








## Review

# Challenges and Prospects of Advancing Groundwater Research in Ethiopian Aquifers: A Review

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**Abstract:** Groundwater is a strategic resource in all climatic regions of Ethiopia, contributing about 80% of the domestic supply of urban and rural populations. However, little research has been available compared with extensive geographical coverage and increasing population growth rates. Hence, the present study aimed to review published groundwater research of Ethiopian aquifers to realize potential research challenges and suggest future research directions. We focused on groundwater potential, recharge process, and qualities. The total potential groundwater of the country ranges from 2.5 to 47 billion cubic meters. The study depicted that the mean annual recharge estimate varies from 24.9 mm to 457 mm at catchments scales. However, the overall country was about 39.1 mm. The study found a need for a detailed investigation of different factors susceptible to groundwater pollution, as some of the evaluations indicated exceeding acceptable standards. This study observed that the main challenge was the lack of data and convergence research trends. Henceforth, future research in different climate regions should focus on multifaceted technical and stakeholder settings. This study gives the insight to integrate palatable research findings with the national policy and decision-making process to enhance the sustainability of groundwater resources significantly.

**Keywords:** aquifers; Ethiopia; groundwater; groundwater recharge; groundwater potential; sustainable management



**Citation:** Mengistu, T.D.; Chung, I.-M.; Chang, S.W.; Yifru, B.A.; Kim, M.-G.; Lee, J.; Ware, H.H.; Kim, I.-H. Challenges and Prospects of Advancing Groundwater Research in Ethiopian Aquifers: A Review. *Sustainability* **2021**, *13*, 11500. <https://doi.org/10.3390/su132011500>

Academic Editors: Hartmut Wittenberg and Hafzullah Aksoy

Received: 24 August 2021

Accepted: 13 October 2021

Published: 18 October 2021

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## 1. Introduction

Groundwater management is a global challenge due to rapid population growth, urbanization, climate change, and anthropogenic activities [1–3]. About 30.1% of global freshwater belongs to groundwater resources [4,5]. A global estimate indicated that nearly half of the global current potable water supplies are groundwater [6,7]. Groundwater is the most substantial clean and significant resource in maintaining human and ecosystems adaptation [8]. However, a lack of effective management strategies in increasing demand and erratic recharge affects groundwater [9,10]. Groundwater abstraction from total global withdrawals takes about 33% and provides water for agronomic (42%), domestic (36%), and manufacturing (27%) requirements [6,11,12]. As a reliable source of water supply, groundwater is dependable and occupies all geologic layers [13–16].

Groundwater development activities face numerous issues from planning to implementation stages. Groundwater is a relatively clean, reliable, and cost-effective resource in parts of Africa that are almost wholly dependent on groundwater [17,18]. Africa's groundwater utilization has been projected to increase in the next few decades due to the rapid increase in population and abstraction for different activities [19]. Since aquifers are

complex systems confined underground, there would be a severe problem due to the lack of proper groundwater management in sub-Saharan Africa, including Ethiopia [15,20].

In Ethiopia, the integrated development of surface water-groundwater interactions is still scarce due to knowledge gaps of the subject [21]. The surface water-groundwater interactions impact water quantity and quality in aquifers and surface water bodies [22]. Surface water and groundwater resources conjunctively met water competition among agricultural, municipal, and industrial zones [23]. Over-extraction causes a decline in the water table, affecting streamflow connected to the aquifer and damaging water resource sustainability and the ecosystem [24,25]. Hence, understanding surface water-groundwater flow dynamics is crucial to address the research gaps and sustainable water resources management scenarios in different climatic regions of the country.

Ethiopia is heavily dependent on groundwater for drinking, livestock production, and industries. More than 80% of the water supply comes from aquifers [26,27]. Groundwater is a renewable crucial water supply for the great majority of the population in different regions [28]. However, the scarcity of in situ soil and groundwater data used in hydrogeological applications limits the ability to evaluate water resources [28,29]. Nevertheless, groundwater is a fundamental element of national development. However, it is not well studied, and valuable information about recharge rates is unavailable due to data paucity [30–33]. Thus, it causes failure to different development projects, resulting in financial expense. Furthermore, groundwater's essential role and contribution to water infrastructure development have not historically been anticipated in Ethiopia. Therefore, studying the spatiotemporal extents of groundwater utilization with a wide range of technical and institutional strategies is significant.

Though Ethiopia has much spatiotemporal distribution and rate of groundwater potential [34,35], there is no agreement on quantitative representation. Various stakeholders [36–38] argued that hydrological features are critical for predicting spatial and temporal variability. Weather variability significantly affects hydrological cycles and water policy provision in the Horn of Africa, including Ethiopia [39]. However, all-controlling parameters have hardly ever been studied in an integrated approach, as conventional strategies tend to be time-consuming and costly [40].

