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Filling streamflow data gaps through the construction of rating curves in the Lake Tana sub-basin, Nile basin

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ABSTRACT

In the past decade, streamflow data remain inaccessible for most river gauges in Ethiopia due to a lack of updated stage–discharge relationships, also called rating curves. In this study, researchers and hydrologic technicians collaborated to fill the recent streamflow data gaps at three gauging stations in the Lake Tana sub-basin of the Nile River. We conducted extensive field campaigns to improve the coverage of stage–discharge measurements for rating curve development. We evaluated the rating curve uncertainty during the time of its establishment and the sensitivity of the rating curves to sample size. The stage–discharge measurements conducted by the hydrological agency during the period 2016–2020 were found inadequate in number and coverage to establish reliable rating curves. Hence, converting recent water level measurements to discharge data was made possible using the rating curves developed in this study. The converted discharge data will be accessible to researchers to investigate the sub-basin's hydrology. Our study emphasizes the need to improve the stage–discharge measurement frequency to keep up with frequent changes in the morphology of the rivers' channels. The study demonstrated that collaboration between the data provider and data users can improve streamflow data availability and accessibility, which has become an increasing global challenge.

Key words: Ethiopia, Lake Tana, monitoring, rating curve, streamflow

HIGHLIGHTS

- The hydrology agency would benefit from revising its strategy and practice of stage–discharge measurement.
- Data users' willingness to share the burden of data collection by hydrologic agencies has immense value in streamflow data availability for the study of water and climate change.
- Cross-validation was applied to evaluate the adequacy of stage–discharge data for rating curve establishment.

1. INTRODUCTION

A rating curve, or stage–discharge relationship, is one of the most important relationships in hydrology since it is used to generate discharge time series from readily available stage (river water level) measurements. Despite its importance, a rating curve is prone to multiple sources of errors that are introduced (i) at the time of the rating curve establishment which is called initial errors or uncertainties and (ii) after the establishment of the curve, also called temporal errors. The errors at the time of rating curve establishment can be caused by imperfection of the selected rating curve equation, the uncertainty of velocity and stage measurement, and the uncertainty in the estimation of the parameters' values (Jalbert *et al.* 2011). The causes of temporal errors are erosion and sediment deposition or vegetation growth that modify the morphology of the river channel and affect the stage–discharge relationship.

The study by Fortesa *et al.* (2019) revealed that the largest source of uncertainty in discharge monitoring was the stage–discharge rating curve. The authors reported that the discharge monitoring uncertainty ranges from 28 to 274% for the analog (manual) gauges and from 17 to 37% for the digital (automatic) river gauges. The root causes of the monitoring uncertainty include using the steady-flow rating curve during significant flood waves, and the extrapolation of the rating curve beyond the

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range of measurements that were used to develop it (Di Baldassarre & Montanari 2009). McMahon & peel (2019) reported that 30% of the published streamflow volumes for their study areas in Australia were based on extrapolated rating curves that introduced large errors in discharge estimation. They also indicated that the errors in the measurement of water level were less than ±10 mm and occasionally reached 100 mm. These stage errors are small compared to discharge measurement errors.

The temporal errors, which are introduced after the rating curve establishment, can increase over time raising the need to regularly update the rating curve. The rating curves can have large temporal errors if the gauging station is installed on a site affected by erosion and sedimentation. In the Omo-Gibe basin in Ethiopia, most stations were installed on an unstable channel bed that can cause large temporal errors on their rating curves due to changes in channel morphology (Haile *et al.* 2022). For the North River Basin in China, Qiu *et al.* (2021) obtained that the cross-section of the gauging station below the 5 m water level mark (on the staff gauge) increased from 565 to 1,678 m^2 over a 4-year observation period. The use of a static (stationary) rating curve for such stations with significant cross-sectional changes over time can significantly affect the accuracy of the discharge estimates. Guerrero *et al.* (2012) reported that the discharge from a temporally variable (dynamic) rating curve can be 0.5–1.5 times the discharge from a static rating curve when stations have changing cross-sections.

Rating curves are mostly non-stationary due to the changing characteristics of rivers at gauging sites. In Australia, it was reported that a rating curve is valid for 1.1 years on average (in terms of median) with an interquartile range from 2.5 years to 0.57 years (McMahon & peel 2019). Similarly, rating curves of 19 stations in Eastern France were found valid from 10 months to 3 years with an average life span of 1.5 years (Jalbert *et al.* 2011). However, there is a lack of studies that report the life span of stage–discharge relationships to inform rating curve updating for stations in developing countries. While evidence for other regions indicates the need for regular updating, rating curves usually remain without any update for many years due to the limited availability of financial resources and other institutional factors.

In Ethiopia, streamflow data archiving and rating curve development is the mandate of the Ministry of Water and Energy (MoWE). The ministry has been collecting river stage and velocity data since 1947 (Nigussie *et al.* 2020). Due to organizational restructuring, these activities were transferred to the Basin Development Offices for three basins, namely Abbay (Blue Nile), Awash, and Rift Valley Lakes Basin in the mid-2010s. However, the organizational restructuring became too frequent (three times for the period after 2015) to properly sustain the hydrologic data collection and management. For instance, the frequency of velocity measurements has substantially decreased during organizational changes (Donauer *et al.* 2020). As a result, the rating curves for stations across the country have not been updated for the recent decade that constrained researchers from investigating the impacts of recent developments, climate change, and variability on the water resources of the country (Goshime *et al.* 2021). Considering the seriousness of the problem, Donauer *et al.* (2020) and Haile *et al.* (2022) investigated the gaps and opportunities of river monitoring in Ethiopia and put forward recommendations to reverse the deterioration of streamflow monitoring across the country. Taye *et al.* (2021) demonstrated the value of a partnership between data providers and users to address such data gaps.

The Lake Tana sub-basin, the source of the Blue Nile River, is one of the locations that was impacted by these streamflow data issues and has had poor data quality in recent years (Abebe *et al.* 2020; Negatu *et al.* 2022). The stations in the Lake Tana basin are managed by the Abbay Basin Development Office (ABDO) which is measuring the stage and velocity data for about 170 stations within the upper Blue Nile basin. Given that the office manages a large number of stations, the frequency of velocity data collection for a given river is very limited. Velocity measurement for the specific stations can be once or twice in the high flow season and once or none in the other flow seasons. These results limited the number and coverage of measurements for rating curve establishment. As a result, river stage measurements were not converted to discharge data for the period from 2015 to the present (Taye *et al.* 2021). Negatu *et al.* (2022) developed a method using historical stage–discharge measurements to account for changes in the height of the channel bed with respect to the zero-gauge height in the Lake Tana sub-basin. Though their work is very useful to account for addressing temporal errors of rating curves, it does not replace the need for regular monitoring of stage–discharge data as the channel bed is not the only channel characteristic that changes with time.

Looking at these current challenges of data availability, the objective of this study is to fill streamflow data gaps through collaboration between a data provider and a data user, calibrate and validate rating curves and compare the sensitivity of the errors of the rating curves to sample size. The rating curves were established at three river discharge stations in the Lake Tana sub-basin, which provides head flows to the Nile River. The study is based on our own stage–discharge measurements conducted through field campaigns in 2021/22, instead of the traditional approach of taking a few measurements per year which has already created data gaps in the study area and elsewhere. Despite the national and international significance of the sub-basin, scientific studies are not exploring its hydrology in the recent decade because of the lack of access to discharge data. Through this process, we aimed at demonstrating how to solve data problems collaboratively with government entities instead of the common practice of only requesting data without offering to help when poor data quality and deterioration are observed.

