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Deterioration of streamflow monitoring in Omo-Gibe basin in Ethiopia

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ABSTRACT

Poor availability and accuracy of streamflow data constrain research and operational hydrology. We evaluated the status of 40 streamflow stations and the quality of their data in the Omo-Gibe basin, Ethiopia. The method included a three-week field inspection of the stations. Inspection of stations followed common WMO guidelines for appropriate gauging sites. Feedback of observers was collected, and the streamflow data was analysed. Most of the stations were installed on rivers at headwater catchments. Only 17% of the stations were fully operational; the remaining stations require major maintenance. Common problems with the time series data include short observation periods, large numbers of missing records, and inhomogeneity. Nearly all observers expressed dissatisfaction due to lack of supervision, uncertain salary payments and lack of recognition of their contribution. The findings of this study indicate the need to investigate the institutional barriers that affect the homogeneity, completeness, and timeliness of the stream data.

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1 Introduction

Despite recent advances, the majority of the rainfall and streamflow datasets across Africa remain inaccessible or have limited utility due to poor data quality and completeness. In general, many observation networks across the globe are in a deteriorating state instead of showing improvements (World Bank 2018), which constrains research and operational hydrology (Dixon *et al.* 2013). For instance, Haile *et al.* (2017) found that most of the stations in the Upper Blue Nile basin did not provide streamflow data fit for rainfall-runoff modelling. For the Ziway-Shalla sub-basin, Goshime *et al.* (2019) had to limit model calibration to the period before 2000 since recent data neither was fit for modelling nor was made available for users. Similarly, the streamflow gauging stations were found inadequate for evaluating the water balance of Lake Tana, which is the source of the Blue Nile River, necessitating the transfer of model parameter values to ungauged catchments (Rientjes *et al.* 2011b). In the Omo-Gibe basin, a large amount of the streamflow data was left out of analyses since the data did not pass quality tests (Mohammed 2013, Degefu and Bewket 2017, Jillo *et al.* 2017). These examples express concerns regarding the lack of reliable streamflow data in Ethiopia, and its impact on research.

Multiple factors contribute to the deterioration of the streamflow observation network. One of these factors is that national hydrological services do not follow up on the recommendation of the WMO (1994) for periodic reviews of the network to identify problems and suggest required actions to address the problems. As a consequence, periodic review of the stations is lacking, data quality is not evaluated, budgets for payments to observers and station maintenance remain too low, data needs in many cases are not clearly defined, and users face issues of poor accessibility as data transfer and storage do not follow strict protocols, etc. Hence, timely actions cannot be taken to fill gaps or to secure access to high quality time series data. In middle- and low-income countries, fragmented and myopic policy environments are obstacles for hydrological services (World Bank 2018). Hydrological monitoring can also receive a low priority as government interest shifts, e.g. to construction of mega water resources projects and development of watershed management plans.

There is evidence that funding constraints, as well as changes in governmental priorities, have led to a decline in networks of river gauging stations (Mishra and Coulibaly 2009, Hannah *et al.* 2010) that once provided time series data of long duration for scientific and technical studies. Mishra and Coulibaly (2009) provided examples of funding cutbacks that caused significant declines in station network density in Canada and the USA. Over the period 1986 to 1999, the decision to interrupt monitoring of medium-sized and small rivers led to a decline of river gauging stations by 79% in Russia and 51% in North America (Shiklomanov *et al.* 2002). Two-thirds of the hydrological monitoring networks in the developing countries are also in poor or declining condition (World Bank 2018). Similarly, many raingauge networks are below the desired density, as only 1% of the earth's surface is represented by the raingauges contributing data to the Global Precipitation Climatology Centre (GPCC) (Kidd *et al.* 2017). It is alarming that even low-density raingauge networks are declining in number, which affects the validation and use of global rainfall products for hydrological impact studies of climate change (Sun *et al.* 2018) and land use change (Rientjes *et al.* 2011a), and for the development of long-term (e.g. 2041–2070) water resource pathways (Haile *et al.* 2017).

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Muchan and Dixon (2014) identified the pressure to rationalize the need for monitoring as one of the main reasons for the decline in gauging stations since the late 1990s. Other obstacles include inadequate institutional capacity, a lack of appreciation of the worth of long-term hydrological data, and, in a few cases, the turmoil caused by wars and other disasters (Mishra and Coulibaly 2009). Corruption is a widespread problem in both public procurement (Ferwerda *et al.* 2017) and aid-funded procurement (Dávid-Barrett and Fazekas 2020). Hence, it can lead to the acquisition of substandard hydrological equipment for monitoring. Hydrological services also face a lack of skilled professionals and technicians, and staff turnover (Houghton-Carr and Fry 2006), that affects the routine maintenance of streamflow stations (Donauer *et al.* 2020).

A periodic review of hydrological data and service has multiple benefits: it provides (i) necessary information to preserve stations that run over long periods (Stewart 2015); (ii) baseline data for evaluation of projects that attempt to improve data collection and service; and (iii) an important contribution to achieving the UN Sustainable Development Goals – a process that, at its core, is data-dependent (Cudennec *et al.* 2020), e.g. transboundary (SDG 6.5) and rational use of water resources (SDG 6.4).

Reliable streamflow observations represent the holy grail for hydrological simulation and projection, which, for instance, provides the base data for flood or drought forecasting (Crochemore *et al.* 2020) and operational water resources management, but long term data also facilitates impact assessments for climate and land use change, including the construction of water resources infrastructures. In this study, we evaluated the current state of streamflow monitoring in the Omo-Gibe basin. The evaluation was supported by field inspection of gauging sites and operation of the instruments to deliver reliable data. The Omo-Gibe basin has received research attention due to its enormous hydropower and irrigation potential (e.g. Avery and Tebbs 2018) and its transboundary nature.

2 Location of Omo Turkana basin

Omo Turkana basin is one of the major transboundary river basins in East Africa which shares a significant portion of the East African Rift system. The area mainly constitutes two river sub-basins: the Omo-Gibe in Ethiopia and Rift Valley Catchment Area in Kenya. Major rivers such as Gibe, Omo, Turkwell, Kerio and Kibish originate at the highland areas of the basin and ultimately drain to Lake Turkana. Also, there are smaller ephemeral rivers and the lake surface itself. These drainage areas cover a total area of 149 360 km^2; the present study mostly focuses on the Ethiopian region (i.e. the Omo-Gibe River basin) that covers a surface area of 79 000 km^2.

The large size of the area and its large differences in altitude (Fig. 1(a)) lead to diversified climatic zones in the basin. The observed annual rainfall in the basin ranges from 1959 mm year^{-1} at Dedo station in the upstream part of Gilgel Gibe catchment, to 188 mm year^{-1} at Lodwar station which is situated close to Lake Turkana. Hence, the annual rainfall shows a decreasing trend that stretches from north to south. The eastern parts of the highlands are mostly rain shadowed. South of the lake, the mean annual rainfall of the Turkwel catchment is approximately 500 mm year^{-1} in the upstream section and less than 200 mm year^{-1} in the downstream section and near Lake Turkana (Stave *et al.* 2005).

Temperature shows a decreasing trend across the basin that stretches from south to north. The mean annual temperature is 15.5°C in the highlands (northern part) at Gedo station but increases to 29.3°C near the west lake shore at Lodwar. This shows a 15.4°C difference in mean annual temperature between the highlands and the west shore of Lake Turkana, causing a substantial spatial difference in evapotranspiration.

