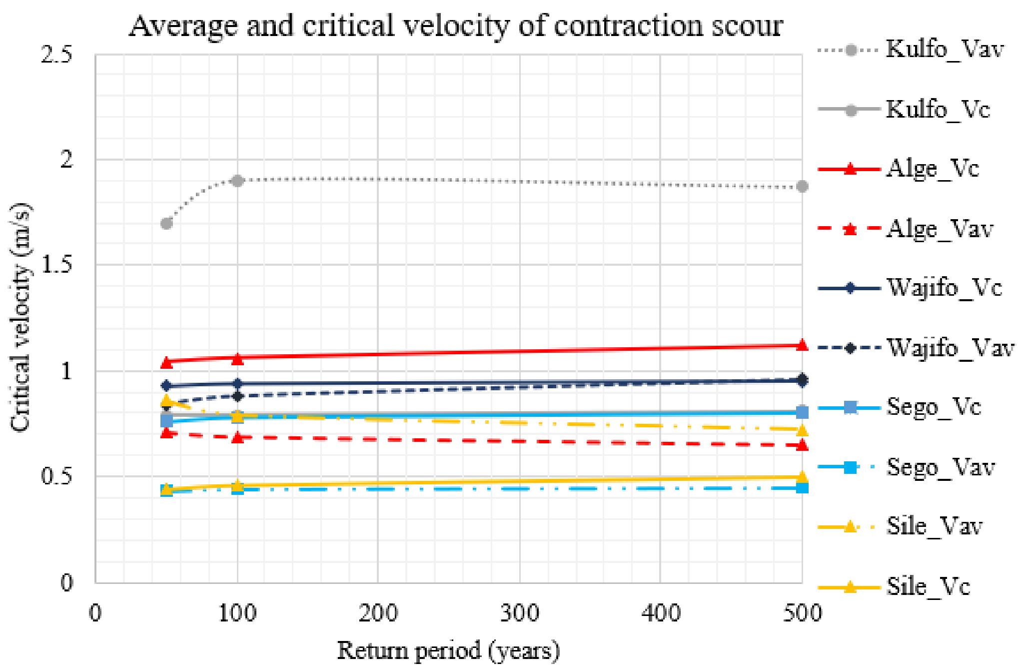

Figure 10. Plot of approach and scour critical velocity

3.1.2 Local scour conditions in the selected bridge sites

3.1.2.1 Pier scour potential

The local scour hole formed around the pier is the horseshoe type for all selected bridges having groups of circular cylinder shapes. During the pier scour analysis of the existing bridges, the CSU equation is recommended (USACE, 2016) and the Froehlich equation result from the HEC RAS model is mostly used to analyze new bridge scour analysis due to its higher scour depth, which is considered as a factor of safety. The result shown in Figure 11 below reveals that the pier scour depth of 50-, 100- and 500-year events of the selected bridges resulted from the Froehlich analysis are greater than the CSU equation analysis. Since all the bridges exist, CSU results are acceptable, and Froehlich equation outcomes are plotted only for comparison. Upper Kulfo bridge is experiencing higher pier scour depth (Figure 12 (a)) and Alge bridge has lower pier scour depth (Figure 12 (b)) in which bed aggradation is happening especially on the left bank of the structure.