Anthropogenic actions have an intense influence on the hydrologic cycle of water flows, storage, soil, and atmosphere [41,42]. The spatiotemporal variability of water storage in Ethiopia faces a range of water management challenges caused by anthropogenic pressures and climate variability [43]. These activities, combined with the natural process such as vegetation, climate, and geology, have influenced water quality and quantity [44]. In addition, vegetation cover and land-use patterns can profoundly affect the aquifer recharge process [45].

Geographic information system (GIS) has been used for decades to identify and assess groundwater pollution in different parts of the world. The vulnerability of groundwater to contaminants was the product of a finite combination of different factors, beginning with hydrogeological settings and human activities whose attachment is formed in a regular pattern [46–48]. Assessment of exposure to groundwater pollution based on GIS has been practiced in some areas of Ethiopia [32,49]. Studies showed that groundwater has a high concentration of nitrates and microbes [50]. Groundwater vulnerability studies using DRASTIC (depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), the impact of the vadose zone (I), and hydraulic conductivity (C)) model estimate the relative chances of groundwater contamination with specific constituents [51]. The DRASTIC model identified the potential risk of aquifers for temporary protection over a large area with minimal cost and time changes essentially on aquifer storage [52]. These changes have impacted the water balance of the watershed by changing groundwater levels due to anthropogenic activities.

Due to rapid population growth, expansion and effective use of shallow groundwater supply for agriculture and domestic services are mandatory [53–55]. Despite the high groundwater potential and opportunity to overcome drought in Ethiopia, no significant

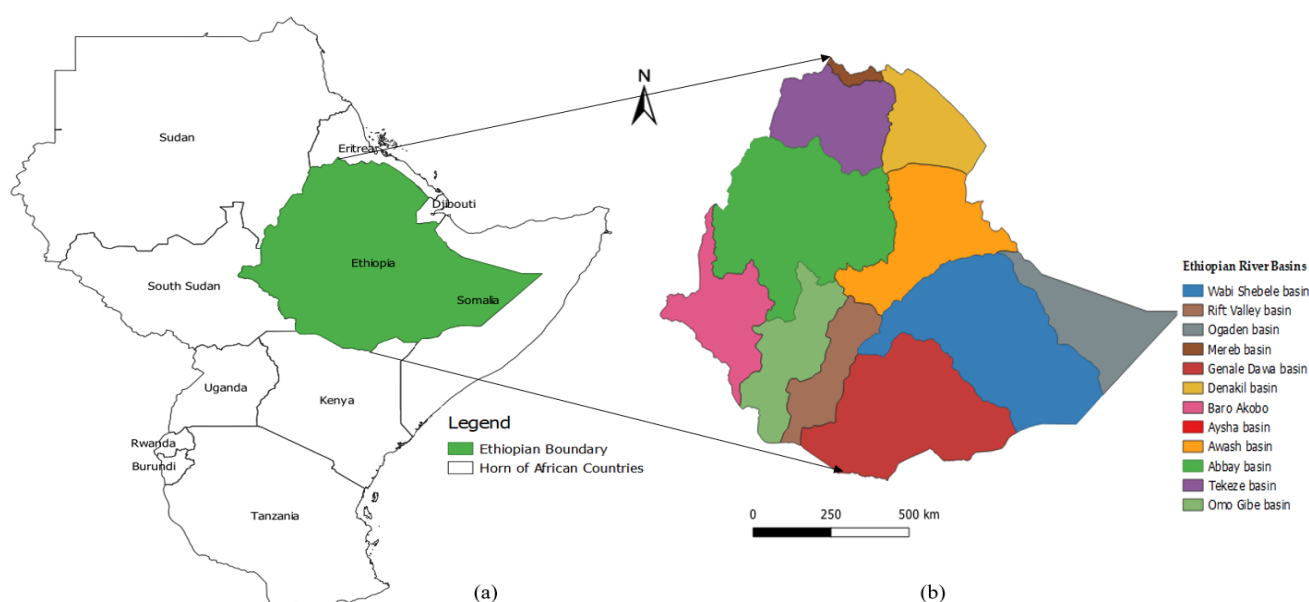
attention has been given to using groundwater for agriculture [56]. Precipitation is generally insufficient to sustain the agriculture needed to alleviate food insecurity. A few places have demonstrated comparative advantages of groundwater irrigation over rain-fed agriculture and surface water irrigation [29,57].