Elevation differences of thousands of metres over relatively short distances make the basin suitable for hydropower generation (Fig. 1(b)). The water bodies in the basin, which include rivers, lakes and reservoirs, are directly entwined with the livelihood of settled farmers and nomadic pastorialist societies living in the area. The reader is referred to Hopson (1982), Velpuri and Senay (2012), and UNEP (2013) for additional information about the hydrological features of the basin. An understanding of these hydrological features requires vast amounts of hydrological data that must be recorded frequently and consistently, to understand the spatio-temporal variation and long-term changes. However, the inadequacy of such data limits evaluation of the influence of the various natural and anthropogenic activities on the water resources and environment of the basin. This has major implications for assessments of climate and land use changes and related hydrological impacts. Climate projection and impact assessments commonly require multi-decadal, baseline, time series data for calibration purposes and to bias-correct outputs from the global and regional circulation models (Haile *et al.* 2017). However, the lack of historical field-observed climatic time series results in unreliable and unwarranted climate change projections that hamper the long-term development strategies. The lack of long-term time series data also hampers impact assessements of land use changes.

3 Methods

3.1 Site inspection of streamflow gauging stations

Site inspection of gauging sites involves the systematic monitoring and recording of the site characteristics. For this study, a three-week field visit was undertaken in 2020. Prior to the field visit a site inspection protocol was developed (Table 1). Seven themes were identified in the protocol to evaluate aspects of the gauging site, the gauging instrument, and observers' feedback (see the Supplementary material for details).

The protocol (Table 1) was used in conjunction with the technical requirements for river gauging sites. We particularly relied on the following 10 technical requirements that should be fulfilled for a typical site for accurate streamflow gauging (Rantz *et al.* 1982, WMO 2010):

(1) The course of the river is straight for about 100 m upstream and downstream from the gauge site.
(2) The total streamflow is confined to one channel at all stages and no flow bypasses the site as subsurface flow.

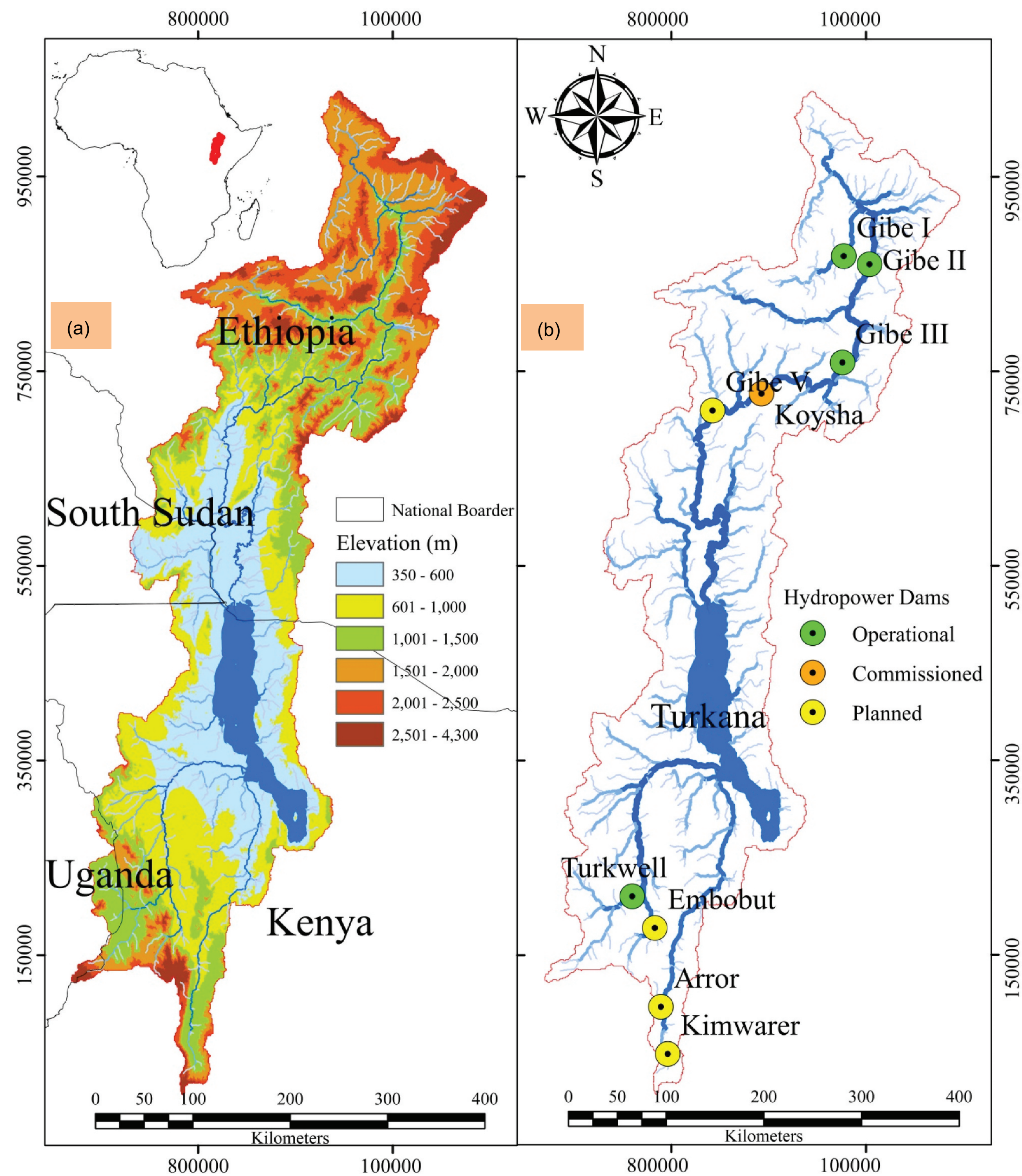

Figure 1. (a) Setting of Omo Turkana basin with elevation variation and (b) locations of hydropower dams with the distribution of the river network in the basin.

(3) The streambed is free of aquatic plants and not subject to scour and fill.
(4) The banks of the river are permanent, high enough to contain floods, and free of aquatic plants.
(5) The stream channel has unchanging natural controls in the form of a bedrock, outcrop or other stable bed material for the low flow and a channel constriction for the high flow that is not submerged at all stages.
(6) A pool is present upstream from the site at extremely low stages to ensure a recording of extremely low flow and to avoid the occurrence of high velocities during periods of high streamflow.
(7) The gauging site is far enough from the confluence with another stream or from tidal effects to avoid any possible impacts on the measurement of stream stage.

Table 1. Salient features of the protocol used during inspection of streamflow gauging sites.

Protocol	Inspected themes	Description of tasks
I	Location and accessibility of gauging site	The accuracy of the coordinates of the gauging sites from the national hydrological service was compared against our own global positioning system recordings. Spatial distribution of the sites and the ease to access the gauging sites were also assessed.
II	Suitability of gauging site	At the gauging site, susceptibility of the riverbed and its to erosion and sedimentation were inspected. At the vicinity of the gauging site, the longitudinal alignment of the river stretch was inspected for the presence of meandering and any obstacles that could affect measurement of water level (river stage).
III	Status of gauging instrument	Level of damage, including sedimentation, to the staff gauge was inspected to serve as an indicator of the reliability of the collected data.
IV	Data recording	The most recent records in the data recording book were visually inspected for readability, to detect suspicious patterns and to look for missing records.
V	Observers' feedback	Observers were interviewed to ascertain existing challenges, observers' level of job satisfaction and their suggestions for (i) improving the data collection process and (ii) increasing their motivation to ensure and sustain reliable data collection.
VI	Overall status of the stations	The operational status of the stations was classified to indicate the state of maintenance, need for relocation of site or any other further interventions.