2. STUDY AREA DESCRIPTION

This study is conducted in the Lake Tana sub-basin of Ethiopia focusing on three main tributary rivers: Gilgel Abay, Gumara, and Ribb (Figure 1). The sub-basin is found between 36.8° and 38.2° East (~155 km) and from 11° to 12.8° North (~200 km). These three tributaries are perennial rivers with more than 80% of flow contribution to Lake Tana. The rivers have historical records of water levels but limited water velocity data (especially after 2015) for rating curve development and discharge conversion.

The Gilgel Abay catchment is located south of Lake Tana. Its elevation ranges from 1,787 to 3,528 m above sea level. The river rises in Gish Abay town at an elevation of 2,900 m above sea level and flows northwards into the southern part of Lake Tana. The entire catchment area of the Gilgel Abay River is approximately 4,479 km^2 (Figure 1), making it the largest tributary of Lake Tana, accounting for almost 30% of the sub-basin's total area.

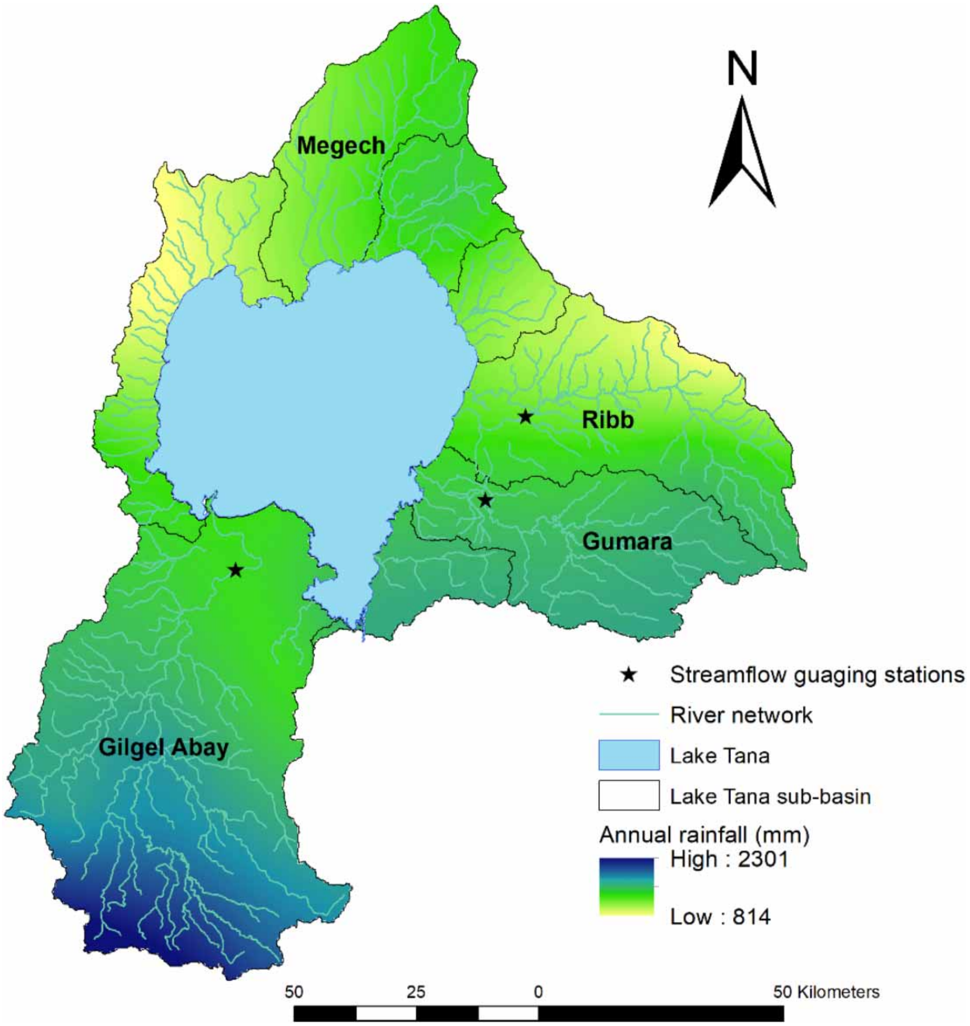

Figure 1 | Lake Tana sub-basin, its four main tributary catchments and streamflow gauging stations of this study.

The Gumara and Ribb catchments are found in the Lake Tana sub-basin's eastern part. The Gumara River springs at roughly 4,000 m above sea level (m.a.s.l.) in Guna Mountain and flows to Lake Tana at 1,784 m. It has a 1,604 km^2 catchment area, which is about 10% of Lake Tana's total sub-basin area. The average annual rainfall in the catchment is 1,326 mm/yr (Abebe *et al.* 2020). The Ribb river flows from Guna mountain at a height of 4,090 m.a.s.l. The catchment has a 2,038 km^2 drainage area (Figure 1), which is about 13% of the total basin's area. The southern part of the sub-basin is the wettest area of the Lake Tana sub-basin with rainfall exceeding 2,300 mm per annum.

3. METHODS

3.1. Dataset

The main data for this study are paired measurements of water level and velocity at three key river gauging stations. These data were obtained from two sources. The first dataset on water level and velocity was collected by the ABDO from 2016 to 2020. The second dataset was obtained from our own field campaign in the year 2021/2022 in collaboration with ABDO.

ABDO typically collects river flow velocity data three times per year during the low, medium, and high flow seasons. The number of measurements was limited due to financial and logistical constraints to cover a large number of stations under their mandate. Although ABDO took measurements for 5 years (2016–2020), they did not establish the rating curves for these periods since the numbers of paired water level and velocity measurements were inadequate with poor coverage. As a result, there is no rating curve to convert recent years' measurements of river water level to discharge data.

Our field campaign addressed some of the challenges of past measurements by designing a sampling method that can capture an adequate number of wide ranges of river water levels and flow velocity in a single year. This involved extended and supervised field measurement campaigns in the three critical flow regimes (low flow in January, medium flow in October, and high flow in August). The velocity measurement was conducted using an AA type of current meter mounted on a crane with sounding cable, rile, depth counter, and suspension loads.

At the gauging site, the river cross-section was divided into several segments from the left to the right bank of the river. Then, velocity, width, and depth measurements were taken for each segment. The width of segments varied based on river width and flow regime. For high flows, the segment width was about 3 m at Gilgel Abay, 2 m at Gumara, and 1 m at Ribb stations but smaller segment width was used for the medium- and low-flow measurements. Along the vertical, two measurements were taken at 0.2 and 0.8 times the water depth from the top surface of the river water. For each of these segments discharge values were calculated using the water depth, width, and velocity measurements. The total discharge was estimated as the summation of the discharge for all segments. Cross-section surveys were also conducted at the three gauging locations during the measurement of the velocity. These surveys were used to obtain initial estimates of hydraulic information that are relevant to the rating curve development process (e.g. the gauge height at zero discharge).

