hydrology

Review

Priority Research Topics to Improve Streamflow Data Availability in Data-Scarce Countries: The Case for Ethiopia

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Abstract: Lack of consistent streamflow data has been an increasing challenge reported by many studies in developing countries. This study aims to understand the current challenges in streamflow monitoring in Ethiopia to prioritize research topics that can support sustained streamflow monitoring in the country and elsewhere. A workshop-based expert consultation, followed by a systematic literature review, was conducted to build a collective understanding of the challenges and opportunities of streamflow monitoring in Ethiopia. The experts' consultation identified the top ten research priorities to improve streamflow monitoring through research, education, remote sensing applications, and institutions. The experts' views were supported by a systematic review of more than 300 published articles. The review indicated scientific investigation in Ethiopian basins was constrained by streamflow data gaps to provide recent and relevant hydrological insights. However, there is inadequate research that seeks solutions, while some researchers use experimental methods to generate recent streamflow data, which is an expensive approach. Articles that attempted to fill data gaps make up less than 20% of the reviewed articles. This study identified research priorities that can benefit streamflow data providers and the research community in alleviating many of the challenges associated with streamflow monitoring in countries such as Ethiopia.

Keywords: streamflow monitoring; data gap; hydrological service; stakeholder consultation; data-scarce countries

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1. Introduction

Streamflow data of adequate accuracy and coverage is essential for water resource planning and management. Despite its importance, there are challenges in maintaining streamflow data availability, particularly in developing countries. The data challenges span the full value chain of hydrological observations, products, and services [1]. The United Nations Educational, Scientific and Cultural Organization's (UNESCO) Intergovernmental Hydrological Programme (IHP) phase IX identified "Bridging the data-knowledge gap" as one of the five priority areas of their strategic plan [2]. Hydrological data have been a constraint to tracking the progress of the Sustainable Development Goals (SDG), which, at its core, is a data-dependent endeavor [1].

Maintaining existing streamflow gauging stations is of great importance for water resource development [3] and for ensuring the continuity of the data for different purposes [4,5]. Long-term streamflow data with reasonable quality is crucial for different applications, including hydrologic model setup [6,7], hydrological extremes analysis [8–10], and evaluating hydrological alteration and biodiversity change due to anthropogenic activities and climate variability [11,12]. For water resource planning and management, a quality-assured minimum record of streamflow observations (30 years of records) is commonly recommended by the World Meteorological Organization [13]. However, longer than 30 years of streamflow observations are needed to conduct reliable hydrological trend analysis [14,15].

Despite the importance of streamflow data, its availability has been declining across all continents [3,16]. According to a 2014 Global Runoff Data Center (GRDC) report, several gauging stations have been declining, from 8000 stations before the 1970s to less than 1000 stations in the 2010s [17]. This decline could be associated with poor reporting systems, lack of funding, and inadequate station maintenance. In Africa, the percentage of operational gauging stations peaked at 70% of installed stations at the end of the 1970s before falling to 20% by 2010 [3]. The decline has been particularly evident in most African nations, where two-thirds of the monitoring network is in poor or declining conditions [18]. Also, the density of streamflow gauges in Africa is far lower than that of the World Meteorological Organization (WMO) recommendations [19]. This problem, nevertheless, is not only in Africa but also common in other countries, including Russia [20], Canada [21], and the United States [22]. Data density and quality are among the most critical issues in regional monitoring networks in Europe [23].

In Ethiopia, the Ministry of Water and Energy (MoWE) has 541 streamflow gauging stations (Figure 1), of which 490 are operational [24], which is far lower than the WMO recommendation of 674–1796 stations for the country [25]. Data discontinuity in many operational gauges imposed a huge challenge in making useful river discharge analysis and modeling. In addition, the dataset itself has a problem of short time duration [26,27] and limited spatial coverage and availability [28]. As a result, recent data collection is relying on individual research project activities [29,30]. For instance, Haile et al. [31] and Taye et al. [32] demonstrated how reversing the unavailability of streamflow data in the Lake Tana sub-basin of Ethiopia is possible through supporting data providers.

Several studies highlighted the decline of streamflow networks in Ethiopia [24] and identified its possible causes [33]. In most places, the need to maintain and strengthen existing monitoring networks faces challenges due to financial and logistical constraints. This problem is not limited to Ethiopia, but it is a global challenge compounded by the lack of support for essential long-term monitoring [15]. Hydrological service-providing agencies in developing countries often do not easily access research evidence that supports them in justifying monitoring activities in socio-economic terms. Overall, there is a lack of literature that highlights how the decline in river flow monitoring affects water resource planning and management decisions and the associated socio-economic implications.

The impetus for this review is the increasing number of studies that reported existing problems of streamflow monitoring in Ethiopia and called for action [32–34]. We also hypothesize that hydrological services in African counties would greatly benefit from the findings of studies that address priority research questions in streamflow monitoring and, hence, the need to identify them for the region. Globally, there are limited publications on the identification of priority research questions that are region-specific. For instance, water@leeds, an interdisciplinary collaboration of academics, identified priority research questions for water in the United Kingdom in 2010 [35]. Mdee et al. [36] identified one hundred priority water-research questions, whereas [37] Blöschl et al. suggested twenty-three unsolved problems in hydrology to be addressed for stronger harmonization of research efforts. The streamflow data problem was among the priority research questions in previous studies [36,37]. However, the identification of research topics for a specific region and a single hydrologic issue (e.g., streamflow monitoring) is not common. In this study, we customize and expand such research topics for a developing country like Ethiopia. The prioritized research topics are expected to harmonize research so that the findings contribute to enhanced availability and quality of streamflow data, including guiding future investments in river monitoring.

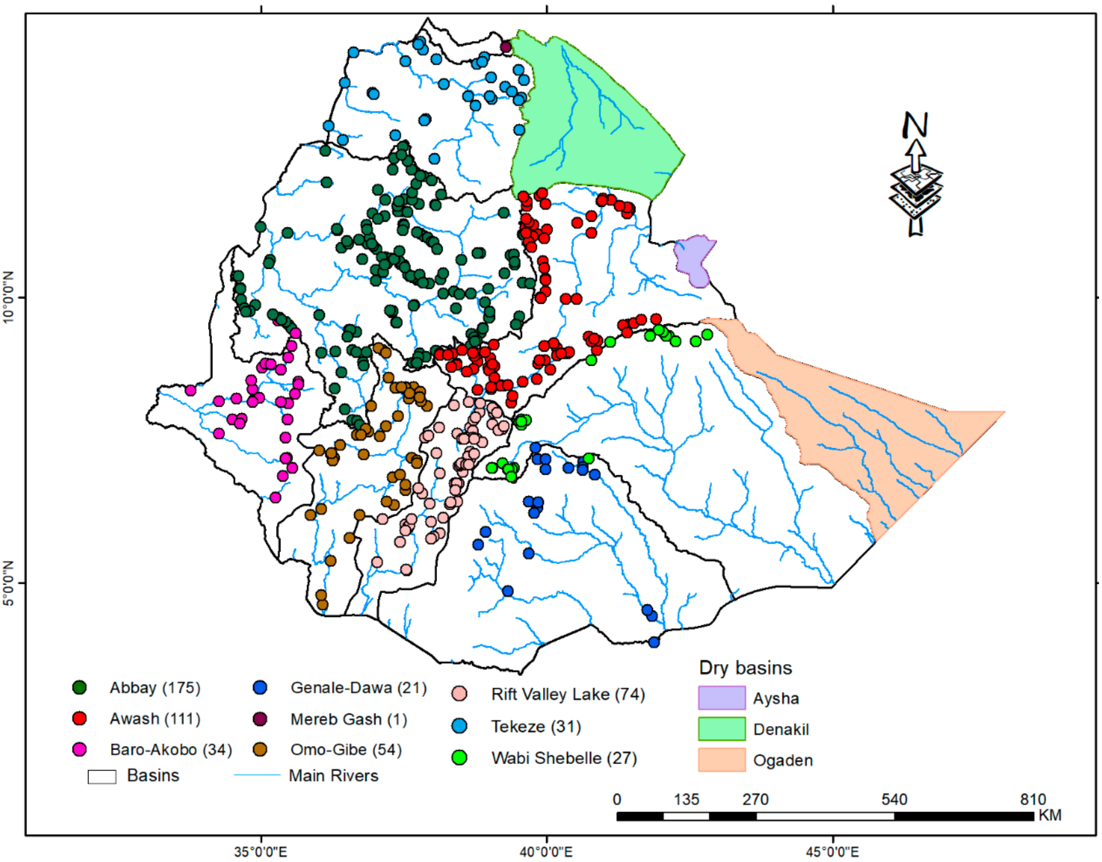

Figure 1. Spatial distribution of streamflow stations in Ethiopia with the total number of stations in each major river basin (source: Ethiopian Ministry of Water and Energy).

2. Methodology

This paper followed two approaches to synthesize the challenges and opportunities of streamflow monitoring and research priorities in Ethiopia: (1) workshop-based consultation and (2) literature review. Initial literature review and current understanding of the Ethiopian context led to employing expert consultation, which led to workshop organization. After obtaining relevant information from the consultation, a detailed literature review was conducted to understand how the priorities align with the wider literature.

2.1. Workshop-Based Expert Consultation

A two-day expert consultation was conducted from 19–20 July 2022 on streamflow monitoring challenges, opportunities, and research priorities in Ethiopia. Thirty participants who are experts in hydrology, water resources, remote sensing, meteorology, and hydrogeology were included. They were representatives from construction, academia, research, and government sectoral offices. They came from Bahir Dar Institute of Technology (BiT), Ethiopian Institute of Water Resources (EIWR), Arba Minch Water Technology Institute (AWTI), Addis Ababa Science and Technology University (AASTU), Ethiopian Meteorological Institute (EMI), Abbay Basin Development Office, Ministry of Water and Energy (MoWE), IRCWaSH, and Ethiopian Construction Design and Supervision Works Corporation (ECDSWC). The institutions and experts were selected to represent the major river basins in Ethiopia, such as Abbay, Awash, Rift Valley Lakes, and Omo-Gibe River basins. The consultation team was composed of data users and data providers who are professionals in their field who frequently require hydrological data for their research, design, and decision-making on investments and policies. Their diversity and proficiency provided the basis for open and unbiased expert participation during the discussions and minimized professional bias.

Four thematic groups (remote sensing, institutions, education and practice, and research) were selected for the discussion by the workshop organizers, also authors of this study. This was based on the WMO hydrological monitoring bulletin [38] that outlined essential elements of a successful hydrological monitoring program that included technology, training, network design, data management, and a quality management system. The technology element aligns with the remote sensing thematic group, while training is related to education. Network design and quality management systems are related to institutions, while data management can be linked with research.

The aim of the workshop and the expected outcomes were shared with the participants a week before the workshop dates. Guiding questions were prepared a priori to guide the discussions on the streamflow data challenges and the potential contribution of research to streamflow monitoring and data availability (Table A1). These questions were displayed for all workshop participants. The questions were grouped into four thematic areas (Figure 2). The main objectives of these questions were to guide discussion on:

1. Enhancing streamflow monitoring continuity and data availability,
2. Realizing the potential of emerging technologies to support streamflow monitoring,
3. Integrating education, research, and practice to ensure streamflow data continuity and availability,
4. Understanding the role of different institutions that can support streamflow data availability and quality, and
5. Finally, identifying research priorities to improve streamflow monitoring and data quality for the scientific community.

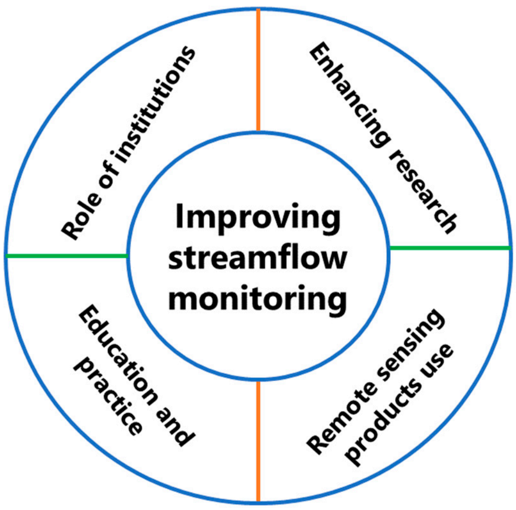

Figure 2. Thematic areas selected for expert-based consultation workshop on streamflow monitoring.

The experts were grouped into the four thematic areas based on their expertise, which covers remote sensing experts, decision makers, university professors, practitioners, and research center staff who are active in conducting hydrological research in Ethiopia. Each group had 7 or 8 members and identified a chairperson and rapporteur. The group discussion lasted for 2 h, followed by reporting back to all participants to build a collective understanding of the challenges, opportunities, and research priorities of streamflow monitoring in Ethiopia. Ensuring open and unbiased expert participation is crucial. Therefore, the participants were given opportunities to discuss in small groups where they could express their unbiased views, which was followed by discussions with all participants.