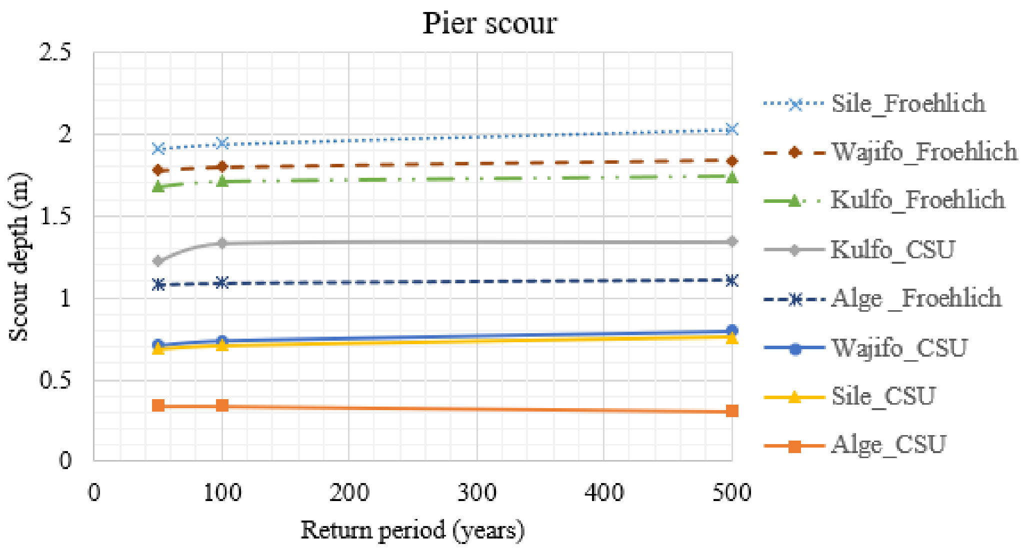

Figure 11. Local pier scour depth plots for the selected bridge sites

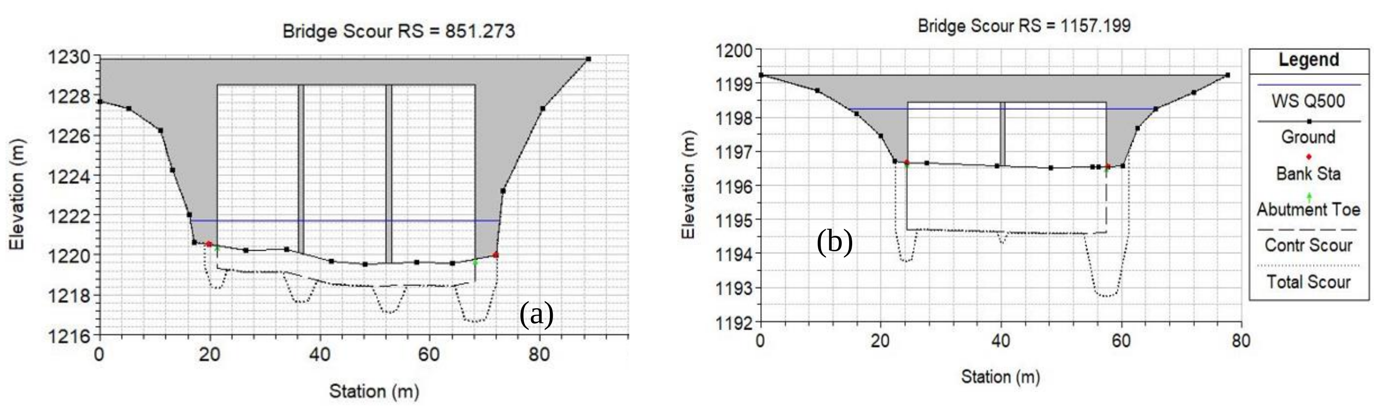

Figure 12. Scour plot for the 500-year event (a) Kulfo and (b) Alge

Concerning Wajifo bridge (Figure 13), pier scour is also dominant, especially within two middle spans due to the impact of a partially failed gabion check dam (Figure 3 (a)) resulting in flow complications upstream of the pier.