3.2. Rating curve development

Rating curves (stage–discharge relationships) are represented by mathematical equations. The most common form of such equations typically follows a power function, often represented by Equation (1). We selected the power function to describe the stage–discharge relationships in this study since it is the widely used form of rating curve function in Ethiopia (e.g. Negatu *et al.* 2022) and elsewhere (e.g. Jalbert *et al.* 2011). The equation reads as follows:

$$Q = c(H - H_0)^n \tag{1}$$

where Q is the discharge (m^3s^{-1}), H is the observed stage (m), H_0, c, and n are site-specific constants. The parameters c and n implicitly represent friction and geometric feature at the gauge site (Sörengård & Di Baldassarre 2017), where n is an exponent (–) that represents the departure of the river bank from the vertical; c is the scale coefficient ($m^{3/n}\ s^{-1}$) that includes the cross-section width, Manning coefficient and the local bottom slope (Zhang *et al.* 2015), and it equals the discharge when $H - H_0$ equals 1.0; and H_0 is a location parameter (m) representing the gauge height at zero discharge.

Equation (1) can be log-transformed to make it linear and for ease of determining the parameters. The log-transformed form of the equation reads as follows:

$$\log(Q) = \log(a) + b \times \log(H - H_0) \tag{2}$$

In this study, we primarily estimated the value of H_0 by visual inspection of the stage–discharge plot, and then validated it based on the river cross-section and longitudinal profile information. Then, *log(a)* and *b* were estimated using the least square method with the objective of minimizing the sum of the squared residuals.

We estimated the uncertainty of the rating curve using the data of 2021/22, i.e. at the time of the rating curve establishment, which is called the initial uncertainty (Jalber *et al.* 2011). The initial uncertainty was estimated in terms of the confidence limits also called the uncertainty band (prediction interval) of the fitted rating curve (Dymond & Christian 1982). The uncertainty band is estimated in terms of the standard error of the sample. A narrow uncertainty band (i.e. the distance between upper and lower limits) shows a relatively accurate rating curve with adequate samples. Here, we computed the standard uncertainty values of the measurements for a 95% confidence interval. Mean absolute percent error (MAPE), Nash–Sutcliffe efficiency (NSE), and coefficient of determination (R^2) were used to evaluate the fitted rating curves.

We conducted cross-validation, which is also called the leave one out validation method, to show the effect of sample size on the established rating curve. When undertaking cross-validation, we left out one paired stage–discharge measurement and established the rating curve for the remaining paired measurements. The error of the rating curve was estimated for the measurement value which was left out. The leave one out process was repeated until each measurement was left out. We used root mean square error (RMSE) to evaluate the errors because of leaving out a measurement. However, the values of RMSE are affected by the discharge magnitude. To compare the errors at the three stations which have different flow magnitudes, the RMSE was divided by the mean of the discharge measurements (Seörengård & Di Baldassarre 2017).

ABDO used the constructed rating curve to convert water levels measured since 2016 to discharge estimates. Then, we evaluated the data quality by visual inspection of the discharge hydrograph, and the annual cycle of the dimensionless discharge estimate.

4. RESULTS

4.1. Characteristics of the stage–discharge data

Figure 2 shows the daily water level for the period 2016–2020 of the three gauging stations on Gilgel Abay, Gumara, and Ribb Rivers based on data from ABDO. Statistics of the water level in 2016–2020 are summarized as maximum, minimum, and average values at a monthly level. The water level variation is largest at the Gumara gauging station, whereas the ranges of the water levels at Gilgel Abay and Ribb are similar. Gilgel Abay experienced peak water levels in the months of May to September. Whereas, the peak water levels of Ribb and Gumara occurred only in July and August. Similarly, statistics of the water levels during paired stage–discharge measurements are shown by the broken lines in Figure 2. It can be seen from the figure that the stage–discharge data that we measured during 2021/22 adequately covered the low, medium, and high flow ranges of the observed data in 2016–2020. The coverage by the stage–discharge measurements accounts for 97, 94, and 90% of the daily water level records for the Gilgel Abay, Gumara, and Ribb rivers, respectively.

The ranges of water levels and discharges measured during the field campaign are shown in Table 1 which illustrates the diverse flow conditions of the rivers. Since the high flow season is characterized by large water level variations, 20 paired stage–discharge measurements were undertaken at each of the three stations. A relatively smaller number of measurements were conducted in the medium (12) and low (4–7) seasons due to the low water level variations in these seasons. During the stage–discharge measurement period, the measured peak discharge varied from 134.38 m^3/s (Ribb) to 452.7 m^3/s (Gilgel Abay). The lowest measured discharge is 0.31 m^3/s at the Ribb station.

In this section, we compared the stage–discharge data of ABDO for a 5-year period against that of our field campaign in 2021/22 (Figure 3). The year 2016/17 had the largest number of measurements (10) though there is some gap in the coverage of water levels. During 2016, ABDO had financial support from different collaborative projects that helped to fund field campaigns during the high flow season. However, this was not sustained in the following years as shown in Figure 3 due to financial constraints that impacted data collection. The size of stage–discharge data declined in the following years and there was no recorded data at all in 2019. Such a data gap is more visible at the Ribb station for all seasons of 2017–2020 when compared to Gilgel Abay and Gumara stations. The main reason for this decline in measurements, particularly during high and medium flow seasons, is that budget allocation and release timing from the ministry of finance, which is not in line with the seasons when high flow measurements needed to be done (personal communication with ABDO staff). Apart from financial constraints, according to ABDO technicians, the biggest problem to measure velocity at the