Although there is little research on potential groundwater assessment in Ethiopia, some has been done in recent studies [35,38,57–60]. The variation of groundwater in the country varies, as observed in different studies, for example, from 2.5 to 6.5 [35,57], 30 [60], 36 [15], 40 [38], and 47 [61] in billion cubic meters (BCM), which can be either an underestimation or overestimation. This vagueness in figures can hinder the pursuit from exploiting its water resources to the limit. This extremely high discrepancy in the potential figures is a challenge for experts and decision-makers. Thus, challenges faced by the water sector lock fund and other supporting agencies to the economic development of Ethiopia's water resources. Detailed studies and surveys are needed to estimate groundwater resources with better accuracy and reliability.

Therefore, the main objective of the present study is to review published groundwater research in Ethiopian aquifers to identify the challenge and prospects of advancing groundwater research. Thus, the study can help identify the possible research gaps that need detailed investigations to enhance the sustainable utilization of groundwater resources of the country.

## 2. Background of the Study Area

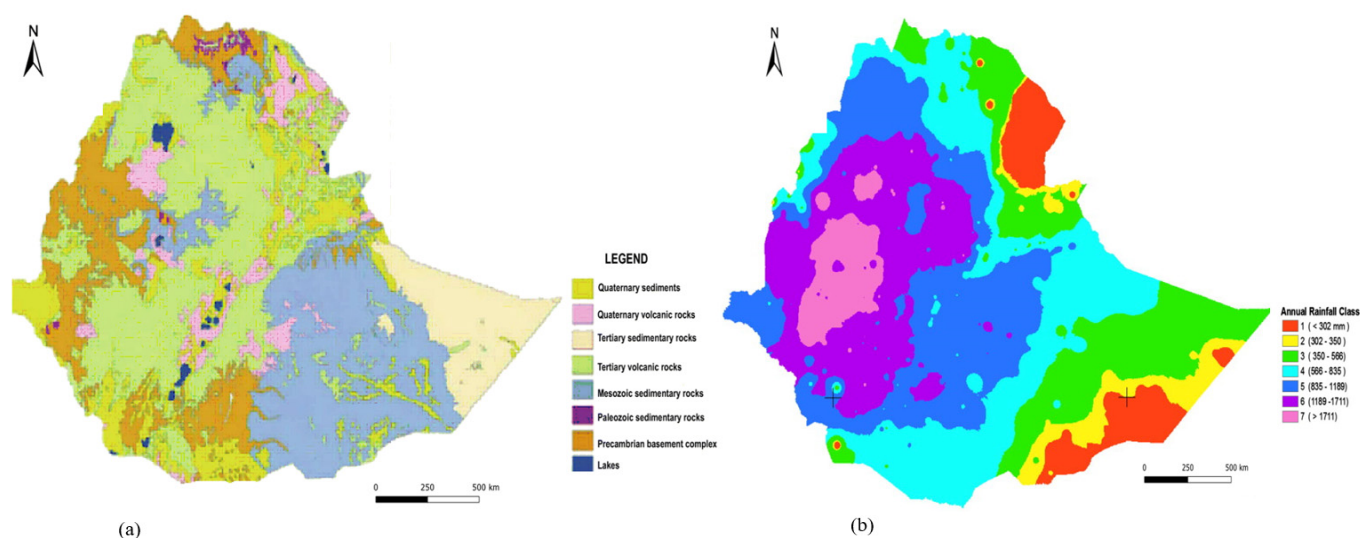
Ethiopia is one of the largest African countries (Figure 1a), surrounded by Eritrea, Sudan, Kenya, Somalia, Djibouti, and South Sudan. The country is scanty in rainfall-dependent agricultural practice with great geological complexity and geographic diversity. Most rivers flow through the country border, and groundwater resources deplete due to poor land use and watershed management practice. The country has twelve River basins: Abay, Awash, Baro-Akobo, Genale-Dawa, Mereb, Omo-Gibe, Tekeze, Wabishebele, and Mereb have water flows. Aysha, Denakil, and Ogaden dry basins with no flow out of the drainage system [57,60]. The spatial distribution of main river basins is shown in Figure 1b.



**Figure 1.** Geographical location of the study area; (a) Horn of African countries; (b) Ethiopian river basins.

The country has varied climatic conditions ranging from arid to humid, a complicated topography, and abundant water resources. The highlands across each corner give way to broad semi-arid lowland regions to the east, west, and south [35]. The average annual rainfall ranges from 141 mm along the country's arid eastern and northeastern borders to

2275 mm in the southwestern highlands, as indicated in Figure 2b [62]. The spatiotemporal distribution of water supply is characterized by multi-weather systems rainfall. Most river courses become fully flooded in their surroundings during the preceding rainy months (June–September). Unlike the northeast and east-flowing rivers, west-flowing rivers receive much rainfall, which is usually low [60,63,64].