(8) The gauging station is far enough from the back-water effects in floodplain areas, or caused by dam construction.
(9) A reach for the measurement of discharge at all stages is available within the environs of the gauge site.
(10) The site is readily accessible for ease of installation, operation, and maintenance of the gauging station.

A safe, accurate and representative measurement of river stage and discharge requires an appropriate gauging site. Here, we applied the Rosgen stream classification (Rosgen 1994) to characterize the river channel at the gauging sites by its proficiency to determine the suitability of the gauging site for proper measurement of river stage (water level) and discharge. It describes the physical condition of a gauging site in terms of the channel stability, alignment, flow confinement, scouring and sediment susceptibility, and range of flow magnitude. In this approach, the river is classified into seven major stream types based on entrenchment, gradient, width/depth ratio, and sinuosity. Then, each river type is further classified into one of six categories based on the type of the riverbed material, which may vary from bedrock to silt/clay. We applied this river characterization based on field observation of the channel and bed material at the gauging site. Additional information on the stream types is included in the Results section of this paper.

3.2 Data completeness and homogeneity

Time series of streamflow data of 32 stations in Omo-Gibe basin were obtained from the Ministry of water, irrgation and energy (MoWIE). We did not receive the data for the remaining eight stations. The data were evaluated in terms of length of the observation period, percentage of days with a missing record and presence of contrasting recordings (i.e. abrupt changes) in the time series. A mean value of streamflow data can experience a notable change due to a station relocation, a change in gauge datum or the use of another measuring device (Buishand 1984). Since there is no widely accepted standardized method for detecting these changes, we arbitrary selected the Buishhand method to test the homegeneity of recordings in the streaflow time series.

In the Buishand method, the annual streamflow data can be represented by $Y_1, Y_2, \ldots, Y_n$, with an annual mean of $\bar{Y}$. The adjusted partial sums are defined as follows (Buishand 1982):

$$S_0^* = 0, S_k^* = \sum_{i=1}^{k}(Y_i - \bar{Y}), k = 1, \ldots, n. \quad (1)$$

Homogeneous multi-decadal streamflow time series do not show abrupt changes (i.e. break points) and the deviation from the mean will fluctuate around the mean ($S_k^* = 0$). In the case of inhomogeneous annual data, the year at which the value of S_k^* attains either a maximum or minimum value is detected as the break year. In this study, the estimated test statistics was compared against the critical value at a 95% confidence interval to statistically detect the significance of abrupt changes.

4 Results

4.1 Spatial distribution of gauging stations

The distribution of the river gauging stations was evaluated for elevation zones and stream orders (Table 2). The low-elevation zones (i.e. elevation less than 800 m) that cover a large part of the basin are hardly monitored. Hence, most of the gauging stations are located on the rivers at the upper and middle parts of the basin. For instance, eight gauging stations are located on Gilgel Gibe River which is a headwater river, and about 82% of the stations are situated on the headwater rivers with low stream orders. This indicates that the number of river gauging stations is low in the valleys and floodplains where streamflow in a river system is largest. Nearly two-thirds of the stations are located on first-order streams, indicating the poor coverage of stations at high stream orders where aggregated streamflow discharges and sediment yields are expected. Stations on the

Table 2. Distribution of streamflow gauging stations across different ranges of elevation and river orders.

Elevation (m)	Number of stations	Stream order	Number of stations
< 800	1 (4%)	1	32 (64%)
800–1500	14 (29%)	2	9 (18%)
1500–2000	33 (63%)	3	7 (14%)
> 2000	2 (4%)	4	2 (4%)

high stream orders would have provided data to evaluate the combined hydrological effects of land use and climate changes in the basin.

4.2 Accessibility of the stations

Accessibility is one of the basic requirements to permit monitoring, supervision, and maintenance of streamflow gauges. This requirement is evaluated for 40 stations in the Omo-Gibe basin in Ethiopia where most stations are located. During the field work, 72.5% of the stations were accessed from the nearest major town via asphalt roads and the remaining stations were accessed by gravel roads (Fig. 2b). The majority of the stations are concentrated at a relatively short radius (up to 60 km) from eight major towns – Ambo, Bako, Bonga, Jimma, Jinka, Sawula, Sodo and Welkitie (Fig. 2a). About half of the stations are within the surroundings of Sodo and Welkitie towns. Based on our inspection, most of the visited stations are easily accessible, favouring periodic follow-up of the stations and the supervision of the observers.

The distance between the house of an observer and a streamflow gauging site is one of the most important factors that affects the number of missing or falsified

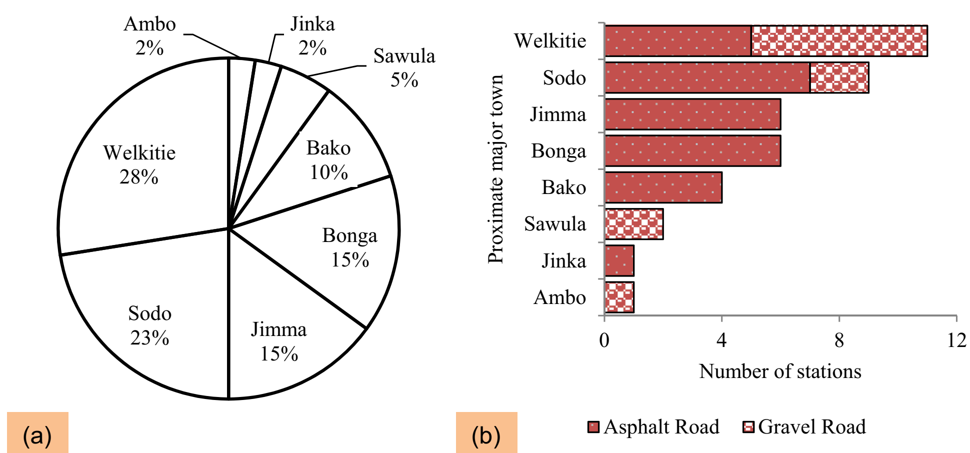

Figure 2. Density of streamflow gauging stations in Omo-Gibe basin with respect to (a) the nearest major town and (b) the type of access road.