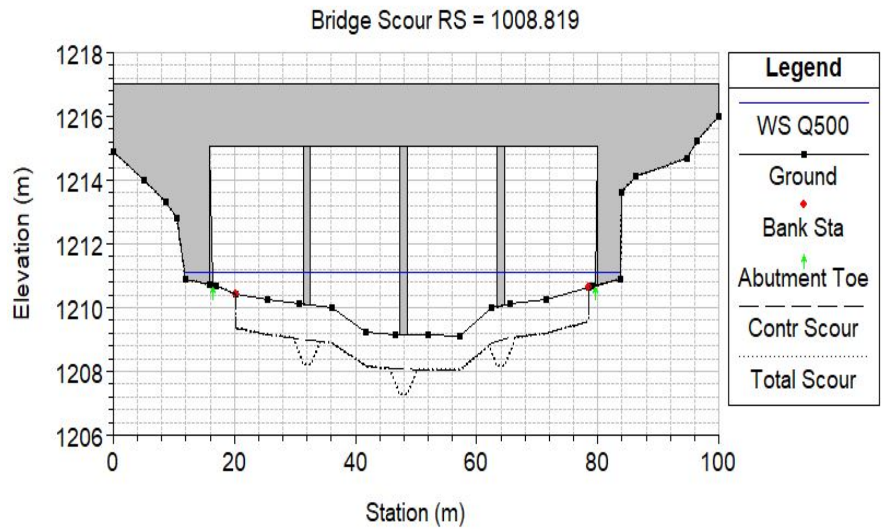

Figure 13. Wajifo scour plot for the 500-year event

3.1.2.2 Abutment scours

The local abutment scour results show that the Sile (Figure 15) bridges are facing higher scour depth because of large flood events and the Wajifo Bridge isn't affected by abutment scour (Figure 13) due to the large span bank to bank opening of 64m