**Figure 2.** Spatial distribution of Ethiopian [62]; (a) geology with central rock units; (b) mean annual rainfall.

In Ethiopia, groundwater abstraction covers about 90% of water for domestic supply and 95% industrial activities [15]. Groundwater tapping systems are springs, widespread in the escarpment and the highlands, which supply the great majority of the rural community. Hand-dug wells and springs often do not withstand prolonged droughts [34]. Therefore, developing artificial springs and wells to acquire water security for drought season is needed [54,65].

The recent increase in groundwater development threatens sustainability, particularly in urban areas that rely on groundwater. Aquifer depletion has increasingly affected water service delivery in large urban areas of Ethiopia. According to Birhanu et al. [66], the continuous groundwater abstractions without considering surface water sources decline groundwater levels in hot spot areas (Addis Ababa, Mekelle, Axum, Harar, and Gondar towns). Over-exploitation damages aquifers if sustainable management strategies are not hosted via interactive utilization of surface and groundwater to enhance balancing supply and demand [67]. The increasing demand from a growing population and high food insecurity in many parts of the country have started to overexploit groundwater, resulting in declining water tables [19].

Groundwater resource in Ethiopia is under a complex geological construction and the diversity of the topography, climate, and soil. Ethiopia's Rift volcanic terrain is complex by the destruction of rock units caused by faults and variability of volcanic structures. Transverse fault zones cross the Rift; up to 50% of recharge of aquifers comes from the plateau as groundwater inflow [68]. The Ethiopian aquifers were clustered as volcanic rock, sedimentary, metamorphic, alluvial lacustrine sediment, and from low to moderate range of productivity [15,19]. Aquifers are dispersed into Precambrian basement (18%), Paleozoic and Mesozoic sedimentary rocks (25%), Tertiary sedimentary and volcanic rocks (40%), and Quaternary sedimentary and volcanic rocks (17%) [34,62].

The geological formations and recharge rates influence the occurrence and distribution of groundwater. The geology, physiography, and climate change conditions are diverse, and groundwater distribution is highly variable, impacting aquifers' productivity [34]. The productivity of aquifers' increases with depth [14]. The groundwater flow system and mechanism of recharge of different aquifers result indicate a quite complex flow



pattern and hydraulic features of the different volcanic aquifers occurred on the inter-basin groundwater transfer conditions. The groundwater from the deep investigative wells was relatively depleted [69].

The temporal and spatial variation of groundwater occurrence is very high due to extreme structural positions and lithological variations. Recharge is highest in the northeastern and southwestern plateau, where annual rainfall is high, as shown in (Figure 2b) [57]. Rapid infiltration occurs in areas covered by fractured volcanic and, to a lesser extent, in sedimentary rocks and thick permeable soils [19]. The volcanic terrain and associated quaternary deposits are complex aquifer systems. The geomorphological architecture of the plateau, escarpments, and Rift valley control groundwater occurrence and distribution [14,56,70,71].

The lateral continuity of aquifers and groundwater flow is disturbed by faults, which divert groundwater to the rift axis. Groundwater flows in the rift and escarpments are controlled mainly through faults with high aquifer hydraulic characteristics and recharge rates [14]. Valley floor Quaternary alluvial sediments and essential Tertiary fractured volcanic aquifers characterize a considerable amount of exploitable hydrostratigraphic units [56]. The groundwater flow converges to the seismically active volcano-tectonic depressions according to geological settings [70]. The study disclosed that recharge supply comprises distinct zones of rift volcanic terrain bordered with highlands and transitional escarpments.

The geological distribution was categorized as sedimentary and Mesozoic sandstone to the southern, karstic rocks to the eastern and southeastern (Figure 2a). Quaternary volcanic rocks, unconsolidated sediments, fractured intrusive rocks, old Precambrian rocks, and metamorphic rocks belong to the western part of aquifer characteristics [62,69,72]. Enormous practical implications for ample groundwater storage at a more considerable depth solve the community's water supply problems in various parts of the country, which is vital for sustaining aquifers' recharge sources and hydraulic conductivity.

### 3. Study Type and Challenges

#### 3.1. Groundwater Potential

Assessing groundwater potential is essential in all climatic regions to its limited vulnerability, low development cost, and drought reliability to sustain water-food security issues [73]. However, estimating groundwater potential is still having uncertainties due to the hydrogeological nature of river basins. The scarcity of water is becoming increasingly prominent. For example, in the millennium declaration, the Ethiopian government adopted sustainable development goals [74]. Maintaining water quality and ensuring safe drinking water is essential to achieving the goal. It strives to achieve this goal by integrating its growth and transformation plan. However, the water management sector could not stay productive yet due to the temporal and spatial variation, the reduction in intensity, and shift in rainfall season [75]. The potential of groundwater development and climate change adaptation is still quite under-investigated [26]. The potential is not always accurately described, as groundwater recharge for the region lacks evaluating tools and proper knowledge on how the groundwater budget behaves [76,77].

