Lake Level Fluctuation Impact on River Morphology Change

Sisay Mengistie Eshetie[1(✉)] and Mengistie Abate Meshesha[2]

[1] School of Civil and Water Resources Engineering, Woldia Institute of Technology, Woldia, Ethiopia
[2] Faculty Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar, Ethiopia

Abstract. In the recent time Ribb River is under immense morphological change due to various natural, planned and unplanned anthropogenic activities such as, lake level regulation for hydropower production, embanking, sand mining, and water extraction. In the present time, Lake Tana level is raised (kept fairly constant) after the Chara-Chara weir construction and Belese Hydropower operation. These will strongly alter both River regime water and sediment discharge to downstream reach and causing morphology adjustment. Hence, this study assessed Lake level fluctuation impact on River morphological change on Ribb River, Lake Tana Basin, Ethiopia for about 20 km. The objectives of this study were to assess lake level impact on river cross-sections of Ribb River and investigate back water extension length and its consequent for River training structures. Primary data (River cross-sections, dyke dimensions and grain sizes) were collected through, surveying using standard measuring equipment's (total station, GPS) and laboratory analysis. Secondary data (stream flow, Lake level, sediment, rainfall and climatic) were also collected from MoWRIE. For data preparation and analysis, Arc GIS and HEC-RAS were used. River bed change has been studied from 2005 to 2014 period and the result show that the reach exhibit both aggradation and degradation. The study reach is affected by back water for about 1.5 km length and this back water effect caused an average annual rate of 0.22 m deposition.

Keywords: Lake Tana · River morphology · Ribb River · HEC-RAS model

1 Introduction

Rivers play most important role in terrestrial and aquatic ecosystem (Kamboj et al. 2017). However, in the recent time alluvial rivers are under immense pressure change due to various kinds of natural, planned and unplanned anthropogenic disturbances (Kamboj et al. 2017). Alluvial rivers in nature adjust their slope, planform and pattern to recover its former equilibrium. Regime rivers are always change their dimensions to response sediment and discharge change due to human and natural influence (Hekal 2018).

Hence, understanding the current, past and future morphological trend and river dynamic is the key role to identify human induced factor and on-going climate changes on the function of rivers. Acquiring this knowledge is the first steps for unscientific

M. L. Berihun (Ed.): ICAST 2021, LNICST 412, pp. 99–111, 2022.
https://doi.org/10.1007/978-3-030-93712-6_7

human activity monitoring and undertake mitigation measures. Ribb River is one of the components of the Blue Nile River system that depict morph dynamic changes due to planned and unplanned human disturbances (SMEC 2008). For long time, the river has been subject to human disturbance like, water diversion, sand mining, trenching and irrigation water in dry season (Mulatu et al. 2018). In addition, back water effect from Lake, after Chara-Chara weir construction has main causes of morphology change and flooding problem in the recent time (Abate et al. 2015).

Flooding problem in lower reach caused loss of human lives, displaced from their homes, swept agricultural lands and adversely affect health centers, schools and hydraulic structure (SMEC 2008). In 2006 E.C. 43,140 people were faced flooding problem and 8,730 displaced from their living home due to channel shifting and flooding (Abera 2011). These damages are mainly caused due to Lake level increment at lake shore when flood coincide with high lake level, sediment supply from breach dyke and insufficient channel flood carrying capacity. Hence, the general objective of this study is to assess Lake level fluctuation impact on morphology change, analyze response of river sedimentation, and change of flow regime on Ribb River, Lake Tana basin.

2 Materials and Method

2.1 Description of Study Area

Ribb catchment is located within Lake Tana basin in Ethiopia (Fig. 1). The river rises from high Ethiopian plateau Guna Mountain and travels 130 km northwestern direction and debouches into Lake Tana at elevation of 1787 m amsl. The river catchment covers 1865 km^2 area and extends 4130 m altitude to 1784.5 m amsl. The average annual maximum temperature in the upper part of Ribb River basin is 27 °C while the minimum falls below 0 °C in December. For long time the river influenced by (sand mining, irrigation, trenching, damming). However, back water extension length from Lake and its consequences along river were not investigated.