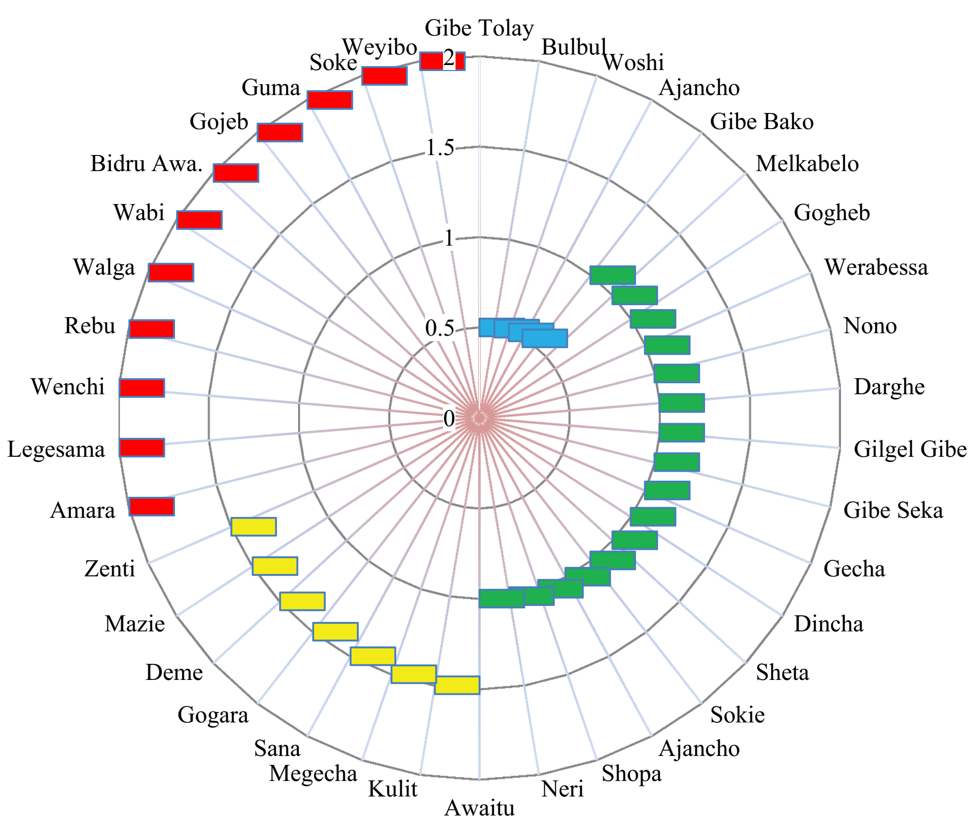

Figure 3. Average daily time (twice in a day) taken by an observer to access the gauging station, record river stage and return back home (30 min in blue, 1 hour in green, 90 min in yellow and 2 hours in red).

records. Nearly all observers are part-timers and hence have other jobs. It is assumed that the observers will not miss recording data when the travel distance is very short. However, a long travel distance to stations may affect the observers' engagement when other income-source jobs or activities require their presence. As a result, they may miss or change the recording time, or they may fill the record with a fictitious value.

For all gauges evaluated in this study, only four observers can take a recording at a travel distance of only a few minutes (Fig. 3). The remaining observers (89%) require at least one hour of travelling for data recording on a daily basis. This covers the twice-a-day activity (morning and evening) for an observer to walk from their house to the gauging station, record the river stage measurements and return to the house. This suggests that the data recording is likely to significantly interfere with the other daily activities (e.g. farming, social obligations) of the observers, possibly reducing their commitment to data recording.

4.3 Type of installed gauging equipment

The state of maintenance of the monitoring equipment affects the reliability of time series records of river stage data but also the accuracy of daily observations. In Omo-Gibe basin, the measuring instruments are either automatic using ultrasonic sensors or manually operated using staff gauges. Ultrasonic sensors can provide hourly or sub-hourly river stage data. This equipment is installed at three locations: Gibe River near Abelti, Gibe-I Dam, and Gojeb River near Shebe. The staff gauges, which are made of fibreglass and steel, are the most commonly used equipment (92.5%) for measuring the river stage in Omo-Gibe basin. The observers are expected to read the stage on the staff gauges twice per day.

4.4 Geographic coordinates of stations

An accurate description of latitude and longitude is very important for accessing the gauging locations. The coordinates of the gauging stations are also critical inputs for the delineation of a watershed boundary and for drainage network extraction. For this study, the coordinates of the stations were received from the hydrological service provider, but for validation purposes, during the field visit coordinates were also recorded using our own handheld Garmin Global Positioning System (GPS). The GPS has a horizontal accuracy of less than 3 m.

The coordinates of some of the stations can be considered accurate for hydrological applications. Coordinates obtained from the data provider for 11 stations showed substantial deviation (> 2 km) from the GPS-based coordinates that we measured in the field (Fig. 4b). A large deviation in station coordinates can cause a substantial under- or overestimation of upstream catchment area during catchment delineation to serve hydrological modelling. Such delineation effects can cause hydrological models to under- or overestimate the simulated runoff, or result in sub-optimal model parameter values. The use of sub-optimal model parameter values leads to flawed and unsound model simulations by virtue of the misfit between real-world and delineated catchment sizes.

4.5 Status of existing gauging stations

One of the aims of the field inspection was to evaluate the operational status of the gauging stations. Although it is commonly assumed that all stations are in an operational state, our field investigation showed that this is not always the case. Only nine stations (17%) were found to be fully operational (Fig. 5a). These stations can function without maintenance, at least in the short term. Fourteen stations (27%) were classified "repairable" (Fig. 5b). These stations were mostly providing river stage data, but the reliability of the data is questionable. They require different maintenance efforts including replacing a corroded or broken staff gauge, removal of sediment or relocation of the gauging staff. The remaining one-third of the stations were collapsed since the staff gauges were missing or submerged by sediment deposition (Fig. 5c). The ultrasonic station that is installed at Gojeb River was not functioning since vining shrubs interfered with the data recording by shading its solar panel and hindering its interface with the river water. Only the stations on the Ethiopian side of the basin were visited. Future studies could evaluate the status of the river gauging stations on the Kenyan side of the basin (Fig. 5d).

The observers at some of the collapsed and repairable stations took the initiative to maintain the continuity of the data recording. Some observers adopted indirect techniques of using two wooden sticks to measure the river stage above a certain reference benchmark. The benchmark was set during staff gauge installation to refer to the marked depths of the river stage (such as 1, 2, 3 or 4 m). It is usually located at the side of the river channel as a painting on a rock or a concrete fill. These benchmarks often were not easily distinguishable as they were covered by silts or disappeared when the riverbank collapsed.

Since the observers were taking the measurement downwards from the water surface, the measurement is affected by the depth of the accumulated sediment on the riverbed and puts the life of the observers at risk during high-flow periods. However, the approach can be accurate for low or medium flows at the gauging sites where the sediment accumulation is insignificant. The observers were forced to take such indirect measurements since the stations were not timely maintained.

4.6 Channel characteristics at gauging sites

Based on the Rosgen stream classification system, the gauging sites in the Omo-Gibe basin were installed on five (A, B, C, D and F) types of streams (Fig. 6). These stream types were further classified based on their channel bed material at the gauging sites. Among the stations visited during the field work, only one station (Walga station near Wolkitie town) was installed on a strong and sound bedrock that is an ideal location for a streamflow measurement. About 61% of the stations were located on sand and silt-clay bed materials. These channel beds are prone to change due to bank erosion, scouring and/or sediment deposition problems. The remaining stations were installed on boulder and gravel bed materials which are relatively convenient for measuring the streamflow without significant change in the channel cross-section over time.