Remote sensing (RS) and GIS techniques were applied to identify potential groundwater zones of Ethiopian aquifers [40,58,78–87], as illustrated in Table 1. The efficacy of RS in hydrogeological research can offer vital spatial and temporal data sets critical for realistic analysis, prediction, and validation of water resource models. In addition, GIS-based overlay analysis combined with pairwise comparison was a promising approach for predicting groundwater recharge zones in different catchments [83,84,87].

**Table 1.** Groundwater potential mapping studies in Ethiopian aquifers using geospatial techniques.

Study Catchments	Area (km <sup>2</sup> )	N	GWPZ	References
Lake Tana	11,733	7	4	[86]
Raya Valley	2750	7	4	[85]
Weito	13,988	8	3	[40]
Guna Tana landscape	3545	7	3	[83]
Megech	689.3	9	3	[84]
Ketar	3354	6	5	[81]
Ethiopian Rift (Ketar)	3580	12	3	[82]
Gerardo	-	8	4	[58]
Beshilo	13,242	6	4	[87]
Golina River	916.77	9	5	[78]
Dhungeta-Ramis	16,076	7	5	[80]
Fincha	82	8	4	[79]

In the potential groundwater zones determination studies, many features have been used based on geologic, hydrologic, hydrogeological, meteorological, and terrain capabilities as selection criteria [80,81,83]. Accordingly, geomorphology, lithology, slope, rainfall, land use, land cover, soil, lineament density, elevation, topographic wetness index, topographic position index, curvatures, stream power index, hydraulic conductivity, distance from the fault, roughness, and drainage density were the main factors affecting groundwater potential. These parameters were classified and ranked depending on the suitability of groundwater potentiality. However, some of the studies were conducted using a limited number of influencing factors that might lead to unsatisfactory decision-making processes.

Nevertheless, the most dominant groundwater potential affecting factors have not been explained other than overlaying random parameters. Therefore, many influencing factors have to be considered and tested for the reliability of a tremendous decision-making process and groundwater yields. The area of coverage (km<sup>2</sup>), study catchments, number of parameters applied (N), and groundwater potential zone (GWPZ) mapping of peer-reviewed studies in Ethiopia at different catchments are shown in Table 1.

### 3.2. Groundwater Recharge

Groundwater is a critical source of agriculture and drinking water supply [88]. Therefore, estimating the recharge rate is significant to assure efficient and sustainable management [61,89]. Furthermore, understanding the rates and locations of recharge is necessary for evaluating the sustainable yields of the groundwater systems [2,90–92]. Recharge estimation could be achieved by assessing development impacts, predicting climate change, and increasing abstraction rates [9,93–95]. However, the recharging mechanism is an essential indicator of hydrologic conditions affecting aquifer production [15,27]. Sources of groundwater recharge in Ethiopia are flood recharge, rainfall recharge, and mountain block recharge [27]. Almost 60% of aquifers receive indirect recharge from storms, mountain runoff, and rapid recharge from heavy rainfall events. Diffuse recharge is restricted to plateau areas, covering approximately 30% of the country and 10% of groundwater recharge from losing streams and flash floods [15]. Ethiopian highlands have high infiltration rates [50]. Extensive percolation through the vadose zone gives reliable recharge for the soil moisture estimation [62,96]. Thus, infiltration takes place from vadose to saturated zone, increasing water table and streamflow.

Many studies in groundwater recharge estimation have agreed on the necessity of quantitative decisions on exploitation activity through recharge studies to safeguard natural resources [94,97]. However, computing recharge is a complicated hydrological parameter [91,98] for many developing countries like Ethiopia, known for abundant water resources [15,88,99]. With the rapidly increasing population growth and escalating water demand, groundwater abstraction appeared to be beyond its recharge rate challenged groundwater development [96]. Though there is little research on groundwater recharge estimation in Ethiopia, some analysis has been done in recent studies [9,10,64,94,97].

In Ethiopia, limited recharge estimation and groundwater flow modeling studies were conducted with limited data availability. Description of peer-reviewed published research articles indicated in Table 2 emphasized estimating groundwater flow dynamics and recharge of aquifers applying the following applications. The Newton-Raphson formulation for modular finite-difference groundwater flow (MODFLOW) was applied to evaluate groundwater flow dynamics [9,26,33,72,95,100]. The model predictions reveal that aquifers increase withdrawal and decrease recharge. Increased pumping and decreased recharge results indicated that there is a decline in lakes and rivers levels [95,100]. Thus, reservoirs and rivers play a crucial role in recharging aquifer systems. Increasing human demand for groundwater and variability in recharge affects groundwater contribution to surface water and ultimately are a supply of concern for future groundwater management.