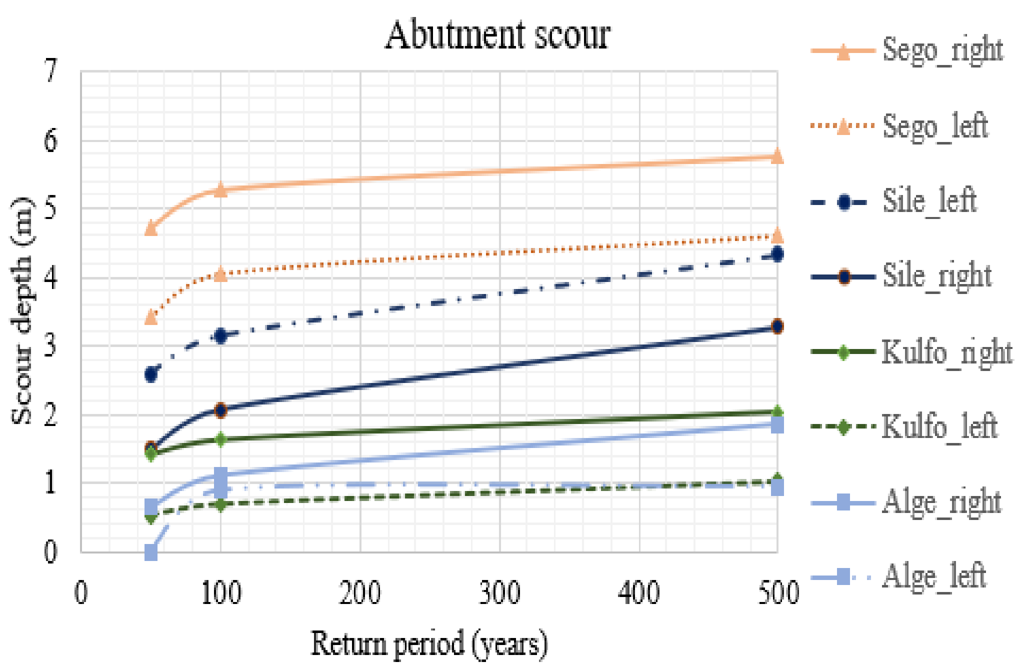

Figure 14. Local abutment scour plot for the selected bridge sites

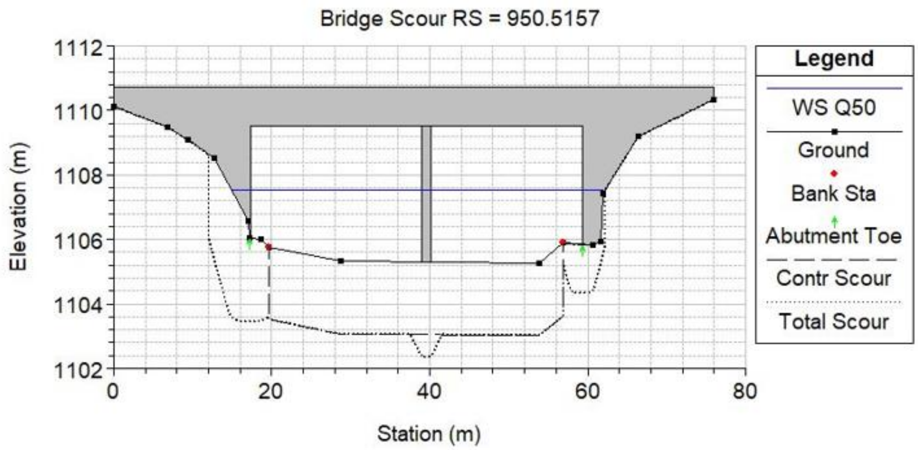

Figure 15. Scour plot result for Sile bridge site

In the case of Alge and Kulfo bridges, the right bank abutments are facing more scour holes (Figure 12). The flow on the Alge Bridge is confined to the right bank (span), hence the left one is clogged with drift accumulation and bed aggradation. Kulfo bed on the left side is used to divert flow to the field by modifying the natural bed and there is a small gap between the right abutment and the old artificially made right guide bank, resulting in vortex flow confined to the abutment.

3.1.3 Major hydraulic factors for the scour problem in the selected sites

The major hydraulic factors for the scour problems in the selected sites are related to both the bridge structural dimension (opening ratio) impact on the flow and the nature of the channel reach geomorphology. The bridge opening ratio (ratio of discharge passing through the bridge opening location before construction to the total flow confined within left up to right abutment after the bridge construction) influences most of the selected bridges. The opening ratio ranges from 0 to 1, representing extremely narrow flow constriction resulting in high afflux and contraction scour to the abutments constructed on the full width of the flood plain experiencing lower contraction scour depth. The minimum opening ratio shows that the natural flood plain is more narrowed (Figure 16). On Wajifo and Kulfo bridge sites, the original flood plain was not narrowed during the construction of the bridge, but in Sego the constriction is higher (minimum opening ratio), resulting in high afflux (Figure 9 (a)) and Sile (Figure 17 (a)) and Alge (Figure 17 (b)) also this factor impacts the flood plain. Even though the narrow opening of the bridge is economically viable, it induces high contraction scour.