The river drains from the western slope of high mountainous area Town of Debre Tabor to very flat to Lake Tana (Abera 2011). In the lower reach of the river, especially near to Lake Tana channel have very flat slope and sediment loading discharge flows slowly that causes sediment deposition and bank over flow (SMEC 2008). The catchment is characterized broad and very flat flood plains, old bench forming terrace and low to high relief basaltic hills with steep to flat slopes (SMEC 2008). The upper catchment is characterized by mountainous wedge-shaped and steep-slope greater than (3.6%) and lower reach near to Lake is characterized by flat slope less than (1%) due to back water effect and channel deposition (Mulatu et al. 2018).

The Ribb catchment have high rainy season from June to September around 1300 mm mean annual rain fall at Adiss Zemen metrological station. In rainy months maximum temperature falls below (22 °C), wind speed (1.2 m/s), and sunshine hours (4.2 h) are low as compared to dry month and relative humidity is high reaching about 80% in the rainy months.

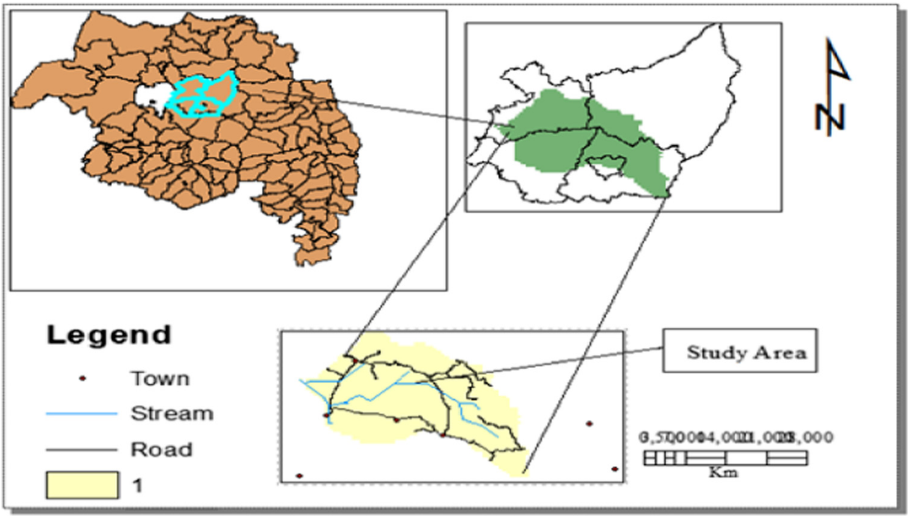

Fig. 1. Location of study Area

2.2 Data Formatting and Preparation

In the study reach more than 118 river cross-sections survey data were collected and laid out normal to the direction of flow at specified interval measured along the center line of the main channel. Mainly cross-section data were collected where, discharge, slope, shape, roughness, and where levees begin and end (Lumpur 2010). These survey data was collected as reference point on left side of the river and with increasing towards right looking down stream and an elevation of point in meter (Fig. 2). To assess water surface profile with and without dyke, 0.33 to 3.4 m height and 3 m set back distance dyke dimensions were collected. These dyke dimensions were fixed after 100-year return period design discharge computed (217 m^3/s). Even if representative samples of river bank material are difficult (van Rijn 1984), six representative river bank and bed samples has been implemented at Bahir Dar soil laboratory (Fig. 5). Other Secondary (stream flow, Lake level, sediment, and rainfall) data were also collected from MoWRIE Office (Table 1).

HEC-RAS has the capability of drawing the spatial plot for many hydraulic characteristics like; sediment transport either quasi-unsteady or unsteady flow, Water surface elevation, shear stress (U.S. Army Corps of Engineers 2016). Quasi-unsteady hydraulic analysis is only used to sediment computation by assumes approximate continuous hydrograph (histograms) with series of discrete steady flow profiles (U.S. Army Corps of Engineers 2016).

Sediment transport in quasi-unsteady flow type is non–linearity and irregular time step. It is desirable by approximating low flow for larger durations and high for relatively short durations (U.S. Army Corps of Engineers 2016). HEC-RAS includes several quasi-unsteady downstream boundary conditions, but only one upstream quasi-unsteady boundary. Therefore, 32-year selected annual record discharge is discretized

Fig. 2. Cross-section survey (January 2021)

Table 1. Summary of primary and secondary input data and their sources

Data Type	Data period	Sources	Purpose
River cross-section	April, 2020	From Field survey	Input for HEC-RAS model
Sediment data	January, 2021	From study reach	To understand bed gradation
Geological map	–	MoWRIE	Study area with soil, sand formation
DEM model	–	Office/institutions	For study area delineation
Streamflow (m^3/s)	2005–2014	MoWRIE	Used for u/s boundary condition
Lake Tana level (m)	2005–2014	MoWRIE	Used for d/s boundary condition
Sediment flow data	1990–2010	MoWRIE	Input for quasi-Unsteady flow

in continues hydrograph with series discrete (histograms) in rectangular shaped for upstream boundary conditions.

