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Management of Drinking Water Source in Rural Communities under Climate Change

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ABSTRACT. In rural communities where central public water supply systems can hardly reach, the acquisition and management of safe drinking water sources are challenging due to population growth, environmental pollution, and climate change. Numerous endeavours have been made over the past several decades to help rural communities manage drinking water sources and obtain safe drinking water under climate change, which are summarized in this review. Firstly, the crises of rural drinking water safety under climate change are overviewed based on the extensive investigation of recent studies on rural water security. Second, the sustainable management of rural drinking water sources are systematically reviewed, mainly focusing on issues of water quality assessments, drinking water quantity and quality improvement, system maintenance and community management, and decision making in rural regions across the world. Finally, knowledge gaps of recent endeavors are highlighted, emerging threats and complications to water security under climate change are identified and perspectives for future works are discussed.

Keywords: drinking water safety, drinking water source management, rural communities, climate change

1. Introduction

Safe water should be affordable and accessible for all by 2030, which has been set as target in the sustainable development goal 6 (UN-SDG 6) (UNDP, 2015). This target is challenging to be achieved in rural areas due to population growth, environmental pollution, and climate change (Kisakye and Van der Bruggen, 2018). Particularly, they are facing serious problems in drinking water resource management, such as water shortage, unsafe drinking water source, incomplete water supply infrastructure, and ineffective management system. Currently, an estimated 16% of the rural population lack access to improved drinking water sources, compared to 4% of the urban population; about 50% of people lack improved sanitation facilities in rural areas, compared to 18% of people in urban areas (UN, 2015). Climate change is generating more challenges; intense rainfall, severe storms, multi-year droughts, excess heat, and other extreme events, may reduce drinking water quality, diminish water resource availability, and damage water supply infrastructure.

In rural communities where central public water supply systems can hardly reach, drinking water sources generally include small-scale waterworks, rainwater harvesting systems, nearby rivers and lakes, tube wells, and boreholes equipped with hand pumps (Cozzetto et al., 2014; Pritchard et al., 2016). Most of rural communities rely on the latter four kinds of drinking water sources; while water can be piped into households in some communities from small-scale waterworks, it is often not reliable or continuously available (Edokpayi et al., 2018). These sources are vulnerable to shortages and contamination, and the communities that rely on a single water source are especially vulnerable, as the failure of the source compromises the community's entire water supply. Such vulnerabilities may be intensified due to the influence of climate change on the quantity and quality of water sources (Macdonald et al., 2009; Delpla et al., 2011; Cozzetto et al., 2014). Climate-related risks to drinking water sources will continue to increase as global warming continues (Harper et al., 2011; Kisakye and Van der Bruggen, 2018). Thus, strategies for drinking water source management that can address climate-related risks are needed to achieve safely managed water services in rural communities. Fortunately, many researchers and organizations are tackling the topic of drinking water source management for rural communities under climate change. Numerous endeavors have been made and various management strategies have been developed to help rural communities obtain safe and reliable drinking water depending on local situation and resource availability (Lynch, 2012; Huang and Kim, 2017; Kohlitz et al., 2020). However, these works have not been systematically reviewed.

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Therefore, the objective of this paper is to summarize the studies on drinking water source management for rural communities under climate change. Based on the extensive investigation of recent works, this paper entails the following sections: (1) the crises of rural drinking water safety under climate change will be analyzed; (2) the efforts for sustainable drinking water source management in rural communities will be presented; (3) critical knowledge gaps of recent endeavors and perspectives for future works will be discussed. Especially, issues of water quality assessments, drinking water quantity and quality improvement, system maintenance and community management, and decision making will be emphasized.

2. Crises of Drinking Water in Rural Communities under Climate Change

Rural communities are facing a number of crises in their drinking water resource acquisition and management. First, many rural populations still lack or have inadequate infrastructure for drinking water treatment and have to use unimproved drinking water sources, such as untreated surface water and rainwater, unprotected groundwater from wells and springs, and etc. Besides, climate change, through normal climate variability or extreme events driven by global warming, affects drinking water safety by reducing the quantity and/or quality of preferred drinking water sources. This may lead to the intensification of water competition among different water users (e.g., economic sectors, upstream and downstream areas) (Lynch, 2012). Thus, people living in rural communities may have to use alternate sources with poor quality due to unavailability of safe water resources and high cost of water purification techniques.

Second, poor drinking water quality is associated with many waterborne diseases in rural areas. Various types of drinking water are associated with different undesirable components or contaminants, such as bacteria (e.g., *Escherichia coli* (*E. coli*)), anions (e.g., sulfate (SO_4^{2-}), nitrate (NO_3^-), fluorides (F^-), etc.), and heavy metals (e.g., arsenic (As), lead (Pb), cadmium (Cd), nickel (Ni), chromium (Cr), etc.), making drinking water unsafe (Huang et al., 2015). The sources of pollutants in rural areas are mainly due to geogenic releases, direct or indirect discharge of domestic sewage into water bodies, poor sanitation, and agricultural run-off containing fertilizers and pesticides, and effluents from nearby industries. For example, water sources in rural areas are more likely to be compromised by fecal contamination compared to urban areas. It has been estimated that approximately 2.2 billion people living in rural areas still rely on water sources contaminated with fecal bacteria (Bain et al., 2014a; 2014b). In addition, hydrometeorological events caused by climate change may affect water quality, especially surface water, through altering the physical, chemical, and biological properties of water bodies (Jovanelly et al., 2015; Mena-Rivera and Quirós-Vega, 2018; Kohlitz et al., 2020; Duan et al., 2021). For instance, associations between weather, water quality, and occurrence of infectious gastrointestinal illnesses (IGI) were explored in rural communities, and the high levels of water volume input (rainfall + snowmelt) was positively associated with elevated levels of raw water bacteriological variables and IGI-related clinic visits (Harper et al., 2011).

Third, there is shortage of effective water quality monitoring and water/wastewater treatment in rural communities, leading to difficulties in water source protection and management. In many regions, even generally reliable water quality data are unavailable. Moreover, inadequate wastewater treatment prior to effluent discharge may contaminate local water sources and place drinking water at risk (Hong et al., 2019; Song et al., 2019; 2021). Rural populations obtain water from drinking water sources where the water quality is often unknown, with potential contamination due to runoff, improper wastewater treatment, and other anthropogenic activities. In many rural communities, natural areas that are being used for passive wastewater treatment may simultaneously serve as a community's drinking water source as well as be used for recreation or food harvesting (Daley et al., 2018). Unreasonable design and poor management of onsite sanitation systems also negatively impact the security and hygiene of rural drinking water wells (Otaki et al., 2021). Within these mixed ecological systems, residents of rural communities may unknowingly be exposed to contaminants, especially pathogens.