The five stream types at the gauging sites in the Omo-Gibe River basin are described as follows:

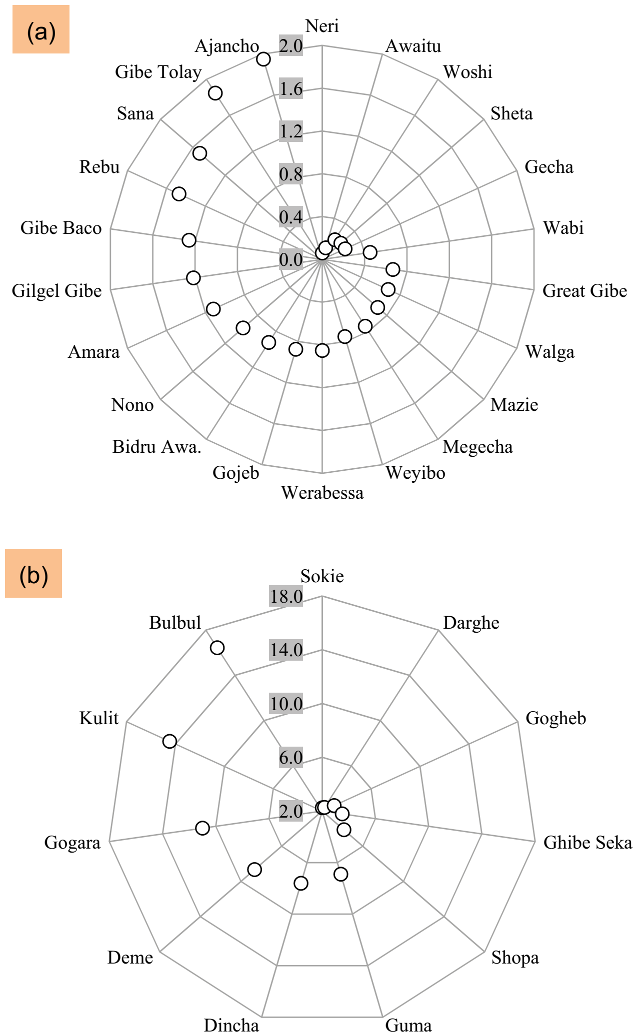

Figure 4. Difference in distance (in km) between station coordinates from MoWIE and station coordinates from our own GPS records: (a) less than 2 km and (b) greater than 2 km deviation.

(1) **Type A** streams usually occur at a low stream order and have a steep channel bank. These types of rivers have a high sediment transport potential and a relatively low sediment storage capacity due to their narrow channel. An accumulation of organic debris is a factor determining the bed form and the overall channel stability of such stream types. Three stations (Ajancho River near Areka, Bidru River near Sokoru, and Awaitu River at Jimma) were installed on Type A streams.

(2) **Type B** streams are characterized by a moderately steep to gently sloped terrain. Such rivers have narrow valleys that limit the development of a wide floodplain. The morphology of their beds is influenced by debris and local confinement that causes scour pools. Because of a low channel aggregation and degradation process, type B streams have a low rate of erosion and lateral expansion. The stations that were installed on Type B streams are Megecha River at Gubre, Bulbula River near Serbo, Neri River near Jinka, Darghe River near Tedelle, Nono River at Darghie, Rebu River near Wolkite, Sheta River at Bonga, Gogheb River near Endeber, Gibe River near Baco and Seka, Melkabelo River near Tibe, Soke River near Hadero and Areka, Werabessa River near Tole, Gicha River near Bonga, and Dincha River at Bonga.

(3) **Type C** includes streams with a well-developed floodplain and made up of relatively flat pool bed forms. In such rivers, processes such as lateral expansion, aggradation and degradation of channel are mainly governed by the natural stability of stream banks, the existing upstream watershed conditions and the flow and sediment regime. The stations installed on Type C streams include Legesama River near Tibe, Sana River near Tunto, Kulit River near Tedelle, Shopa River near Areka, Woyibo River near Areka, Woshi River near Dimbira, and Amara River near Sheboka.

(4) **Type D** streams distinctively occur as multiple-channel systems (composite cross-sections) exhibiting a series of various bar types and bare islands in the channel that shift position frequently during runoff events. These rivers are found in valleys with moderately steep slopes to very wide, flat, low-gradient valleys containing very coarse and finer materials. Channels of such stream types are found in landforms and related valley types consisting of steep depositional fans, broad alluvial mountain valleys, and deltas. The extreme flows of these rivers cause a high rate of erosion and sediment supply. The stations that were installed on Type D streams include Gogora River near Dana1, Deme River at Oreta Alem, Mazie River near Morka, and Zenti River near Mella.

(5) **Type F** streams occur in valleys within the lowland areas and are characterized by a very wide channel at the bankfull stage. The channel width of such streams consistently increases until it establishes a stable and functional floodplain. In this river system, very high bank erosion and lateral expansion rates are noticeable since the channel is characterized by a highly weathered rock or erodible material, with several moderated riffle and pool-shaped bedform features that are arranged in a sequence following the flow pattern. In addition, these rivers experience significant deposition and accelerated channel aggradation. Consequently, they have very high sediment supply and storage capacities. The stations that are installed on Type F streams include Wabi River near Wolkitie, Great Gibe River near Abelti, Ajancho River near Bombe, Gojeb River near Shebe, Walga River near Wolkite, Guma River near Andaracha, Gilgel Gibe River near Asendabo, and Gibe River on Tolay Road.

4.7 Data completeness

Poor quality of streamflow time series data is a problem that is familiar to hydrologists. Two common causes of this problem were identified when inspecting the recording book. The first is poor or untidy handwriting. This issue becomes a source of error during conversion of the data into a digital system. The other issue concerned the credibility of the records, since equal river stage records were