From 32-year recorded stream flow data (2005–2014) maximum monthly flow data were used to upstream boundary condition for this study (Fig. 3). In the other hand, HEC-RAS includes three options for setting quasi-unsteady downstream boundary conditions such as, stage time series, rating curve, or normal depth. Since study deals about back water extension length and its effect stage time Series was selected for downstream boundary condition (Fig. 6).

Sediment transport is process interrelating erosion and deposition for natural stream channels. When the rate of upstream sediment supplies higher than stream's sediment transport capacity, stream bed will start to aggrade at the rate defined by the difference between the rate of sediment supply and sediment transport rate of the stream (Bekić et al. 2015). However, if a stream's sediment transport capacity exceeds the rate of sediment supply from upstream, the balance sediment load has to come from channel itself. These two condition causses morphological unbalance between aggradation and degradation along river reach (Hekal 2018). Sediment transport from given set of steady-state hydraulic parameters and sediment properties are predicted using sediment continuity Exner equation (Eq. 1). Erosion and deposition of sediment by Exner equation translates differencing between inflow and out flow load in to bed change, eroding (degradation) or deposition (aggradation) of channel. This equation written as shown below;

$$(1-\lambda p)B*\frac{\partial \eta}{\partial t}=-\frac{\partial Qs}{\partial x} \tag{1}$$

where; B, channel width, η, channel bed elevation, x, distance of control volume, Qs, Transport sediment load, p, active layer porosity, T, Time. From Eq. (1) above, left hand side shows change in sediment volume and right hand shows the difference between inflow sediment and outflow sediment load. The equation used to calculate transport capacities for each cross section in downstream direction. If flow capacity greater than supply, the model satisfies its deficit by eroding from the bed and if supply exceeds than flow capacity the model can deposits surplus sediment (U.S. Army Corps of Engineers 2016).

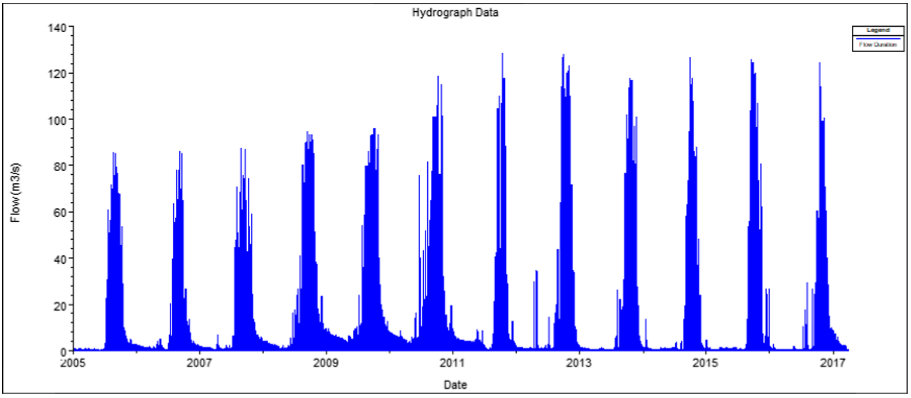

Fig. 3. Quasi-unsteady flow series for upstream boundary conditions (2005–2017).