Identification of Top Ten Research Priorities

In the workshop, the groups of experts were given the opportunity to prioritize the top ten research topics on streamflow monitoring in Ethiopia. The main factors considered during prioritization were the fact that many studies are reporting challenges of data quality, accessibility, and the urgency of finding solutions to the current scanty situation. Each group selected 10 topics they thought were relevant to improving streamflow monitoring and data quality during the workshop. These were screened for further analysis based on their relevance to streamflow monitoring by the authors of this paper. This reduced the topics by half. Then, a merging of similar ideas was conducted to come up with either 3 or 2 topics from each group. With these steps, from the four thematic groups, ten research priorities were identified.

2.2. Literature Review

Following the expert-based consultation, a search of research articles was conducted to gain a complete understanding of the current literature on streamflow monitoring and data in Ethiopia. Moreover, to better understand how the selected priorities align with wider literature. Published studies on topics pertinent to streamflow monitoring were downloaded from reputable publishers that commonly cover studies of Ethiopian river basins. The search was conducted on ScienceDirect, Springer Link, the online library Wiley, Taylor & Francis online, IWA publishing, and HESS Copernicus. The search keywords used were "Ethiopia AND (streamflow data monitoring OR hydrology)". The search was conducted on 7 November 2022 with no cutoff date. This search resulted in a total of 3440 publications covering review articles, research articles, encyclopedias, book chapters, book reviews, and conference abstracts.

After reviewing the title of the publications, papers that were outside of the intended topic (relevance to streamflow monitoring and data use) and those conducted outside of Ethiopia were excluded. This resulted in 308 relevant articles for further analysis (Table A2). The number of identified articles per publisher was 130 (ScienceDirect), 94 (Springer Link), 22 (Wiley), 28 (Taylor & Francis), 14 (HESS), and 20 (IWA). However, seven articles were excluded due to inadequate details of the methods in their write-up. As a result, only 301 articles were reviewed further. Two of these articles covered more than one river basin and, hence, for basin-level analysis, these articles were counted per basin, making the total count 306. Figure 3 illustrates the process of selecting the publications.

Subsequently, the 306 articles were categorized into six groups to systematically synthesize the results and to find out which topics received more attention in published literature. These categories were based on how streamflow data was acquired in the papers that focus on gauged and ungauged basins. The next step was to identify whether recent or old data were used in the articles. The end year of streamflow data used in the articles was compared with the publication year of those articles. The purpose of this comparison was to understand how streamflow data availability impacts water resource research in Ethiopia. Moreover, this analysis will help to better capture how researchers dealt with the data availability problems.

One important note is that the articles reviewed for this study address various aspects of hydrology and may not specifically address streamflow monitoring; thus, the "streamflow related" phrase is used in referring to such articles.

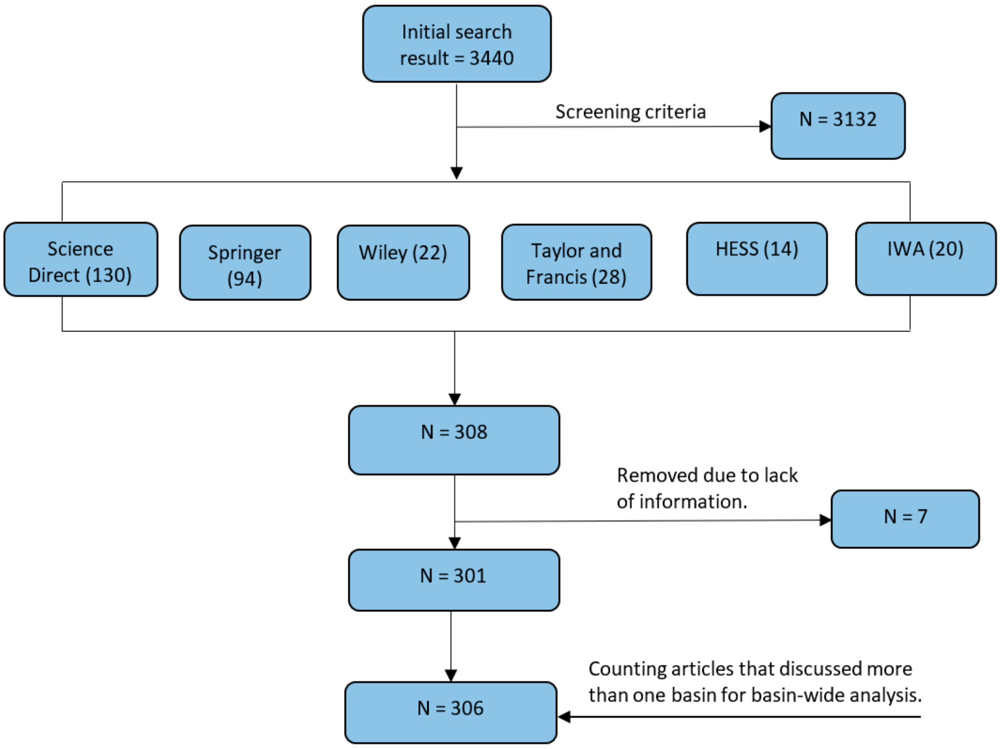

Figure 3. Flow chart on article selection process. 'N' refers to the number of articles.

3. Streamflow Monitoring in Ethiopia—The Workshop Discussion Synthesis

Improving and supporting streamflow monitoring in Ethiopia requires interventions from different sectors and angles. Firstly, research is found to be important in the entire value chain of streamflow monitoring, from data collection to data utilization. Secondly, the education sector is one avenue that can contribute to advancing streamflow monitoring strategies by incorporating the topic into the curriculum at the university and high school levels. Third, recent advancements in technologies are encouraged to be used to have a consistent data monitoring system in the country. This can be done through the use of remote sensing and other advanced systems. Lastly, all technical and engineering solutions will bear fruit only when institutional settings and responsibilities are in place with clear mandates and financial support. Supporting existing institutions through the approach of co-production of data and knowledge was found to be an important approach for the current state of streamflow monitoring in Ethiopia. The following sections elaborate on the specific aspects that can be done through research, education, remote sensing, and institutions.

3.1. Research for Streamflow Monitoring

Two aspects of research support were identified in improving efforts regarding data collection and capacity development.

3.1.1. Data Collection

In Ethiopia, research can support streamflow data collection efforts by identifying priority gauging stations that must be maintained under all circumstances, such as resource constraints. This can be accomplished by conducting sound research and identifying reference gauging stations where continuous streamflow data monitoring and gauging station maintenance will be unaffected. Though reference (also called "Benchmark") stations are common in Europe and North America [39], their value in providing data for analyzing climate change impact on basin hydrology is not recognized as much as it should be in Ethiopia. Whitfield et al. [40] listed a set of criteria to identify the location of reference gauging stations that can be adopted.

Additionally, engaging citizens in streamflow monitoring and research around it was discussed. The applicability of the citizen science approach to support hydrological data monitoring is gaining attention globally, and pilot citizen science programs exist in Ethiopia [41,42]. Such research can continue providing evidence on the scope and added value of the citizen science approach for different locations. Research can explore the practical use of the approach in filling data gaps and how to integrate it with traditional streamflow monitoring. This can be a useful approach in resource-limited conditions to cover large networks of monitoring gauges.

Advanced research can contribute to developing tailor-made modern sensors for streamflow monitoring, lowering the cost of importing instruments, which is hindering the advancement of monitoring systems. It is also important to support the Ethiopian hydrological agency in calibrating and validating the existing telemetric stations while exploring the improvement of temporal frequency of velocity measurements to update and validate rating curves. For instance, researchers can support applying Acoustic Doppler Current Profiler (ADCP) tools for real-time monitoring and completing flow measurements in a short time.

3.1.2. Support Capacity Development

Research institutes can support two important aspects of streamflow monitoring and data collection. The first is strategic assistance, such as increasing data value by assisting the hydrological agency in the creation and distribution of hydrological bulletins and forecasts. Contributions through developing strategies for making the limited historical data useful for attribution studies can be made by research. Additionally, advancing regionalization applications, for example, by adopting empirical equations to transfer streamflow data to ungauged watersheds and extending temporal coverage of data from short-lived stations, can be supported through research. The second aspect involves working together with stakeholders to improve the technical capabilities of hydrological agencies by training their staff in various streamflow monitoring and data management topics and tools, developing short- and long-term partnerships, sharing calibrated and validated models, and sharing quality-checked data with adequate documentation.

3.2. Revisiting Hydrology Education in Ethiopia

Universities provide education on different topics of the hydrological cycle. In order to support streamflow monitoring, they may engage in investigating new methods for archiving and storing data, creating data repositories at their centers, and preparing guidelines for metadata preparation. It is also important to develop a protocol and platform for data sharing between hydrological agencies, universities, and other stakeholders. The existing data-sharing approach and format in Ethiopia require revisiting in the view of improving the accessibility and suitability of the data for research and design, as well as reducing the data quality processing time. Making data publicly available for those stations that are not sensitive as per the country's guidelines will reduce the amount of effort required to collect the data from the agencies.

Strengthening University–Industry Linkage

A specific suggestion was raised regarding university–industry linkage, which can be a vehicle for greater cooperation and change in improving streamflow monitoring strategies. Historically, a collaboration between the Water Development Commission (WDC-Ethiopia) and Arba Minch Water Technology Institute (AWTI) started in the late 1980s. It produced several responsible hydrological monitoring technicians for some time, and then the program stopped. This initiative is suggested to be reinitiated and practiced for monitoring system continuity. This will require tailoring the educational policy to include the needs of current streamflow monitoring and a collaborative effort between universities, research institutions, and the hydrological agency.

Furthermore, encouraging universities to set up experimental monitoring networks in partnership with basin offices is important. These monitoring networks can be used to test new monitoring sensors and techniques as well as provide high-quality data. In addition, internship opportunities allow university staff and students to provide support at the various stages of the hydrological services, data collection, archiving, quality assessment, and data analysis. Universities may align their curricula to create courses that are more practical-oriented. It has been found that working with the hydrological agencies to collaboratively develop or identify research themes is essential for supporting hydrological services. Graduate studies that focus on problem-solving themes instead of activities that only end up on the shelf may have to be encouraged.

3.3. Remote Sensing for Streamflow Monitoring

With the advancement of science and technologies, recent hydrology studies have been using remote sensing data [43,44]. The use of remote sensing techniques for various operational applications requires awareness raising for the stakeholders about the availability of global streamflow data (from remote sensing and a global model). Data providers need to be aware of the opportunities of using global data.

The awareness raising could be through presenting a synthesis of research findings to the data providers and users, conducting awareness-raising events on the use of advanced products for hydrological services, and the applicability and reliability of remote sensing data. It is crucial to offer tailor-made training to various sector offices and data users who are engaged in the construction and design of water infrastructures and the management of water resources. Various media outlets can be used for targeted audiences to improve the users' understanding and confidence levels in utilizing remote sensing and other global products.

Research is required to demonstrate the remote sensing product's practical application and to improve its accuracy in Ethiopia. This requires strengthening the computational skills of academicians to analyze big geo-data using the Google Earth Engine and other tools by offering on-the-job training. If satellite outputs, global runoff data, and observed runoff are integrated, streamflow data will be more consistent and usable.

Limitations of Remote Sensing—Research Needs

The workshop participants identified the spatial and temporal scales of remote sensing data as major limitations for its application in streamflow monitoring. The limitation of the time scale is due to the long revisit time of satellites to cover a given area. As a result, peak streamflow occurrences between consecutive revisit times are often missed by the remote sensing data. The limitations related to the spatial scale are due to poor resolution and resolution mismatch from different satellites. Most open-source remote sensing data have poor spatial resolution and usually provide useful data only for monitoring large river basins. The satellites also fail to capture low flows due to their poor resolution.

Researchers attempt to overcome the aforementioned limitations by merging data from different satellite products, which necessitates the use of re-sampling methods. However, more caution is necessary in choosing appropriate resampling methods, as the errors stemming from the resampling methods could propagate into the streamflow data. Therefore, the following remote sensing challenges require more research to improve the remote sensing products to:

1. Increase revisiting time by integrating multiple satellite data sources,
2. Enhance remote sensing applicability to small size rivers,
3. Research to investigate the comparative advantages of resampling methods,
4. Identify satellites with revisit times that enable them to capture salient features of the diurnal cycle of streamflow, and
5. Investigate how to overcome the limitations of low-flow measurement.

In Ethiopia, the remote sensing products being used for water balance component estimation are dominantly rainfall estimates and evapotranspiration. Currently, these products are not widely evaluated and used for streamflow monitoring of Ethiopian basins despite current advances in remote sensing techniques for streamflow monitoring.

3.4. Institutional Responsibilities

Conducting an inventory of the human and material resources of the data providers can be the first step in improving data monitoring and provision. This will help to better understand what they have, how to use it, and identify and fill any gaps. After demonstrating how the institute's resources are being used effectively and efficiently, it is possible to engage with the management body to develop a good plan for providing an effective service.

To demonstrate how the institution is consistently improving its performance, deliverables that can be used to track progress on a regular basis might be included in the strategy. Based on the audit, to become more efficient, data providers may focus on filling any existing capacity gaps, especially through on-the-job training and by transitioning from a paper-based system to an online system.