Fourth, many rural communities also have inadequate facilities for drinking water acquisition, storage, distribution, and protection. Most of these facilities may not be up-to-date or cannot keep up with the increasing water demand. Many rural facilities are aging and gradually losing efficacy due to a lack of repair and maintenance. For example, about one third of hand pumps in rural sub-Saharan Africa are non-functional at any one time, and many are never repaired (Nagel et al., 2015). Water system breakdowns frequently occur due to faulty hardware (e.g., aprons in Liberia, pipes in Tanzania and Uganda, taps/spouts in Tanzania and Uganda, and lift mechanisms in Nigeria) (Klug et al., 2018). With the increased use of rainwater harvesting (RWH) as a water source and a potential adaptation measure to climate change, the capacity of corresponding storage facility is also far from enough due to lack of funding (Ishaku et al., 2012).

Finally, poor water resource management in rural communities has stimulated a number of problems relevant to water supply and human health. National water management frameworks do not clearly define the key roles at the district, community, and household levels. There may be large gaps between water experts/authorities and local knowledge/community participation in achieving clean water. Another troublesome aspect is that resources and capacity for consistent water resource management in rural and informal urban areas are limited (Rahman et al., 2011). Local households may not be able to afford to pay much for improved water service due to the poverty stricken nature of many rural communities, as a result, the finances of many rural water management committees are in poor shape (Whittington et al., 2009). Machingambi and Manzungu (2003) found that rural populations are willing to contribute to water point maintenance and water source management. However, such contributions are usually limited, because they do not have a determinant role to play and enough financial capacity.

3. Management of Drinking Water Source in Rural Communities

3.1. Water Quality Assessments

Gaining a full understanding of the water quality status in rural communities and the potential impact on local human health is the first step towards sustainable drinking water source management. Effective and continuous monitoring of physical, chemical, and microbiological parameters to ascertain the possible risks that are associated with particular water sources is necessary to prevent water pollution (Huang and Xia, 2001). Accurate assessments of drinking water quality, and household hygienic practices are critical for developing effecttive water source management strategies. Quality investigation of drinking water source includes processes of sampling, measurement, recording, and analysis. Many studies related to regional water quality monitoring and assessment have been undertaken, which were summarizes in Table 1.

For example, Chen et al. (2016) assessed drinking water quality from private wells in a rural agricultural area of Ningxia province, Northwest China. The mean concentration of NO_3^-–N was found as 12.15 ± 12.92 mg/L and about 40.7% of water samples were not suitable for drinking purpose due to high nitrate concentrations. They also assessed the nitrate and fluoride contamination in drinking groundwater from Zhongning area of Ningxia province, and high NO_3^-–N and F^- levels (exceeding WHO limits listed in Table 2: 10 and 1.5 mg/L) were found in 60% and 8% of water samples, respectively (Chen et al., 2017). Chuah et al. (2016) found that deeper aquifers did not always have cleaner and safer drinking water. They mapped the high-fluoride endemic areas and described the relevant fluoride transport processes in two provinces (ChiangMai and Lamphun) in Northern Thailand. At ChiangMai, the fluoride concentrations in 31% of shallow wells exceeded hazardous levels (≥ 1.5 mg/L), compared with the 18% observed in deep wells. However, at Lamphun, such high concentration of fluoride was found in samples from 35% of deep wells and only from 7% of shallow wells (Chuah et al., 2016). Thus, groundwater quality at any depth should be tested before well construction.

Khan et al. (2013) examined the concentrations of various pollutants in drinking water and investigated the health risk in Charsadda district, Pakistan. Physical parameters and concentrations of anions, heavy metals, and coliform bacteria in water samples collected from 46 sites of groundwater sources (dug-wells, tube-wells, and hand pumps) were analyzed. It was found that the sulfate concentrations (505 ~ 555 mg/L) in 9 sites exceeded the WHO limit (500 mg/L), and coliform bacterial contaminations (2 ~ 5 cfu/100 mL) were detected in some water sources. Improper disposal of sewage and solid waste, over applications of pesticides and fertilizers, and deteriorating condition of distribution system were the main reasons for the drinking water source contamination in this area (Khan et al., 2013). Arshad and Imran (2017) also detected high concentrations of arsenic, fluoride, and bacteria from 91, 74, and 77% of drinking groundwater sources in Punjab, Pakistan. Particularly, very high concentrations of arsenic were found, ranging from 58 to 3,800 μg/L. In the southwest Punjab, India, Kaur et al. (2021) evaluated the relationship between groundwater quality and cancer incidence in the rural areas. The mean concentrations of As, Pb, U, NO_3^-, and F^- were determined to be 27.59, 48.3, 96.56, 67.32, and 4.7 mg/L, respectively, exceeding the WHO drinking water limits. Such high concentrations were identified as one of the potential causes for cancer incidences in the area through health risk analysis (Arshad and Imran, 2017).

Recently, Daniel et al. (2020) carried out a microbial quality assessment for household water storage containers and points of collection (POC) in remote rural communities of western Nepal. About 81% of stored drinking water samples and 68% of the POC samples had detectable *E. coli*. The stored water quality was significantly affected by the quality at POC, and its microbial contamination was intensified due to the presence of livestock near the water storage container (Daniel et al., 2020). In Iran, Mosaferi et al. (2014) studied the drinking quality in rural areas in Tabriz County, and found the local people drank groundwater with high hardness (52 ~ 476 mg/L) and serious arsenic contamination (69 μg/L). The overall water quality of drinking sources in rural Khuzestan province was found to be good and a large proportion of recorded water quality issues was related to acceptability aspects (Abtahi et al., 2015). The proportions of the drinking water sources with excellent, good, fair, marginal, and poor qualities were determined as 6.7, 59.1, 26.2, 7.8 and 0.1%, respectively, and the groundwater quality was better than the surface water quality at this province.

In Africa, Pritchard et al. (2016) undertook an extensive field sampling programme to investigate groundwater quality in rural villages throughout Malawi. About 95% of shallow wells failed to provide safe drinking water during the wet season due to microbiological contamination, while the percent of contaminated wells was about 80% in the dry season (Pritchard et al., 2016). Anornu et al. (2017) applied an integrated hydrochemical and isotopic technique to trace the sources of drinking water nitrate contamination in the Upper East Region of Ghana. The mean nitrate concentrations in water from boreholes, hand dug wells, and surface water were examined as 36.09, 21.54, and 5.01 mg/L, respectively. In the study area, about 95% of the groundwater and 45% of the surface water had nitrate concentrations above the WHO baseline value (Anornu et al., 2017). Edokpayi et al. (2018) provided a comprehensive descripttion of drinking water quality across seasons in a low-resource rural community in South Africa. Water sources in this study area were found to be highly contaminated with *E. coli* in both the wet and dry seasons, while the *E. coli* level in municipal treated water met the WHO standard. Particularly, *E. coli* was detected in the water samples from boreholes at local clinics, indicating inadequate access to safe water for potentially immunocompromised patients (Edokpayi et al., 2018). Later, Potgieter et al. (2020) evaluated the occurrence of enteric pathogens in rivers which provided drinking water for rural communities in Vhembe District of South Africa. *E. coli* was also detected in the collected samples, and some other indicator bacteria counts were found to exceed drinking water quality guideline limits. *Vibrio spp.* and *Salmonella spp.* were detected in all involved rivers; parasites were found in four rivers, and Enteric viruses were the major one in winter season (Potgieter