**Table 2.** Groundwater recharge and flow modeling application studies in Ethiopian aquifers.

Study Site	Area (km <sup>2</sup> )	Recharge (mm)	Applied Model	References
Werii	1797	30.06	WetSpass	[64]
Illala	340	66	WetSpass	[88]
Lake Tana	15,321	37.5	SWAT-MODFLOW	[21]
Dire Dawa	1333	28	SWB	[99]
Akaki	1462	179	SWAT-MODFLOW	[10]
Upper Kliti	188	457	SWB, WetSpass, WTF, CMB	[94]
Gilgel-Abay	4622	-	MODFLOW	[26]
Akaki	1462	-	MODFLOW	[72]
Modjo River	1984	197	MODFLOW	[9]
Geba	5260	98.6	WetSpa	[93]
Birki	45	24.9	WetSpass	[96]
Kombolcha	68	-	MODFLOW	[95]
Upper Awash	6735	-	MODFLOW	[100]
Gumera	1600	-	MODFLOW	[33]
Akaki	1464	189	SWB, CMB	[97]

The Soil and Water Assessment Tool (SWAT) coupled with MODFLOW (SWAT-MODFLOW) were also applied to determine the recharge process through surface water-groundwater interactions [10,21]. The studies disclosed that robust interactions between the stream and groundwater advance flow dynamics of hydrogeological conditions. Surface water-groundwater exchange rates are highly variable; the annual alteration is from hydrogeological system to streams indicating that streams are gaining. Throughout the wet seasons, the flow is preponderantly from the stream system to the aquifer. Moreover, recharge takes place from the aquifer to the stream from July to October. In addition, the groundwater head converges towards the mainstream, revealing that a high rate of pumping declines groundwater level and substantial river base flow.

Soil water balance (SWB) [94,97,99], chloride mass balance (CMB) [94,97], water table fluctuation model (WTF) [94], and water balance model (WetSpass) [64,88,93,96] were applied for appraisal of groundwater recharge and other water balance components. Studies support that evapotranspiration is happening from the groundwater to the unsaturated soil zone before the percolation of groundwater [94]. Studies in Ethiopian aquifers revealed that recharge is high during the summer season and minimum in winter. The average annual groundwater recharge is 4.2% of annual precipitation occurs during the wet season as in [64]. During the spring season, percolation is minimal due to unrestricted movement of water in the soil zone with a low antecedent moisture content of the soil [64,94,97,99].

According to studies, the mean annual rate of recharge varies at catchment scales from 24.9 mm [96] to 457 mm [97] as compared with the overall country's estimate made between 39 mm [15] and 39.1 mm [61]. This non-uniformity is mainly due to multiple influencing factors for groundwater recharge and potential [34]. However, the lack of up-to-date spatial

and temporal information is becoming an increasingly prominent challenge to indicate sustainability considerations.

The absence of recent information on the spatiotemporal distribution of groundwater resources is Ethiopia's critical concern and issue [58,82]. GIS and RS applications can be applied to tackle data scarcity of the area as suggested by [12], after reviewing various studies conducted on groundwater recharge estimation in Africa's semi-arid and humid regions. The source and spatial distribution of groundwater recharge in Ethiopia are not well described yet. Some peer-reviewed published groundwater recharge and flow application studies in Ethiopian aquifers with catchment name, the total area of coverage (km<sup>2</sup>), mean annual recharge of the catchment (mm), and applied techniques are presented in Table 2.

### 3.3. Groundwater Quality

Groundwater development has combined effects on human development: food security, drinking water, sanitation, and climate change mitigations [101–104]. However, groundwater quality has declined due to industrial effluents and domestic wastes and the widespread use of fertilizers for agricultural purposes in shallow aquifers [48,84,102]. Therefore, overexploitation and utilization must be well managed, especially in areas threatened by contamination.

Human activities have disrupted hydrogeological and chemical conditions [69–71,105]. The most severe issue is a lack of knowledge about pesticides and other chemical pollutants such as personal care items in groundwater and agricultural areas irrigated by highly polluted waters [106–109]. Therefore, determining the nature of chemical pollutants in groundwater and their vulnerability and their persistence is paramount. However, such studies were conducted in limited parts of the country, as described in Table 3, though many areas need in-depth investigations. For example, the distribution of existing studies are found in Lake Tana basin [76] and Megech watershed [48] (Northwest Ethiopia); Dire Dawa (Eastern Ethiopia) [51]; Elalla-Aynalem well fields [110] (Northern Ethiopia); Lower Ketar [111], Adama Town [101], and Modjo River catchment [112] (Central Ethiopia).