Co-Production

Over the past few years, several training courses have been organized on the use of streamflow and associated hydro-meteorological data in the water sector. These training courses targeted different staff of the hydrological agency. However, the training outputs and deliverables have not been monitored and evaluated. According to the experts' opinions, training fatigue was observed in both the trainers and the trainees. It is becoming apparent that the productivity of the agency will not be as expected in the absence of a fundamental strategic adjustment in the design and delivery of training in the future. Therefore, future training must incorporate knowledge co-production activities between trainer institutes (e.g., research centers) and the trainees. Donors must encourage knowledge co-production, and this can be used as one of the funding requirements.

The experts noted that users of data should support data collection in addition to using the data. On this topic, the experts gave suggestions to use citizen science as one approach to deal with data gaps and support monitoring. This can be seen as one of the methods of co-production at a lower level. However, there is a need to go beyond the citizen science approach and encourage co-production at higher institutional levels (e.g., co-production of rating curve development and updates).

The experts noted that it is necessary to create pertinent processes for data collection, data sharing, and quality control in line with WMO guidelines. This requires technical support from qualified individuals in the fields of data management and/or data science, as well as cooperation from pertinent organizations like the Ethiopian Standard Agency and the Geospatial Institute.

4. Literature Evidence on the Status of Streamflow Monitoring

A thorough systematic literature review that supported the experts' opinions highlighted certain important aspects of streamflow monitoring status and related research in Ethiopia. According to the United States Bureau of Reclamation (USBR) report on the establishment of gauging stations in the Blue Nile of Ethiopia, there is no evidence of the existence of river flow measurement before the early 1960s [44]. Similarly, according to the Ministry of Water and Energy, the streamflow record in the Lake Tana sub-basin of the Blue Nile began in the 1960s [44,45].

For this study, the selected 306 articles were published after the early 1990s. According to the review, prior to 2012, the number of published articles addressing streamflow-related topics in Ethiopia was less than five articles per year (Figure 4). However, there has been a notable increase in the amount of published research since 2012. Recently, approximately 30 articles per year have been published, demonstrating increased research emphasis on streamflow-related topics in the Ethiopian basins. Possible explanations for such a rise include an expansion in higher education institutes, graduate programs, and publications as a prerequisite for graduate students.

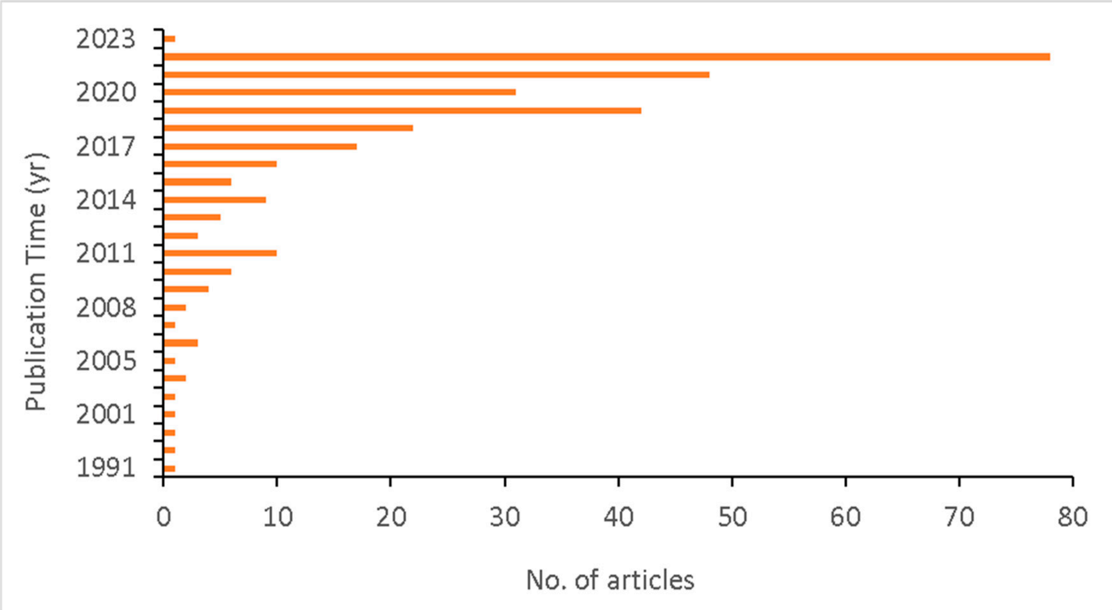

Figure 4. Temporal distribution of number of articles reviewed in this study during 1990–2023.

4.1. Data Gaps

The six groups used to systematically synthesize the results based on streamflow data sources are as follows. The first group used existing streamflow data from data providers, the second group used experimental measurements conducted by the researchers of the papers, the third group focused on rating curve updates of existing records to generate streamflow data for the period used in the studies, the fourth group applied remote sensing products for streamflow estimation, the fifth group used global runoff data for their research, and the last group focused on the application of different approaches for ungauged basins' streamflow estimation. The following phrases are used to represent the six groups in the figures and discussion: "historical streamflow", "experimental measurement", "rating curve update", "remote sensing products", "global runoff data", and "ungauged flow estimation", respectively.

According to the systematic review, hydrological researchers in Ethiopia have been using decade-old data, as evidenced by the gap between publication year and end year of the data utilized in their study (Figures 5 and 6). The minimum, average, and maximum gaps between the publication year and the end year of the streamflow data used for analysis were 1, 9, and 28 years, respectively. In the recent decade, from 2015 onwards, the review revealed an overall rise in the streamflow data gap. This shows that most researchers rely on decade-old data since recent data are either unavailable or inaccessible. Furthermore, Figure 5 shows that the Abbay basin received the most attention in research, followed by the Awash and Rift Valley Lake basins. The focus on the Abbay is assumed to be related to the national and international significance of its water resources as the source of the Blue Nile River. The other basins have a relatively low number of publications related to streamflow monitoring. The shortest data gap was observed in Tekeze (an average of 7.7 years), followed by the Abbay basin (an average of 9.8 years). Despite this, similar trends were observed for all basins in terms of the 9-year gap between the publication year and the end year of the data used in the studies. Additionally, studies published in the same years have varying lengths of data gaps, which could be due to inconsistent access to the data and/or different data sources or approaches used in the studies.

Figure 6 shows similar gaps between the publication year and the end year of the streamflow data used in the studies based on the thematic topics. Most recent articles that used existing historical streamflow data experienced large data gaps. However, the use of alternative data sources, such as remote sensing products and ungauged flow estimation approaches, has increased in the recent decade. These methods reduced the observed data gaps for historical streamflow. Except for some cases, experimental measurements led to the smallest data gaps, as expected from experimental studies. Some of the exceptions might be related to delays in the publication of results.

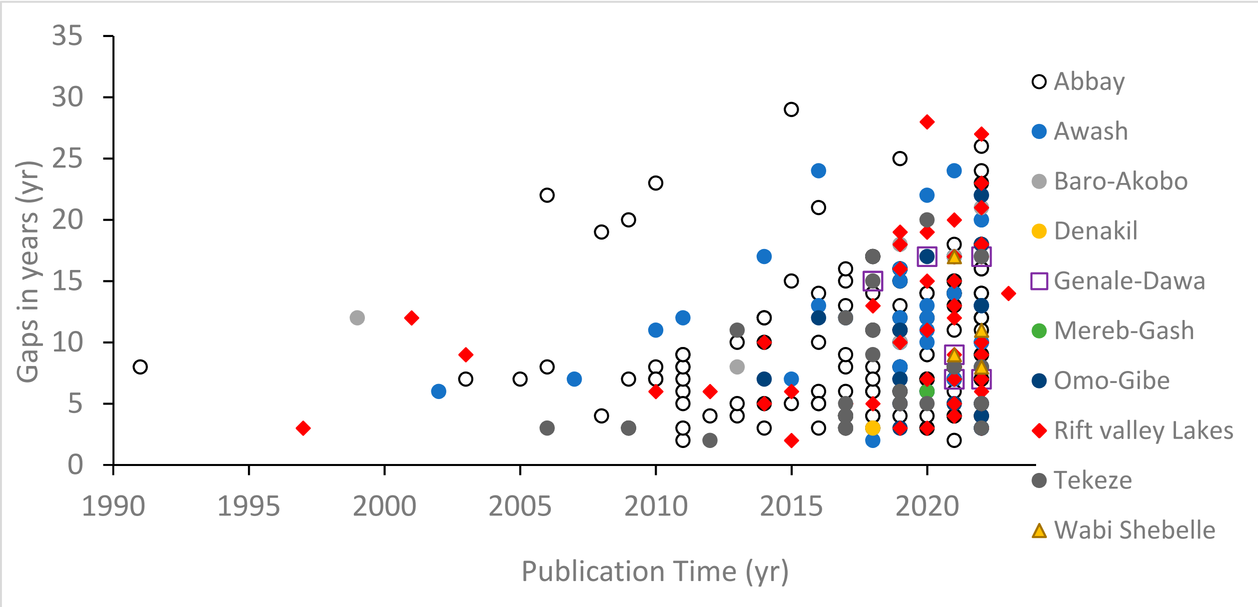

Figure 5. Temporal gap between the end year of data in the analysis and year of publication categorized based on major basins of Ethiopia.

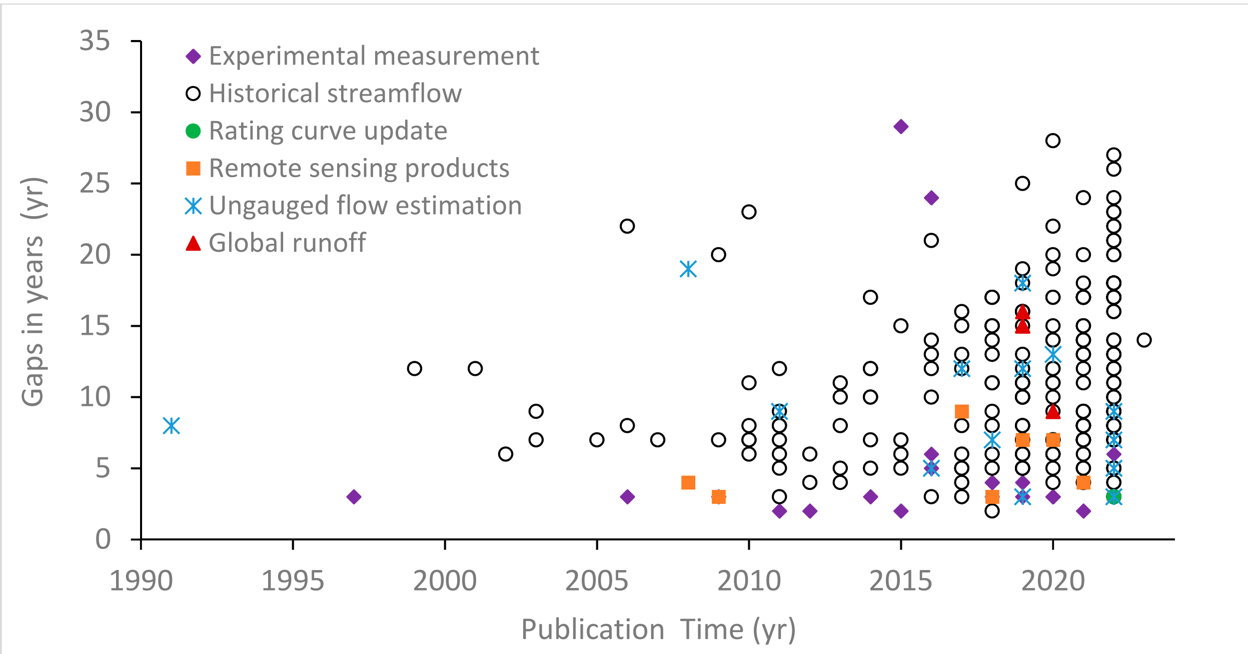

Figure 6. Temporal gap between the end year of data in the analysis and year of publication categorized based on type of research.

4.2. Implication of Streamflow Data Gaps

Hydrology research relying on decade-old streamflow data has been common in most parts of Ethiopian river basins due to data scarcity. Previous studies showed the difficulty in accessing reliable streamflow data for hydrological modeling [26,27,46–49]. For instance, Haile et al. [46] reported that two-thirds of the gauging stations lacked reliable streamflow data suitable for hydrological modeling in the upper Blue Nile basin. Worku et al. [47] calibrated and validated a hydrologic model for climate change assessment using the daily streamflow data prior to 2008 from the Beressa, 2002 from the Robi-Gumero, and 1997 from the Jemma gauging stations. Worqlul et al. [48] used old streamflow data from surrounding catchments to parametrize a hydrologic model in the Robit and Dangishta catchments of the upper Blue Nile basin. Moreover, unreliable streamflow data was observed in the low flow of the Gilgel Abay river after 2006, which jumped from the long-term average by about 200% [32,50,51].

Goshime et al. [27] calibrated a hydrologic model in the Ziway-Shalla basin using streamflow data before 2000. Moreover, Nannawo et al. [26] pointed out the lack of reliable streamflow data to assess the hydrological processes in the Bilate catchment. In the Omo-Gibe basin, a large amount of the streamflow data was excluded from analyses in various studies because it did not pass quality tests [49,52]. Haile et al. [33] identified deterioration of the streamflow monitoring network in the Omo-Gibe basin, which resulted in insufficient spatiotemporal streamflow records for hydroclimatic investigations. These authors further emphasized the need for a collaborative effort to ensure that existing stations are fully operational, and that data are credible and accessible.