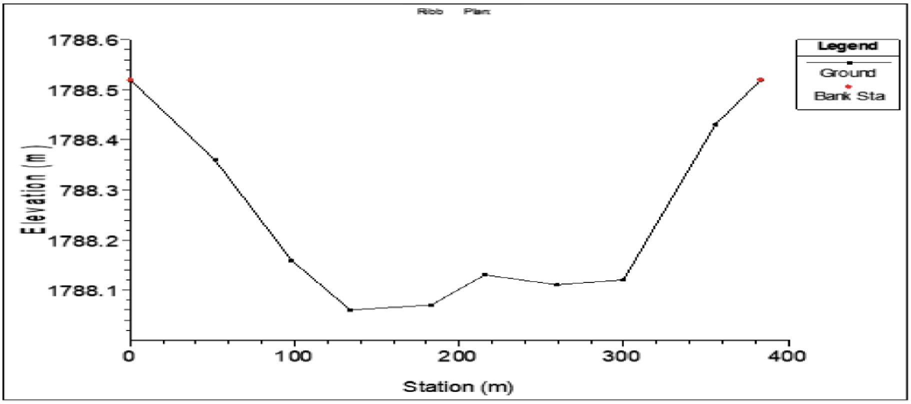

Fig. 4. Cross section. (Station - 35) without proposed dyke

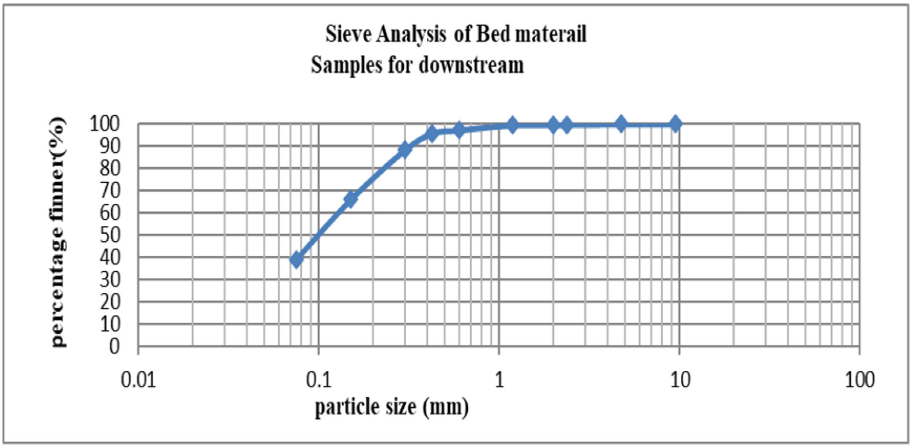

Fig. 5. The grain size distribution (January, 2021)

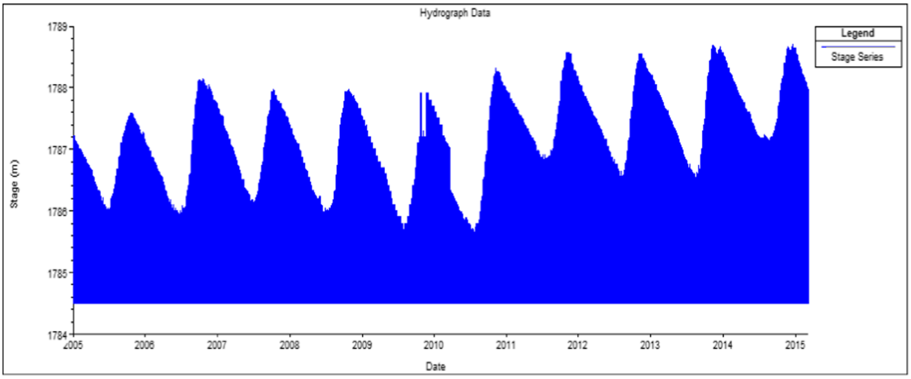

Fig. 6. Lake stage-time series data for downstream boundary conditions (2005–2015)

3 Results

3.1 One Dimensional Steady Flow Analysis

Water surface profile computation for different return period discharge is essential for flood plain management, flood insurance and channel modification studies (U.S Army Crop of Engineers 2016). In recent time in lower Ribb River reach close to Lake Tana crop yields and human lives are under risk every summer season. This is mainly caused by Lake back water due to lake level raising after artificial weir constructing and several human interventions. Hence, the study assessed back water extension length, channel carrying capacity, water surface increment and dyke carrying capacity for 100-year return period discharge using HEC-RAS model.

For one dimensional steady flow analysis the model was simulated with and without considering dyke dimension. From simulation result for 10, 50 and 100-year return period discharge, averagely the channel cannot convey for 100-year return period design discharge safely and flood raises about 1.5 m height above normal flood plain (Fig. 7). On contrary (Fig. 8) right bank side may accommodate forecasted flood with planned dyke dimensions, because terrain situated at relatively higher elevation on the right side of flood. Generally flooding problem in lower Ribb reach is mainly caused insufficient channel carrying capacity due to channel aggradation and degradation, because alluvial rivers are self-regulatory. They change their longitudinal bed slope, flow velocity and sediment settling velocity due to external human disturbances.