Table 1. Summary of Studies on Water Quality Monitoring and Assessment in Rural Communities

Study area	Intake water mode	Number of samples	Physical parameter	Chemical parameter	Biological parameter	Reference
Malawi	Groundwater (shallow wells)	2700	Dry season: pH: 6.9, TDS: 369 mg/L, EC: 605 μS/cm, Turbidity: 7.2 NTU; Wet season: pH: 6.8, TDS: 369 mg/L, EC: 564 μS/cm, Turbidity: 17.9 NTU.	Dry season: F^-: 1.8 mg/L, Hardness: 163 mg/L, NO_3^-: 0.51 mg/L; Wet season: F^-: 2.1 mg/L, Hardness: 213 mg/L, NO^-_3: 0.38 mg/L.	About 83% of wells failed to meet the FC guideline value of 50 cfu/100 mL in the wet season, while about 50% of the wells failed in the dry season.	Pritchard et al., 2016
Northern Thailand	Groundwater (wells)	995	pH: 4 ~ 9.58.	F^-: 0.01 ~ 9.6 mg/L. About 22.75% of the wells reached hazardous levels (≥ 1.5 mg/L) of F^-.	-	Chuah et al., 2016
Ningxia, Northwest China	Groundwater (wells)	86	-	NO_3^-: 0.49 to 62.20 mg/L with a mean of 12.15 ± 12.92 mg/L. About 40.7% of samples are unfit for drinking purpose.	-	Chen et al., 2016
Tabriz county, Iran	Groundwater (wells, springs and qanats)	32	TDS: 364.1 mg/L.	N: 11.91 ± 10.49 mg/L, F^-: < 0.5 mg/L.	-	Mosaferi1 et al., 2014
Charsadda district, Pakistan	Groundwater (dug-wells, tube-wells and hand pumps)	951	pH: 6.5 ~ 7.02, Conductivity: 0.32 ~ 0.66 mS/cm, DO: 0.06 ~ 0.1 mg/L, Salinity: 0.01 ~ 0.03%.	NO_3^-: 8.1 ~ 13.69 mg/L, Cl^-: 19.73 ~ 92.11 mg/L, SO_4^{2-}: 286 ~ 535 mg/L, Pb: 30.7 ~ 117.5 ug/L, Cr: 2.1 ~ 10.3.	2 ~ 5 cfu/100 mL	Khan et al., 2013
Ghana	Boreholes, standpipes, wells, and trucked water	199	pH: 3.69 ~ 8.88, Turbidity: 0.793 NTU.	Al: 8.5 mg/L.	-	Rossiter et al., 2010
Andhra Pradesh, India	Bore well and tank water	78	pH: 6.36 ~ 7.8, TDS: 188.7 ~ 5802 mg/L, Total hardness: 52 ~ 1664 mg/L, EC: 308 ~ 8590 mS/cm.	Cl^-: 29.4 ~ 2058.2 mg/L.	-	Reddy and Behera, 2006
Republic of Togo	Boreholes and hand dug wells	82	pH: 7.23, EC: 380.14 mS/cm, TDS: 207.7 mg/L.	F^-: 0.685 mg/L, Cl^-: 20.3 mg/L, NO_3^-: 28.84 mg/L.	-	Anornu et al., 2017
	Surface waters (dams and rivers)	11	pH: 6.91, EC: 148.17 mS/cm, TDS: 94.45 mg/L.	F^-: 0.17 mg/L, Cl^-: 3.27 mg/L, NO_3^-: 5.01 mg/L.	-	
Punjab, Pakistan	Groundwater (injector pump and wells)	86	pH: 7.63, TDS: 1199 mg/L.	F^-: 1.47 mg/L, As: 150.4 ug/L.	-	Arshad and Imran, 2017
Ningxia, Northwest China	Hand-pumping wells	50	pH: 7.9, TDS: 1225 mg/L.	Mg: 136 mg/L, Ca, 64.7 mg/L, Cl^-: 148 mg/L, SO_4^{2-}: 328 mg/L, NO_3^-: 17.9 mg/L, F^-: 6.33 mg/L.	-	Chen et al., 2017
Limpopo Province, South Africa	Multiple sources	720	Dry season: pH: 5.8 ~ 8.7, EC: 8 ~ 402 uS/cm; Wet season: pH: 5.5 ~ 7.3, EC: 24 ~ 405 uS/cm.	Al: 39.18 ~ 438 ug/L; Fe: 35.21 ~ 1354 mg/L.	For untreated water: about 12000 cfu/100 mL in dry season, about 7000 cfu/100 mL in wet season.	Edokpayi et al., 2018

Continued

Study area	Intake water mode	Number of samples	Physical parameter	Chemical parameter	Biological parameter	Reference
Vanuatu	Groundwater (handpump)	32	pH: 7.3, EC: 1694 uS/cm.	-	About 26.1% of groundwater sources had 'high-risk' or 'very high risk' *E. Coli* contamination (> 10 MPN/100 mL).	Foster and Willetts, 2018
	Rainwater (tank)	32	pH: 7.1, EC: 91 uS/cm.	-	About 56.5% of rainwater sources had 'high-risk' or 'very high risk' *E. Coli* contamination.	
Sixaola district, Limón, Costa Rica	Groundwater extracted from wells	72	pH: 6.45 ± 2.6, Conductivity: 289 ± 151 uS/cm, Turbidity: 4.67 ± 9.37 NTU, TDS: 205 ± 92 mg/L, Hardness: 133 ± 81 mg/L.	F^-: 0.12 ± 0.06 mg/L, Cl^-: 16.65 ± 16.54 mg/L, NO_3^--N: 8.76 ± 14.39 mg/L, SO_4^{2-}: 16.69 ± 24.37 mg/L, Mg: 8.8 ± 8.7 mg/L.	TC: 3.1×10^4 MPN/100 mL, FC: 3×10^4 MPN/100 mL, *E. coli*: 1.1×10^3 MPN/100 mL.	Mena-Rivera and Quirós-Vega, 2018
Rural Quebec, Canada	Groundwater	314	-	The following numbers denote the highest concentration: Mefenamic acid: 1848 ng/L, Yclophosphamide: 1233 ng/L, Metolachlor: 856 ng/L.	-	Husk et al., 2019
Mid and Far-Western Nepal	Household water storage containers	512	-	-	1.16 cfu/100 mL (SD = 0.84).	Daniel et al., 2020
	Water points of collection	167	-	-	0.57 cfu/100 mL (SD = 0.86).	
Ethiopia	Groundwater (handpump-boreholes)	142	TDS: 428 ± 45 mg/L.	F^-: 402 ± 89 ug/L; NO_3^-: < 15 mg/L; Mn: ~30 ug/L.	TTC: 15 ± 3 cfu/100 mL.	Lapworth et al., 2020
Malawi	Groundwater (handpump-boreholes)	162	TDS: >1000 mg/L.	F^-: 336 ± 87 ug/L, NO_3^-: < 15 mg/L, Mn: ~50 ug/L.	TTC: 6.3 ± 6.5 cfu/100 mL.	
Uganda	Groundwater (handpump-boreholes)	124	TDS: 266 ± 023 mg/L.	F^-: 116 ± 16 ug/L, NO_3^-: < 15 mg/L, Mn: ~150 ug/L.	TTC: 0.2 ± 0.4 cfu/100 mL.	Potgieter, et al., 2020
Limpopo Province, South Africa	River water	40	pH: 6.79 ~ 8.42, TDS: 26.8 ~ 348.5 mg/L.	-	TC: 1732 ~ 2420 MPN/100 mL, *E.coli*: 12.2 and 2420 MPN/100 mL.	Potgieter, et al., 2020
South West Punjab, India	Groundwater	42	pH: 7.7, TDS: 2236 mg/L, EC: 2787 uS/com, Hardness: 636 mg/L.	As: 27.59 mg/L, Pb: 48.3 mg/L, U: 96.56 mg/L, NO_3^-: 67.32 mg/L, F^-: 4.7 mg/L, Cl^-: 627.3 mg/L, SO_4^{2-}: 143.5 mg/L.	-	Kaur et al., 2021
Rural Maine, USA	Wells	141	-	A: 11.3 ~ 18.7 ppb, Pb: 3.2 ~ 10 ppb.	-	Segev et al., 2021
	Municipal water	122	-	As: 0.2 ~ 0.6 ppb, Pb: 3.2 ~ 4 ppb.	-	