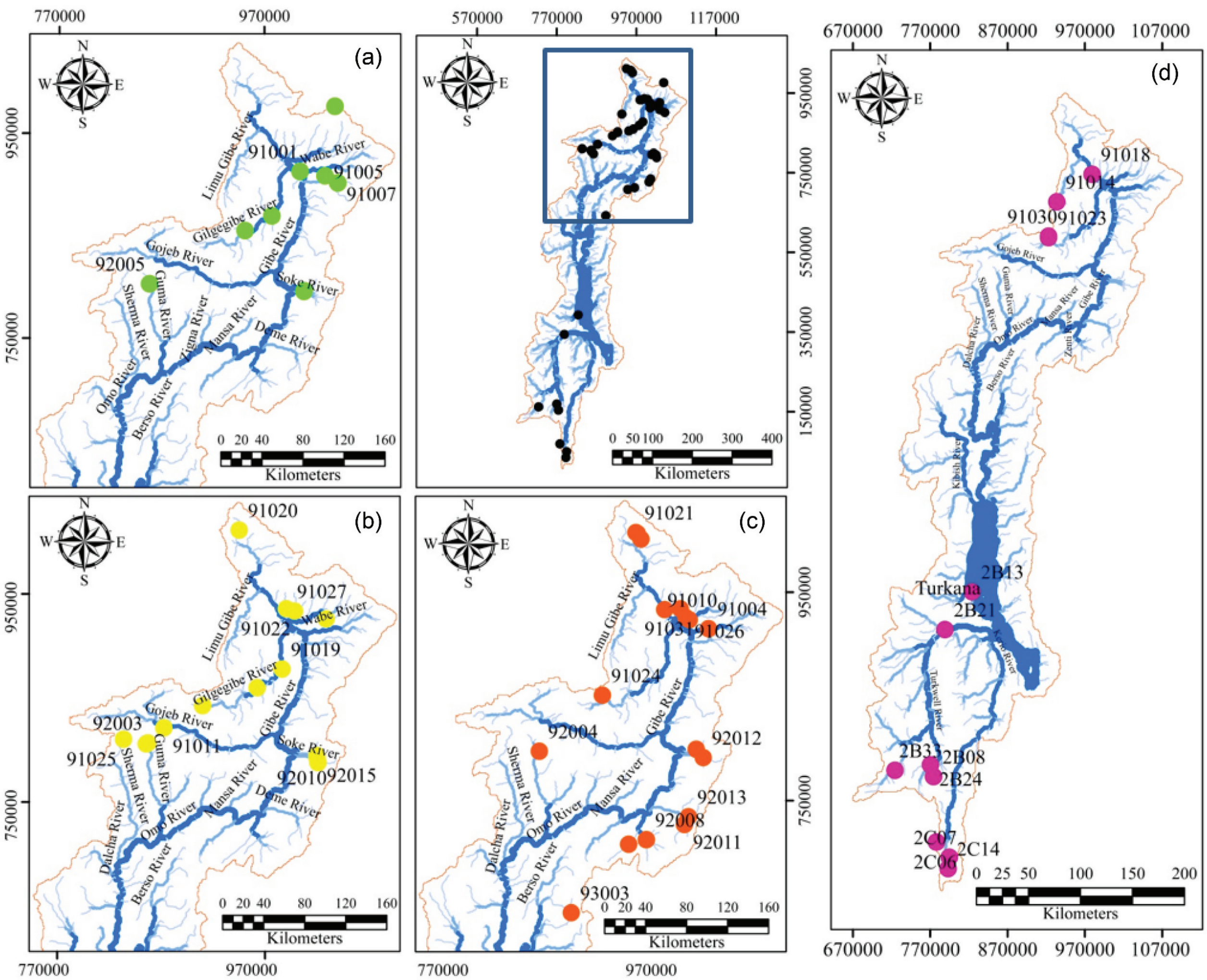

Figure 5. Operational status of existing streamflow gauging stations in Omo Turkana River basin: (a) fully operational, (b) repairable, (c) collapsed and (d) unknown.

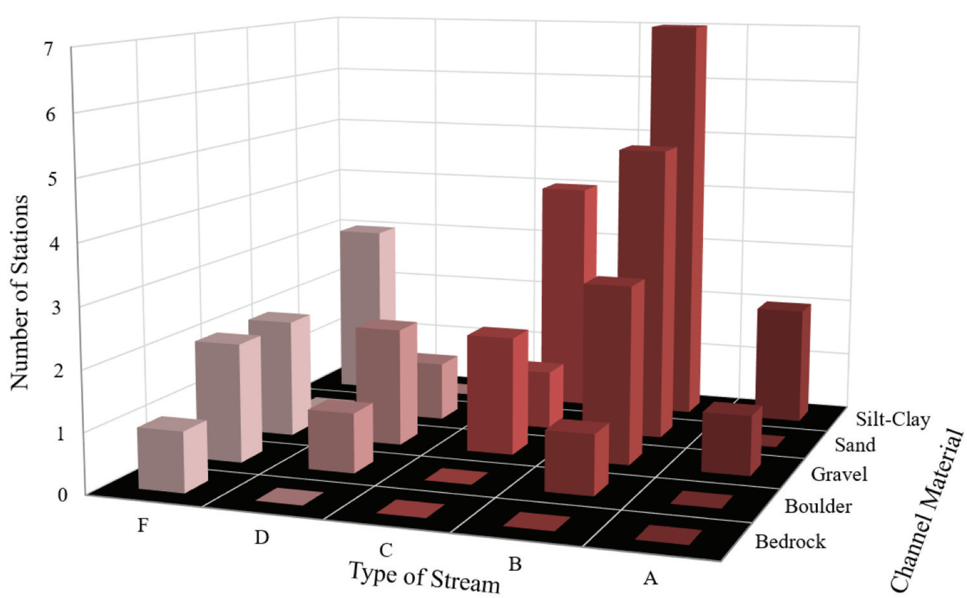

Figure 6. Type of stream and channel bed material of the gauging sites in Omo-Gibe basin.

written with the same tone of ink for several continuous days. This could suggest that the records were filled in without visiting the gauging site.

Useability of the data can also be affected by its completeness. In the study area, the streamflow data from the different stations covers unequal observation periods. Only 12 stations recorded the data for more than 20 years, whereas the remaining stations recorded the data for 10 to 20 years (Fig. 7). This shows only a few stations provide adequate data to study the long-term hydrological changes within their respective gauged cachments. This problem is further exacerbated by data access since the data for the most recent 10–15 years mostly was not accessed since the river stage data was not converted to indicate discharges. This is not only due to a gap in converting the river stage to river discharge data but also caused by the absence of a data quality assessment and timely feedback to the observers.

The time series data of 24 stations shows less than 15% missing records (Fig. 7). Provided that the missing records are not confined to a single season, this can be considered acceptable since a signficant amount of the data is recorded that can be used for further analysis. However, the data of eight stations contains more than 15% missing records. Rebu station has up to 30% missing records.

Proof that a long-term streamflow data series is homogeneous is required before the data can serve applications such as impact assessments or trend analysis. In general, when the hydrological data series is homogeneous, this means that data were recorded with similar instruments, techniques, and environments (Kang and Yusof 2012). However, Table 3 shows that not all stations provided homogeneous data in Omo-Gibe, as abrupt changes in the time series was detected. Most of the abrupt changes (break points) occurred between 1997 and 2004. The data length before and after the break point is too short to undertake an independent trend analysis at many stations. It is important to prioritize sustained data collection at the stations that provided a homogeneous dataset.

During the field visit, we received feedback from the observers about the monitoring process. They identified a lack of periodic supervision and follow-up as a major omission. In addition, observers did not receive quick responses when they reported damaged stations. Their monthly salary often was not paid on time and there were also delays in receiving the data recording book. Five years ago, the daily payment for the job was increased from 8 to 20 ETB (currently, 1 Ethiopian Birr equals 0.019 USD), but the salary has not been increased since then despite a high inflation rate. Hence, the salary is low considering living expenses and does not follow inflation rates. Observers also indicated that the local governance structure has not well acknowledged their work. This can be addressed by establishing a formal link between the local government and the observers.

5 Discussion

Most gauging stations of the Omo-Gibe basin were installed on small rivers at highland areas. Hence, the data from the stations can be used to study the headwater catchments where the runoff is generated. However, medium- and large-scale projects often are constructed on large rivers (high stream order). Also, these rivers contribute to the widespread flooding problem in the basin. Considering these factors and the transboundary nature of the Omo-Gibe River, it is imperative to instal new streamflow stations on the high-order streams.