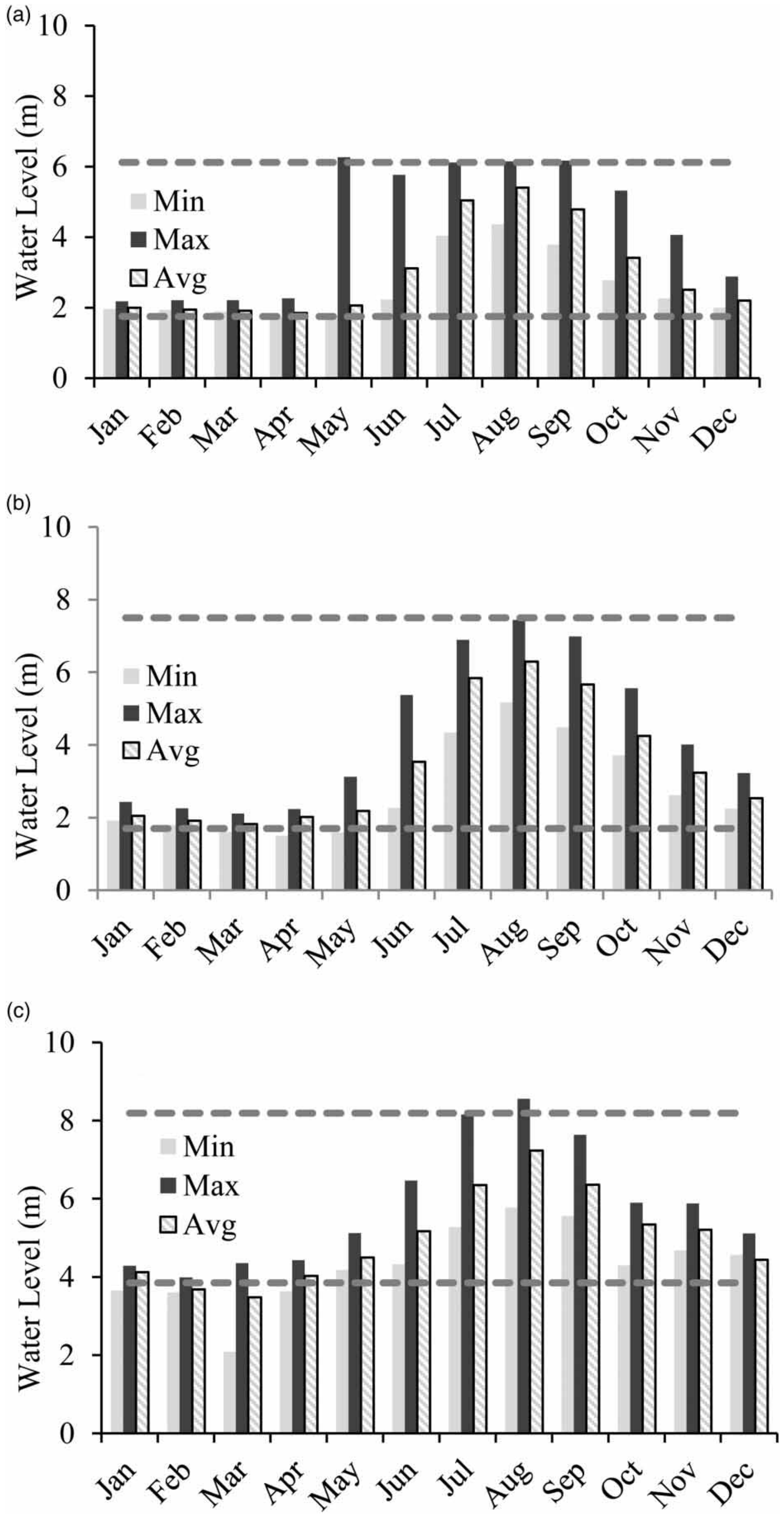

Figure 2 | Monthly water level for the period from 2016 to 2020 at (a) Gilgel Abay near Chimba, (b) Gumara near Lake Tana, and (c) Ribb near Addis Zemen. Broken lines show the range of water level covered by the stage–discharge measurements in 2021/22. Max refers to maximum water level, Min refers to the minimum water level, and Avg refers to the average water level of the 2016–2020 measurements.

Table 1 | Water level and discharge data range coverage during velocity measurement campaign in 2021/22

Station	Water level (m)	Discharge (m^3/s)	Flow season	No. of measurements (data size)
Gilgel Abay	3.94–6.12	150.5–452.7	High	20
	2.84–5.3	74.36–257.81	Medium	12
	1.75–1.77	7.8–8.6	Low	4
Gumara	4.35–7.5	84.84–348.67	High	20
	2.84–5.3	74.36–257.81	Medium	12
	1.75–1.77	7.8–8.6	Low	7
Ribb	4.8–8.19	8.3–134.38	High	20
	4.38–4.86	0.31–9.54	Medium	12
	3.85–4.1	0.36–1.44	Low	7

Ribb station is that they do not feel safe to conduct the measurement because of the traffic congestion on the bridge where this measurement is conducted.

Our own field campaign in 2021/22 provided data coverage that is much better than that of ABDO during the years 2016–2020. For instance, our data in 2021/22 covered a larger range of stage–discharge values at Gilgel Abay including data on peak flows (Figure 3(a)). Above 6 m reading of the staff gauge, the discharge increases without significant increment of water level suggesting increased wetted width of the channel for high flows. Similarly, in the Gumara river, the peak flow events above 7 m were not captured by ABDO in the previous years (2016 to 2020) but our field campaign provided data up to 7.5 m stage reading. At the Ribb station, ABDO's data have a similar range of stage–discharge values to those captured in our field campaign but it missed the stages from 4.5 to 6.0 m. Capturing paired stage–discharge measurements for the peak flows is of paramount importance in calibrating a rating curve that minimizes extrapolation of data (Figure 3(a) and 3(b)).

4.2. Rating curve establishment and analysis

Determining the water level of zero discharge (H_0) is a key aspect in developing rating curves. It especially controls the shape of the lower section of the curve. All stage–discharge measurements taken during the field campaign were plotted on log–log paper, and the point of zero flow was identified using a visual inspection of the plot. The points of zero flow for the Gilgel Abay, Gumara, and Ribb river stations are at 1.45, 1.4, and 3.5 m of staff gauging reading, respectively. The determined H_0 values were then compared to the water level height of the potentially ponded water as estimated from the elevation profile of the river's bed around the gauging site. The determined values of H_0 at the three gauging locations are in line with that obtained from a graphical inspection of the riverbed profile, as shown in Figure 4.

Reliable rating curves were developed for each of the three stations. The observed flow and the estimated values using the developed rating curves show an excellent relationship for all three stations, as seen by a low standard error of estimate and a low mean absolute percent of error (Table 2). We used a two-segment rating curve for the stage–discharge relationship of the Gilgel Abay station (Figure 5(a)). The first applies to water levels of less than 6 m, while the second applies to water levels greater than or equal to 6 m. This agrees with our field observation at Gilgel Abay where the water upstream of the station overflows the channel after the stage reaches 6 m, but it returns back to the channel and is captured by the station after a few hours' delay.

The stage–discharge relationship at Gumara does not vary greatly for stages lower than 4.5 m. However, an additional rating curve equation was needed for the stage–discharge relationship from 4.5 to 7.0 m to account for cross-section changes. Therefore, a two-segment rating curve was developed for Gumara near the Lake Tana station. The first curve represents gauge values less than 4.5 m, whereas the second curve represents gauge readings higher than 4.5 m (Figure 5(b)). Ribb's stage–discharge relation was captured by only a single rating curve. The data of all stations are within the 95% confidence interval of the rating curve, suggesting a very low uncertainty.

Except for the lower segment curve of the Gumara station, which can still provide a model result that is extremely near to the observed values, the NSE and correlation coefficient (R^2) of the fitted curves are greater than 90% (Table 2). The strong relationship between the observed and estimated discharges indicates that the method used was reliable enough to predict discharge at the gauging stations.