Similarly, Mengistu et al. [53] used regional flood frequency analysis because streamflow data at gauging locations are unavailable in the Genale–Dawa River Basin. Woldegebriel et al. [54] observed a lack of spatiotemporal streamflow data in the Baro-Akobo River basin for water resource assessment using hydrological modeling. All these examples raise concerns about the lack of reliable streamflow data in Ethiopia, which may impede hydrology and water resource research and practice. Moreover, the unreliable streamflow data increases uncertainty in water resource planning and management [16,55]. This also affects the plan for water and climate services [6,56,57], as well as assessing and defining the streamflow regime of river basins [58].

4.3. Current Research Practices to Fill Data Gaps in Ethiopia

Several studies have focused on addressing the data gap in streamflow using three approaches: primary data collection, hydrological modeling, and remote sensing. For example, Nigatu et al. [45] employed a primary data collection approach in conjunction with historical data to construct rating curves in the Lake Tana sub-basin. Lakew and Moges [59] used global streamflow data validated with local in situ measurement. Moreover, Nega and Seleshi [60] generated continuous streamflow data using hydrologic models, while Lazin et al. [61] applied remote sensing-based hydrological modeling approaches to generate streamflow in the ungauged catchments. Figure 7 demonstrates that primary data collection is the most common approach in the reviewed articles to fill the streamflow data gaps in Ethiopia. However, one has to note that this is expensive, and researchers are investing their time in data collection at the expense of losing time for research.

Although the data-filling methods applied in Ethiopian river basins are mostly limited to primary data collection and regionalization approaches, various types of techniques are available at the global scale. For instance, [62] suggests an approach known as group-based neural network models to infill missing hydrological records in monthly streamflow. The approach was tested in Canadian watersheds and found to be promising. In the African context, ref [63] applied a Self-Organizing Map (SOM) approach, which is a form of artificial neural network in the Shire River basin of Malawi, while [64] applied it to the Logone catchment in the Lake Chad basin. The approach is found to be useful, particularly for data-scarce countries with a high proportion of missing values to support water resource assessment. The advancements in the application of artificial neural networks, different types of statistical methods, and other advanced approaches for infilling streamflow data will be beneficial to the water resources sector in developing countries.

The prospect of new streamflow data from satellite sources is given high regard by the scientific community. The Surface Water and Ocean Topography (SWOT) mission by The National Aeronautics and Space Administration (NASA) is designed to acquire elevations of water surfaces at spatial and temporal scales necessary for answering key water cycle and water management questions of global importance. This is expected to be a good alternative in the future for data-scarce regions.

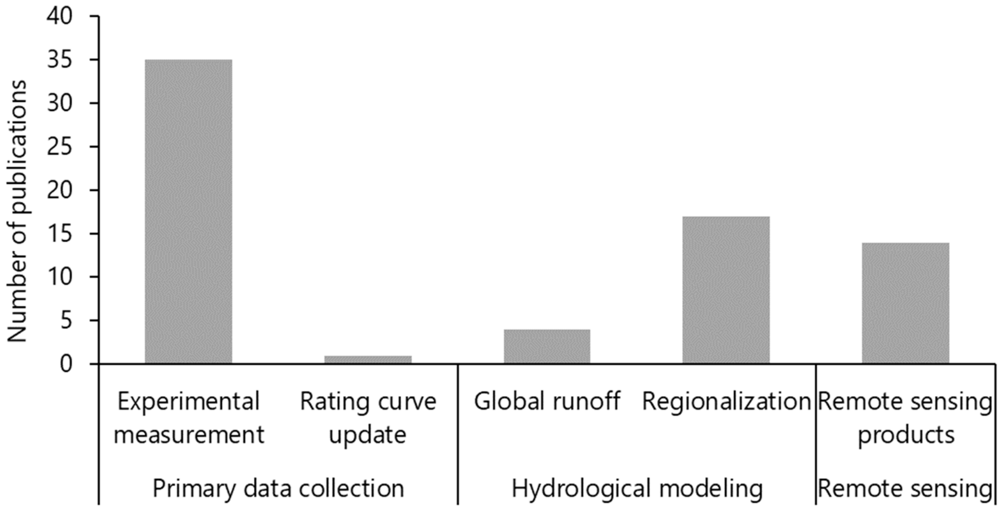

Figure 7. Strategies used by researchers to fill streamflow data gaps.

5. Top Ten Research Priorities for Streamflow Data Monitoring in Ethiopia

Generally, the workshop synthesis highlighted that the most relevant key measures to improve streamflow monitoring are demonstrating the added socio-economic value of streamflow data and enhancing collaboration between data providers and users. These and other research topics identified through this study, such as the use of citizen science for contributing to data generation [65] and testing advanced technologies, are relevant in addressing many of the challenges associated with streamflow monitoring in countries such as Ethiopia. Table 1 shows the research topics that are the final selections for each discussion group.

The identified research priorities are reframed as follows to make up the list of top ten research priorities. The key phrases are highlighted in bold to emphasize the main topic of each research idea for those who will explore them further:

1. **Rating curve** development, validation, and quantifying uncertainties for limited data.
2. Evaluation of streamflow **data gap-filling** methods and reconstruction of data from missing years.
3. Developing **regionalized** equations for hydrological modeling in ungauged basins.
4. Enhance the accuracy of **global runoff data** by bias correction and merging/blending with historical data to generate locally usable streamflow data.
5. Generate streamflow data from multiple **remote sensing data** sources to enhance spatio-temporal resolution and coverage.
6. Assess the implication of the current **organizational structure** for hydrological service in Ethiopia and suggest alternative and supplementary approaches to enhance its performance.
7. Testing the **citizen science** approach to support streamflow monitoring to show quality data can be collected by citizens and to use this as an opportunity to support monitoring.
8. The use and development of **parsimonious models** to generate streamflow data in data-scarce regions.

9. Investigate the **economic value** of observed streamflow data measurement and maintenance, the implication of using poor-quality data in economic terms, and its general implication for water resource development.
10. **Experimental monitoring** of geomorphology and discharge of selected streamflow gauging sites to develop, calibrate, and validate runoff data from global data and remote sensing.

Table 1. Selected research priorities per each thematic group.

No	Thematic Group	Research Priorities
1	Research	Evaluation of streamflow data filling methods.
2		Rating curve development, validation, and quantifying uncertainties.
3		Developing regionalized equations for estimation of hydrological extremes.
4	Remote sensing	Enhance global model runoff data accuracy using bias correction and merging with historical observed data to generate reliable streamflow data.
5		Generate streamflow data from multiple remote sensing data/products to enhance spatio-temporal resolution.
6	Education	Evaluate uncertainties of observed streamflow and its implication for water resource development (e.g., structural effect, socio-economic effect).
7		Assess the implication of the current organizational structure for hydrological service in Ethiopia and suggest alternative or supplementary approaches to enhance its performance.
8	Institutions	Ungauged streamflow estimation methods, including the use and development of parsimonious models.
9		Testing citizen science approach to support streamflow monitoring.
10		Investigate the economic value of streamflow data measurement, maintenance, and the implication of using poor-quality data in economic terms.

The keywords from each of the selected top ten research topics to improve streamflow data monitoring are indicated in Figure 8 for ease of recalling the selected topics. The identified priorities align well with wider literature; however, they are not given enough attention in data-scarce countries. More attention is being given to advanced technologies, which is a justifiable approach; however, neglecting basic observational measurements will have negative implications for properly utilizing advanced approaches and technologies.

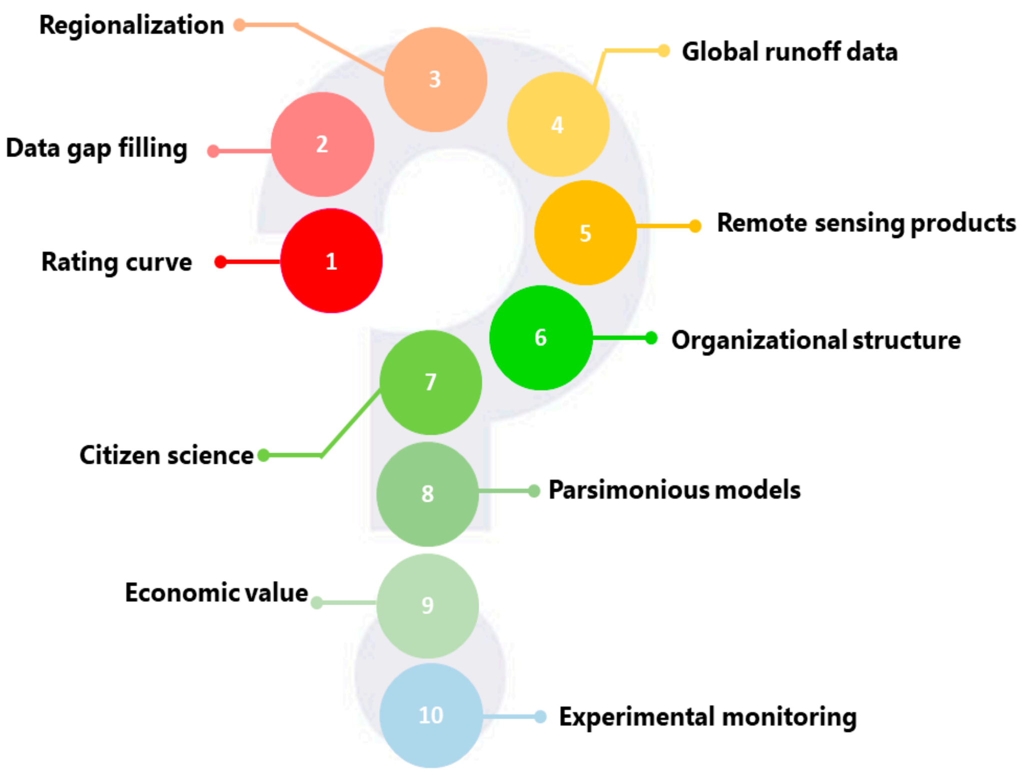

Figure 8. Keywords of the selected top research topics to enhance streamflow data monitoring.

6. Conclusions

Based on a shared understanding of the existing status and gaps, this review aims to guide researchers to play a key role in streamflow monitoring in a developing country like Ethiopia. This review highlighted the decline of streamflow data in space and time, which will have major ramifications for water resource development in general, and for food and water security in particular. It identified the top ten research topics that can be addressed by different universities, research centers, and other concerned stakeholders. However, it is important to recognize that the prioritized research topics can be continuously revised and expanded as the science and practice of monitoring streamflow advances.

The prioritized research topics can be used for several purposes, including facilitating and guiding effective collaboration among researchers towards filling streamflow data gaps and sustaining its monitoring system in Ethiopia and other data-scarce countries. Furthermore, hydrology graduate students can make meaningful contributions by aligning their research towards the priorities identified in this study. Moreover, donor organizations can play a key role in filling current gaps in streamflow monitoring by funding projects. Donors can also encourage knowledge co-production between providers of streamflow data and researchers. Prioritization of such research topics aids in the allocation of grants and initiatives that can collectively bring about the desired changes.

This review provided key recommendations, such as demonstrating the added socio-economic value of streamflow data, the establishment of reference stations, the use of advanced technology such as remote sensing, and increased research in Ethiopia. It showed researchers can support data providers to justify and find evidence for continuous streamflow monitoring from an economic standpoint. Decision-makers who are aware of the financial and economic benefits of installing adequate streamflow gauging stations and continuously monitoring streamflow data will steer the water sector in the right direction. For this, researchers can generate evidence on the socio-economic value of having continuous credible data. The identified research topics are relevant in addressing many of the challenges associated with streamflow monitoring and thus encouraged to be taken up by the research community.

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Appendix A

Table A1. List of thematic research questions for the groups' discussions.

Theme	Thematic Questions
Enhanced research to deal with an increasing data deterioration	• How are the current research activities dealing with the streamflow data gap, as most studies seem to rely on data as old as before 2005? • How do we tackle the data issue to conduct attribution studies in hydrology? • What other research methods can assist in overcoming the streamflow data gap of the recent decade in Ethiopia? • What role can researchers play to enhance the collaboration between data users and data providers to improve streamflow monitoring across the country? • What are the top ten research topics that can be identified as burning research topics in relation to streamflow monitoring, particularly dealing with missing data gaps?
Remote sensing use for streamflow monitoring	• What top ten research questions can be developed to realize the potential of remote sensing applications in streamflow? • What is the role of the latest technologies for monitoring river geomorphological parameters derived from remote sensing products for river discharge estimation?
Education and practice to improve streamflow monitoring in Ethiopia	• How can post-graduate studies and students support improving streamflow monitoring in Ethiopia? • What kind of scientific evidence can they generate to improve streamflow monitoring other than collecting data? • How can data collected by students be accessed? • Is there any data portal that needs to be organized? • What kind of additional educational program should be in place as a short-term and long-term program to support/improve streamflow monitoring in Ethiopia? • How can we develop a demand-driven curriculum that deals with practical problems in the country? • How do water projects overcome the current streamflow data gap to plan, design, and implement?