et al., 2020). These results indicated the poor water quality and potential health risks in the study area, which posed the need for river catchment management in these rivers. Lapworth et al. (2020) assessed the water quality of hand pump equipped boreholes (HPBs) across the Ethiopia Highlands, Malawi, and Uganda in the dry season. They found that the majority of

HPBs (72%) provided drinking water with adequate quality which met the WHO criteria. However, thermo tolerant coliforms (TTCs) were detected in 21% of assessed sites, and contamination was found to have a significantly positive correlation with annual average rainfall. For chemical parameters of drinking water quality, the concentrations of manganese, fluoride, and nitrate in about 4.0, 2.6, and 2.5% of sites exceeded WHO standard, respectively; arsenic concentrations were in range of 0.5 ~ 7.0 μg/L, below the WHO guideline value (10 μg/L) (Lapworth et al., 2020). Such results suggest that, in comparison to chemical contamination, microbiological contamination may be a greater barrier to achieving the target of improved drinking water quality under the UN-SDG 6 at a national level in these three countries.

Table 2. Water Quality Guideline/Standard (Maximum) Values of WHO, 2011

Parameter	Guideline value	Unit
Biological		
Total coliform content	0	cfu per 100 ml
Faecal coliform content	0	cfu per 100 ml
Physical and organoleptic		
Turbidity	5	Nephelometric turbidity units (NTU)
Total dissolved solid (TDS)	1000	mg/L
Electrical conductivity (EC)	N/A	μS/cm
pH	6.5 ~ 8.5	N/A
Chemical		
Sulphate	250	mg/L
Hardness	500	mg/L
Nitrate	50	mg/L
Nitrite	3	mg/L
Ammonia	1.5	mg/L
Fluoride	1.5	mg/L
Copper	2	mg/L
Arsenic	10	ug/L
Antimony	20	ug/L
Cadmium	3	ug/L
Chromium	50	ug/L
Cyanide (free)	70	ug/L
Lead	10	ug/L
Manganese	400	ug/L
Mercury	6	ug/L
Nickel	70	ug/L
Selenium	10	ug/L

Additionally, in the Caribbean region, Mena-Rivera and Quirós-Vega (2018) evaluated well water quality in a rural settlement (Vegas-Las Palmas) of Costa Rica from 2014 to 2016. Faecal coliforms and *E. coli* were found with maximum concentrations of 4.6×10^4 and 1.1×10^4 cfu/100 mL, respectively. Some physical (i.e., pH, conductivity, and turbidity) and chemical (i.e., Ca, Mg, K, Fe, Mn, Cd, and Pb) parameters were also found to be over standard limits for drinking water. Hydrometeorological and anthropogenic factors, such as the application of latrines, the lack of sewerage, the usage of agrochemicals and animals near the wells, as well as geomorphological characteristics of the area were identified as possible sources of such contamination (Mena-Rivera and Quirós-Vega, 2018).

Overall, these studies on water quality monitoring and assessment are focused on rural regions in Africa and Asia, where communities suffer from scarce water resource, high population density, and underdeveloped economy. Only a small portion of communities in these studied regions have reliable access to safe drinking water sources. Most of the communities are facing varying degrees of drinking water pollution problems due to either microbiological contamination, chemical contamination, or a combination of both.

3.2. Drinking Water Quantity and Quality Improvement

When facing the challenge of relatively poor water quality, the purification of drinking water to make it safe for human consumption has become a critical problem for rural communities. Generally, drinking water is transported to and purified at a water treatment facility and then supplied to consumers through municipal waterworks in developed areas. Advanced flocculation, coagulation, filtration, adsorption, disinfection, and sterilization techniques are used to produce safe drinking water (Chen et al., 2018; 2020; Liu et al., 2020; Chen et al., 2021a; Li et al., 2021). However, these conventional treatment methods are not readily accessible and relatively expensive for developing areas, which limits their applications. Thus, to improve the drinking water quantity and quality for rural communities, researchers and engineers have sought for other more appropriate technologies and methods.

For example, various point-of-use (POU) water treatment devices have been developed and considered as an attractive alternative to improve water quality in households. They can be easily transported, setup, and operated by users without the requirement of on-site technical visit. Sobsey et al. (2008) critically examined the performance and sustainability of five POU technologies (i.e., chlorination with safe storage, combined coagulant-chlorine disinfection systems, solar disinfection, ceramic water filter, and biosand filter) which were used for improving household water quality and thus reducing waterborne disease and death. Among them, ceramic and biosand water filters were identified to be the most effective and sustainable in terms of microbiological removal efficacy and diarrheal disease reduction, and regarded as having the greatest potential for widespread application (Sobsey et al., 2008). Mwabi et al. (2011) evaluated the performance of four household treatment devices (e.g., biosand filter, bucket filter, ceramic candle filter, and silver-impregnated ceramic pot filter), using surface water samples obtained from the Wallmansthal Waterworks in Pretoria, South Africa. Parameters of permeate flux and removal rates of physicochemical and microbial contaminants were investigated. Results shown that all the permeate fluxes were within the recommended limits and all filters decreased contaminant concentrations in test water source. The average turbidity removal rate was between 90% and 95% for all filters. However, they all showed poor removal efficiencies of fluorides (16 ~ 48%). The bucket filter had a higher performance in chemical contaminant removal, but the lowest efficiency in bacterial removal (20 ~ 45%). In comparison, the silver-impregnated ceramic pot filter displayed moderate chemical contaminant removal, but the highest bacterial removal efficiency (99 ~ 100%) (Mwabi et al., 2011).