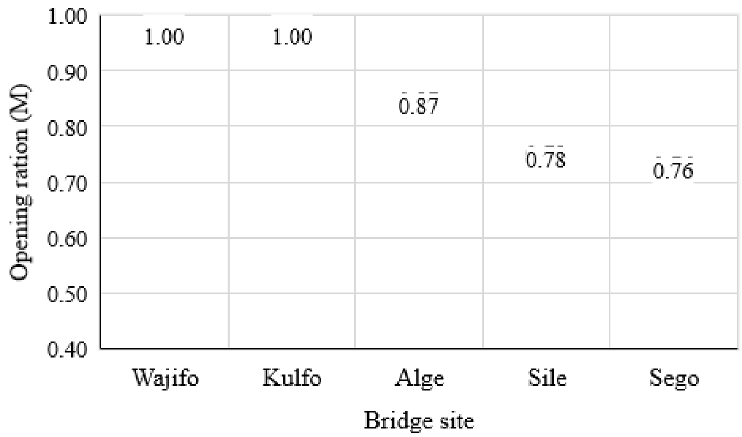

Figure 16. Bridge opening ratio for the selected sites

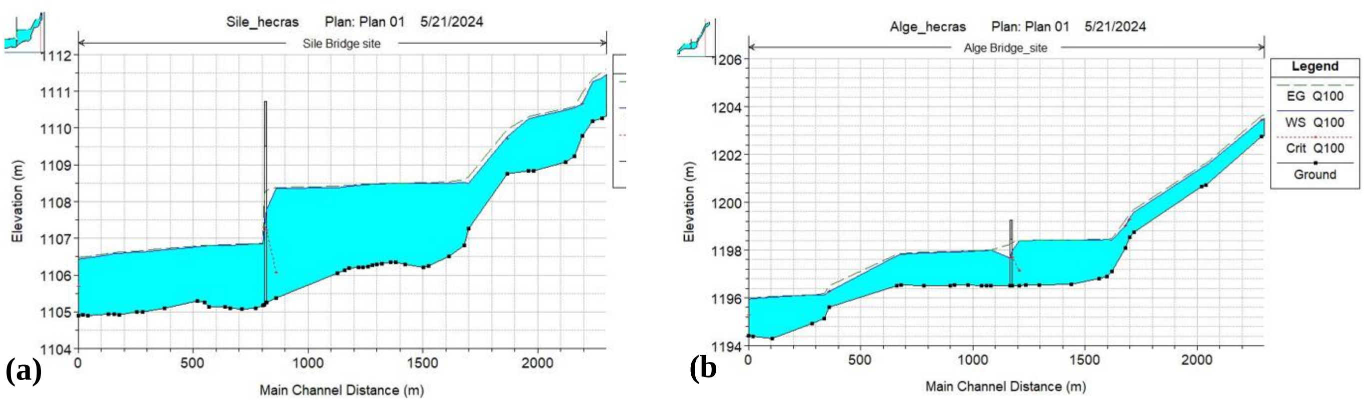

Figure 17. Flow depth variations due to the bridge opening ratio (a) Sile site (b) Alge site

Morphodynamics of the channel has also another impact on bridge scour evolution. Channel, reach migration rate (Figure 6 and 7) through time impose significant impacts to the scour process. All the selected bridges are located in the lower reaches of the channels with low and undefined banks confining the flow. Thus, it results in frequent lateral migration and widening of the channel through time. Lateral channel migration affects the channel, left and right over bank flow magnitudes, velocities, angle of attack, and flow depth.

3.1.4 Remedial alternatives for scour conditions

Prudent scour countermeasures for scouring critical bridges are based on both observed current scour susceptibility in bridge pier and/or abutment. The scour analysis evaluation results for the 100-year event indicate critical conditions that align with FHWA guidelines(FHWA, 2009).

The current field observation of the selected sites confirms the analysis results of the HEC RAS model. The current field status of the Kulfo, Wajifo, and Alge bridges shows that there are active local bed scour (Kulfo & Alge) and bank scour (Wajifo upstream right bank) conditions. However, the analysis results for high flood events revealed that there were low-risk bridges that could be mitigated by relatively minimal efforts. Wajifo Bridge was not affected by the abutment scour problem with all flood events, but local pier scour was developing in the middle span owing to the partial failure of the gabion check dam near the upstream face of the bridge. The bed gabion treatment was proposed in the original design of the bridge. Therefore, the maintenance of the bed according to the design would secure the vulnerability of the pier scour. However, the scour analysis result indicated low risk on the Alge bridge site. The right abutment scour was developing because of the flow confinement to the span and the drift accumulation of the wood and banana trees on the left span of the bridge blocking the flow.

In the case of New Sile bridge there was no current scour effect in the field, but for large flood events the scour effect was significant (scour critical). However, on the Sego bridge site, the current status showed that the banks near the bridge were protected by the gabion rock and masonry but the approaching upstream flood plain was facing active bank degradation and lateral widening. In addition to this, the long-term large flood event analysis indicated that the bridge's scouring was critical (Figure 18).