Table A1. *Cont.*

Theme	Thematic Questions
Role of institutions (academic, research, data providers) in hydrological data monitoring and services	• What kind of platform do you suggest for the future that can be run by academic and research institutions to tackle the data challenges? • What will be the role and responsibility of such platforms, and how can it be operationalized? • What are the top ten burning research topics to increase attention given to hydrological monitoring and services in the country?
Research priorities in order to sustain streamflow data monitoring in Ethiopia	• List the top ten research priorities to improve streamflow data monitoring
Key messages	• What are the 3 key messages to communicate with professionals and the public to increase attention given the current gaps in streamflow monitoring in Ethiopia?

Table A2. List of articles reviewed for this study.

Title of the Articles	Year of Publication
Does the recent afforestation program in Ethiopia influenced vegetation cover and hydrology? A case study in the upper awash basin, Ethiopia	2022
Impact of climate change on future precipitation amounts, seasonal distribution, and streamflow in the Omo-Gibe basin, Ethiopia	2022
Streamflow and sediment yield estimation, and area prioritization for better conservation planning in the Dawe River watershed of the Wabi Shebelle River Basin, Ethiopia	2021
Comparison and evaluation of gridded precipitation datasets for streamflow simulation in data scarce watersheds of Ethiopia	2019
Climate change impact assessment on the hydrology of a large river basin in Ethiopia using a local-scale climate modelling approach	2020
Potential climate change impact assessment on the hydrology of the Lake Tana Basin, Upper Blue Nile River Basin, Ethiopia	2020
Merging satellite rainfall estimates and daily rain gauge observations for improved flood simulation in MelkaKuntire catchment, upper Awash Basin, Ethiopia	2022
How suitable are satellite rainfall estimates in simulating high flows and actual evapotranspiration in MelkaKunitre catchment, Upper Awash Basin, Ethiopia?	2021
Impacts of land use and land cover changes on hydrology of the Gumara catchment, Ethiopia	2019
Observed and model simulated twenty-first century hydro-climatic change of Northern Ethiopia	2019
Effects of climate change on water resources in the upper Blue Nile Basin of Ethiopia	2018
An evidence for enhancing the design hydrograph estimation for small and ungauged basins in Ethiopia	2022
Climatic controls of ecohydrological responses in the highlands of northern Ethiopia	2017
Spatial and temporal variability evaluation of sediment yield and sub-basins/hydrologic response units prioritization on Genale Basin, Ethiopia	2021
Evaluating satellite-based evapotranspiration estimates for hydrological applications in data-scarce regions: A case in Ethiopia	2020
Hydrological impacts of climate change in selected ungauged sub-watersheds of Lake Tana Sub-Basin, Upper Blue Nile Basin, Ethiopia: A regionalization approach	2022
Implications of water abstraction on the interconnected Central Rift Valley Lakes sub-basin of Ethiopia using WEAP	2021

Table A2. *Cont.*

Title of the Articles	Year of Publication
Investigation of non-stationarity in hydro-climatic variables at Rift Valley lakes basin of Ethiopia	2012
Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia	2017
Quantifying sensitivity of groundwater recharge to land use and land cover changes by improving model performance on the wetland dominated Tikur Wuha Watershed, Ethiopia	2022
Groundwater modeling in data scarce aquifers: The case of Gilgel-Abay, Upper Blue Nile, Ethiopia	2020
Multi-site calibration of hydrological model and the response of water balance components to land use land cover change in a rift valley Lake Basin in Ethiopia	2022
Modeling the impact of climate change on hydrological responses in the Lake Tana basin, Ethiopia	2022
Modeling projected impacts of climate and land use/land cover changes on hydrological responses in the Lake Tana Basin, upper Blue Nile River Basin, Ethiopia	2021
Streamflow variability and its linkage to ENSO events in the Ethiopian Rift Valley Lakes Basin	2021
Effect of irrigation water withdrawal on the hydrology of the Lake Tana sub-basin	2021
Rainfall-runoff modeling using HEC-HMS model for Meki river watershed, rift valley basin, Ethiopia	2023
Water balance components of the potential agricultural grabens along the Rift Valley in northern Ethiopia	2019
Curve number calibration for measuring impacts of land management in sub-humid Ethiopia	2021
Climate-induced flood inundation in Fogera-Dera Floodplain, Lake Tana basin, Ethiopia	2019
Modelling hydrological processes under climate change scenarios in the Jemma sub-basin of upper Blue Nile Basin, Ethiopia	2021
Reduced runoff and sediment loss under alternative land capability-based land use and management options in a sub-humid watershed of Ethiopia	2022
Regionalization of catchments for flood frequency analysis for data scarce Rift Valley Lakes Basin, Ethiopia	2022
Attributing the hydrological impact of different land use types and their long-term dynamics through combining parsimonious hydrological modelling, alteration analysis and PLSR analysis	2019
Impacts of Climate and Land Use Change on Hydrological Response in Gumara Watershed, Ethiopia	2021
Investigation of runoff response to land use/land cover change on the case of Aynalem catchment, North of Ethiopia	2019
Performance of bias corrected MPEG rainfall estimate for rainfall-runoff simulation in the upper Blue Nile Basin, Ethiopia	2018
Climate change impacts on water resources in the Upper Blue Nile (Abay) River Basin, Ethiopia	2021
Evaluation of observed and satellite-based climate products for hydrological simulation in data-scarce Baro-Akobo River Basin, Ethiopia	2022
Evaluation of lag time and time of concentration estimation methods in small tropical watersheds in Ethiopia	2022
Modeling of sediment yield in Maybar gauged watershed using SWAT, northeast Ethiopia	2015
Three-dimensional groundwater flow modeling to assess the impacts of the increase in abstraction and recharge reduction on the groundwater, groundwater availability and groundwater-surface waters interaction: A case of the rib catchment in the Lake Tana sub-basin of the Upper Blue Nile River, Ethiopia	2021
SWAT and HBV models' response to streamflow estimation in the upper Blue Nile Basin, Ethiopia	2021
Climate change and the response of streamflow of watersheds under the high emission scenario in Lake Tana sub-basin, upper Blue Nile basin, Ethiopia	2022

Table A2. *Cont.*

Title of the Articles	Year of Publication
Analysis of rainfall and streamflow trend and variability over Birr River watershed, Abbay basin, Ethiopia	2022
Hydrologic response to land use land cover change in the Upper Gidabo Watershed, Rift Valley Lakes Basin, Ethiopia	2020
Effect of spatial scale on runoff coefficient: Evidence from the Ethiopian highlands	2018
Analyzing the variability of sediment yield: A case study from paired watersheds in the Upper Blue Nile basin, Ethiopia	2018
Is observation uncertainty masking the signal of land use change impacts on hydrology?	2019
Effects of land use on catchment runoff and soil loss in the sub-humid Ethiopian highlands	2017
Hydro-meteorological trends in the Gidabo catchment of the Rift Valley Lakes Basin of Ethiopia	2018
Sediment Yield Estimation and Effect of Management Options on Sediment Yield of Kesem Dam Watershed, Awash Basin, Ethiopia	2020
Application of CORDEX-AFRICA and NEX-GDDP datasets for hydrologic projections under climate change in Lake Ziway sub-basin, Ethiopia	2020
Modeling blue and green water resources availability at the basin and sub-basin level under changing climate in the Weyb River basin in Ethiopia	2020
Impact of climate change on groundwater recharge and base flow in the sub-catchment of Tekeze basin, Ethiopia	2018
Satellite-based rainfall estimates evaluation using a parsimonious hydrological model in the complex climate and topography of the Nile River Catchments	2022
Simulated surface and shallow groundwater resources in the Abaya-Chamo Lake basin, Ethiopia using a spatially-distributed water balance model	2019
Comprehensive hydrological and hydrogeological study of topographically closed lakes in highland Ethiopia: The case of Hayq and Ardibo	2007
Application of ANN and HEC-RAS model for flood inundation mapping in lower Baro Akobo River Basin, Ethiopia	2021
Impact of landscape pattern changes on hydrological ecosystem services in the Beressa watershed of the Blue Nile Basin in Ethiopia	2021
Evaluation of climate anomalies impacts on the Upper Blue Nile Basin in Ethiopia using a distributed and a lumped hydrologic model	2015
Prioritization of watershed management scenarios under climate change in the Jemma sub-basin of the Upper Blue Nile Basin, Ethiopia	2020
Hydrological evaluation of open-access precipitation and air temperature datasets using SWAT in a poorly gauged basin in Ethiopia	2019
Recharge variability and sensitivity to climate: The example of Gidabo River Basin, Main Ethiopian Rift	2015
Assessing the effect of water harvesting techniques on event-based hydrological responses and sediment yield at a catchment scale in northern Ethiopia using the Limburg Soil Erosion Model (LISEM)	2017
Identifying sustainability challenges on land and water uses: The case of Lake Ziway watershed, Ethiopia	2017
SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia	2017
Dynamics of land use land cover and resulting surface runoff management for environmental flood hazard mitigation: The case of Dire Daw city, Ethiopia	2019
Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia	2019

Table A2. *Cont.*

Title of the Articles	Year of Publication
Spatial mapping and testing the applicability of the curve number method for ungauged catchments in Northern Ethiopia	2017
Modeling the hydrological impacts of land use/land cover changes in the Andassa watershed, Blue Nile Basin, Ethiopia	2018
Regional flood frequency curves for remote rural areas of the Nile River Basin: The case of Baro-Akobo drainage basin, Ethiopia	2019
Impacts of land use/land cover change on stream flow and sediment yield of Gojeb watershed, Omo-Gibe basin, Ethiopia	2019
Hydrological performance evaluation of multiple satellite precipitation products in the upper Blue Nile basin, Ethiopia	2020
Precipitation and streamflow variability in Tekeze River basin, Ethiopia	2019
Effects of the floodplain on river discharge into Lake Tana (Ethiopia)	2014
Application of parameter estimation and regionalization methodologies to ungauged basins of the Upper Blue Nile River Basin, Ethiopia	2008
Evaluation of CFSR, TMPA 3B42 and ground-based rainfall data as input for hydrological models, in data-scarce regions: The upper Blue Nile Basin, Ethiopia	2017
Application of a spatially distributed water balance model for assessing surface water and groundwater resources in the Geba basin, Tigray, Ethiopia	2013
Disentangling the impacts of climate change, land use change and irrigation on the Central Rift Valley water system of Ethiopia	2014
Determinants of peak discharge in steep mountain catchments—Case of the Rift Valley escarpment of Northern Ethiopia	2015
Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia	2017
Built Environment, flooding regime change, and its effect on adaptation to climate change in the cities of developing countries: Learning a lesson from Addis Ababa City, Ethiopia	2019
Flood hazard mapping using FLO-2D and local management strategies of Dire Dawa city, Ethiopia	2018
The impact of climate change on mean and extreme state of hydrological variables in Megech watershed, Upper Blue Nile Basin, Ethiopia	2019
Effect of land use land cover dynamics on hydrological response of watershed: Case study of Tekeze Dam watershed, northern Ethiopia	2017
Combined uncertainty of hydrological model complexity and satellite-based forcing data evaluated in two data-scarce semi-arid catchments in Ethiopia	2014
Predicting streamflow for land cover changes in the Upper Gilgel Abay River Basin, Ethiopia: A TOPMODEL based approach	2014
Estimating the effect of climate change on water resources: Integrated use of climate and hydrological models in the Werii watershed of the Tekeze river basin, Northern Ethiopia	2018
Evaluating InVEST model for estimating soil loss and sediment export in data scarce regions of the Abbay (Upper Blue Nile) Basin: Implications for land managers	2021
Hydro-climatic trends in the Abay/Upper Blue Nile basin, Ethiopia	2013
Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia	2006
Evaluation of the Hyper-Resolution Model-Derived Water Cycle Components Over the Upper Blue Nile Basin	2020
Impact of conservation agriculture on catchment runoff and soil loss under changing climate conditions in May Zeg-zeg (Ethiopia)	2012
Probabilistic characterization of hydrological droughts in the Blue Nile River, Ethiopia	2019
Evaluating the applicability and scalability of bias corrected CFSR climate data for hydrological modeling in upper Blue Nile basin, Ethiopia	2019