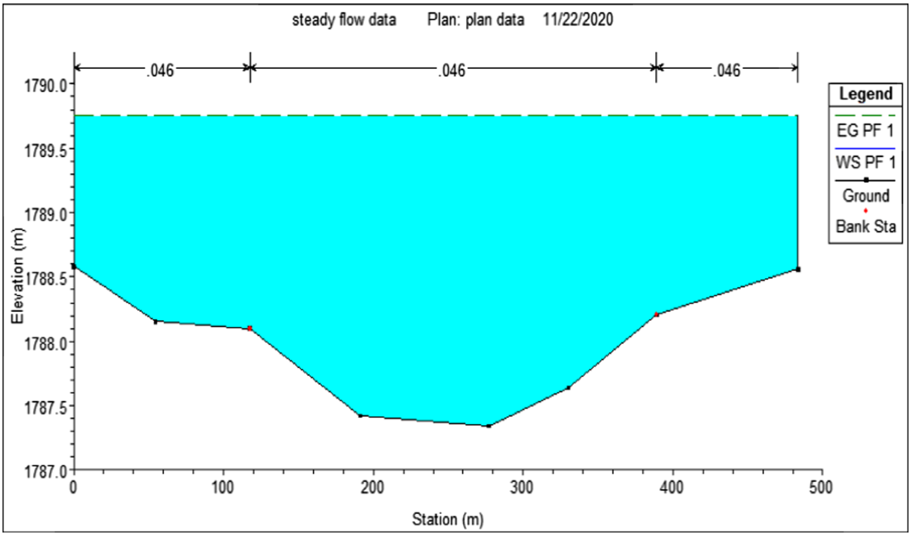

Fig. 7. Plot of inundate cross-section at river station-35 without proposed dyke.

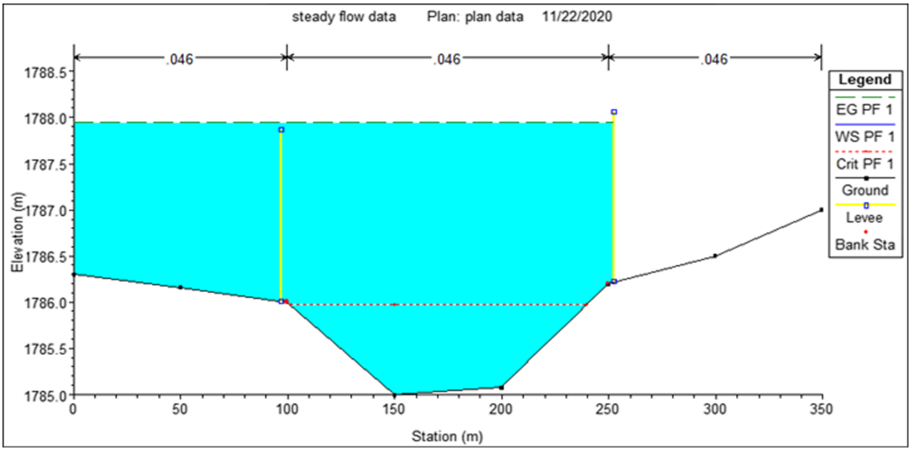

Fig. 8. Plot of inundate cross-section study reach at river station-35 with proposed dyke

3.2 Back Water Profile Computation

The term backwater expresses long water surface profile from obstructions like, Reservoirs, Lakes, Sea, Dams, weir and Flume. This phenomenon is occurred when the normal natural flow goes from mild to milder slope (Chow 1959). It is common in lower Ribb River reach mouth join to Lake Tana after lake level regulation that caused longitudinal slope reduction and settling velocity increment. The back water extension length for this study was assessed after some year Lake Level and channel normal flow depth computation. The average Lake depth was computed by deduct average Lake bed elevation (1784.5 m amsl) to 100-year computed Lake level flood (1788.2 m amsl) which is 3.7 m and normal depth was obtained using manning equation which is (3 m). From calculation there is 0.7 m elevation difference in between Lake Level and normal river flow depth.

This elevation difference makes the Lake push the river towards up for about 1.5 km extension length (Fig. 9) until the river attains its normal depth. The elevation difference between Lake and stream creates wave celerity that pushes the river toward up and additional flood. These mainly caused river morphology change, insufficient sediment carrying capacity, bed slope reduction, channel aggradation and increasing sediment settling velocity.

