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# Review: Groundwater research in the Ethiopian Rift Valley Lakes region

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Despite its proximity to many research institutions in the country and prevailing environmental and water security challenges, water resources research in the Central Rift Valley of Ethiopia has few decades of history. Research undertaken so far, mainly focus on the lakes' environment and anthropogenic activities in their proximities. Worsening deterioration of the water resources and environmental conditions; and the need to address overlooked but determinant natural and anthropogenic processes spurred a critical review of what has been done so far. This work provides an overview of the history of water research in the central rift valley and tries to reveal research gaps related to surface water-groundwater interaction, water quality, and changing trends in the hydro ecosystem and possible causes. Apart from this, articles dealing with the geological and structural setup of the central rift valley were systematically reviewed to show their control over the hydrologic system. The review work has revealed that although the current state of the central rift valley is a product of anthropogenic and geogenic processes; which are happening within the sub-basin and its adjacent basins that need to be addressed at a higher thematic, spatial, and temporal scopes, there is gap in reviewed research, to address the issue at this level. The forefront environmental challenges and the need for quick fixes, lack of data, and funding are found to be some of the reasons to limit the scope of research activities, mainly to shallow groundwater zones and surface hydrological processes around the lakes. This approach has hindered seeing the bigger picture and resulted in ineffective environmental and natural resources restoration measures and policy decisions.

KEYWORDS

**Rift Valley Lakes, Ethiopia, groundwater-surface water interaction, groundwater flow controls, Ethiopian wetlands**

## Introduction

Research in earth sciences is relatively getting more attention in recent decades. There were few research works undertaken by foreign researchers in the Ethiopian Rift Valley Lakes area, during the 1920s; as part of the main colonial time objective of looking for natural resources. The opening of Addis Ababa University (AAU) in 1950 and the subsequent opening of the geology department, as one of the first four fields of studies, created a leap in research in earth sciences (AAU, 2013). The establishment of the Geological Survey of Ethiopia (GSE) in 1968 and Arba Minch Water Technology Institute in 1986 were decisive steps that helped to investigate and map the geology and structural set-up of Ethiopia and its water resources (GSE, 2021). Since its establishment, the GSE has conducted regional geologic, geophysical (land gravity and airborne), and geochemical mapping works that were used as a basis for various groundwater related research (Gasse and Street, 1978; Chernet, 1982; Chernet et al., 1988; Darling et al., 1996; Benvenuti et al., 2002). Earlier research works in water resources were limited to expeditions in search of the Nile Source. Research in groundwater was not area of attention till the increased water demand, deteriorating water quality and quantity conditions and degradation of the hydro-ecosystem forced the intensification of water research in recent decades. At present, water education and research activities are carried out by more than eight universities found across the country. Research topics like groundwater hydraulics, interactions between groundwater and rivers, lakes, and wetlands; land use and climate changes; pollution, trans basin flows (Alemayehu et al., 2018) and evaluation and modeling are on the rise (Ayenew, 2001, 2002; Tekle-Haimanot et al., 2006; Kebede et al., 2007, 2008; Belete et al., 2016; Bonetto et al., 2021).

Despite all the efforts, a clear understanding of the hydro-ecosystems of the CRV is lacking. The causes for the alarmingly degrading lakes' environment, the diminishing river flows, the drying up of springs and the lowering of the groundwater tables on one hand; and the emergence of new lakes and swamps on, the other hand, are not well-explained. The ever-increasing water demand for irrigation, industrial use and domestic purposes led to the emerging water management and governance problems that need policy adjustments, which are based on good understanding of the hydrological dynamics in the basin. This work aims to identify major gaps required to understand the CRV in a better way; without which managing the water resources of the CRV and ensuring water security for generations to come is difficult. Although the focus of this paper is on groundwater-related research, it also touches on aspects affected by the missing gaps in the core task of a clear understanding of the hydro-geo-environment.

# Objectives

The main objective of this work is to identify gaps in groundwater and related studies undertaken in the CRV to help understand the CRV's hydrodynamics and the hydro-ecosystem in a better and wholistic manner; for better management of the water resources and ensuring water security.

# Methodology

## The study area

The Central Rift Valley (CRV) lake basin system is part of the Main Ethiopian Rift (MER) that includes four present-day residual lakes, Zeway, Langano, Abijata, and Shalla; and a tectonically controlled endorheic basin (Street, 1979; Chernet, 1982). It covers a total area of 14,480 km$^2$ bounded by $7^\circ 00' 56''$ to $8^\circ 28' 8''$N latitude and $38^\circ 03' 38''$ to $39^\circ 24' 48''$ E longitude (Figure 1). The rainfall distribution over the study area has wide spatial variability ranging from mean annual rainfall of 700 mm in the lowlands to 1,200 mm in its eastern and western highland parts. The CRV has been designated as a potential core site by the ERICA Project ("Environmental Research for Intertropical Climate in Africa") for being under the influence of the Intertropical Convergence Zone seasonal migration.