Table A2. *Cont.*

Title of the Articles	Year of Publication
Upper Blue Nile basin water budget from a multi-model perspective	2017
How well do gridded precipitation and actual evapotranspiration products represent the key water balance components in the Nile Basin?	2021
Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia	2003
Hydrologic response to cattle grazing in the Ethiopian highlands	1997
Combined 3D hydrodynamic and watershed modelling of Lake Tana, Ethiopia	2011
Runoff and sediment-associated nutrient losses under different land uses in Tigray, Northern Ethiopia	2009
Flooding and sustainable land–water management in the lower Baro–Akobo river basin, Ethiopia	1999
Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia)	2001
Spatial and temporal simulation of groundwater recharge and cross-validation with point estimations in volcanic aquifers with variable topography	2022
Evaluation of satellite rainfall products for modeling water yield over the source region of Blue Nile Basin	2020
Impacts of projected change in climate on water balance in basins of East Africa	2019
Impact of land use and land cover dynamics on ecologically-relevant flows and blue-green water resources	2022
Sediment balances in the Blue Nile River Basin	2014
Evaluating hydrologic responses to soil characteristics using SWAT model in a paired-watersheds in the Upper Blue Nile Basin	2018
Evaluating runoff and sediment responses to soil and water conservation practices by employing alternative modeling approaches	2020
Groundwater recharge estimation using empirical methods from rainfall and streamflow records	2021
Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: A combined analysis of statistical tests, physically-based models and landuse maps	2013
Revisiting storm runoff processes in the upper Blue Nile basin: The Debre Mawi watershed	2016
Hydrological modeling, impact of land-use and land-cover change on hydrological process and sediment yield; case study in Jedeb and Chemoga watersheds	2022
Prediction of sedimentation in reservoirs by combining catchment based model and stream based model with limited data	2019
Identifying sources of temporal variability in hydrological extremes of the upper Blue Nile basin	2013
Assessing the implications of water harvesting intensification on upstream–downstream ecosystem services: A case study in the Lake Tana basin	2016
Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin	2013
Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin	2017
Simulation of streamflows for ungauged catchments	1991
The response of water balance components to land cover change based on hydrologic modeling and partial least squares regression (PLSR) analysis in the Upper Awash Basin	2019
Flood Risk and Vulnerability of Addis Ababa City Due to Climate Change and Urbanization	2016
Evaluation of globally available water resources reanalysis (WRR-1) runoff products for assessment and management water resources in the Upper Blue Nile basin: A data scarce major subbasins of the Nile basin	2019
Assessment of catchment water resources availability under projected climate change scenarios and increased demand in Central Rift Valley Basin	2019

Table A2. *Cont.*

Title of the Articles	Year of Publication
Influence of climate variability on representative QDF predictions of the upper Blue Nile basin	2011
Modelling ungauged catchments using the catchment runoff response similarity	2018
Characterizing water storage trends and regional climate influence using GRACE observation and satellite altimetry data in the Upper Blue Nile River Basin	2018
Climate Change Impact on the Hydrology of Tekeze Basin, Ethiopia: Projection of Rainfall-Runoff for Future Water Resources Planning	2018
Evaluation of the WEAP model in simulating subbasin hydrology in the Central Rift Valley basin, Ethiopia	2021
The impacts of LULC and climate change scenarios on the hydrology and sediment yield of Rib watershed, Ethiopia	2022
Land Use/Cover Change Impacts on Hydrology Using SWAT Model on Borkena Watershed, Ethiopia	2022
Modeling Climate Change Impact on the Hydrology of Keleta Watershed in the Awash River Basin, Ethiopia	2019
Evaluation of streamflow response to climate change in the data-scarce region, Ethiopia	2022
A scenario-based modeling of climate change impact on the hydrology of Ketar watershed, Central Rift Valley Basin, Ethiopia	2022
Land Use and Climate Change Impacts on Streamflow Using SWAT Model, Middle Awash Sub Basin, Ethiopia	2022
Evaluating the dynamics of hydroclimate and streamflow for data-scarce areas using MIKE11-NAM model in Bilate river basin, Ethiopia	2022
Application of ANN-Based Streamflow Forecasting Model for Agricultural Water Management in the Awash River Basin, Ethiopia	2011
Hydrological responses to land use/land cover change in Tikur Wuha Watershed in Southern Ethiopia	2022
Model parameter transfer for streamflow and sediment loss prediction with SWAT in a tropical watershed	2016
Analysis and Characterization of Hydrological Drought Under Future Climate Change Using the SWAT Model in Tana Sub-basin, Ethiopia	2022
Streamflow response to climate change in the Greater Horn of Africa	2019
Streamflow prediction uncertainty analysis and verification of SWAT model in a tropical watershed	2016
Stream flow modeling using SWAT model and the model performance evaluation in Toba sub-watershed, Ethiopia	2021
The dual impact of climate change on irrigation water demand and reservoir performance: a case study of Koga irrigation scheme, Ethiopia	2022
Hydro-meteorological impact assessment of climate change on Tikur Wuha watershed in Ethiopia	2021
Modeling the impact of climate change on the hydrology of Andasa watershed	2022
Multi-variable calibration of hydrological model in the upper Omo-Gibe basin, Ethiopia	2020
Modeling Hydrological Responses to Land Use Dynamics, Choke, Ethiopia	2019
Stochastic Forecasting Models of the Monthly Streamflow for the Blue Nile at Eldiem Station	2018
Impact of water resource development plan on water abstraction and water balance of Lake Ziway, Ethiopia	2021
Drought Analysis in the Awash River Basin, Ethiopia	2010
Optimal surface water allocation under various scenarios in the Central Rift Valley basin in Ethiopia	2022
Impact of climate change on surface water availability and crop water demand for the sub-watershed of Abbay Basin, Ethiopia	2019

Table A2. *Cont.*

Title of the Articles	Year of Publication
Trend and variability of hydrometeorological variables of Tikur Wuha watershed in Ethiopia	2020
Climate Change Induced Precipitation and Temperature Effects on Water Resources: the Case of Borkena Watershed in the Highlands of Wollo, Central Ethiopia	2020
Surface runoff modeling using SWAT analysis inÂ Dabus watershed, Ethiopia	2021
Modeling runoff-sediment influx responses to alternative BMP interventions in the Gojeb watershed, Ethiopia, using the SWAT hydrological model	2022
Land use and land cover change dynamics and its impact on watershed hydrological parameters: the case of Awetu watershed, Ethiopia	2022
WEAP modeling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia	2016
Modeling runoff and sediment yield of Kesem dam watershed, Awash basin, Ethiopia	2019
Impacts of climate change on water balance components of Guder Catchment, Upper Abbay Basin, Ethiopia: SWAT model	2022
Assessment of run-of-river hydropower potential in the data-scarce region, Omo-Gibe Basin, Ethiopia	2022
Evaluation of Global Water Resources Reanalysis Runoff Products for Local Water Resources Applications: Case Study-Upper Blue Nile Basin of Ethiopia	2020
Evaluation of SWAT performance in modeling nutrients of Awash River basin, Ethiopia	2019
Modeling future flood frequency under CMIP5 Scenarios in Hare watershed, Southern Rift Valley of Ethiopia	2021
Multi-site multi-objective calibration of SWAT model using a large dataset for improved performance in Ethiopia	2022
Prediction of flood frequency under a changing climate, the case of Hare watershed, Rift Valley Basin of Ethiopia	2021
Exploring future global change-induced water imbalances in the Central Rift Valley Basin, Ethiopia	2021
Enhancing the Forecasting of Monthly Streamflow in the Main Key Stations of the River Nile Basin	2018
Integrated water resources management under climate change scenarios in the sub-basin of Abaya-Chamo, Ethiopia	2018
Flood hazard mapping under a climate change scenario in a Ribb catchment of Blue Nile River basin, Ethiopia	2019
A compendious approach for renewable energy assessment based on satellite and ground truth data: Bilate catchment, Rift Valley Basin, Ethiopia	2022
Evaluation of rainfall -runoff and suspended sediment concentration in the semi-arid Ethiopian highlands, Tekeze Basin, Ethiopia	2022
Performance assessment of SWAT and HEC-HMS model for runoff simulation of Toba watershed, Ethiopia	2021
Assessment of the impact of climate change on surface hydrological processes using SWAT: a case study of Omo-Gibe river basin, Ethiopia	2016
Stream flow dynamics under current and future land cover conditions in Atsela Watershed, Northern Ethiopia	2022
Evaluating the Effectiveness of Best Management Practices On Soil Erosion Reduction Using the SWAT Model: for the Case of Gumara Watershed, Abbay (Upper Blue Nile) Basin	2021
Climate change impacts analysis on hydrological processes in the Weyib River basin in Ethiopia	2018
Ethiopia's Water Resources: An Assessment Based on Geospatial Data-Driven Distributed Hydrological Modeling Approach	2022
Hydrological impacts of climate change in gauged sub-watersheds of Lake Tana sub-basin (Gilgel Abay, Gumara, Megech, and Ribb) watersheds, Upper Blue Nile Basin, Ethiopia	2022
Detection of trends in hydrological extremes for Ethiopian watersheds, 1975 to 2010	2019

Table A2. *Cont.*

Title of the Articles	Year of Publication
Groundwater Potential Mapping Using SWAT and GIS-Based Multi-Criteria Decision Analysis	2020
Effect of land use/land cover change on the regimes of surface runoff: the case of Lake Basaka catchment (Ethiopia)	2019
Sediment Yield Modeling and Evaluation of Best Management Practices Using the SWAT Model of the Daketa Watershed, Ethiopia	2022
Impact of land use/land cover change on stream flow in the Shaya catchment of Ethiopia using the MIKE SHE model	2021
Regionalization of mean annual flow for ungauged catchments in case of Abbay River Basin, Ethiopia	2021
Development of hybrid baseflow prediction model by integrating analytical method with deep learning	2022
Assessment of consumption and availability of water in the upper Omo-Gibe basin, Ethiopia	2019
Assessment of climate change impact on hydro-climatic variables and its trends over Gidabo Watershed	2022
Understanding Catchments Hydrologic Response Similarity of Upper Blue Nile (Abay) basin through catchment classification	2022
Application of hydrodynamic models for designing structural measures for river flood mitigation: the case of Kulfo River in southern Ethiopia	2021
Evaluation of Water Provision Ecosystem Services Associated with Land Use/Cover and Climate Variability in the Winike Watershed, Omo Gibe Basin of Ethiopia	2022
Current and projected water demand and water availability estimates under climate change scenarios in the Weyib River basin in Bale mountainous area of Southeastern Ethiopia	2018
Modelling hydrological response under climate change scenarios using SWAT model: the case of Ilala watershed, Northern Ethiopia	2018
Hydrological modeling in the Upper Blue Nile basin using soil and water analysis tool (SWAT)	2022
Efficiency of soil and water conservation practices in different agro-ecological environments in the Upper Blue Nile Basin of Ethiopia	2018
Modeling the rainfall-runoff using MIKE 11 NAM model in Shaya catchment, Ethiopia	2021
Rainfall variability and its influence on surface flow regimes examples from the central highlands of Ethiopia	2002
Comparison of HEC-HMS hydrologic model for estimation of runoff computation techniques as a design input: case of Middle Awash multi-purpose dam, Ethiopia	2022
A modeling approach for evaluating the impacts of Land Use/Land Cover change for Ziway Lake Watershed hydrology in the Ethiopian Rift	2022
Assessment of the effects of agricultural management practices on soil erosion and sediment yield in Rib watershed, Ethiopia	2022
Characteristics of hydrological extremes in Kulfo River of Southern Ethiopian Rift Valley Basin	2020
Prioritization of sediment yield at sub-watershed level using swat model in Fincaha watershed, Abay Basin, Ethiopia	2022
Suitability of global precipitation estimates for hydrologic prediction in the main watersheds of Upper Awash basin	2020
Assessment of the spatial and temporal distribution of groundwater recharge in data-scarce large-scale African river basin	2022
Assessment of water resource and forecasting water demand using WEAP model in Beles river, Abbay river basin, Ethiopia	2022

Table A2. *Cont.*

Title of the Articles	Year of Publication
Analysis of ambo water supply source diversion weir sedimentation and assessing impact of land management practice through hydrological studies	2020
Evaluating InVEST model for simulating annual and seasonal water yield in data-scarce regions of the Abbay (Upper Blue Nile) Basin: implications for water resource planners and managers	2022
Assessment of hydro-meteorological regimes of gidabo river basin under representative concentration pathway scenarios	2022
Evaluation of TRMM 3B42V7 and CHIRPS Satellite Precipitation Products as an Input for Hydrological Model over Eastern Nile Basin	2020
Impacts of climate change on stream flow and water availability in Anger sub-basin, Nile Basin of Ethiopia	2019
GIS-Based Multi-criteria Approach Surface Irrigation Potential Assessment for Ethiopian River Basin: in Case of Upper Awash River Basin	2022
Climate change impact on extreme precipitation and peak flood magnitude and frequency: observations from CMIP6 and hydrological models	2022
Modelling of river flow in ungauged catchment using remote sensing data: application of the empirical (SCS-CN), Artificial Neural Network (ANN) and Hydrological Model (HEC-HMS)	2019
Assessment of the impact of climate change on future hydropower production from Koka Reservoir under two representative concentration pathways (RCP) emission scenarios	2018
Modeling multivariate standardized drought index based on the drought information from precipitation and runoff: a case study of Hare watershed of Southern Ethiopian Rift Valley Basin	2021
Analyzing the hydrologic effects of region-wide land and water development interventions: a case study of the Upper Blue Nile basin	2016
Biohydrology of low flows in the humid Ethiopian highlands: The Gilgel Abay catchment	2014
Runoff and suspended sediment yield and implications for watershed management	2022
Ensemble data-driven rainfall-runoff modeling using multi-source satellite and gauge rainfall data input fusion	2021
Effects of Different Retention Parameter Estimation Methods on the Prediction of Surface Runoff Using the SCS Curve Number Method	2014
Impact of climate change on the hydroclimatology of Lake Tana Basin, Ethiopia	2011
Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia	2005
Model-Based Characterization and Monitoring of Runoff and Soil Erosion in Response to Land Use/land Cover Changes in the Modjo Watershed, Ethiopia	2015
Partitioning the impacts of land use/land cover change and climate variability on water supply over the source region of the Blue Nile Basin	2020
Modeling of Sediment Yield From Anjeni-Gauged Watershed, Ethiopia Using SWAT Model	2010
Trends in rainfall and runoff in the Blue Nile Basin: 1964–2003	2010
Recession flow analysis of the Blue Nile River	2003
Change in low flows due to catchment management dynamics—Application of a comparative modelling approach	2020
El Niño Southern Oscillation link to the Blue Nile River Basin hydrology	2009
Land Use/Land Cover Changes and Associated Impacts on Water Yield Availability and Variations in the Mereb-Gash River Basin in the Horn of Africa	2020
Estimation of evaporation over the upper Blue Nile basin by combining observations from satellites and river flow gauges	2016
The role of input and hydrological parameters uncertainties in extreme hydrological simulations	2022
The Role of Global Data Sets for Riverine Flood Risk Management at National Scales	2022