Sediment transport functions were developing under different conditions, wide range can be expected from one function to others (U.S Army Crop of Engineers 2016). Some functions computed suspended load, bed load and others computed total load. For the study, power-law equation (discharge versus suspended sediment data) was prepared using both discharge and sediment recorded data at gauge station. Sediment-rating curve is relation between sediment load and river discharges which used to compute total sediment load. Such relationship is usually established by regression analysis, and the curves are generally expressed in the form of power-law type

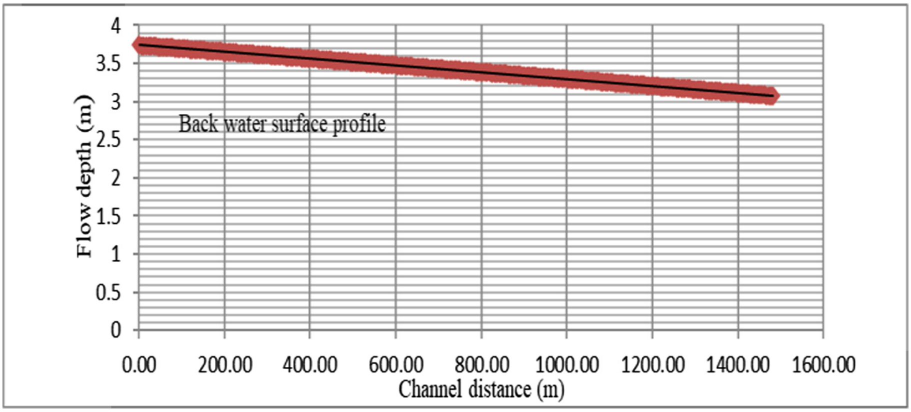

Fig. 9. Back water surface profiles near Ribb River mouth joining Lake Tana

Table 2. Maximum aggradation and degradation results

Sediment formulae	Study reach length	Simulation period (year)	Maximum aggradation (m)	Maximum degradation (m)
Engelund-Hansen	20	2005–2014	0.25	0.1
Yang	20	2005–2014	0.25	0.1
Wilcock-Crowe	20	2005–2014	0.21	0.1

equation. In sand-bed streams like, Ribb river with high transport rate, it is common for the suspended load to be orders of magnitude higher than in gravel-cobbled streams (Hekal 2018). Hence, from soil lab and power-law equation results (Engelund-Hansen, Yang and Wilcock-Crowe) transport formulae were appropriate with field as shown the result (Table 2).

Regarding to secondary and primary data results, the model was tested by three adopted sediment transport functions i.e., Engelund–Hansen, Yang and Wilcock-Crowe. The model runs for the existing conditions after calibration was achieved using 5-year recorded data from (2009–2014) and. From analysis the simulation result shows that the river reach exhibit both aggradations and degradation along study reach for three common transport functions (Table 2). The transport formulae were selected based on channel bed particle median size specification (D50) < 0.075 mm and total sediment load calculation. From (Table 2) Wilcock-Crowe transport shows maximum aggradation and degradation result than other functions. The main reason is that Wilcock-Crowe computes the influence of gravel and coble sand bed with hiding functions. However, Ribb River reach is not influenced by gravel and coble, rather it is dominated by fine sand and these results, high quantity degradation on some sections and aggradation on other sections resulting by Wilcock-Crowe equation. Generally, from three sediment transport result, the lower reach of the river is highly aggraded due to backwater effect and upstream sediment supply by dyke breaching that contribute additional sediment load for channel. For model calibration and validation, the optimum manning coefficient is 0.047 for main and river banks. Engelund-Hansen shows good agreement with measured documents with minimum RMSE (0.507).

4 Discussions

4.1 River Response to Lake Back Water Effect

The major observed bed change on river system was simulated from 2005–2014 channel avulsions for 20 km reach length in between Lake and main Bahir Dar-Gondar Bridge. The effect of lake level increment to the study reach was assessed using HEC-RAS model simulation and direct step iteration computation method. The contribution of Lake Tana level regulation is caused the River course variation and Lake rise from river mouth join to Lake for 100-year frequency analysis. The result indicates Lake propagates for about 1.5 km length until reach achieves its normal depth. This back water flow effect leads the river excess aggradation in some cross-section and degradation on other cross-section along the study reach.