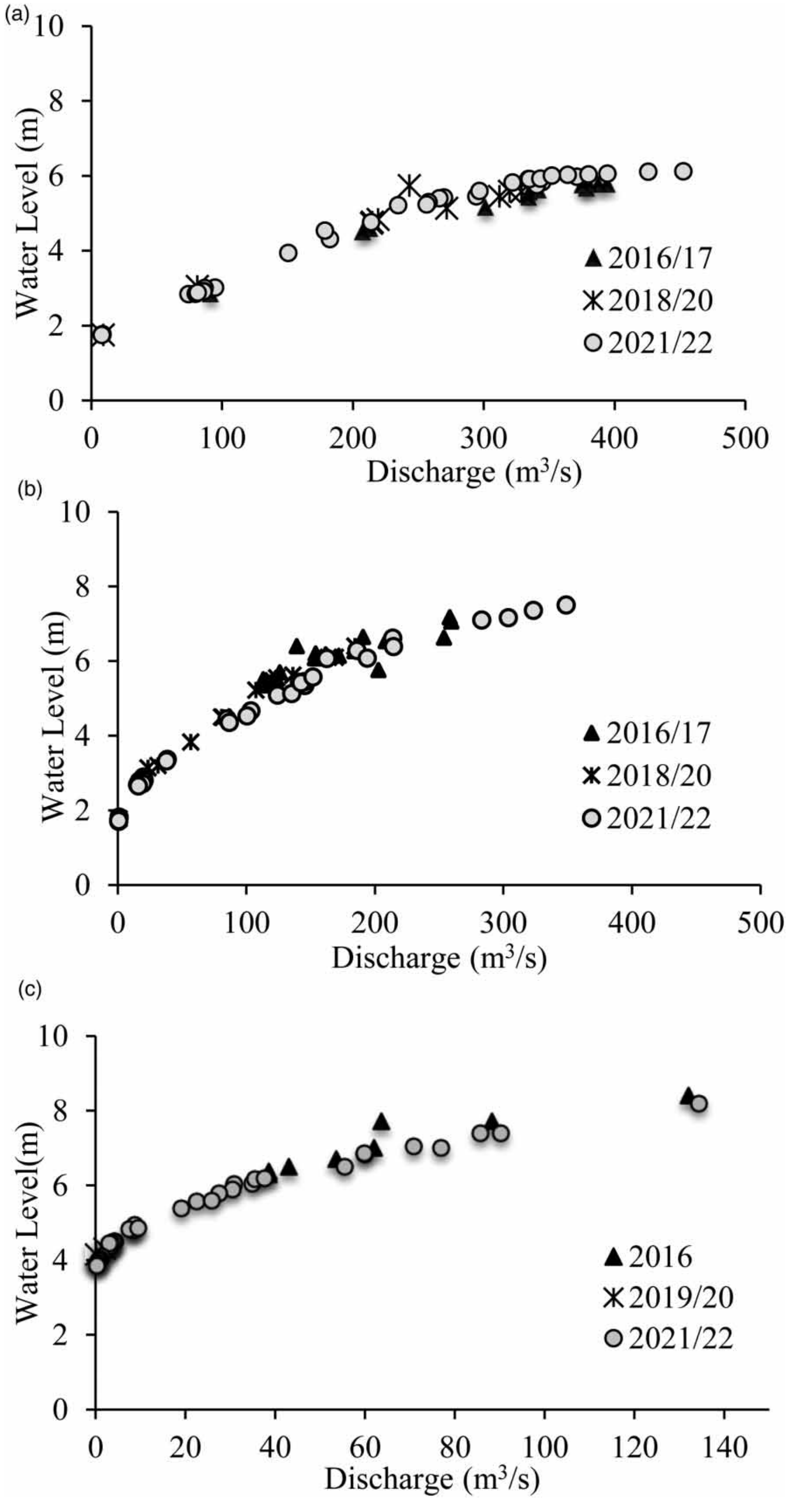

Figure 3 | Water level and discharge relationship based on measurements collected in 3 years (2016/17, 2018/20, and 2021/22) for rivers at (a) Gilgel Abay near Chimba, (b) Gumara near Lake Tana, and (c) Ribb near Addis Zemen. Note: (c) *x*-axis is not to scale.

We applied the cross-validation method to evaluate the adequacy of the data size for the established rating curve of the three stations. The cross-validation showed most of the errors are smaller than 10% of the discharge magnitude (Figure 6). For most water level ranges at the three stations, the established rating curves are not significantly sensitive to the number

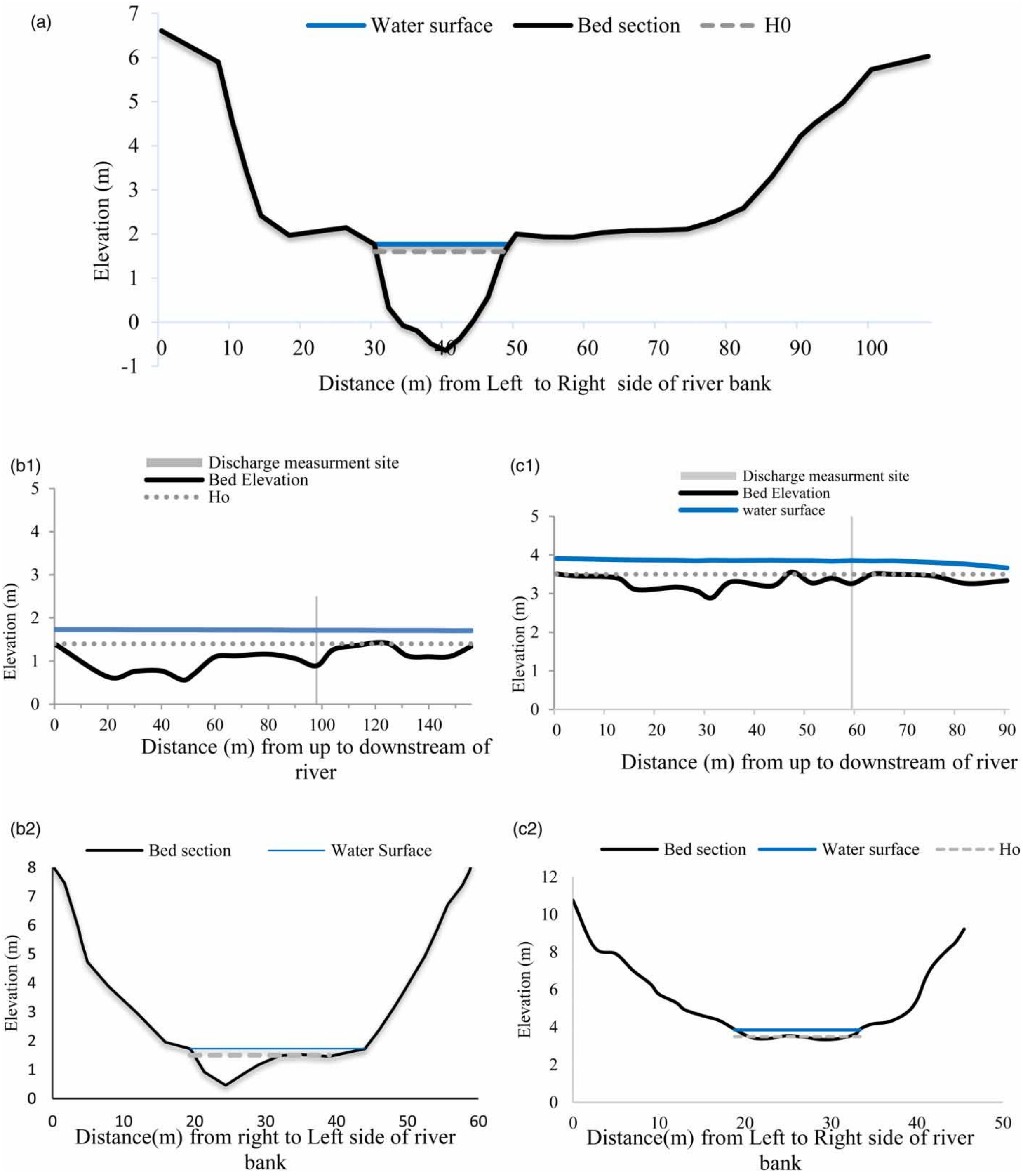

Figure 4 | Longitudinal and cross-sectional profiles at the gauging sites, (a) Gilgel Abay cross-sectional profile; (b1) Gumara River longitudinal profile; (c1) Ribb River longitudinal profile; and (b2 and c2) cross-sectional profiles of Gumara and Ribb River at the measurement position in their respective longitudinal profiles. The water surface represents the river's flowing section during the survey, the bed section represents the cross-section at the flow measuring station, and H_o represents the water level for zero flow.

of the concurrent stage–discharge measurements, which indicates the sample size is adequate. However, the errors can approach 25% (Gumara and Ribb) for extremely low discharges. This indicates that care must be exercised to ensure an adequate number of low-flow measurements are taken. Overall, the established rating curve did not incorporate significant errors as indicated by the results of the cross-validation.