Table A2. *Cont.*

Title of the Articles	Year of Publication
Using the Climate Forecast System Reanalysis as weather input data for watershed models	2014
Temporal and spatial dynamics of surface run-off from Lake Basaka catchment (Ethiopia) using SCS-CN model coupled with remote sensing and GIS	2020
Sediment Loss Patterns in the Sub-Humid Ethiopian Highlands	2017
Intra-Annual Variation of High and Low-Flow Extremes Associated With Land Use and Climate Change in the Upper Tekeze of the Nile River Basin	2022
Temporal variability of hydroclimatic extremes in the Blue Nile basin	2012
Climate Change Impacts on Water Resources in the Upper Blue Nile River Basin, Ethiopia	2009
Water balance dynamics in the Nile Basin	2009
Investigation of the Curve Number Method For Surface Runoff Estimation In Tropical Regions	2016
Rainfall-runoff modelling using artificial neural networks technique: a Blue Nile catchment case study	2006
Error propagation of climate model rainfall to streamflow simulation in the Gidabo sub-basin, Ethiopian Rift Valley Lakes Basin	2022
Modelling the effects of climate change on streamflow using climate and hydrological models: the case of the Kesem sub-basin of the Awash River basin, Ethiopia	2021
Modelling climate change impact on the streamflow in the Upper Wabe Bridge watershed in Wabe Shebele River Basin, Ethiopia	2021
A linear geospatial streamflow modeling system for data sparse environments	2008
Multi-method groundwater recharge estimation at Eshito micro-watershed, Rift Valley Basin in Ethiopia	2020
Effect of land use/land cover changes on surface water availability in the Omo-Gibe basin, Ethiopia	2021
Characterization of regional variability of seasonal water balance within Omo-Ghibe River Basin, Ethiopia	2017
Daily streamflow prediction in ungauged basins: an analysis of common regionalization methods over the African continent	2021
Changes in water availability in the Upper Blue Nile basin under the representative concentration pathways scenario	2017
Spatial and seasonal water level dynamics in dryland grabens along the Rift Valley of northern Ethiopia	2022
Land use dynamics and base and peak flow responses in the Choke mountain range, Upper Blue Nile Basin, Ethiopia	2021
Assessment of spatial and temporal distribution of surface water balance in a data-scarce African transboundary river basin	2022
Modelling rainfall-runoff processes of the Chemoga and Jedeb meso-scale catchments in the Abay/Upper Blue Nile basin, Ethiopia	2015
Responses of water balance component to land use/land cover and climate change using geospatial and hydrologic modeling in the Gidabo watershed, Ethiopia	2022
Integrated water availability modelling to assess sustainable agricultural intensification options in the Meki catchment, Central Rift Valley, Ethiopia	2022
Water balance variability in the confined Aba'ala limestone graben at the western margin of the Danakil depression, northern Ethiopia	2018
Impact of irrigation on the water level of Lake Maybar, Northeast Ethiopia	2019
Modeling the impacts of land use and land cover dynamics on hydrological processes of the Keleta watershed, Ethiopia	2021
Forecast-informed reservoir operations to guide hydropower and agriculture allocations in the Blue Nile basin, Ethiopia	2021

Table A2. *Cont.*

Title of the Articles	Year of Publication
Hydrological responses to human-induced land use/land cover changes in the Gidabo River basin, Ethiopia	2021
Modeling sediment yield of Rib watershed, Northwest Ethiopia	2022
Hydrological modelling uncertainty analysis for different flow quantiles: a case study in two hydro-geographically different watersheds	2019
Uncertainty assessment in river flow projections for Ethiopia's Upper Awash Basin using multiple GCMs and hydrological models	2020
Hydrologic and hydraulic assessment of scour problems at bridge sites in Tigray region, northern Ethiopia	2022
Climate change impact on Lake Tana water storage, Upper Blue Nile Basin, Ethiopia	2022
Landscape pattern and climate dynamics effects on ecohydrology and implications for runoff management: case of a dry Afromontane forest in northern Ethiopia	2022
A grid-based runoff generation and flow routing model for the Upper Blue Nile basin	2006
Evaluating the potential impact of climate change on the hydrology of *Ribb* catchment, Lake Tana Basin, Ethiopia	2022
Impact of climate change on streamflow of Melka Wakena catchment, Upper Wabi Shebelle sub-basin, south-eastern Ethiopia	2022
Effect of climate change on streamflow in the Gelana watershed, Rift valley basin, Ethiopia	2022
Response of climate change impact on streamflow: the case of the Upper Awash sub-basin, Ethiopia	2022
Hydrological evaluation of satellite and reanalysis-based rainfall estimates over the Upper Tekeze Basin, Ethiopia	2022
Coupled application of R and WetSpa models for assessment of climate change impact on streamflow of Werie Catchment, Tigray, Ethiopia	2021
Modeling the hydrological characteristics of Hangar Watershed, Ethiopia	2022
Statistical analysis of rainfall and streamflow time series in the Lake Tana Basin, Ethiopia	2020
Hydrologic responses to climate and land-use/land-cover changes in the Bilate catchment, Southern Ethiopia	2021
Flood inundation mapping under climate change scenarios in the Boyo watershed of Southern Ethiopia	2022
Evaluating watershed hydrological responses to climate changes at Hangar Watershed, Ethiopia	2021
Implication of bias correction on climate change impact projection of surface water resources in the Gidabo sub-basin, Southern Ethiopia	2022
Evaluation of the impacts of land use/cover changes on water balance of Bilate watershed, Rift valley basin, Ethiopia	2021
Climate change and hydrological analysis of Tekeze river basin Ethiopia: implication for potential hydropower production	2020
Climate change impact on river flow extremes in the Upper Blue Nile River basin	2019
Future climate change and impacts on water resources in the Upper Blue Nile basin	2022
Climate change impacts on the water and groundwater resources of the Lake Tana Basin, Ethiopia	2021
Modeling the spatio-temporal flow dynamics of groundwater-surface water interactions of the Lake Tana Basin, Upper Blue Nile, Ethiopia	2020
Impact of climate change on the streamflow of the Arjo-Didessa catchment under RCP scenarios	2021
Modeling the impact of agricultural crops on the spatial and seasonal variability of water balance components in the Lake Tana basin, Ethiopia	2019
Temporal and spatial changes of rainfall and streamflow in the Upper Tekeze–Atbara River Basin, Ethiopia	2017

Table A2. *Cont.*

Title of the Articles	Year of Publication
Analysis of the combined and isolated effects of LULC and climate change on the Upper Blue Nile River Basin's streamflow using statistical trend tests, remote sensing landcover maps, and the SWAT model	2017
Quantifying the Regional Water Balance of the Ethiopian Rift Valley Lake Basin Using an Uncertainty Estimation Framework	2021
Changes in land cover, rainfall and stream flow in Upper Gilgel Abbay catchment, Blue Nile basin—Ethiopia	2011
Streamflow sensitivity to climate and land cover changes: Meki River, Ethiopia	2010
A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia	2010
Flow regime change in an endorheic basin in southern Ethiopia	2014
Assessment of satellite rainfall products for streamflow simulation in medium watersheds of the Ethiopian highlands	2011
Regionalisation for lake level simulation—the case of Lake Tana in the Upper Blue Nile, Ethiopia	2011
Water balance modeling of Upper Blue Nile catchments using a top-down approach	2011
The effect of slope steepness and antecedent moisture content on interrill erosion, runoff and sediment size distribution in the highlands of Ethiopia	2011
Sediment management modelling in the Blue Nile Basin using SWAT model	2011
Hydrological characterization of watersheds in the Blue Nile Basin, Ethiopia	2011
A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia	2010
Establishing Stage–Discharge Rating Curves in Developing Countries: Lake Tana Basin, Ethiopia	2022

References

1. Cudennec, C.; Lins, H.; Uhlenbrook, S.; Arheimer, B. Editorial—Towards FAIR and SQUARE hydrological data. *Hydrol. Sci. J.* **2020**, *65*, 681–682. [CrossRef]
2. UNESCO. *IHP-IX: Strategic Plan of the Intergovernmental Hydrological Programme: Science for a Water Secure World in a Changing Environment, Ninth Phase 2022–2029*; UNESO, Division of Water Sciences: Paris, France, 2022; 51p.
3. Crochemore, L.; Isberg, K.; Pimentel, R.; Pineda, L.; Hasan, A.; Arheimer, B. Lessons learnt from checking the quality of openly accessible river flow data worldwide. *Hydrol. Sci. J.* **2020**, *65*, 699–711. [CrossRef]
4. Papa, F.; Bala, S.K.; Pandey, R.K.; Durand, F.; Gopalakrishna, V.V.; Rahman, A.; Rossow, W.B. Ganga-Brahmaputra River discharge from Jason-2 radar altimetry: An update to the long-term satellite-derived estimates of continental freshwater forcing flux into the Bay of Bengal. *J. Geophys. Res. Ocean.* **2012**, *117*, C11021. [CrossRef]
5. Walker, D.; Forsythe, N.; Parkin, G.; Gowing, J. Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. *J. Hydrol.* **2016**, *538*, 713–725. [CrossRef]
6. Donnelly, C.; Ernst, K.; Arheimer, B. A comparison of hydrological climate services at different scales by users and scientists. *Clim. Serv.* **2018**, *11*, 24–35. [CrossRef]
7. Beck, H.E.; Vergopolan, N.; Pan, M.; Levizzani, V.; Van Dijk, A.I.; Weedon, G.P.; Brocca, L.; Pappenberger, F.; Huffman, G.J.; Wood, E.F. Global-scale evaluation of 22 precipitation datasets using gauge observations and hydrological modeling. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 6201–6217. [CrossRef]
8. Blöschl, G.; Hall, J.; Parajka, J.; Perdigão, R.A.; Merz, B.; Arheimer, B.; Aronica, G.T.; Bilibashi, A.; Bonacci, O.; Borga, M.; et al. Changing climate shifts timing of European floods. *Science* **2017**, *357*, 588–590. [CrossRef]
9. Kuentz, A.; Arheimer, B.; Hundecha, Y.; Wagener, T. Understanding hydrologic variability across Europe through catchment classification. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 2863–2879. [CrossRef]
10. Gudmundsson, L.; Do, H.X.; Leonard, M.; Westra, S. The Global Streamflow Indices and Metadata Archive (GSIM)–Part 2: Quality control, time-series indices and homogeneity assessment. *Earth Syst. Sci. Data* **2018**, *10*, 787–804. [CrossRef]
11. Zolfagharpour, F.; Saghafian, B.; Delavar, M. Hydrological alteration and biodiversity change along the river network caused by anthropogenic activities and climate variability. *Ecol. Process.* **2022**, *11*, 19. [CrossRef]
12. Seyam, M.; Othman, F. Long-term variation analysis of a tropical river's annual streamflow regime over a 50-year period. *Theor. Appl. Climatol.* **2015**, *121*, 71–85. [CrossRef]
13. WMO. *Guide to Hydrological Practices, Vol. I: Hydrology—From Measurement to Hydrological Information*, 6th ed.; WMO: Geneva, Switzerland, 2008; No. 168.