Various studies show that the basin has been subjected to changes in water level and water salinity, at least during the Late Pleistocene (Le Turdu et al., 1999). The Zeway–Shala closed basin is the central part of the Main Ethiopian Rift (MER), which is used as a reference site for regional to global paleoclimatic reconstructions.

The valley supports wide-ranging socio-economic and ecosystem services. In terms of landuse, 76.8% of its area is dominantly under rainfed agriculture. Irrigated agriculture covers <3% of the basin. About 44% of the existing irrigated areas rely on surface water from streams. Thirty-one percentage pump directly from Lake Zeway, and about 25% from groundwater.

# Data sources, materials, and review steps

Most of the published articles used for this paper were collected from online sources such as a simple google search, Semantic Scholar, Google Scholar, ResearchGate, Science Citation Index Expanded (SCIE) bibliographic database, which is maintained by Thomson Reuters, and SCI-Expanded, which indexes the world's leading journals of science and technology. The privilege from home University was used to acquire e-journals from a few publishers. Published maps and books in Ethiopian Geological Surveys and Addis Abeba University Libraries were also used. The 5Ws framework (Who—What—When—Where—Why) was used to frame the search. Articles that are not available online were supplied by authors on request. Search terms including "geology," "rifting," "groundwater," "Central Rift Valley Lakes," "Main Ethiopian Rift," "water quality," "climate," and "Ethiopia" were used to locate publications related to the topics under consideration.

A total of 496 journal articles, book chapters, reports and PhD theses were collected, among which 94 are analyzed. Available publications were checked for their originality and published in reputable peer-reviewed journals to minimize bias. Collected books, reports and articles were grouped into five major groups under "geology and structure," "groundwater and surface hydrology," "Climate," and "Landuse—landcover," and "others" categories and organized in EndNote Library (Table 1).

The selection of articles to be reviewed for groundwater and related research were done based on their research objectives, time of research undertakings, scope, and level of study and scores of researchers on known online rating sites. Rather than focusing on the nitty-gritty of individual papers, research papers are grouped into thematic areas and qualitatively reviewed for common and important missing gaps needed to better understand and characterize the basin. Articles were carefully read, compared, interpreted, and checked for their complementarity. Finally, results were discussed and narrated. A simplified flow diagram of steps followed during the review process is shown in Figure 2.