Table 2 | Rating curve parameters for specific gauge height ranges and statistical goodness of fit test values

	parameters				**Statistical test**			
Station	***c***	***H_o***	***n***	**Gauge height**	**SE (–)**	**MAPE (%)**	**NSE (–)**	***R^2***
Gilgel Abay	55.13	1.6	1.21	1.6–6.0	0.17	7.7	0.99	0.98
	846.8	–	−4,738.1	>6.0[a]	0.01	[b]	[b]	0.97
Gumara	10.12	1.4	1.95	1.4–4.50	0.12	2	0.81	0.98
	8.77	1.4	2.01	>4.50	0.06	0.1	0.98	0.98
Ribb	4.37	3.5	2.21	3.5–9.0	0.10	8	0.99	0.98

Note: SE is standard error of estimate, MAPE is mean absolute percent error, NSE is the Nash–Sutcliffe efficiency, and R^2 is correlation coefficient.

[a] Linear fit is used as $Q = cH + n$.

[b] the sample size is small to do statistical test.

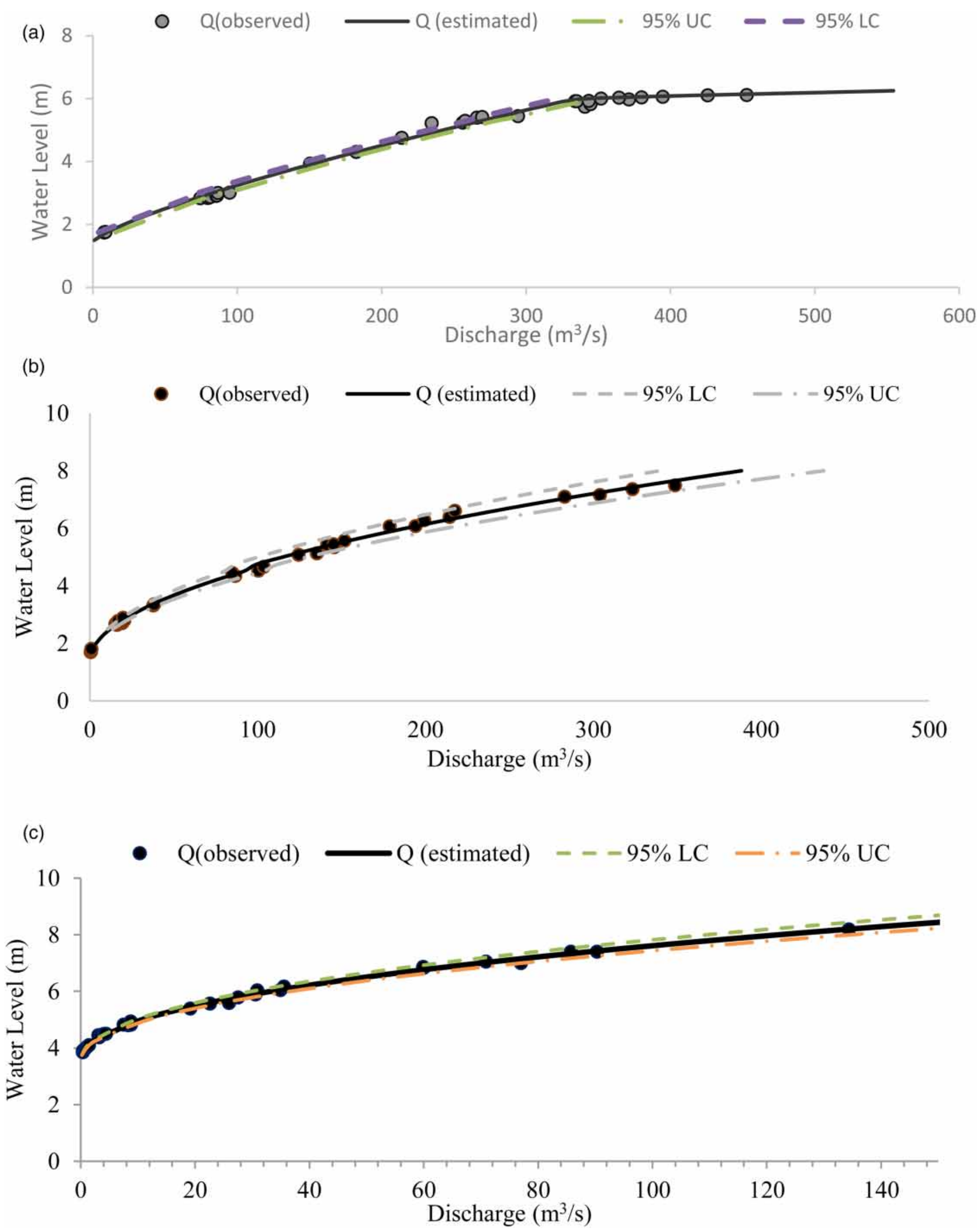

Figure 5 | Water level (stage) and discharge relations – rating curves of Gilgel Abay near Chimba (a), Gumara near Lake Tana (b), and Ribb near Addis Zemen (c).

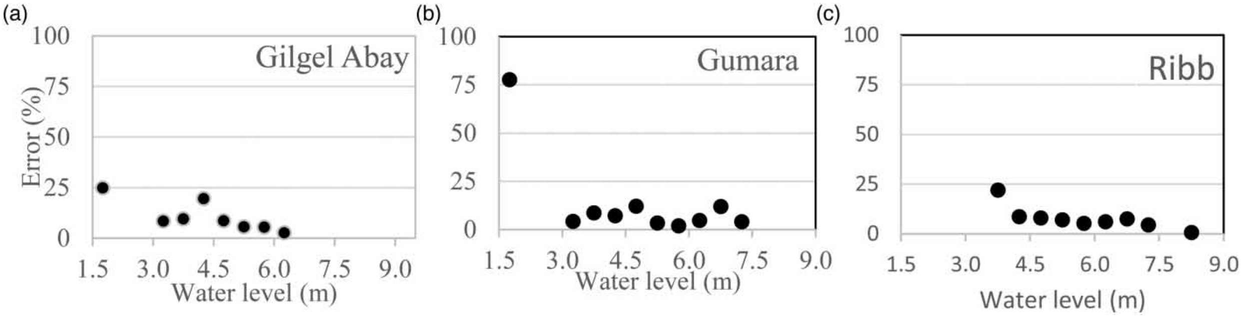

Figure 6 | Relative absolute error, defined as absolute value of the discharge error divided by the discharge magnitude, of the rating curve based on cross-validation. The error was aggregated for a water level range of 0.5 m (e.g. 3.5–4.0, 4.0–3.5, etc.).

4.3. Water level to discharge conversion

Using the developed rating curve equations, ABDO converted the water level record of the stations to discharge time series as shown in Figure 7. The overall shape of the discharge hydrograph of Gilgel Abay does not show significant inter-annual variation (Figure 7(a)). However, the discharge magnitudes show a large inter-annual variation. Its discharge was very low in