Later, the social, economic, and environmental sustainability of silver-impregnated ceramic water filters (CWFs) for POU drinking water treatment in developing countries were evaluated (Ren et al., 2013). The water consumption of a typical household over ten years (37960 L) was used as the functional unit, as delivered by either CWFs or centralized drinking water system. Results indicated that, in developing countries, the ceramic filter POU technology could be a more sustainable choice for drinking water treatment than the centralized water system. The silver-impregnated CWFs were 3 ~ 6 times more cost-effective than conventional CWFs while yielding comparable reduction of waterborne diarrheal illness. The CWFs also exhibited better environmental performance in energy use, water use, greenhouse gas emissions, and particulate matter emissions (PM10) during life cycle impact analysis. Therefore, CWF has been considered as one of the most practical and sustainable POU technologies with features of high effectiveness, low cost, and ease of use for household water purification (Yang et al., 2020).

In addition, nanotechnologies have provided new opportunities for development of CWFs. Many studies on low-cost CWFs functionalized with nano materials for the removal of microorganisms and physicochemical contaminants from drinking water. For example, Huang and his research team developed nano-TiO_2 and nano-ZnO-coated CWFs for improving the effectiveness in *E. Coli* removal (He et al., 2018; Huang et al., 2018). To further improve bacterial removal, porous CWFs functionalized with several advanced nanocomposites (e.g., Fe/TiO_2, Ag/ZnO, and chitosan/TiO_2) were developed (Huang et al., 2020; Xu et al., 2020; Zhao et al., 2020). The bacterial removal through these CWFs could be attributed to the physical retention through micropores in CWFs, the cell membrane damage by the attached nanocomposites, and the oxidative stress to cells through radicals generated by nanocomposites. An effort to remove Arsenic from drinking water through CWFs coated with nano CeO_2 was also developed by Yang et al. (2021), where ion-exchange and electrostatic attraction were identified as the main mechanisms.

Besides POU technologies mentioned above, efforts have also been made to develop and apply many other low-cost and sustainable technologies for safe drinking water supply in rural communities. For example, researchers in Leeds Beckett University and the Polytechnic of the University Malawi found that the extract of the *Moringa oleifera* (*M. oleifera*) plant could be used to improve water quality as a flocculating agent (Pritchard et al., 2016). *M. oleifera* is a locally available plant which grows wildly throughout rural areas in tropical region. The flocculent capacity of the extract was comparable to that of aluminium sulphate. About 94% of FC and 80% of turbidity could be removed from water through using the extract, compared to 99% of FC and 92% of turbidity using aluminium sulphate. Though the removal efficiency with *M. oleifera* extract was lower, it indeed significantly improved the water quality with a much lower cost and chemical use. A variety of low-cost emergent adsorbents were synthesized and used for arsenic decontamination from water source in rural and peri-urban areas (Kumar et al., 2019). Technology of aquifer storage and recovery (ASR) in brackish aquifers was demonstrated as an option for climate-resilient and year-round water supplies in rural communities with abundant monsoon precipitation (Sultana et al., 2015). Low-cost ASR schemes were constructed at 13 villages in three Bangladeshi coastal districts by developing storage in shallow confined fine to medium sand aquifers. Each ASR scheme consisted of a double-chambered graded sand filtration tank that fed filtered water to 4 ~ 6 infiltration wells through PVC pipes fitted with stop valves and flow meters. The infiltration wells were completed at 18 ~ 31 m below ground and filled with well-sorted gravel, then capped with a thin layer of fine sand that could act as a second stage filter. Over one year of operation, the average infiltration rate of the 13 sites was 3 m^3 per day, and the water recovery rate was 5 ~ 40% at 11 sites where water was abstracted. After sand filtration, the water turbidity was reduced from ≥ 100 NTU in raw pond water to 5 NTU in recovered water. *E. coli* counts were also reduced, though *E. coli* still could be detected in about half of the samples. Moreover, to mitigate the excessive use of groundwater resources and increase the resilience of rural communities in terms of their drinking water supply, targeted managed aquifer recharge on agricultural land (Ag-MAR) near rural communities was proposed to improve water security for communities. It could potentially stabilize groundwater tables and maintain or improve water quality in nearby supply wells (Marwaha et al., 2021).

Rainwater harvesting (RWH) is also listed among the specific adaptation measures which can be employed to cope with future climate change and its impacts on rural communities, particularly in regions of Africa. Generally a RWH system consists of waterproof catchment surfaces for rainwater collection (e.g., roof or ground surfaces), a delivery system (e.g., gutters or surface drains) for transporting rainwater from the catchment to storage tank. Gutters and pipes are usually made from plastics or metals, since these materials are relatively low-cost and durable (Gould and Nissen-Petersen, 1999). Sturm et al. (2009) investigated the application of RWH in central northern Namibia. Through comparing the amortisation times and prime costs with other water source (e.g., communal water point, private water tap, and water vendors), it was found that RWH in terms of the roof catchment systems was economically feasible and could provide comparable benefits to public water supply (Sturm et al., 2009). Mwenge Kahinda et al. (2010) presented a methodology to incorporate the climate change component during the design phase of domestic RWH systems in South Africa. They used the Roof model to calculate the optimum volume of the RWH tank and evaluate its water security (i.e., percentage of demand satisfied) with and without climate change. Results indicated that the optimum RWH tank size was 0.5 m^3. According to forecasted rainfall downscaled from six global circulation models, the ranges of water security obtained through a 0.5 m^3 RWH tank were 10 ~ 15% in arid quaternary catchments (QC), 15 ~ 20% in both semi-arid and dry sub humid QCs, as well as 30 ~ 40% in humid QC, respectively (Mwenge Kahinda et al., 2010). Kisakye and Van der Bruggen (2018) assessed the effects of climate change on water saving and water security from RWH for Kabarole district, Uganda, where RWH has become a major adaptation strategy for helping to ensure safe water access. Six top performing Global Circulation Models (GCMs) using projections for 2040s and 2070s periods were applied. Seasonal analysis revealed that water saving and security will be reduced in the dry season of December, January, February (DJF) and the rainy season of March, April, May (MAM), but increase in the other dry season of June, July, August (JJA) and the other rainy season of September, October, November (SON). Households should utilize the increased water savings in JJA and SON to overcome the challenge of lower water availability in MAM and DJF. Therefore, the combination of a large tank of 5 m^3, a least roof size of 50 m^2, and a low-cost household water treatment (i.e., CWFs) was recommended to help ensure safe drinking water supply (Kisakye and Van der Bruggen, 2018).

3.3. System Maintenance and Community Management

Many interventions and projects to supply safe water to rural communities have been marked by poor sustainability records. Plenty of resources have been committed to the development of lower-cost technologies that are easy for rural communities to use and maintain the sustainability of safe water supply, but technologies that require significant operation and maintenance are often abandoned prematurely. Considerable progress has been made for water system maintenance and management in the postconstruction period to ensure the long-term sustainability of water treatment strategies. Dynamic operation and maintenance of safe water supply system is critical, which everyone should pay attention to, especially providers, operators, and managers (Montgomery et al., 2009). Community-based initiatives and participation are necessary in the planning, designing, implementation, and management of local water resources (Fonjong et al., 2005; Strauch and Almedom, 2011). Community-based management has been embraced as a fitting approach to drinking water supply in rural communities. Under this approach, community-based water committees are assumed responsibility for the operation and maintenance of water supply systems, including tariff setting, revenue collection, hardware repairs, and equipment upgrade (Foster, 2013).