In our study, the gauging sites were already selected by the national hydrological service and the stations have been operational for several years. Hence, we only checked whether the extent of seasonal vegetation growth and scour and fill has

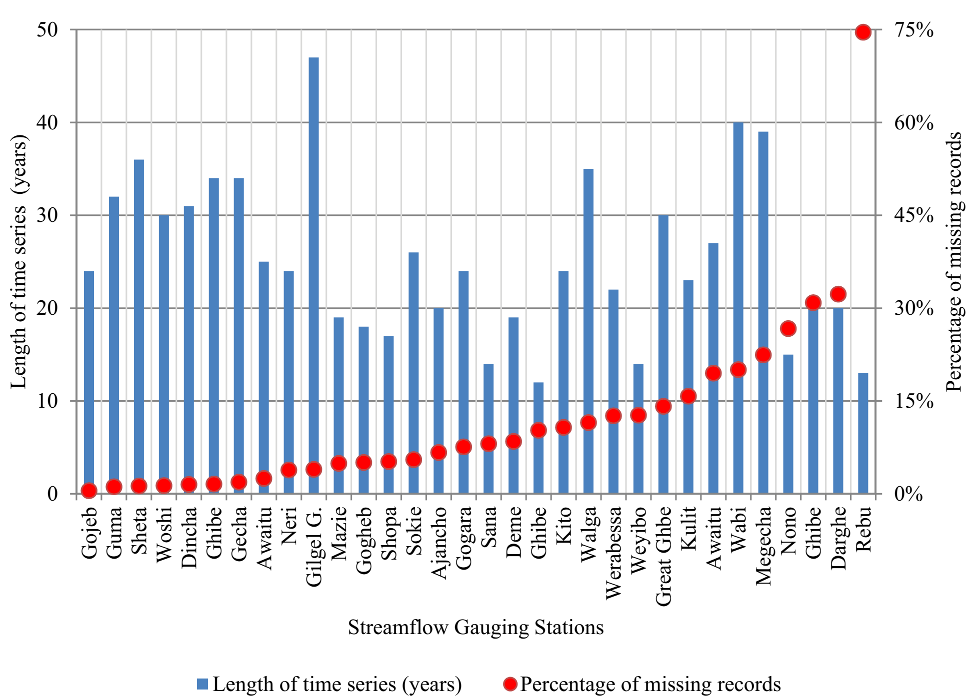

Figure 7. Length of time series of observed river discharge and percentage of missing records from various gauging stations in Omo-Gibe basin.

Table 3. Results indicating homogeneity of the streamflow time series data from the stations in Omo-Gibe (signficance level α = 0.05).

Name of station	Total period	Homogeneity test	Before break point	After break point
Ajancho Nr Areka	1985–2005	Homogeneous		
Awaitu@Jimma	1982–2007	Inhomogeneous	1982–1998	1999–2007
Darge Nr Tedele	1987–2005	≫	1987–1999	2000–2005
Gibe@Abelti	1980–2010	≫	1980–1987	1988–2010
Gecha Nr Bonga	1982–2016	≫	1982–1999	2000–2016
GilgelGibe Nr Asendabo	1967–2014	Homogeneous		
Gibe Nr Limu	1984–1999			
Gogob Nr Endeber	1989–2007			
Gojeb Nr Shebe	1980–2004	Inhomogeneous	1980–1987	1988–2004
Guma Nr Andaracha	1981–2008	≫	1981–2003	2004–2008
Kito Nr Jimma	1982–2005	≫	1982–1994	1995–2005
Kulit Nr Tedele	1984–2005	≫	1984–1991	1992–2005
Megech Nr Gubre	1981–2006	Homogeneous		
Nono@Darge	1990–2005			
Rebu@Wolkite	1989–1993	Inhomogeneous	Discarded data from this station	
Sheta@Bonga	1980–2016	Homogeneous		
Sokie Nr Areka	1987–2006	Inhomogeneous	1987–1998	1999–2006
Wabi Nr Wolkite	1967–2007	Homogeneous		
Walga Nr Wolkite	1971–2006			
Woshi Nr Dimbira	1984–2014	Inhomogeneous	1984–2001	2002–2014
Dincha@Bonga	1982–2013	Homogeneous		
Demie@Orota Alem	1987–2006			
Shapa Areka	1989–2006			
Gogera River Nr Dana1	1982–2006			
Gibe Nr Tollay	2000–2012			
Maize Nr Morka	1987–2006	Inhomogeneous	1987–1991	1992–2006
Nerie Nr Jinka	1982–2006	Inhomogeneous	1982–1998	1999–2006
Gibe Nr Seka	1980–2014	Inhomogeneous	1980–2004	2005–2014
Weybo Nr Areka	1992–2006	Inhomogeneous	1992–1999	2000–2006
Sana Nr Tunto	1992–2006	Inhomogeneous	1992–1999	2000–2006
Awaitu Nr Babu	1989–2016	Inhomogeneous	1989–1997	1998–2016
Werabesa Nr Selkamba	1982–2004	Inhomogeneous	1982–1999	2000–2004

significantly interfered with streamflow measurements at the gauging sites. This study did not explore how riparian vegetation affects the hydraulics at the stations, but we refer the reader to Tabacchi *et al.* (2000) where scientific evidence is provided on such effects. Modelling approaches are available that simulate the dynamics of riparian areas and are able to project their future conditions (Merritt *et al.* 2010). The applications of such approaches for river gauging site selection still need to be explored by future studies.

Channel erosion and bank instability are noticeable problems around most gauging stations, indicating that the WMO guidelines on installing gauges were not strictly followed during site selection. The poor condition of the sites exposed the monitoring instruments to frequent damage, causing interruption in data recording. The problem is greatly exacerbated by a lack or absence of regular and timely maintenance of the stations, which is a common problem for river monitoring across Africa. This is in line with Blume *et al.* (2017) who gathered the opinion of 336 hydrologists through an online survey. The hydrologists acknowledged the importance of monitoring but highlighted the challenges associated with the maintenance of the stations.

Despite advances in hydrological sensors and computational facilities (Tauro *et al.* 2018), the historical networks are deteriorating and declining in number at a global scale,[1] but the problem is particularly widespread in African basins. For instance, 350 stations were monitored on the Congo River in the 1960s but the number of stations declined to only 10 by 2013 (Croneborg 2013), while rating curves have not been updated for several decades (Alsdorf *et al.* 2016). Similarly, river gauging in Niger basin has experienced a decline, with most stations ceasing data collection in early 2000 (Schröder *et al.* 2019). In 2006, 31 data collection platforms (DCPs) of rivers were lost over a period of 5–8 years in southern African countries due to lack of resources for maintenance (Houghton-Carr and Fry 2006). Similarly, some of the streamflow monitoring sites are lost in Omo-Gibe. Nearly all the gauging stations had not been maintained for more than five years. As a result, some of them collapsed, causing a complete or partial interruption of the river monitoring activity. The recent discharge data (since 2005) of the stations has not been made accessible to researchers and practitioners. This inaccessibility of the recent 10 to 15 years' worth of data is impeding research on the impacts of climate variability, climate change, land use change and intervention, and anthropogenic activities in the basin. The reason for the inaccessibility is that the river stage data has not been converted to discharge data. However, the findings of this study and informal communication with local experts suggest that the problem goes beyond data conversion and requires further investigation. For instance, the institutional aspects of hydrological data storage and provision deserve attention as open data policies have become a new standard in many countries.

Since river stage data is not converted to discharge data, the river stage data is less likely to adhere to the data quality standards as outlined in the Guide to Hydrological Practices (WMO 2009). This is in line with the conclusion of Hudson *et al.* (1999) regarding the absence of quality assurance of hydrometric networks around the world. Hence, not only is

[1]http://www.bafg.de/SharedDocs/Bilder/Bilder_GRDC/grdcStations_tornadoChart.jpg

the density of the streamflow monitoring network deteriorating but also the quality of the data obtained from the network is becoming more questionable.