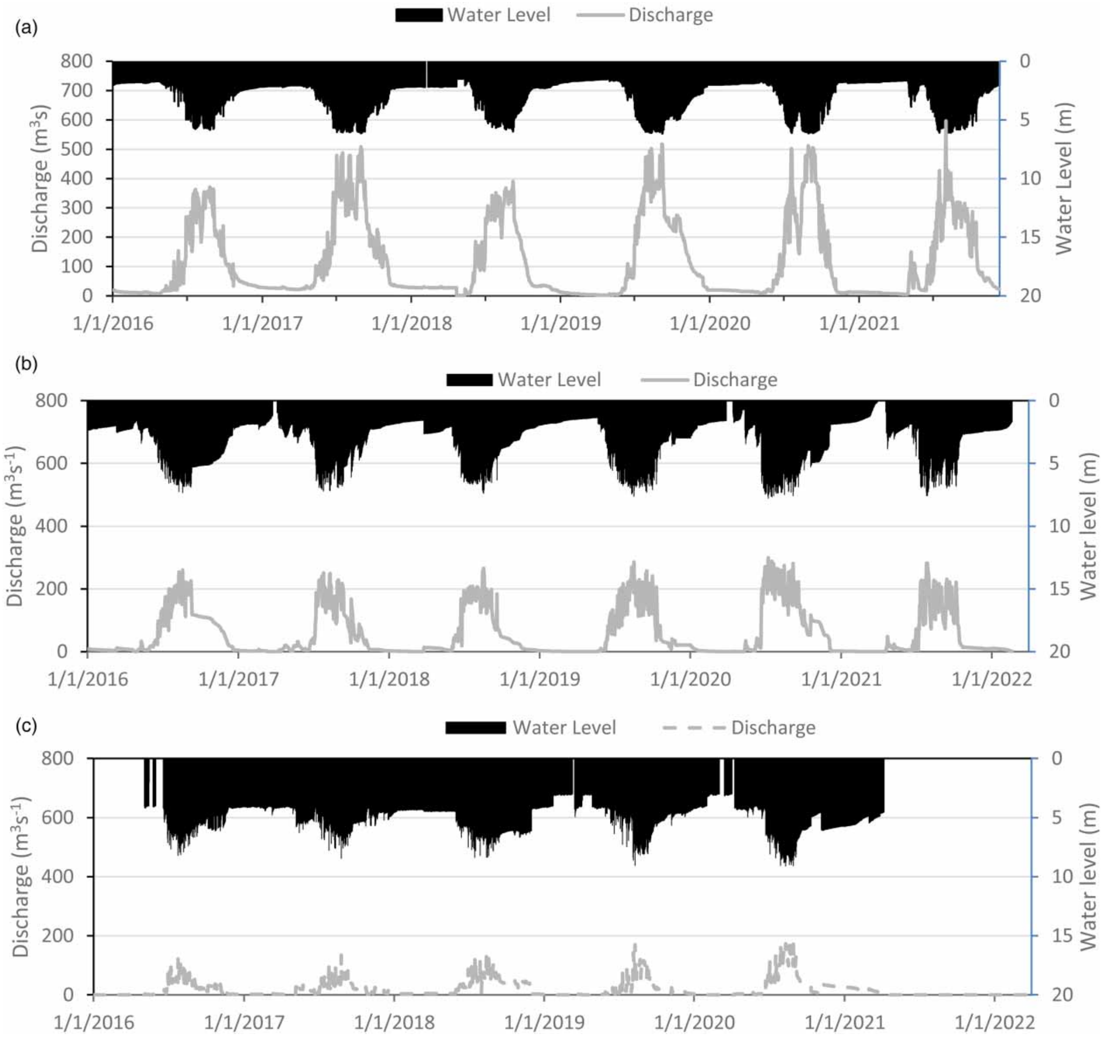

Figure 7 | Discharge hydrographs and water of Gilgel Abay near Chimba (a), Gumara near Lake Tana (b), and Ribb near Addis Zemen (c).

2016 and 2018 while it had very high flows in the other years. The baseflow in 2016 and 2017 was larger than the other years whereas the dry season flow noticeably declined in 2018.

For the Gumara catchment, 2020 was the wettest year with the discharge exceeding 200 m^3/s for several days (Figure 7(b)). In March of recent years since 2019, the catchment experienced near zero discharge. Among the three catchments, Ribb had the lowest flows as expected (Figure 7(b)). Its hydrograph has sharp peaks whereas its dry season flow occasionally dropped to near zero values.

Considering the three catchments are situated in the same sub-basin, some similarity in their discharge hydrographs is expected. The annual cycle of the observed discharge at the three stations is shown in Figure 8. For the sake of comparison, the discharge is normalized by the peak discharge of the respective catchments over the analysis period. Figure 8 shows that the timing of peak discharge of the three gauging locations is mostly synchronized, and it occurs in August. However, the peaks of these locations occurred in different months of 2020 which was an extremely wet year across the country. June and July were the peak flow months of 2020 at Gumara and Ribb, respectively, but the discharge of Gilgel Abay peaked in September.

The slope of the rising limb of the hydrographs is similar at Gilgel Abay and Gumara. There is also a similarity in the time of the rise of their hydrographs. However, the shape of the rising limb of Ribb's hydrograph was mostly different from that of the other two gauging locations.

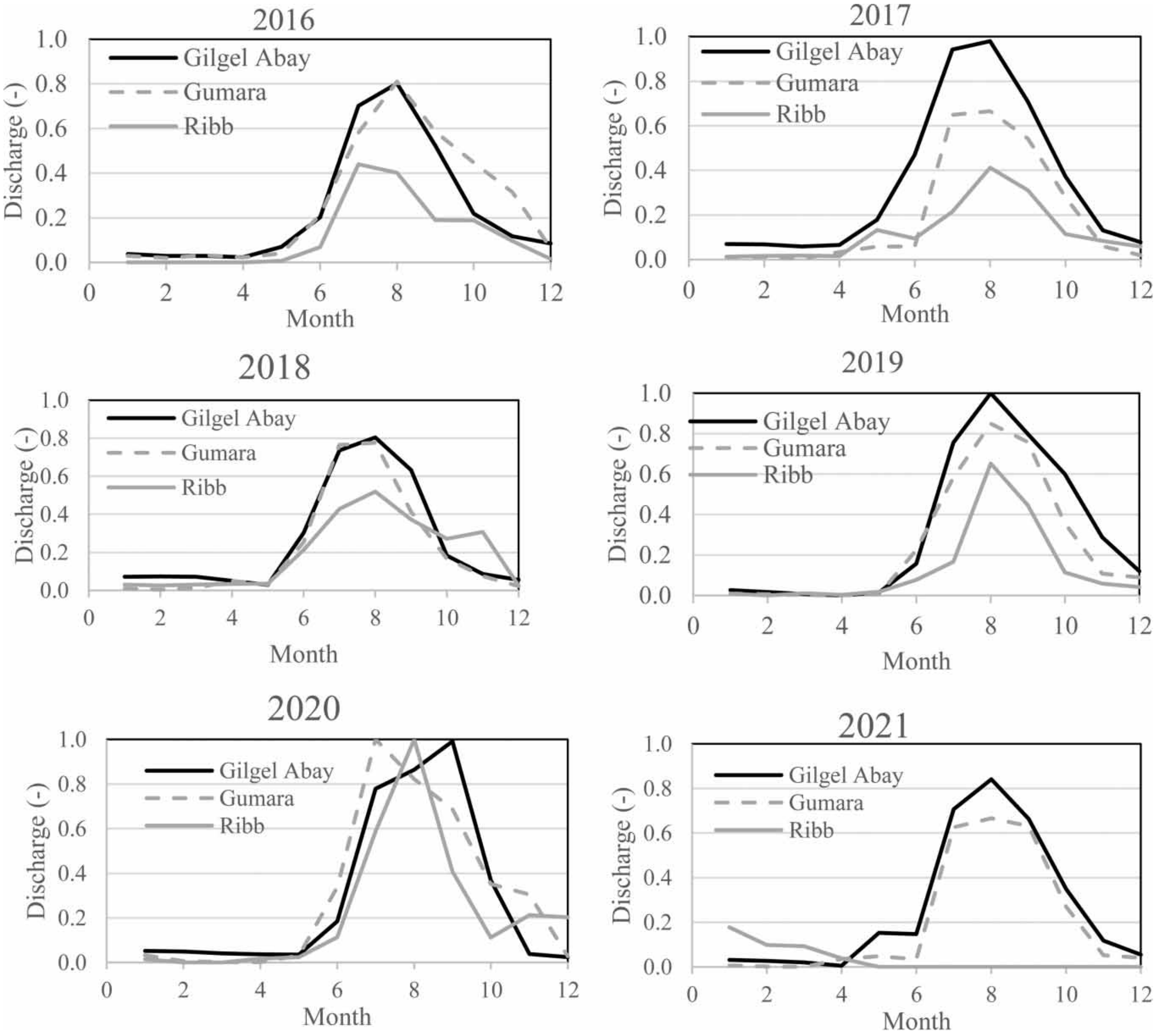

Figure 8 | Annual cycle of the normalized discharge at the three stations. The discharge was divided by the peak discharge of the corresponding station.