These agradation and degrardation may cause many environmental problems such as, River course change, flooding and hydraulic structure damage. The simulated analysis shows that 0.7 m lake level increment have caused 0.25 m, 0.21 m and 0.33 m average River bed deosition for Engelund-Hansen, Yang and Wilcock-Crowe sediment

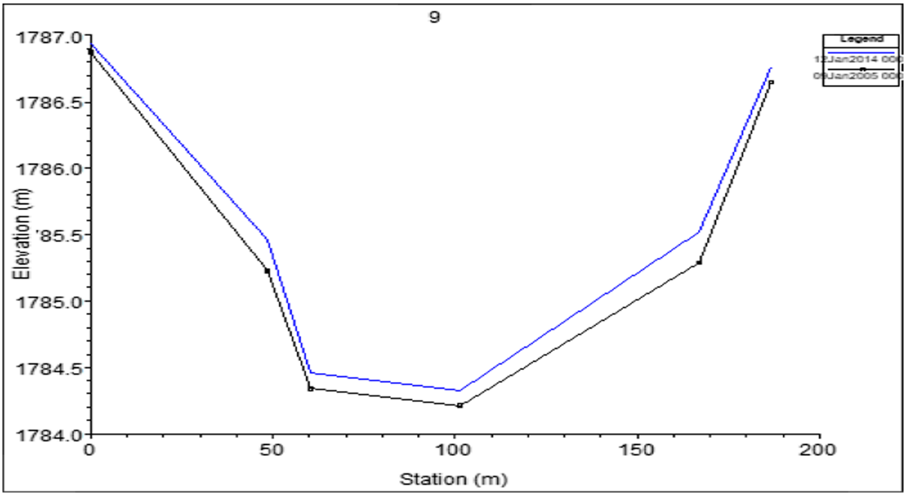

Fig. 10. Bed change plot for 10-year simulation period according to Engelund-Hansen

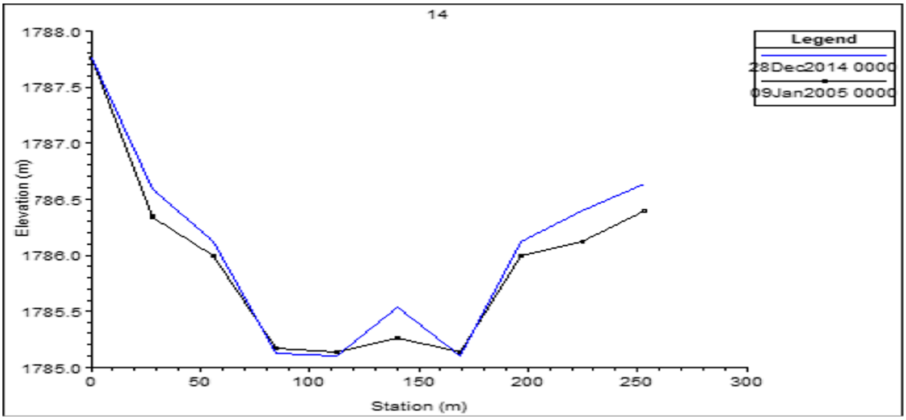

Fig. 11. Bed change plot for 10-year simulation period according to Wilcock-Crowe

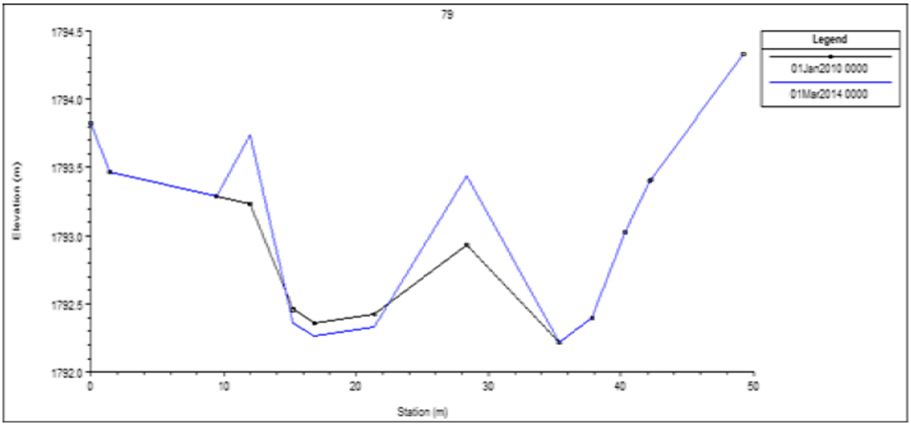

Fig. 12. Bed change plot for 10-year simulation period according to Yang

transport formulae respectively. This means that lake level regulation has direct contributed to the closure of the old channel which leads to channel shifting and severe flooding problem resulting by Wilcock-Crowe equation. Generally, from three sediment transport simulation result, lower reach the river is highly aggraded due to backwater effect and dyke breaching that contribute additional sediment load for channel. The optimum manning coefficient is 0.047 for both main channel and River banks. Engelund-Hansen shows good agreement with measured documents with minimum RMSE (0.507).