Based on its importance, a number of community-based studies have been carried out to help establish effective and efficient programs for rural drinking water supply. Dungumaro and Madulu (2003) analyzed the importance of community participation in the process of water resources management in Tanzania. They found that a successful and sustainable water resource management strategy required the aid of knowledge, opinions, and experience from local communities who would be the key stakeholders in resource conservation (Dungumaro and Madulu, 2003). Gleitsmann et al. (2007) assessed participatory water management strategies at community level in rural Mali, and indicated that community-based rural water supply was a positive step in responding to local needs. Community-based management could mobilize the assets and insights from different social actors, which may influence decision making at all stages, including the choice and design of technologies and water supply interventions (Gleitsmann et al., 2007). However, in general, the roles of key actors at each level of district, village and household were not clearly defined in national water frameworks. This led to management confusion in rural communities since they did not have a specified role. Thus, the role of community management needs to be defined to offer realistic and feasible frameworks in rural water provision. Madrigal et al. (2011) explored how rural communities solved their water provision problems in Costa Rica through making rules. The most important mechanisms which resulted in high performance of water provision were identified to include the dynamic interaction of working rules imposed by the local communities and properly specified local accountability, and the capacity of local committees to generate suitable incentives to involve the community in sustainable solutions. Involvement of communities in institution design, infrastructure construction, and system maintenance, and organization of communities to resolve pressing problems and bear relevant expenses, were crucial ways to create a sense of ownership that positively affected performance of water provision (Madrigal et al., 2011).

Besides, the sense of ownership of all community members should not mean that communities take all responsibility and willingness to finance and manage. Mandara et al. (2013) proposed that community management should be comprehensive and include actors, structures, obligations, implications and the mechanisms of accountability. The demand for resources and capabilities should be reflected and the development of integrated institutional capacity should be included. Ongoing institutional support was required due to changes of policies, knowledge, and technologies. Non-monetary and non-fee resource mobilization mechanisms were also used to support rural water systems (Mandara et al., 2013). Behnke et al. (2017) identified several such mechanisms, including mobilization of personal and community assets, community institutions, and community labor. Water fees did not necessarily capture the diverse realities of rural water resource mobilization. Enabling community actors to adapt their rural water supply projects and programs to be more inclusive was recommended (Behnke et al., 2017). In addition, it is important to balance the responsibilities of rural communities and external support for operation and maintenance to avoid overburden. Hutchings et al. (2017) suggested loose and overlapping collection of models with varying degrees of community involvement and external support instead of single community management model. Identifying the role of a suitable support environment was essential to the sustainability of community management. They thus made an interface between community contribution and external support as the basis for new conceptual models to take better account of differences (Hutchings et al., 2017).

External bodies, such as government, non-governmental organizations (NGOs), or other agencies, should also play a role in monitoring performance and provide continuous support. External support programs may include administrative, financial, and technical assistance; they have been hypothesized to contribute to sustainable rural water services (Koehler et al., 2018; Miller et al., 2019). The contribution of postconstruction support (PCS) to the sustainability of rural water supply systems has been investigated in Peru, Bolivia, Kenya, Zambia, and Ghana (Davis et al., 2008; Whittington et al., 2009; Klug et al., 2017; Kelly et al., 2018). Community actors were commonly involved in hardware rehabilitation of water supply system. Rapid rehabilitation was difficult since communication challenges with external actors always existed when external support was needed. Thus, rural communities received management-oriented PCS visits and with system operators who attended training workshops, had more systems with better performance than communities that did not receive such support (Davis et al., 2008; Klug et al., 2017). The combination of demand-driven community management model (that community can and should fully take responsibility for its systems), coupled with reasonable access to spare parts and technical expertise, was suggested as a step forward in unraveling the issue of sustainable design and implementation of water supply programs in rural communities (Whittington et al., 2009). Besides, seasonality affected water availability, system breakdowns, resource mobilization, committee activity, and external support availability. In rainy seasons, less time and money were spent for water collection since rainwater harvesting and seasonal water sources were available; in dry seasons, more efforts were made to collect water and more groundwater sources were used. However, rural water committees generally had less money, time and access to external support during the rainy season, making them less able to carry out system maintenance and management. Thus, community engagement should be carried out over a long period of time so that seasonal patterns in water system maintenance and management can be understood and incorporated into training. External support actors should also make targeted efforts to understand the seasonally economic patterns in communities, in order to support and train committees with appropriate maintenance and management strategies (Kelly et al., 2018). Furthermore, the reliability and sustainability of rural safe water supply required effective long-term monitoring for responsive maintenance. For example, Nagel et al. (2015) demonstrated that a sensor-based service model for hand pumps in rural Rwanda was associated with substantial reductions in repair interval when compared to the nominal service model without sensor data. Equal resources could yield greater per-pump functionality when sensor data triggered technician response. With the help of sensor data, which was available to the implementer and used to dispatch technicians, the successful repair interval of hand pumps decreased from 152 days to nearly 21 days and the functionality mean increased from about 68% to nearly 91% (Nagel et al., 2015). Researchers from Massachu-setts Institute of Technology (MIT) and the Sipayik Environmental Department (a tribal government department), engaged local communities to implement a participatory science project to analyze drinking water quality in three remote coastal communities in northeastern Maine (Segev et al., 2021). Methodologies were developed in this project to build long-term relationships with local scientists and to enhance the environmental literacy of the rural communities. Establishing partnerships, maintaining communication, and inviting the relevant stakeholders to community meetings were vital to the success of project. Throughout the project, community members knew their drinking water quality and had improved public education, local researchers from Sipayik built technical capacity, and MIT researchers obtained cultural understanding of diverse communities.

Therefore, the model of community management combined with external support has far-reaching benefits to rural water supply. For local communities, their needs of safe drinking water could be met and their abilities to manage and maintain water supply could be enhanced. For external experts, they may also benefit from community support to inform scientific processes, such as collecting data that spans across a large geographic region and having an enhanced understanding of community interests. Furthermore, this model could help increase scientific awareness among community members and engage the community with the environment.

3.4. Decision Making for Management

For the sustainability of rural water resource management and drinking water supply, sound and effective water governance policies are crucial. Establishing such policies involves multi-party participation, including governmental agencies, professionals, and the general public. Many aspects should be considered in the water governance policies, for instance, how drinking water should be supplied and distributed, how much water should be consumed, how and what measures should be taken to ensure water quality. Besides, it is inevitable to encounter the issue of regional cooperation during rural water resource management. For example, the collaboration of riparian communities for developing shared river systems are essential due to upstream-downstream interdependencies. Successful regional cooperation can bring additional political, economic, social, and environmental benefits for all partners (Rasul, 2013). All of these requires an interdisciplinary political ecology and efficient decision-making support.