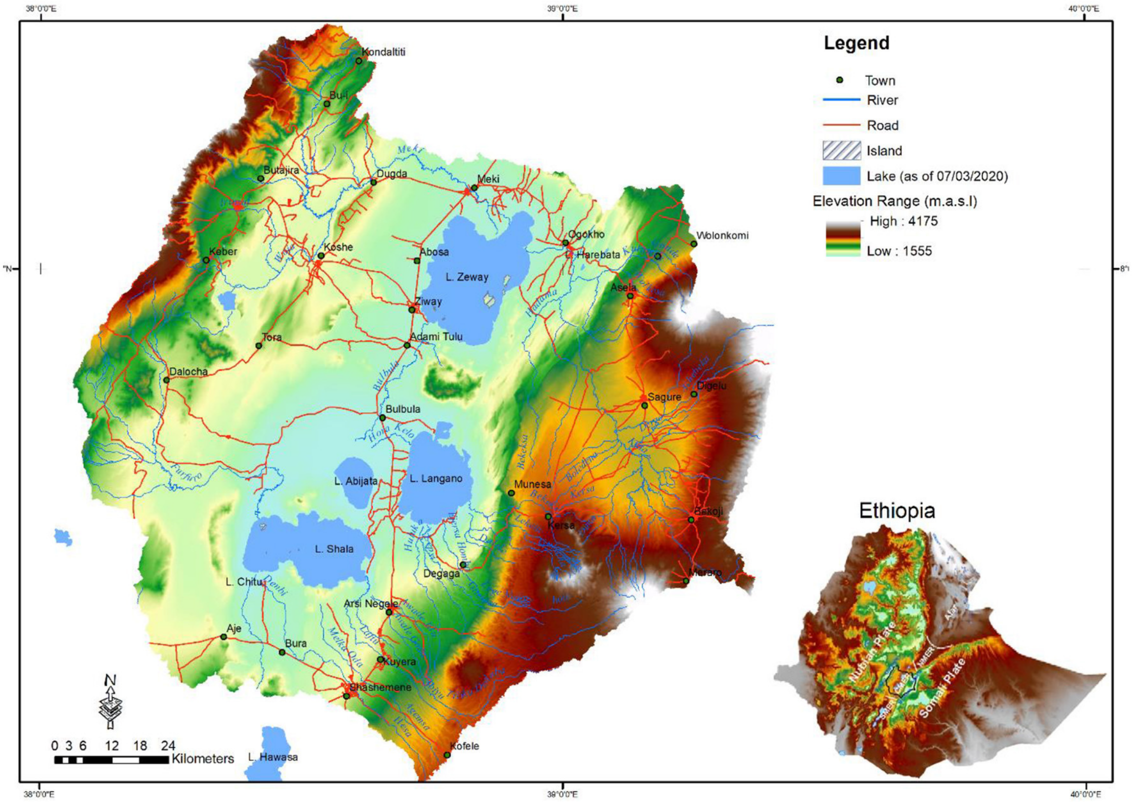


FIGURE 1
Location map of the Central Rift Valley.

TABLE 1 Overview of collected data.

| Category | Source | Year of publication | Retained in EndNote Library | Analyzed |
|---|---|---|---|---|
| Geology and structure | Online e-journals, reports, and books | 1920–2021 | 194 | 27 |
| Groundwater and surface hydrology | Online e-journals, reports, and books | 1932–2021 | 198 | 42 |
| Climate | Online e-journals, and reports | 1978–2021 | 43 | 13 |
| Landuse-landcover | Online e-journals | 1999–2020 | 32 | 10 |
| Others | Online e-journals, and reports | 1995–2018 | 29 | 2 |

# Results and discussion

## Triggers for groundwater and related research

Research activities in groundwater and water-related topics in the CRV are preceded by researches done in areas of geological and structural settings of the CRV. As part of the Greater East African Rift System (EARS), the CRV was studied by several international and local geoscientists, with main objectives of investigating the rifting process, paleoclimate and sedimentation, and exploring mineral resources associated with rifting processes and lake environments. The earlier works include that of Mohr (1970), Paola (1971), Street (1979), Browne and Fairhead (1983), Wolde (1989), Lars et al. (1991), and Ebinger et al. (1993). These research works were followed by more organized and systematic research works, such as the EAGLE Project (Bastow et al., 2011). The discovery of geothermal energy (Paola, 1971; Kandie, 2014; Sisay, 2016; Boone et al., 2019) and industrial minerals like diatomite (Million, 1989; Abera, 1994) and soda ash (EIGS, 1989) also initiated the need for detailed geological mapping in the basin (Tadesse et al., 2003).

Groundwater and related research were, predominantly, the focus of academic institutions abroad and within Ethiopia. In this regard, opening the field of specialization in hydrogeology at AAU and Arba Minch Water Technology Institute in 1986 created a significant leap. Understanding the paleoclimate, lake-level fluctuation, the geochemistry of sediments, isotope pattern of precipitation, fluid-rock interaction, lake-groundwater relationships, and understanding the hydrogeological system of the CRV were among the topics that attracted researchers (Baumann et al., 1975; Gasse and Street, 1978; Darling et al., 1996; Rozanski