Except in 2016, the inflection point (where the slope declines) of the hydrographs of Gilgel Abay and Gumara occurred in the same month. The inflection point of Gumara's hydrograph occurred 1 month later than that of Gilgel Abay in 2016. However, there is inconsistency in the timing of the hydrograph inflection point of Ribb. As a result, the recession limb of the hydrograph at this station shows a large year-to-year variation.

5. CONCLUSION

This study explored an approach for filling streamflow data gaps which are becoming a common problem across many basins. Primary data were collected from the field and analyzed to evaluate data adequacy and coverage to establish rating curves.

- The approach followed by the hydrology agency to measure stage–discharge over the recent 5-year period had significant limitations to establish rating curves. This 5-year dataset (i) missed peak flows at two out of the three stations evaluated in this study and (ii) was inadequate in number and coverage of stage–discharge magnitudes to establish a rating curve at the three stations. Therefore, the hydrology agency would benefit from revising its strategy and practice of stage–discharge measurement.
- Through collaboration between the data provider and user, we demonstrated that properly planned field campaigns over 1 year can provide adequate stage–discharge data for establishing rating curves. We were able to capture such rich data due to the approach we took, which is camping at the site for continuous days during the high flow season and measuring data in the morning and evening hours. Hydrologic agencies can adopt our approach by partnering with data users who are willing to share the financial burden of this kind of data collection.
- Our paired stage–discharge data covered 90–97% of the daily discharge observed over the period from 2016 to 2020. The cross-validation results showed that the collected data were adequate for rating curve establishment. Thus, our data collection approach minimizes the extrapolation of rating curves for the estimation of extreme discharges.
- The pattern of the annual cycle of the time series discharge data has some similarities at Gilgel Abay and Gumara stations though some unexpected differences were noticed. However, the annual cycle of Ribb's discharge is mostly different from that of the other two stations. Future studies can explore the causes of these unexpected differences that may be related to climatic and non-climatic factors (e.g. the construction of a dam) as well as observation errors.
- Overall, a systematic collaboration between the data provider and data user (i.e. researchers in this study) enabled better coverage of possible ranges of stage–discharge values in 1 year as compared to data coverage over a 5-year period by only the data provider. As a result, we were able to establish rating curves and enable the data provider to use discharge data of recent years at three key stations. This shows the immense value of data users in supporting data collection.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abebe, W. B., Tilahun, S. A., Moges, M. M., Wondie, A., Derseh, M. G., Nigatu, T. A., Mhiret, D. A., Steenhuis, T. S., Van Camp, M., Walraevens, K. & McClain, M. E. 2020 Hydrological foundation as a basis for a holistic environmental flow assessment of tropical highland rivers in Ethiopia. *Water* **12** (2), 547. https://doi.org/10.3390/w12020547.

Di Baldassarre, G. & Montanari, A. 2009 Uncertainty in river discharge observations A quantitative analysis. *Hydrol Earth Syst Sci.* **13**, 913–921.

Donauer, T., Haile, A. T., Goshime, D. W., Siegfried, T. & Ragettli, S. 2020 *Gap and Opportunity Analysis of Hydrological Monitoring in the Ziway-Shala Sub-Basin, Ethiopia*. International Water Management Institute (IWMI), Colombo, Sri Lanka, p. 40. (IWMI Working Paper 192). https://doi.org/10.5337/2020.210.

Dymond, J. R. & Christian, R. 1982 Accuracy of discharge determined from a rating curve. *Hydrol Sci J* **27** (4), 493–504. https://10.1080/02626668209491128.

Fortesa, J., García-Comendador, J., Calsamiglia, A., López-Tarazón, J. A., Latron, J., Alorda, B. & Estrany, J. J. 2019 Comparison of stage/discharge rating curves derived from different recording systems: consequences for streamflow data and water management in a Mediterranean island. *Sci. Total Environ.* **665**, 968–981.

Goshime, D. W., Haile, A. T., Absi, R. & Ledésert, B. 2021 Impact of water resource development plan on water abstraction and water balance of Lake Ziway, Ethiopia. *Sustain. Water Resour. Manag.* **7**, 36.

Guerrero, J.-L., Westerberg, I. K., Halldin, S., Xu, C.-Y. & Lundin, L.-C. 2012 Temporal variability in stage–discharge relationships. *J. Hydrol* **446–447**, 90–102.

Haile, A. T., Wegayehu, A., Rientjes, T. & Adimasu, W. W. 2022 Deterioration of Streamflow Monitoring in Omo-Gibe basin in Ethiopia. *Hydrol Sci J*. https://doi.org/10.1080/02626667.2022.2060110.

Jalbert, J., Mathevet, T. & Favre, A.-C. 2011 Temporal uncertainty estimation of discharges from rating curves using a variographic analysis. *J. Hydrol.* **397**, 3–92.

McMahon, T. A. & Peel, M. C. 2019 Uncertainty in stage–discharge rating curves: application to Australian hydrologic reference stations data. *Hydrol Sci J* **64** (3), 255–275.

Negatu, T. A., Zimale, F. A. & Steenhuis, T. S. 2022 Establishing stage–discharge rating curves in developing countries: Lake Tana Basin, Ethiopia. *Hydrology* **9** (1), 13. https://doi.org/10.3390/hydrology9010013.

Nigussie, L., Haile, A. T., Gowing, J., Walker, D. & Parkin, G. 2020 *Citizen Science in Community-Based Watershed Management: an Institutional Analysis in Ethiopia*. International Water Management Institute (IWMI), Colombo, Sri Lanka, p. 25. (IWMI Working Paper 191). https://doi.org/10.5337/2020.207.

Qiu, J., Liu, B., Yu, X. & Yang, Z. 2021 Combining a segmentation procedure and the BaRatin stationary model to estimate nonstationary rating curves and the associated uncertainties. *Hydrol Sci J* **597**, 126168.

Sörengård, M. & Di Baldassarre, G. 2017 Simple vs complex rating curves: accounting for measurement uncertainty, slope ratio and sample size. *Hydr Science* **62** (13), 2072–2082.

Taye, M. T., Haile, A. T., Fekadu, A. G. & Nakawuka, P. 2021 Effect of irrigation water withdrawal on the hydrology of the Lake Tana sub-basin. *J. Hydrol. Reg. Stud.* **38**, 100961.

Zhang, W., Wang, W. G., Zheng, J. H., Wang, H. G., Wang, G. & Zhang, J. S. 2015 Reconstruction of stage–discharge relationships and analysis of hydraulic geometry variations: the case study of the Pearl River Delta, China. *Glob Planet Change Glob Planet Change* **125**, 60–70.

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