Water governance studies that integrate descriptive analytical functions, solution-oriented components, and problem-solving efforts are desired to help support sustainable water management. Decision support models are powerful methods to help reach sustainable solutions and policies in complex problems of water resource management (Zhang et al., 2021). A number of tools and models have been widely applied in this field to provide bases for decisions, such as comparative analysis of water governance policies, allocation of water loading to receiving community, and implementation of system management activities (Zeng et al., 2014). Henriques and Louis (2011) applied Capacity Factor Analysis which was a decision support system to help select appropriate technologies for sanitation services in rural communities, to choose safe and affordable drinking water supply systems in Cimahi Indonesia. Kuzdas et al. (2014) employed sustainability appraisal tool to evaluate the water governance in rural Guanacaste, Costa Rica, and provided solutions to improve groundwater management and protection. Kayser et al. (2015) analyzed the challenges of drinking water governance in Brazil, Ecuador, and Malawi using a clustering model. The model integrated political, economic, social, and environmental variables which affected water sector performances. It was found that the access to safe drinking water could be improved through addressing certain water governance challenges (e.g., monitoring and enforcement of water quality policies, sufficient capacity for administrative and technical management) (Kayser et al., 2015).

Given the complexity of rural water resource management and the jurisdiction of different institutions and organizations, the water-related problems at different levels should be considered during decision making. Integrated Water Resources Management (IWRM) was thus proposed to promote the coordinated management of natural resources (e.g., water and land) to maximize the resultant economic and social welfare without compromising the sustainability of eco-systems (Agarwal et al., 2000). IWRM was explicitly developed to challenge conventional and fractional water management systems, focusing on integrated approaches with coordinated decision making across sectors and scales. It was implemented in the sustainable management of Cameroon's water resources and identified as a promising approach (Ako et al., 2010). Besides, a mixture of stakeholders (e.g., local households, community members, NGOs, and governmental agencies) play key roles in promoting, installing, and maintaining rural water supply and water sources. An increasing number of studies have been done to analyze and understand the multi-stakeholder governance arrangements that emerge from the cross-scale nature and multi-functional role of water. Stein et al. (2011) used social network analysis (SNA) to map collaborative social networks between actors which either directly or indirectly influenced water flows in the Mkindo catchment in Tanzania. Social network data of 70 organizations, ranging from local users and community leaders, to governmental agencies, universities, and NGOs was generated through questionnaire and interviews. No organization was found to coordinate the various land and water-related activities at the catchment scale. Community leaders played crucial roles in linking otherwise disconnected actors that were not adequately integrated into the formal water governance system. Instead of imposing new institutional arrangements to bring these actors together, they argued that it was more promising to build upon existing social structures, such as water user associations (Stein et al., 2011). Walters and Javernick-Will (2015) evaluated stakeholder alignment in rural water system management at Terrabona, Nicaragua, through the analysis of stakeholder value networks. The networks were formed by interactions among stakeholder values which were identified from data gathered in key stakeholder groups and evaluated by cross-impact analysis. The alignment degree of stakeholders based on the structural interaction of their values could be highlighted (Walters and Javernick-Will, 2015).

Developing sustainable water supply systems for rural communities is an increasing challenge with increasingly stringent criteria of sustainability and impacts of climate change. Various factors (social, technical, administrative, financial, and environmental) may affect the system establishment and contribute to difficulties (Li et al., 2007). In light of such challenges, Schweitzer and Mihelcic (2012) developed a sustainability assessment tool composed of eight essential indicators and then used the tool to evaluate the sustainability of community management for water supply systems in 61 rural communities of the Dominican Republic. The developed framework served as a diagnostic tool to inform decision making through characterizing specific needs during water system management and identifying weaknesses in training or support (Schweitzer and Mihelcic, 2012). Enéas da Silva et al. (2013) identified a framework for meeting multiple sustainability criteria of rural water supply development in a demonstration project in rural areas of Ceara, Brazil. A set of tools that allowed water supply development to be carried out under diverse physical and social conditions were incorporated within the framework. Community engagement was emphasized in the project in both the assessment and analysis of water supply needs, as well as in the selection of preferred alternatives (Enéas da Silva et al., 2013).

Dwivedi Arun and Bhadauria Sudhir (2014) used an analytical hierarchy process to develop decision making metrics for rural drinking water supply in the Dhule district of Maharashtra State, India, through establishing the weights of 5 factors and 25 subfactors. The derived metrics could be useful for decision makers to discover the trade-offs among factors and for recommending postconstruction support for rural water utilities (Dwivedi Arun and Bhadauria Sudhir, 2014). Xu et al. (2016) proposed an analysis framework which integrated Order Preference by Similarity to Ideal Solution (TOPSIS) method, analytic hierarchy process, and Shannon's Entropy and applied it for a case study of rural drinking water supply in Hebei, China. The economic condition was identified as the key point of long-term system operation in the area (Xu et al., 2016). To examine the impacts of socioeconomic development on rural drinking water safety in China, Li et al. (2019) applied Pressure-State-Response framework to organize existing data into state and pressure indicators, and then used Canonical Correlation Analysis to analyze relationships between the indicators at provincial level. It was found that recent and rapid socioeconomic development could bring substantial benefits for rural drinking water safety. However, such development may lead to groundwater over-exploitation, water resource reduction, and environmental contamination, which negatively affected rural drinking water safety in certain extent (Li et al., 2019). Molinos-Senante et al. (2019) evaluated the service quality of 40 rural drinking water supply systems in Chile based on an analytic hierarchy process and Monte Carlo simulations. The weights of 14 indicators were determined by representatives of community managers and external experts. No system achieved the maximum index (score = 1.0), which indicated that all systems had room for improving its service quality. The service quality of older systems was better than that of newer systems, revealing the importance of experience in management and operation of rural water supply systems (Molinos-Senante et al., 2019).

To reduce the risk of drinking water shortage, conjunctive use of multiple water sources should be considered in most circumstances, though improved water quantity does not neces-