The time series data of some stations contain more than 15% missing records, although the time series from most stations can be considered complete. The large number of missing and unreliable records of some stations can undermine the usability of the data to serve water resources studies. Also, most of the stations failed to provide time series data that is homogeneous, and hence the data are not fit for use to serve trend analysis. Under such circumstances, the hydrological data service providers are expected to show a reluctance to cooperate (e.g. share data), undermining their importance and credibility (Stewart 2015). This may partly explain why recent data has not been made available to users. It is important to recognize that urgent action is needed in terms of applying corrective measures to faulty instruments, rating curves and data recording. Any further delay only will contribute to a perception by responsible organizations that data collection is not considered a key priority.

All rating curves (stage–discharge relationships) are stored at the national hydrological service, with limited access to users. Therefore, we did not access the rating curves at the time of writing this manuscript. However, it is known that rating curves are not error free, and large errors can be introduced by many factors including velocity and cross-sectional area measurement, interpolation and extrapolation of stage–discharge values, and changes in river cross-section due to erosion and sedimentation (Domeneghetti *et al.* 2012). The error of the rating curve is largest for peak flows due to the limited sample size and overtopping of river channel at some stations, and for low flows due to changes in channel morphology. For instance, Kiang *et al.* (2018) reported that the full width 95% uncertainties of rating curves can reach up to 200% for high flows and 100% for low flows. These uncertainties affect the calibration and validation of rainfall-runoff models and streamflow simulations.

Personal communication with staff of the hydrological service indicates that rating curves of the gauging sites in Omo-Gibe have not been updated for several years. Observers also noticed a decline in field visits by hydrology technicians, which indicates a decline in the number of velocity measurements per year that serve to evaluate and update the rating curves. Therefore, urgent action is needed to reverse this decline of velocity measurements. Researchers can contribute by identifying site-specific factors that affect the accuracy of stage–discharge relationships at the gauging sites and by demonstrating approaches to minimize their effects.

Hydrological data and service are deteriorating not only in Omo-Gibe but also in the other Ethiopian basins. For instance, Goshime *et al.* (2019) and Donauer *et al.* (2020) concluded that the hydrological data and service in the Central Rift Valley sub-basin of Ethiopia is facing a serious problem, to the extent that it is not fit for studying the causes of recent lake storage changes. Hence, there is a strong need to examine the entire hydrological monitoring system including the gaps and opportunities related to institutional aspects of it. This will help to identify the points of leverage and prepare a strategy for the hydrological data and service to provide timely data that also is reliable. An institutional analysis can reveal whether the current institutional arrangement is serving its purpose or whether other arrangements are needed to improve the state of monitoring, quality assessment and data sharing. Studies are needed to evaluate the advantages of joining the hydrological services with meteorological services or re-establishing the hydrological service as a separate agency. In this context we note that for many countries open data policies are in place or under development – a development that the authors strongly support.

In Ethiopia, the valorization of the hydrological database is lacking (World Bank 2014). Hence, empirical evidence on the importance of hydrological data does not exist to convince donors and decision makers that they should be committed to maintaining and improving the service. It is important to demonstrate that the data from the observation network remains critical as:

(1) Field hydrology is on the decline (Burt and McDonnell 2015).
(2) The need is increasing to evaluate the integrated effects of climate variability, climate change, land use changes and interventions, and anthropogenic activities, and to develop adaptation strategies (IPCC 2021, Worako *et al.* 2021).
(3) The importance of data for process understanding as input to the prediction of streamflow in ungauged catchments is acknowledged (Selker and Ferre 2009). In fact, the design hydrograph estimation in ungauged basins represents one of the most common practices and, yet, is a challenging open research topic for hydrologists especially when discharge observations are not available (Grimaldi *et al.* 2021).
(4) Remote sensing and new innovations in ground-based sensors still require data from the traditional stations for calibration and validation (Mastrantonas *et al.* 2019).

The World Bank (2019) reports that the socio-economic benefit–cost ratio of hydrological services can exceed 3–4. The Global Hydrometry Support Facility (WMO HydroHub) also demonstrates the benefits of investments in hydrometeorological data and services (https://hydrohub.wmo.int/en/home). Similar initiatives at the basin or sub-basin scale can be helpful to bring the issue of hydrological data and service to the front and attract investment. There is a strong need to synergize the efforts by various donors and other organizations to pool resources for maintaining and sustaining the service. National governments also must recognize that the cost of collecting data of the required quality and accuracy is outweighed by the ensuing benefits, especially in a changing and highly variable world (Stewart 2015).

There are opportunities for improving hydrological data and service in Ethiopia: (i) innovation in sensor technologies and data processing are presenting opportunities for enhancing the observation networks that are not being realized (Dixon *et al.* 2020); (ii) bottom-up approaches through citizen science engagements can be further investigated (Nigussie *et al.* 2020); and (iii) donors have been investing to improve hydrological data and service in Ethiopia, but the impact of these investments has yet to be evaluated.

The approach in this study can guide timely improvement of hydrological services. However, the following can be addressed in the future to best benefit from the approach: (i) the field inspection of stations and data quality checks must be conducted on a regular basis, (ii) the data collection protocol needs to be continuously updated with feedback from relevant institutions and experts, and (iii) snap streamflow velocity measurements (Drogue and Plasse 2014) during the field visit can provide an opportunity for rapid evaluation of the accuracy of rating curves.

6 Conclusions and recommendations

This study addressed a wide scope of aspects that concern the provision of accurate and reliable streamflow time series data for Omo-Gibe basin. On the performance of the current network we draw the following conclusions:

- There is a notable reason to be concerned about the state of the streamflow monitoring network and quality of streamflow data in Omo-Gibe basin. The time series data of most stations is not long enough or sufficiently homogeneous to serve the analysis of climate and/or land use change impacts. The lack of sound hydrological projections carries a potential for danger with unknown adverse consequences to society and future livelihoods.
- Nearly two-thirds of the gauging stations are located on first-order streams, with most stations having poor site accessibility. The current network hampers hydrological impact assessments of climate and land use changes in the basin.
- The reliability and continuity of water level records in the basin are affected by inappropriate site selection and lack of proper maintenance. Three out of five stations were installed on an unstable channel bed that results in an unreliable stage–discharge relationship. One-third of the stations can be considered non-operational by virtue of missing staff gauges and sediment accumulation.
- A coordinated effort is needed to ensure all existing stations are fully operational, that data is reliable, and that users have access to data. We suggest a prompt action to maintain the stations and avail the recent 10–15 years' worth of streamflow data in the Omo-Gibe basin.

Recommendations of this study that also apply to other streamflow networks in Ethiopia and Africa at large are the following:

- Preparation of a protocol is recommended to label individual gauging sites, with the aim to identify a country-wide network with key stations to serve strategic aims, risk and hazard assessments, and national policies on distribution and provision of water resources.
- This study identified a strong need for a proactive and committed engagement of researchers, government, and donors to underline and emphasize the importance of maintaining and sustaining the streamflow stations, and to reverse the deterioration of hydrological services.
- At the relevant institutional levels, we recommend intensified efforts to identify bottlenecks in data collection and opportunities to improve data collection with quality assessment. Open data policies with data sharing and data access are strongly recommended, where descriptions of data quality and reliability should be given by data providers.

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