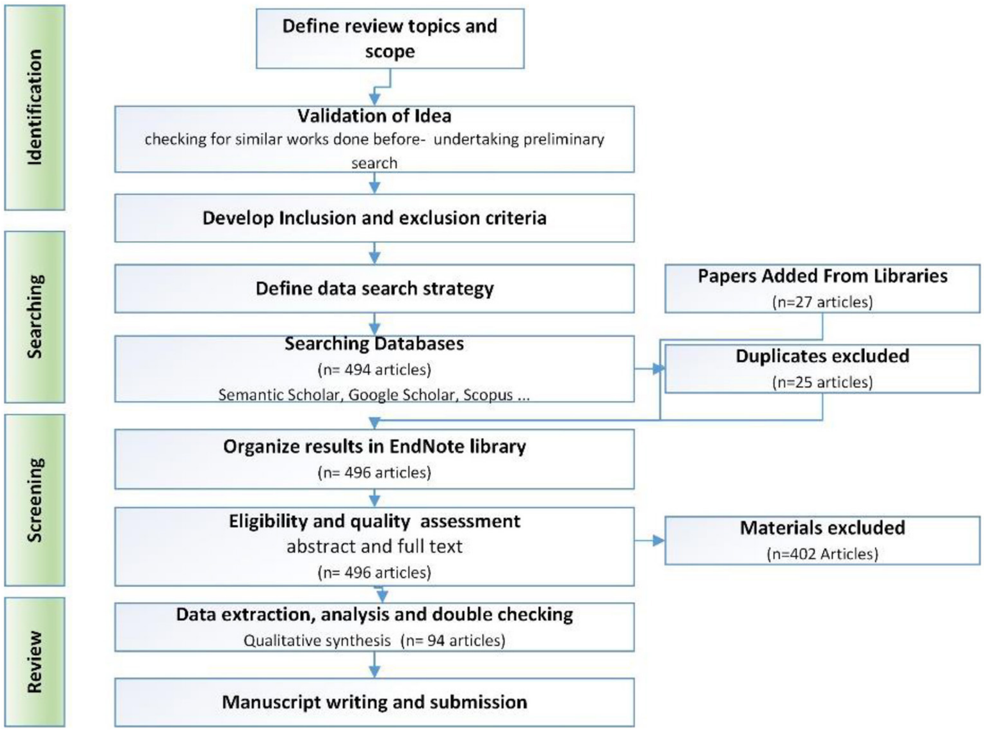


FIGURE 2
Simplified review flow diagram.

et al., 1996; Ayenew, 1998). Water quality deterioration and degradation; and modeling and evaluation of the water resources are emerging research issues (Haji et al., 2018; Thomas et al., 2019; Abraham et al., 2021; Bonetto et al., 2021; Kebede et al., 2021; Ligate et al., 2021). The increasing need for the development of water resources initiated mapping projects at different scales, and the development of master plan studies (Chernet, 1982; Chernet et al., 1988; HALCROW, 1989; MoWR, 2009). These works have laid the basis for groundwater and related research activities.

## Geological and structural setup of the CRV

The geology and structural setup of CRV are, relatively speaking, the most researched thematic area. Many research works were done in the past half a century in these areas. Among many earlier works, the research by WoldeGabriel et al. (1990) is a comprehensive work on geology, geochronology, and rift basin development. Benvenuti et al. (2002) undertook and interpreted a stratigraphical, pedological, and geomorphological study, including a new geological map scale 1:250,000, to provide a Late Quaternary-centered revised geological history of the basin.

The tectonic analysis of the Asella-Langano Margin by Corti et al. (2020), the study on the Wonji fault belt by Pizzi et al. (2006) and on the volcanism, tectonics and fault architecture of the Main Ethiopian Rift by Le Turdu et al. (1999) and Agostini et al. (2011a,b), showed the configuration of regional and local geological structures that are one of the major groundwater flow controlling factors in the basin. The depth estimates of anomalous subsurface by Kebede et al. (2021), examine the depth to the crystalline basement, which is important to determine the groundwater flow dynamics in the basin. The CRV was part of the giant research project: "The Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE)" that probed the transition from continental rifting to incipient seafloor spreading (Bastow et al., 2011). The structural connectivities of CRV with adjacent basin was indicated in the works of Gasse and Street (1978), WoldeGabriel et al. (1990), and Tiercelin and Lezzar (2002). Explorations for geothermal energy also provided highly valuable data that is necessary for a thorough understanding of the basin. Drilling at Aluto geothermal site provided lithological and structural information as deep as 2,500 meters (Meseret and Bayne, 2005). At Tulu Moye, recently completed drilling stopped at 2,900 meters. Ongoing drilling activities in all the three exploration sites for geothermal energy: Aluto, Tulu Moye, and Corbetti are expected to highlight the nature of aquifers at more depth. These works are key to establishing the hydrological connectivity of CRV with adjacent basins and determining regional flows.

The research by Sagri et al. (2008), on the reconstruction of the paleo river network; by Jones and Mgbatogu (1977) on Late Quaternary lake levels in southern Afar and the adjacent Ethiopian Rift; and the work on the influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation in the Zeway–Shalla Lakes Basin system by Le Turdu et al. (1999), provided evidence-based knowledge on the formation process and evolution of the lakes. Similar studies on Late Quaternary lake-level fluctuations and environment of the Northern Rift Valley and Afar Regions by Gasse and Street (1978), and on the evolution of Zeway–Shala lake basin by Benvenuti et al. (2002), reached to similar conclusions on lakes formation processes.