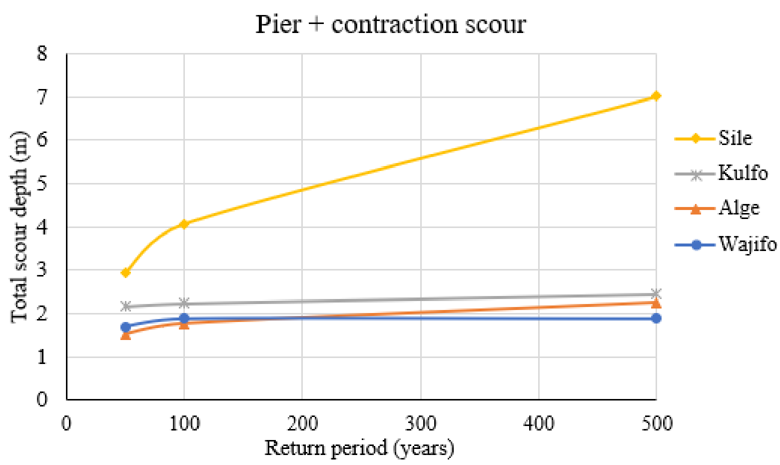

Figure 18. Total pier scour plot for selected bridge sites

As in Figure 18, Sile Bridge faced appreciable pier scour depth during large flood events, but for the rest of the sites the total pier scour depth varied between 1.51m for the Alge site during the 50-year return period and 2.45m for the Kulfo site during the 500-year return period.

The result of the total abutment scour depth (Figure 19) showed that both abutments of the Sego Bridge were highly scouring susceptible as compared to others. In the site of Sile, the left abutment was more susceptible to the migration tendency of the channel to the left bank in the downstream vicinity of the bridge. The right abutment of Alge Bridge was susceptible as the flow channel was confined to the right bank throughout time. The total scour depth obtained in this analysis could be interpreted as overestimated values rather than the actual values (Cooperative et al., 2006; Hong & Abid, 2015) due to the effect of scaling in analysis equations. The relative importance of the highway route was based on the ADT Significant factors influencing the frequency of inspection strategies in a plan of action(FHWA, 2009). In this connection, the relevance of the Sodo to the Konso-Jinka federal highway was not compromised. Therefore, the Sile and Sego bridges had critical scour, demanding timely, frequent scour inspection and monitoring.

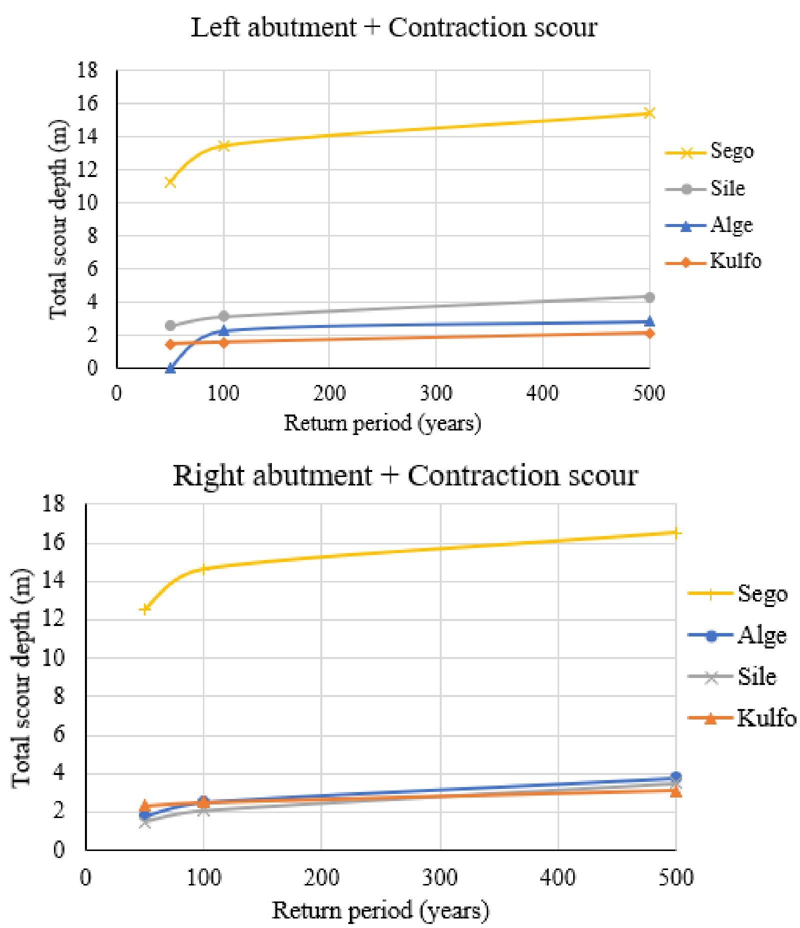

Figure 19. Total abutments scour at the selected sites

Retrofitting the scour countermeasures to stabilize existing scour susceptible bridges was good engineering practice in terms of economy and targeting the desired limitation on the useful life of the structure due to scour problems (FHWA, 2009).