**Table 3.** Peer-reviewed groundwater vulnerability and quality assessment in Ethiopian aquifers.

Study Catchment	Area (km <sup>2</sup> )	Applied Model	References
Lake Tana	3156	DRASTIC	[76]
Dire Dawa	1333	DRASTIC	[51]
Lower Ketar	3467	GIS and AquaChem	[111]
Adama Town	45	GIS and WQI	[101]
Modjo River	1984	GIS and WQI	[112]
Elalla-Aynalem	493	DRASTIC	[110]
Megech	664	DRASTIC	[48]

The vulnerability of groundwater to contaminants resulted from a finite combination of hydrogeological setting and human activities [46–48]. GIS has been used to assess groundwater pollution in different parts of the world for decades. Assessment of exposure to groundwater pollution based on GIS has been practiced in some areas of Ethiopia [48,51,76,110]. Studies showed that groundwater has a high concentration of nitrates and microbes [13,43,49,50]. Groundwater vulnerability studies using the GIS-based DRASTIC model to estimate groundwater pollution were also practiced [51]. Sustainable groundwater vulnerability management can be achieved when potential pollutants, users, and other stakeholders are actively involved, including planning and implementing effective regulations [52]. Therefore, the evaluation of vulnerability and groundwater quality is needed, which helps to check groundwater sustainability. Although there is little research on groundwater quality in Ethiopia, some analysis has been done in recent studies using GIS-based DRASTIC and water quality index (WQI) methods, as depicted in Table 3.

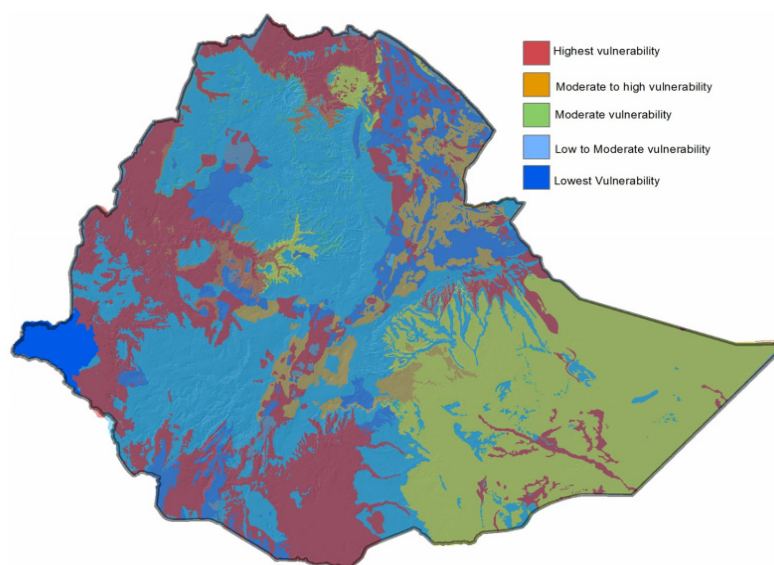


The DRASTIC model identified the potential risk of aquifers for temporary protection over ample aquifer storage effectively [48,51,76,110]. The vulnerability assessment identified and delineated aquifer vulnerability spatial extent to pollution of the area. Vulnerability evaluation has been analyzed with depth to the water table, net recharge, aquifer media, soil media, topography, vadose zone, hydraulic conductivity, and land use and land cover as essential parameters [48,51,76,110]. The study results indicated that catchment characteristics impacted the vulnerability of aquifers investigated. The findings suggested that groundwater pollution risk needs immediate implementation of acceptable practices. Thus, the increasing risks of groundwater pollution could also be related to farming and urban expansion. These areas provide water to urban and farming intensifications, and chemicals will deteriorate groundwater quality.

Most observation wells with high nitrate contamination fall in agricultural and urban areas and transport levels exceeding criteria set by World Health Organization (WHO) [48,51]. Aquifers extremely at risk of pollution are found in urban areas such as Gondar, Bahir Dar, and Dire Dawa. Accordingly, the instability of aquifers varies from low to high. It should be applied with similar or different agro-climatic and management conditions to forward practical and updated information for policymakers [51]. Therefore, the DRASTIC method was recognized to be an auspicious method for rectifying vulnerable groundwater sites. Evaluating the extent of groundwater vulnerability is considerably needed in different parts of the country, especially agricultural and urban landscapes.