14. Hamed, K.H. Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. *J. Hydrol.* **2008**, *349*, 350–363. [CrossRef]
15. Wilby, R.L.; Beven, K.J.; Reynard, N.S. Climate change and flood risk in the UK: More of the same? *Hydrol. Process.* **2008**, *22*, 2511–2523. [CrossRef]
16. Bierkens, M.F. Global hydrology 2015: State, trends, and directions. *Water Resour. Res.* **2015**, *51*, 4923–4947. [CrossRef]
17. GRDC. *River Discharge Data*; GRDC: Koblenz, Germany, 2014; p. 56068.
18. World Bank. *Assessment of the State of Hydrological Services in Developing Countries*; International Bank for Reconstruction and Development/The World Bank: Washington, DC, USA, 2018; 55p.
19. Rodda, J.C. Hydrological networks need improving. In *Water: A Looming Crisis? Proceedings of the International Conference on World Water Resources at the Beginning of the 21st Century, Paris, France, 3–6 June 1998*; Technical Documents in Hydrology—No. 18; UNESCO International Hydrological Programme: Paris, France, 1998; pp. 91–102.
20. Shiklomanov, A. World water resources and water use: Modern assessment and outlook for the 21st century. *Adv. Water Sci.* **1999**, *10*, 219–234.
21. Goodison, B.E.; Brown, R.D.; Brugman, M.M.; Duguay, C.R.; Flato, G.M.; LeDrew, E.F.; Walker, A.E. CRYSYS-Use of the cryospheric system to monitor global change in Canada: Overview and progress. *Can. J. Remote Sens.* **1999**, *25*, 3–11. [CrossRef]
22. Lanfear, K.J.; Hirsch, R.M. USGS Study reveals a decline in long-record stream gages. *Eos Trans. Am. Geophys. Union* **1999**, *80*, 605–607. [CrossRef]
23. Pozzoni, M.; Salvetti, A.; Cannata, M. Retrospective and prospective of hydro-met monitoring system in the Canton Ticino, Switzerland. *Hydrol. Sci. J.* **2022**, *67*, 2386–2400. [CrossRef]
24. Nigussie, L.; Haile, A.T.; Gowing, J.; Walker, D.; Parkin, G. *Citizen Science in Community-Based Watershed Management: An Institutional Analysis in Ethiopia*; IWMI Working Paper 191; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2020; 25p.
25. Belete, A.B. To upgrade the hydrometeorological network in Ethiopia. In Proceedings of the 25th WEDC Conference, Integrated Development for Water Supply and Sanitation, Addis Ababa, Ethiopia, 30 August–2 September 1999; pp. 211–214.
26. Nannawo, A.S.; Lohani, T.K.; Eshete, A.A.; Ayana, M.T. Evaluating the dynamics of hydroclimate and streamflow for data-scarce areas using MIKE11-NAM model in Bilate river basin, Ethiopia. *Model. Earth Syst. Environ.* **2022**, *8*, 4563–4578. [CrossRef]
27. Goshime, D.W.; Absi, R.; Ledésert, B. Evaluation and bias correction of CHIRP rainfall estimate for rainfall-runoff simulation over Lake Ziway watershed, Ethiopia. *Hydrology* **2019**, *6*, 68. [CrossRef]
28. Rientjes, T.H.M.; Perera, B.U.J.; Haile, A.T.; Reggiani, P.; Muthuwatta, L.P. Regionalisation for lake level simulation: The case of lake Tana in the upper Blue Nile, Ethiopia. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1167–1183. [CrossRef]
29. Tekleab, S.; Uhlenbrook, S.; Savenije, H.H.G.; Mohamed, Y.; Wenninger, J. Modelling rainfall–runoff processes of the Chemoga and Jedeb mesoscale catchments in the Abay/Upper Blue Nile basin, Ethiopia. *Hydrol. Sci. J.* **2015**, *60*, 2029–2046. [CrossRef]
30. Kebede, M.G.; Wang, L.; Li, X.; Hu, Z. Remote sensing-based river discharge estimation for a small river flowing over the high mountain regions of the Tibetan Plateau. *Int. J. Remote Sens.* **2020**, *41*, 3322–3345. [CrossRef]
31. Haile, A.T.; Geremew, Y.; Wassie, S.; Fekadu, A.G.; Taye, M.T. Filling streamflow data gaps through construction of rating curves in the Lake Tana Sub-basin, Nile basin. *J. Water Clim.* **2023**, *14*, 1162–1175. [CrossRef]
32. Taye, M.T.; Haile, A.T.; Genet, A.; Geremew, Y.; Wassie, S.; Abebe, B.; Alemayehu, B. *Data Quality Deterioration in the Lake Tana Sub-Basin, Ethiopia: Scoping Study to Provide Streamflow and Water Withdrawal Data*; IWMI Working Paper 204; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2022.
33. Haile, A.T.; Asfaw, W.; Rientjes, T.; Worako, A.W. Deterioration of streamflow monitoring in Omo-Gibe basin in Ethiopia. *Hydrol. Sci. J.* **2022**, *67*, 1040–1053. [CrossRef]
34. Donauer, T.; Haile, A.T.; Goshime, D.W.; Siegfried, T.; Ragettli, S. *Gap and Opportunity Analysis of Hydrological Monitoring in the Ziway-Shala Sub-Basin, Ethiopia*; IWMI Working Paper 192; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2020; 40p. [CrossRef]
35. Brown, L.E.; Mitchell, G.; Holden, J.; Folkard, A.; Wright, N. Priority water research questions as determined by UK practitioners and policy makers. *Sci. Total Environ.* **2010**, *409*, 256–266. [CrossRef]
36. Mdee, A.; Ofori, A.; Lopez-Gonzalez, G.; Stringer, L.; Martin-Ortega, J.; Ahrari, S.; Dougill, A.; Evans, B.; Holden, J.; Kay, P.; et al. The top 100 global water questions: Results of a scoping exercise. *One Earth* **2022**, *5*, 563–573. [CrossRef]
37. Blöschl, G.; Bierkens, M.F.P.; Chambel, A.; Cudennec, C.; Destouni, G.; Fiori, A.; Kirchner, J.W.; McDonnell, J.J.; Savenije, H.H.G.; Sivapalan, M.; et al. Twenty-three unsolved problems in hydrology (UPH)—*A* community perspective. *Hydrol. Sci. J.* **2019**, *64*, 1141–1158. [CrossRef]
38. WMO. *The 5 Essential Elements of a Hydrological Monitoring Programme*; World Meteorological Organization: Geneva, Switzerland, 2012; p. 61.
39. Stahl, K.; Hisdal, H.; Hannaford, J.; Tallaksen, L.M.; van Lanen, H.A.J.; Sauquet, E.; Demuth, S.; Fendekova, M.; Jódar, J. Streamflow trends in Europe: Evidence from a dataset of near-natural catchments. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 2367–2382. [CrossRef]
40. Whitfield, P.H.; Burn, D.H.; Hannaford, J.; Higgins, H.; Hodgkins, G.A.; Marsh, T.; Looser, U. Reference hydrologic networks, I. The status and potential future directions of national reference hydrologic networks for detecting trends. *Hydrol. Sci. J.* **2012**, *57*, 1562–1579. [CrossRef]

41. Tedla, H.Z.; Haile, A.T.; Walker, D.W.; Melesse, A.M. Evaluation of factors affecting the quality of citizen science rainfall data in Akaki catchment, Addis Ababa, Ethiopia. *J. Hydrol.* **2022**, *612*, 128284. [CrossRef]
42. Haile, A.T.; Gowing, J.; Parkin, G. Scope of citizen science for hydrologic monitoring in small watersheds in Ethiopia. In *Extreme Hydrology and Climate Variability*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 435–444. [CrossRef]
43. Kebede, M.G.; Wang, L.; Yang, K.; Chen, D.; Li, X.; Zeng, T.; Hu, Z. Discharge Estimates for Ungauged Rivers Flowing over Complex High-Mountainous Regions based Solely on Remote Sensing-Derived Datasets. *Remote Sens.* **2020**, *12*, 1064. [CrossRef]
44. Sneddon, C. *Concrete Revolution: Large Dams, Cold War Geopolitics, and the Bureau of Reclamation*; The University of Chicago Press: Chicago, IL, USA, 2015.
45. Nigatu, Z.M.; Fan, D.; You, W.; Melesse, A.M.; Pu, L.; Yang, X.; Wan, X.; Jiang, Z. Crop production response to soil moisture and groundwater depletion in the Nile Basin based on multi-source data. *Sci. Total Environ.* **2022**, *825*, 154007. [CrossRef] [PubMed]
46. Haile, A.T.; Akawka, A.L.; Berhanu, B.; Rientjes, T. Changes in water availability in the Upper Blue Nile basin under the representative concentration pathways scenario. *Hydrol. Sci. J.* **2017**, *62*, 2139–2149. [CrossRef]
47. Worku, G.; Teferi, E.; Bantider, A.; Dile, Y.T. Modelling hydrological processes under climate change scenarios in the Jemma sub-basin of upper Blue Nile Basin, Ethiopia. *Clim. Risk Manag.* **2021**, *31*, 100272. [CrossRef]
48. Worqlul, A.W.; Dile, Y.T.; Schmitter, P.; Jeong, J.; Meki, M.N.; Gerik, T.J.; Srinivasan, R.; Lefore, N.; Clarke, N. Water resource assessment, gaps, and constraints of vegetable production in Robit and Dangishta watersheds, Upper Blue Nile Basin, Ethiopia. *Agric. Water Manag.* **2019**, *226*, 105767. [CrossRef]
49. Degefu, M.A.; Bewket, W. Variability, trends, and teleconnections of stream flows with large-scale climate signals in the Omo-Ghibe River Basin, Ethiopia. *Environ. Monit. Assess.* **2017**, *189*, 142. [CrossRef]
50. Worqlul, A.W.; Dile, Y.T.; Ayana, E.K.; Jeong, J.; Adem, A.A.; Gerik, T. Impact of Climate Change on Streamflow Hydrology in Headwater Catchments of the Upper Blue Nile Basin, Ethiopia. *Water* **2018**, *10*, 120. [CrossRef]
51. Taye, M.T.; Haile, A.T.; Fekadu, A.G.; Nakawuka, P. Effect of irrigation water withdrawal on the hydrology of the Lake Tana sub-basin. *J. Hydrol. Reg. Stud.* **2021**, *38*, 10. [CrossRef]
52. Jillo, A.Y.; Demissie, S.S.; Viglione, A.; Asfaw, D.H.; Sivapalan, M. Characterization of regional variability of seasonal water balance within Omo-Ghibe River Basin, Ethiopia. *Hydrol. Sci. J.* **2017**, *62*, 1200–1215. [CrossRef]
53. Mengistu, T.D.; Feyissa, T.A.; Chung, I.M.; Chang, S.W.; Yesuf, M.B.; Alemayehu, E. Regional Flood Frequency Analysis for Sustainable Water Resources Management of Genale–Dawa River Basin, Ethiopia. *Water* **2022**, *14*, 637. [CrossRef]
54. Woldegebriel, T.; Garg, V.; Gupta, P.K.; Srivastav, S.K.; Ranjan, R. Ethiopia's Water Resources: An Assessment Based on Geospatial Data-Driven Distributed Hydrological Modeling Approach. *J. Indian Soc. Remote Sens.* **2022**, *50*, 1031–1049. [CrossRef]
55. Archfield, S.A.; Clark, M.; Arheimer, B.; Hay, L.E.; McMillan, H.; Kiang, J.E.; Seibert, J.; Hakala, K.; Bock, A.; Wagener, T.; et al. Accelerating advances in continental domain hydrologic modeling. *Water Resour. Res.* **2015**, *51*, 10078–10091. [CrossRef]
56. WMO. *Weather Extremes in a Changing Climate: Hindsight on Foresight*; World Meteorological Organization, WMO: Geneva, Switzerland, 2011; No. 1075.
57. Hurk, B.J.; Bouwer, L.M.; Buontempo, C.; Döscher, R.; Ercin, E.; Hananel, C.; Hunink, J.E.; Kjellström, E.; Klein, B.; Manez, M.; et al. Improving predictions and management of hydrological extremes through climate services. *Clim. Serv.* **2016**, *1*, 6–11. [CrossRef]
58. Post, D.A.; Jones, J.A. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. *Adv. Water Resour.* **2001**, *24*, 1195–1210. [CrossRef]
59. Lakew, H.B.; Moges, S.A. Dynamical bias correction procedure to improve global gridded daily streamflow data for local application in the Upper Blue Nile basin. *J. Hydrol. Hydromech.* **2021**, *69*, 41–48. [CrossRef]
60. Nega, H.; Seleshi, Y. Regionalization of mean annual flow for ungauged catchments in case of Abbay River Basin, Ethiopia. *Model. Earth Syst. Environ.* **2021**, *7*, 341–350. [CrossRef]
61. Lazin, R.; Shen, X.; Koukoula, M.; Anagnostou, E. Evaluation of the Hyper-Resolution Model-Derived Water Cycle Components Over the Upper Blue Nile Basin. *J. Hydrol.* **2020**, *590*, 125231. [CrossRef]
62. Khalil, M.; Panu, U.S.; Lennox, W.C. Groups and neural networks based streamflow data infilling procedures. *J. Hydrol.* **2001**, *241*, 153–176. [CrossRef]
63. Mwale, F.D.; Adeloye, A.J.; Rustum, R. Infilling of missing rainfall and streamflow data in the Shire River basin, Malawi—A self organizing map approach. *Phys. Chem. Earth Parts A/B/C* **2012**, *50–52*, 34–43. [CrossRef]
64. Nkiaka, E.; Nawaz, N.R.; Lovett, J.C. Using self-organizing maps to infill missing data in hydro-meteorological time series from the Logone catchment, Lake Chad basin. *Environ. Monit. Assess.* **2016**, *188*, 400. [CrossRef] [PubMed]
65. Buytaert, W. Citizen science in hydrology and water resources: Opportunities for knowledge generation ecosystem service management and sustainable development. *Front. Earth Sci.* **2014**, *2*, 26. [CrossRef]