In addition to these works, the broad review of 300 million years of Rift Valley Lakes in central and east Africa (Benvenuti et al., 2002), the Paleoenvironment of Lake Abijata, Ethiopia, during the past 2000 years by Bonnefille et al. (1986), the study on the Late Quaternary lacustrine sediments of the Zeway–Shala Basin by Balemwald (1998), the research on Late Quaternary Lake Levels in the Rift Valley of Southern Ethiopia and elsewhere in Tropical Africa by Grove and Goudie (1971) and Grove et al. (1975), examined the paleolake environment which is a key to understand the present hydrological dynamics in the CRV. The study on the evolution of the northern part of the Ethiopian Rift by Kazmin et al. (1980) and the work of that of Giday et al. (2016) and related the structural and geomorphic features of the EARS with the genesis of the rift valley lakes.

These systematic evidence-based researches, which were based on field investigation, radiometric dating, and data from deep drilling for geothermal energy provide in-depth analysis of the CRV. Research in the CRV has gradually evolved to a higher level, addressing topics which are complementary to each other. These works provide some of the required information to establish the relationship between CRV and adjacent hydrogeological regimes. They revealed the complex lithological and structural setups of the basin to help characterize the groundwater dynamics in it.

Geological map of Ethiopia by Kazmin et al. (1980), Geological Map of the Lake Zeway-Asella region by Abebe et al. (1998), Geological map of the Zeway-Shala lakes basin by Dainelli et al. (2001) and the Geological map of the Asella-Langano margin by Corti et al. (2020) are important sources of the geological information on the CRV. Apart from their limitations in scale, lack of detailed information on deep structures and lithological configuration, and presence of little inconsistencies in terminologies and dating of ages of events and rocks, these works are sufficient for hydrogeological characterization of the aquifers and other water-related research.

## Groundwater and related research in the CRV and their connections with geological research

Research on water resources of Ethiopia has an older beginning but a retarded development. In his work on the history of the scientific study of Tropical African inland water, Talling (2006) mentioned the period 1925 to 1945 as a period of advancing colonial administration in many African territories, during when research was stimulated by economic and social issues. According to this work, the two main areas of interest were hydrology and fisheries. The work on hydrology evolved into the estimation of water budget and flow gauging of many rivers. In Ethiopia, however, only a few expeditions including the Cambridge Expedition in 1930, to the East African Lakes (Beadle, 1932), were recorded before 1935. Water samples were collected and analyzed during this expedition. Later, during the brief period of Italian occupation, several surveys of major rift valley lakes and the elevated Lake Tana were made (Talling, 2006). However, this move remained discontinued till the 1970s.

In the 1970s, groundwater research and related topics made a slow restart in the CRV. Few researchers that were seen doing related works across many years, were actively engaged. The work on water chemistry, mineralogy, and geochemistry of sediments in the Ethiopian Rift by Baumann et al. (1975), is probably the oldest available research followed by Chernet (1982) work on the hydrogeology of the Lakes Region. The study by HALCROW (1989) and MoWR (2009), which was done as part of the rift valley lakes integrated natural resources development master plan, is a basin-wide work that addressed various aspects of the CRV. One of the few studies on lake-groundwater relationships and fluid-rock interaction in the East African Rift Valley was that of Darling et al. (1996), which was based on isotopic evidence. A PhD research by Ayenew (1998), examined the hydrogeological system of the CRV using mainly remotely sensed data. He probably is the one who first attempted to perform numerical flow modeling of the groundwater of the CRV (Ayenew, 2001) and to use environmental isotope-based integrated hydrogeological study of some of the Ethiopian Rift Valley Lakes (Ayenew, 2003). Environmental isotopes and geochemistry were used by Kebede (2004) in investigating groundwater and lake hydrology of the Ethiopian Rift. The hierarchical cluster analysis of hydrochemical data as a tool was used by Ayenew et al. (2009) to assess the evolution and dynamics of groundwater across the Ethiopian Rift.

Few research works were made regarding groundwater-surface interaction and trans-basin flows. Among these, the study on Meki River's streamflow sensitivity to climate and land cover changes by Legesse et al. (2010); Modeling for Inter-Basin Groundwater Transfer Identification: The Case of Upper Rift Valley Lakes and Awash River Basins of Ethiopia by Mohammed and Ayalew (2016); the SWAT based hydrological assessment and characterization of Lake Zeway sub-watersheds, Ethiopia, by Desta and Lemma (2017) are to be mentioned. One of the few works on lake–groundwater interactions is that of Tenalem and Tilahun (2008). It assessed the lake–groundwater interactions and anthropogenic stresses, using a numerical groundwater flow model (Tenalem and Tilahun, 2008). Kebede (2013) briefly discussed the typical feature of the Butajera-Asella transect.