4.2 Effect of Dyke Construction on Channel Aggradation

The additional observed factor of river bed aggradation has been caused by upstream sediment supply and dyke failure in middle reach. In 2014, river training flood protection dyke was constructed more than 17 km between Lake and main bridge reach length with the aim of confining river water during high flood due to artificial Lake level rising (ADSWE 2019). However, due to design limitation, the dyke was failed before its design period. For study, one dimensional steady water surface profile analysis was simulated using HEC-RAS model for 10, 50 and 100-year return period discharge with and without planned dyke dimensions. From simulation results for 100-year return period discharge the channel cannot enough to convey without bank overflow for all cross-sections and the flood raises about 1.5 m height above normal flow depth for some stations. And extends more than 200 m both sides. Therefore, dyke height or set back distance increment is the main options to resist incoming flood from back water and surrounding flood.

5 Conclusion

This study investigates Lake level fluctuation impact on river morphology change of Ribb River. The main task is analyzing steady water surface profile, vertical bed level change and Lake back water extensions length determination using HEC-RAS model with and without considering planned dyke dimensions. From simulation result for 100-years return period discharge channel cannot convey without bank overflow and rises about 1.5 m height above normal flow depth, In addition the flood extended more than 200 m for 100-year return period discharge. This insufficient channel capacity is resulting due to Lake Level rising after artificial Chara-Chara weir construction and upstream sediment supply. The back water extendes for about 1.5Km length starting from river mouth join to the Lake until the river achieves its normal depth.. This extension length was computed using HEC-RAS model and direct step iteration method. Due to this back water effect, the reach exibits 0.22m depostion and 0.1m erosion in the lower and uper reach for 10-year simulation period for the study reach. These depostion and erosion mainly due to sediment migration from dyke slid, longitudinal bed slope reduction and sediment settling incensement.

Acknowledgments. I would like to thanks Amahara design work and supervision enterprise for total station equipment support for survey data collection, Ministry of Water, Irrigation and Electricity for supplying secondary data. Finally, would like to thanks international conference on advancements of science and technology (EAI ICAST, 2021) and springer publisher.

References

Abate, M., et al.: Morpho-logical changes of Gumara River channel over 50 years, upper Blue Nile basin, Ethiopia. J. Hydrol. **525**, 152–164 (2015)

Abera, Z.: Flood mapping and modeling on Fogera flood plain. Addiss Ababa (2011)

ADSWE: Feasibility study & detail design of lower Ribb river flood mitigation and community resilience project (dyke, suspension bridge and water control gates) (2019)

Bekić, D., Mikoš, M., Oskoruš, D.: To-wards practical guidance for sustainable sediment management using the Sava river basin as a showcase establishment of the sediment monitoring system for the Sava river basin (2015). (Issue November)

Chow: Poen channel hydraulic, in development of uniform flow and its formula, pp. 89–101. McGraw (1959)

Hekal, N.: Evaluation of the equilibrium of the River Nile morphological changes throughout "Assuit-Delta Barrages" reach. Water Sci. **32**(2), 230–240 (2018)

Kamboj, V., Kamboj, N., Sharma, S.: Environmental impact of river bed mining- a review. Int. J. Econ. Environ. **7**(1), 504–520 (2017)

Lumpur, K.: Ministry of natural resources and environment department of irrigation and drainage Malaysia (2010). (Issue August)

Mulatu, C.A., Crosato, A., Moges, M.M., Id, E.J.L., Mcclain, M.: Morpho dynamic trends of the Ribb river, Ethiopia, Prior to Dam Construction (2018)

Sewnet, A.: Water level fluctuations of lake Tana and its implication on local communities' livelihood, northwestern Ethiopia. J. River Basin Manage. **18**, 503–510 (2019)

Snowy Mountains Engineering Corporation (SMEC): Hydrological study of the tana-beles sub-basin: surface water investigation, January 2008

U.S Army Crop of Engineers: HEC-RAS river analysis system user's manual version 5.0 February 2016, institute of water resources engineering center. In Army Crop of Engineers, pp. 12–25 (2016)

Van Rijn, L.C.: Sediment transport, part III: bed forms. J. Hydraul. Eng. **110**(12), 1733–1754 (1984). In two companion papers (see Ref. [37])