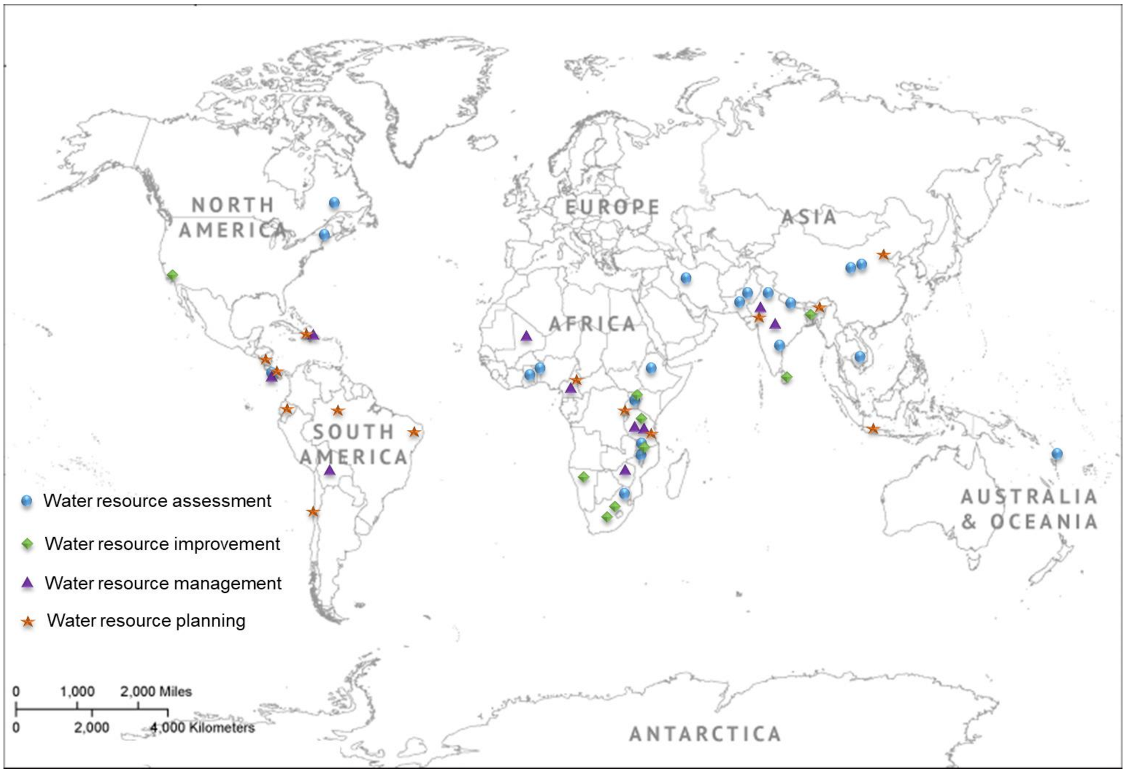

Figure 1. Research and corresponding areas involved in this review.

sarily mean improved water quality. Some efforts have been made to support the conjunctive use of water sources in rural communities. Hoque et al. (2016) assessed spatial vulnerabilities to salination of various drinking water sources due to meteorological variability and climate change along the coastline of South and Southeast Asia using a vulnerability index. Surface and near-surface drinking water sources in the mega-deltas in Vietnam and Bangladesh-India were identified to be the most vulnerable to contamination by salt water, which may lead to more than 25 million people at risk of drinking 'saline' water (Hoque et al., 2016). Climate change was likely to intensify this situation. Ngasala et al. (2018) applied a Water Quality Index (WQI) to assess the overall water quality of three main water sources (surface water, shallow wells, and deep wells) in a pastoral community in northern Tanzania. The reliability of each water source was then analyzed, through quantifying five factors that limited water access, including seasonal availability, distance to water sources, cost of purchasing water, community preference, and water quality. Surface water was identified to be the most reliable for local community members although it was highly contaminated (Ngasala et al., 2018). Peters et al. (2019) used multi-criteria decision analysis (MCDA) methods to assess the probable success of multiple drinking water sources in southwestern Bangladesh, including RWH, ponds, pond sand filters, managed aquifer recharge (MAR), and tube wells. According to analyses of technical, economic, social, and environmental factors, they suggested that RWH was the most likely to be a reliable drinking water source, and MAR was the least preferred alternative in the region (Peters et al., 2019).

4. Conclusions and Perspectives

This literature review has indicated that significant efforts and achievements have been made in drinking water source management for rural communities under climate change, including extensive monitoring for water quality assessments, developing technology for water source improvement, exploring framework for community management, and system modeling for decision making. Figure 1 summarizes the involved research and corresponding areas. Studies have been spread across the major developing regions of the world, though there is little research in the areas of Central Asia and the Middle East. Nevertheless, it is necessary to continue the works of crisis mitigation for rural drinking water security.

Understanding the status of drinking water quality and related health risks to rural communities is the basis for the protection and management of drinking water sources. Long-term monitoring of drinking water quality in rural communities is usually difficult to sustain due to capacity limitations of finance and technology. Besides, more and more emerging chemicals are synthesized and used with the development of industry and agriculture, which leads to that more and more emerging contaminants are being released into aquatic environments, such as new pesticides, pharmaceuticals and personal care products (Geissen et al., 2015; Husk et al., 2019). These emerging contaminants may enter drinking water sources and then pose potential risks to human health. Their toxicity and behavior are diverse, and their detection and monitoring are challenging. At current stage, it may be impossible for rural communities to monitor these emerging contaminants on their own. Thus, more external support is required from researchers to explore possible solutions and from government organization to establish long-term monitoring programmes. Research projects about the detection and removal of emerging contaminants can be particularly encouraged.

Researchers and engineers have developed a number of water purification technologies to improve the drinking water quality for rural households, such as economical flocculating agents and various point-of-use devices. Particularly, low-cost CWFs have been considered one of the most practical and sustainable POU technologies with advantages of high effectiveness and ease of use. The development of nano technology significantly advances the research on these water purification technologies. However, the long-term effects of nanomaterials on drinking water sources and human health have not been broadly evaluated in rural communities. Community members should be educated to properly use and then safely dispose of products containing nanomaterials.

During the management of rural drinking water sources, a hybrid modality in which community management is the mainstay with supplement from external support from other organizations is highly recommended. Community cultures, economies, and environments differ across countries and regions. These differences should be considered when designing hybrid management strategies, so that all actors can be appropriately enabled and the mechanism which is most effective for the given community can be identified. Water governance should also adapt to local situations, avoiding over burdening of community participation in the maintenance of water management. Committee training and technical support are both necessary for post-construction system operation and maintenance. Thus, research projects with close collaboration among governments, scientists, and general public could be particularly encouraged.

Policy and decision making is the primary basis for sustainable drinking water source management in rural communities. Drinking water inequality and conflict commonly exit in rural-urban, provincial, center-periphery and inter-national, which may be magnified due to climate change under current trend (Anthonj et al., 2020). This is a critical issue which should be explicitly recognized and addressed through policy and programming efforts. A variety of factors (e.g., social, technical, financial, and environmental) have nonnegligible effects on rural drinking water source management. A number of studies have been carried out to analyze of such effects, whereas few of them consider uncertainties that are widely existent in many factors. Thus, more research is necessary to evaluate these effects under uncertainties, which can provide valuable information and support for policy and decision making in complicated systems.

Climate change affects drinking water safety of rural communities in a multi-dimensional way (Kohlitz et al., 2020; Chen et al., 2021b). The reliability, affordability, and physical accessibility of safely managed drinking water source may be influenced. Not all of these effects and their risks can be predicted, and some of them may emerge over many years because climate change continues to accelerate (Kohlitz et al., 2020). Currently, a few studies have been carried out to pursue technological and infrastructural improvements for managing risks from hazards caused by climate change, such as rainwater harvesting. On this basis, it is essential to expand research area to study the various threats from climate variability to rural drinking water safety, and then to develop corresponding measures to address those threats to water security.

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