There are studies done to assess and evaluate the water resources in the CRV and the Rift Valley. Among these studies are: Comparative assessment of the water balance and hydrology of selected Ethiopian and Kenyan Rift Lakes (Ayenew and Becht, 2008); Rift Valley Lakes Basin Integrated Resources Development Master Plan Study (MoWR, 2009); the Study on Groundwater Resources Assessment in the Rift valley Lakes Basin in Ethiopia (JICA, 2012); estimation of groundwater recharge and water balance of the Rift Valley Lakes by Kebede (2013); Quantifying Increased Ground Water Demand from Prolonged Drought in the East African Rift Valley (Thomas et al., 2019); Analytical Hierarchal Process (AHP) based analysis of groundwater potential in the western escarpment of the Ethiopian rift valley (Abrar et al., 2021); Groundwater Resources in the Main Ethiopian Rift Valley: An Overview for a Sustainable Development (Bonetto et al., 2021); and Quantifying the Regional Water Balance of the Ethiopian Rift Valley Lake Basin Using an Uncertainty Estimation Framework (Abraham et al., 2021). However, there are significant differences in the figures they are providing, and in the approaches, they are following.

## Water quality

Results of the Cambridge Scientific Expedition in 1930 to the East African Lakes (Beadle, 1932) is probably the oldest work on sampling and analysis of the waters of the CRV lakes. The research on water quality of the CRV, was mainly focused on the existing fluoride problem in the basin. Some of these research works include, the work Tekle-Haimanot et al. (2006) on the geographic distribution of fluoride in surface and groundwater, Ayenew (2008) work on the distribution and hydrogeological controls of fluoride in the groundwater of central Ethiopian rift and adjacent highlands; and Demelash et al. (2019) systematic review and meta-analysis on fluoride concentration in groundwater and prevalence of dental fluorosis in Ethiopian Rift Valley. Kebede (2013) summarized the geochemistry and water quality of the groundwater of Ethiopia. In this work, the geochemistry of fluoride was found expressive of groundwater situation in the CRV.

Although works on fluoride are dominating, some researchers were dealing with the general water quality aspects. The work on water chemistry, mineralogy and geochemistry of sediments in an Ethiopian Rift by Baumann et al. (1975) is one of the oldest research. The mechanism of water quality degradation in the lake regions of Ethiopia was analyzed by Chernet et al. (2001). Zinabu et al. (2002) investigated the long-term changes in chemical features of waters of the seven Ethiopian Rift Valley lakes, including those of the CRV. Ayenew (2005) research on major ions composition of the groundwater and surface water systems and their geological and geochemical controls in the Ethiopian volcanic terrain is the most cited and comprehensive analysis. The research by Kebede et al. (2008) dealt with groundwater origin and flow along selected mountain-valley transects in Ethiopian rift volcanic aquifers. Hydrochemical characterization and quality assessment of groundwater of Meki River basin were done very recently (Mesele and Mechal, 2020). Zeway Lake was included in Masresha et al. (2011) research on the speciation of selected trace elements in three Ethiopian Rift Valley Lakes, including Koka, Zeway, and Awassa; and their major inflows. Lake Shala was one of the East African Soda Lakes studied by John and MacIntyre (2016), for its morphometry and physical processes, chemical stratification and mixing, temperature trends, and climate changes.

Water development in Ethiopia, particularly groundwater development, is at its initial development stage. Potable water supply coverage in Ethiopia, during the late 1980s, was below 20%. Groundwater use for irrigation is only a decade old. Compared with this slow pace of groundwater development, the growth in groundwater research is encouraging. These researches have set the basis for groundwater research in the CRV. Although the knowledge on the deeper groundwater aquifers is limited, the shallow groundwater aquifers are better understood. This research helped developers to make informed development plans.

## Climate and the hydro-ecosystem

Similar to the hydro-ecosystem, geological processes, such as rifting and uplift and the hydrogeomorphology setting have modified the present climate condition of the CRV and the hydrology of the lakes. Aside from analyzing the paleoclimate, paleo river network and lake environments discussed above, many researchers have attempted to research the contemporary climate situation and the state of water resources in the CRV. Nicholson analyzed the historical fluctuation of the rift valley lakes as part of the comprehensive study that covered Lake Victoria and lakes in the Northern Rift Valley of East Africa (Nicholson, 1998). Ayenew (2002) studied the recent changes in the Lake level of Abijata, followed by his work under the title "The changing face of the Ethiopian rift lakes and their environs: call of the time" (Ayenew and Legesse, 2007). Legesse et al. (2004) analyzed the hydrological response of Lake Abijata to changes in climate and human activities. Similarly, Abraham et al. (2018) studied the hydrological responses of climate change on Lake Zeway Catchment. Seyoum et al. (2015) investigated the relative impacts of natural processes and human activities on the hydrology of the CRV lakes. Characterization of water level variability of the Main Ethiopian Rift Valley Lakes was done by Belete et al. (2016) and environmental assessment of the East African Rift Valley lakes was done by Eric et al. (2003). Research by Gadissa et al. (2018) analyzed sedimentation and loss of lake volume in the CRV that happened due to changes in climate.