WQI evaluates the suitability of water for domestic and agricultural purposes. Anthropogenic activities of urban and fertilizers govern the groundwater chemistry. [101,112]. Almost all groundwater studies conducted in Ethiopia indicated limited to fixing single model analysis. Thus, public policies should be implemented to reduce the potential points and sources of contamination affecting the catchments in wastewater effluents from industry, increasing pollution and toxicity in river waters and plants [44].

The erratic variability in rainfall distribution (Figure 3) and shortage of perennial streams have augmented the dependability of groundwater for irrigation [32,54–57]. However, people have been using groundwater from wells without understanding the consequence of over-pumping. Regulating and maintaining groundwater storage in dynamic equilibrium is crucial without disturbing the natural conditions. Ethiopia has been limited to combat droughts to improve irrigation practices for supporting an agricultural-dependent economy [113].



**Figure 3.** Vulnerability map of Ethiopian aquifers to changes in recharge [15].

The main challenge of groundwater and drought resilience was that most hand pumps, springs, hand-dug wells, and boreholes are not functional due to deterioration, improper positioning, and maintenance [65]. Hence, comprehensive and integrative approaches are needed to evaluate anthropogenic activities with the alarmingly increasing global warming and climate change. The existing national level groundwater vulnerability rates spatial distribution as indicated in Figure 3. However, as the multiple input parameters of the models vary with time and other human and natural activities, the investigation should be updated at the national level and catchment-specific conditions for the sustainable management and decision-making process.

#### 4. Summary and Future Directions

In this study, we assessed peer-reviewed published groundwater research conducted in Ethiopian aquifers. The assessment covers groundwater potential, groundwater recharge process, and groundwater qualities. As a result, the groundwater potential of the nation shows from 2.5 to 47 billion cubic meters, and there is no consensus on the numerical value of groundwater potential in Ethiopia. Groundwater potential zonation was conducted with a limited number of influencing factors. A dominant influencing factor has not been identified yet. However, influencing parameters have a direct impact on the decision of planning resource allocation. The recharge estimation assessment indicated that the mean annual groundwater recharge varies from 24.9 mm to 457 mm at catchment scales.

Susceptibility of groundwater to pollutants was a product of a finite mixture of different factors that need a detailed investigation, and some of the assessments indicate exceeding acceptable levels of WHO. Therefore, producing and disseminating practical information about groundwater trends to policymakers and development practitioners is critical. Furthermore, integrating groundwater research into national policies provides an adequate and influential contribution to economic development plans that need an integrated research output. Due to hydrogeological variability, multi- and inter-disciplinary research approaches are vital to address the intricate relations in the hydrologic cycle and interactions with the broader societal, physical, ecological, and environmental policy issues. However, the lack of data and convergence research approaches found a fundamental challenging problem of the assessment. Groundwater abstraction for domestic water demand and the cumulative effect of abstraction for industrial uses and livestock impacted the aquifer system. Hence, it would be better to address the following gaps and insights to have comprehensive groundwater management.

1. The continuous dynamics of land use and climate change have multiple impacts on groundwater recharge in different regions. Hence, the drivers of combined effects of land use and climate change on aquifer recharge and quality require detailed investigation.
2. Sustainability indicators are indispensable to increase policymakers' awareness of the safe yield of groundwater for sustainable development strategies. Therefore, groundwater sustainability should be evaluated with leading sustainability indicators and integrated with the national policy.
3. Coupled hydrologic models can quantify and qualify water availability under current and future scenarios and enhance urban and rural water security. Hence, the application of coupled hydrological modeling is required to properly quantify the combined effects of groundwater abstractions with surface water utilization.
4. Groundwater is the most significant source of domestic supplies for urban and rural populations. The scarcity of reliable data on groundwater is the main challenge of many developing countries such as Ethiopia. Hence, as most Ethiopian aquifers lack relevant data, researchers should use GIS and RS technology to determine dependable recharge that resembles the actual values. In addition, the use of current advanced knowledge of artificial intelligence techniques is required to increase water resources research predictive capability and sustainable management insights.

**Author Contributions:** Conceptualization, T.D.M. and I.-M.C.; writing—original draft preparation, T.D.M.; writing—review and editing, B.A.Y. and I.-M.C.; resources and data curation, J.L., H.H.W. and M.-G.K.; visualization, M.-G.K. and I.-H.K.; supervision, I.-M.C. and S.W.C.; funding acquisition, I.-M.C. and S.W.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by a grant from the Development Program of Minimizing of Climate Change Impact Technology funded through the National Research Foundation of Korea (NRF) of the Korean government (Ministry of Science and ICT, Grant No. NRF-2020M3H5A1080735) and the Korea Ministry of Environment (MOE) as a Demand Responsive Water Supply Service Program (146515).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data available in a publicly accessible repository.

**Conflicts of Interest:** The authors declare no conflict of interest.

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