3.1.4.1 Countermeasures proposed for contraction scour

According to the analysis, Sego Bridge was adversely affected by the contraction scour. In this case, a relief bridge or culvert near the left bank was alternatively needed to alleviate the contraction of the flow (Figure 20). Gabion check dam across the bed of the channel would prevent degradation of the bed.

Figure 20. Proposed relief bridge or culvert site at Sego

Sile Bridge was also suspected to have a high contraction scour potential next to the Sego site. Hence, the rock gabion check dam across the bed of the channel could reduce this effect in the Sile site.

3.1.4.2 Countermeasures for local scour problem

Effective countermeasures for local scour at bridge piers are essential to ensure the long-term stability and safety of bridge structures, particularly in alluvial rivers where sediment transport and channel dynamics are active. These countermeasures aim to either prevent excessive flow concentration around the pier or protect the foundation from erosion. Commonly adopted solutions include the installation of riprap or armor layers, guide vanes, collars, and scour-resistant footing designs, such as deep foundations or pile extensions below the maximum predicted scour depth. Additionally, geotextile mats, gabions, and encased rock aprons can be used to shield the bed from shear stress and flow turbulence. The selection of an appropriate countermeasure should be based on a detailed hydraulic analysis, site-specific flow conditions, sediment characteristics, and long-term channel stability assessments. Incorporating such protective measures not only mitigates scour risk but also extends the service life of the bridge and reduces maintenance and repair costs. Therefore, at the Sego bridge site, abutment scour is notably severe and can be effectively mitigated through the application of armoring techniques (Coleman, 2000), with rock gabion mesh identified as a particularly cost-effective solution. Moreover, to enhance flow alignment and reduce hydraulic stress near the bridges, the installation of guide banks is recommended at the Sego, Sile, Alge, and Wajifo bridge locations

4. CONCLUSION

Bridge scour analysis was conducted at 5 selected bridge sites in the HEC RAS hydrodynamic model in addition to the 38-year morphodynamic analysis of the reach geomorphology from landsat images to identify scour critical bridges for high flood events. The scour analysis results were interpreted comparatively with the observed site conditions. The main findings of the comparative analysis indicated that the reach spatial and temporal morphodynamic change of the bridge sites showed lateral widening of the floodplain. The river channels were becoming wider near upstream and downstream of the bridge through time. In addition to this, there were active sediment bars and channel bank modifications, especially near the upstream floodplain of the Wajifo, Alge, and Sego bridge sites. Scour analysis for high flood events showed that the contraction scour potential was dominant at the Sego, Sile, and Alge bridges. This was mainly due to the narrow opening of the bridge in contradiction to the upstream channel widening from time to time. Local scouring of piers and abutments had effect on the safety of these bridges. Sego and Sile bridges were highly suspicious of the local scour for high flood events. These two bridges needed timely, frequent monitoring systems and remedial countermeasures. On the other hand, the Wajifo, Alge, and Kulfo bridges were less suspicious of the effect. Thus, a detailed geomorphological understanding of the channel reach was an important aspect to understand the evolution of the floodplain and provision of the bridge opening ratio in addition to the geotechnical, hydraulic, and structural analysis.

Author contributions:

Aklilu Alemayehu Kassaye: contributed to project administration, methodology, investigation, conceptualization, formal analysis, validation, supervision, resource management, and both original drafting and reviewing/editing of the manuscript.

Mesele Markos Forsido: contributed to the project by writing the original draft, validating the results, developing software, designing the methodology, performing formal analysis, curating data, and conceptualizing the study.

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Declaration

We here submitted the manuscript entitled "Morphodynamic Alterations and Scour Processes around Bridge Openings: A Case Study of Selected Bridges on the Sodo-Konso Highway, Ethiopia" to be considered for publication. We declare that this is our original research work.

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