Apart from the degradation of the lake environment, there are huge landuse/landcover changes taking place affecting the hydro-ecosystem. There are few studies addressing causes and effects of this alarming trend at the CRV level. The followings are among the few works to be mentioned. Impact of land use/land cover changes on the lake ecosystem of Ethiopia's central rift valley by Elias et al. (2019) addressed changes taking place in the lake environment. The work by Mengesha et al. (2014) uncovered the impacts of land use, land cover and climate change on the bird community in and around Lake Zeway. Another research by Muluneh et al. (2017), investigated the effects of long-term deforestation and remnant forests on rainfall and temperature in the CRV.

Most wetlands in the CRV, on which the existence of the lake systems is dependent, are largely controlled by geological structures. However, their existence is threatened, research on wetlands of the CRV is almost non-existent. Some of the wetlands in the CRV are included in the country-wide overview undertaken by Leykun (2003). Studies on local ecological knowledge and wetland management in the Ethiopian Rift Valley (Gebrehiwot, 2020) and Gap and Opportunity Analysis of Hydrological Monitoring in the Zeway-Shala Sub-basin, Ethiopia (Donauer et al., 2020) are also among the few research done on the wetland systems. Although not exhaustive in exploring the wetland of the CRV, these works highlight the state of the endangered wetlands and create awareness on their vulnerability to anthropogenic and climate variabilities.

## Limitations and gaps in groundwater and related research

Despite the availability of the above-mentioned geological research, efforts to make use of them for groundwater and related hydrological studies were not going in parallel. Most hydrogeological research and related mapping activities have been affected by the lack of lithological log data, pumping test results, water quality data, and poor data quality (Chernet et al., 2001). As a result, there are important groundwater characterization factors of the CRV, which were not well-addressed or missing. The followings are the main gaps in the groundwater and related water research mentioned above.

- Unable to establish relationship between fault swarm vis-à-vis groundwater divide, which is required to establish regional and local flow paths and consider its impact on water budget calculation and allocation efforts.
- The hydrogeological and hydrological significance of the dominant structural features in the basin- Wonji Fault Belt (WFB) and Silti Debrezeit Fault System (SDFS) convergence zone, is not well-established.
- There is limitation in understanding the paleogeomorphology of the CRV and the grabens formed by each fault zone, the obscured valleys that may have been buried along the rift aquifers. Understanding these helps to identify where filled grabens with good aquifer characteristics and the good aquifer and horsts are located, and the possibility of finding buried river networks that may have been filled with pyroclastics, as that of the nearby Kessem-Kebena River system (WoldeGabriel et al., 1992).
- Possible modification of the hydraulic property of aquifers by the progressing rifting is not analyzed.
- Response of the hydrogeological system to seismicity, which are happenings in the CRV, is unknown (e.g., the 2017 Langano earth quack, with a magnitude of 5.3).
- The undetermined hydrological connection between the CRV and following flow controlling features: Awash River basin in the northeast that is connected through fault swarms along the Gurage escarpment; similar possible connections with Hawassa and Agere Selam escarpment; and Wabe Shebelle River Rift zone; Bilate River basin (through Awassa caldera); the Omo River canyon; and Abaya-Chamo lakes.
- Unknown regional connectivity role of the regional Ambo lineament, which cuts across different basins, including the CRV.
- The regional hydraulic connectivity with Karoo Rift in the south, the Blue Nile Rifted basin, which is truncated by MER from Ogaden rifted basin, and Anza Rift in the south are also not determined.
- The hydrogeological implications of the general basement gradient, which is toward Awash River Basin, and the narrow-uplifted block (Mt. Damot) between MER and Omo Rift are not yet investigated.
- The tendency to use various models to determine the water balance and characterize the basin with little or no reference to other model outputs—unfit models to the hydrological and hydrogeomorphological setup of the CRV.
- The main limitations of research in water quality are:

TABLE 2 Major gaps and challenges in groundwater water and related research in the CRV.

| Category | No. of articles | Study objective | Similarities and differences | Strength | Gaps/limitation | Challenges |
|---|---|---|---|---|---|---|
| Geology and structure | 27 | Dominated by the rifting process | Studies complement each other and show continuity | Systematic evidence-based research, supported by field surveys available techniques and instrumentations | Very much focused on the rifting processes and poorly linked with other disciplines | Difficult to replicate methods and approaches used by international scientists due to the capacity limitations and awareness at the policymakers' level, locally |
| Groundwater, surface hydrology, water quality, wetland | 42 | Development and academic research | Based on limited primary data, not at a basin scale | Provide good information on the shallow groundwater | • Limited to shallow groundwater<br>• Poorly address groundwater-surface water interaction<br>• Pollution fragmented studies that failed to see the broader/regional aspects | • Limited funding, local capacities to handle high-level research limited<br>• Insufficient groundwater and lake level, and flow data<br>• Weak policy and funding support |
| Climate | 13 | Academic and grant driven | Strong paleo-climate analysis | Established a link between climate variability and changing lakes environment | Studies of the present scenario are fragmented | No sufficient measured climate data |
| Landuse-landcover | 10 | Investigate current problems and suggest solutions | Focus on the lakes' environment and land degradation | Able to show trends and send alarm | • Not at a basin scale and poorly established cause-and-effect relationships<br>• However, many papers put anthropogenic factors as the major driver of land degradation | Poor coordination among researchers to do multidisciplinary integrated research |

- The scale in determining the spatial distribution of fluoride, as concentration may vary depending on lithology, climate, and hydrological factors.
- Unable to fully capture the vertical variation in concentration, and variations across the different hydrogeological regimes.
- Impact of the calc-alkaline nature of Butajera ignimbrite on the water chemistry of the CRV was not investigated.
- Capacity gaps to analyze hazardous toxic substances and heavy metals discharges as industrial effluents and impacts of the increasing long-term application of agricultural inputs.

The biggest problem observed in research that attempted to analyze impacts of the changing land use-landcover and climate change on the CRV lakes, the wetlands and the water resources is the failure to address problem at a basin scale and failure to see connectivity with adjacent basins. Ignoring the influence of topography, hydrogeomorphic structures, and the earth's thermal influence, particularly in such a rifting area like the CRV, and the spatial variability controlled by the two adjacent plateaus. Unlike many other parts of the country, there is visible variation in moisture vegetation response observed on the leeward vs-a-vis the windward sides, which is not well-captured. Most of the works overlooked the impacts of the increasing temperature trend in the basin on the lake water level. Studies on sedimentation, little uncover the contribution from anthropogenic processes (Le Turdu et al., 1999) and changes in the hydrological processes and in the rivers' flow pattern and their sediment loads as a result of changes in land use/landcover. There is increasing blame on water abstraction for development from lakes and rivers. This conclusion failed to analyze the emergence of new lakes and wetlands in upstream areas; the expansion of mangroves because of the increasing silt accumulation and geological structural controls; expansion of irrigation in the highlands that didn't allow return flows to river systems; impacts of changed land tenure system; and the ever-increasing abstraction of groundwater for domestic and industrial water demands. The strength and gaps of research undertakings in the past decades are summarized in Table 2.

## Conclusions

Research on the geology and structures of the CRV and the rifting process is continuously progressing and provides the necessary knowledge required for proper hydrogeological characterization of the basin and to show its hydrological connectivity with adjacent basins and regional structures. The lack of an integrated-multidisciplinary basin-wide approach and focusing only on lakes-side activities are major drawbacks of the water-related research activities in the CRV. Although the socio-economic processes, such as population growth, urbanization, competing water demands between irrigation, domestic, and industrial demands and climate change are major water security problems, the geological and structural setup of the CRV has a lot to contribute. The hydrogeological dynamics in the highly porous aquifers; the influence of the perpendicularly striking structures to the surface water flow direction and the nearly vertically dipping parallel, and transecting structures; the hydrogeological relationships with adjacent basins; and the connection of the lakes with these phenomena are not well-investigated. The impacts of the anthropogenic and geogenic processes need to be analyzed in an integrated manner and at a basin level. Unless such knowledge gaps of the CRV are addressed, proper evaluation and optimum and sustainable use of the water resources will be difficult. The current approach of providing piecemeal solution, to tackle basin level problems of degradation of the hydro-ecosystem, may not provide lasting solution to avert potentially irreversible damage happening to the lakes' environment.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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