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Assessing the water quality and status of water resources in urban and rural areas of Bhutan

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ABSTRACT

Access to safe drinking water and improved sanitation are important fundamental rights of people around the world to maintain good health. However, freshwater resources are threatened by many anthropogenic activities. Therefore, sustainable water supply is a challenge. Limited access to safe drinking water and unimproved sanitation facilities in some of its urban and rural areas are two of the major challenges for Bhutan in the 21st century. The water quality in the natural water systems in the cities and suburbs has significantly decreased while the urban infrastructure is being improved in Bhutan. Therefore, this study presents the state-of-the-art of water resources in Bhutan and the challenges for a sustainable water supply system. The current water status, drinking water sources and accessibility, factors affecting water quality degradation in urban and rural areas, water treatment methods, and implementation of sustainable drinking water accessibility with population growth in Bhutan are discussed in detail. Results of the review revealed that the water quality has deteriorated over the last decade and has a high challenge to provide safe water to some of the areas in Bhutan. Geographic changes, financial difficulties, urban expansion, and climate change are the reasons for the lack of safe drinking water accessibility for people in town areas. It is, therefore, recommended to have a comprehensive integrate water resources management (IWRM) approach while considering all stakeholders to find sustainable solutions for the challenges showcased in this paper.

1. Introduction

Access to safe and clean water is one of the most essential requirements for humankind, which also is a fundamental right (Abegaz and Mideksa, 2021; U.N. Resolución A/RES/64/292, 2010). Even though the majority of the earth's surface is covered with water, most of it has a higher salt percentage (Dinka, 2018), making it unsuitable for direct drinking purposes. Fresh water can be considered scarce but a manageable resource (World water vision: A Water Secure World - Vision for Water, Life, and the Environment, 2000; Kumar, 2019). It has been found that more than 300,000 children under the age of 5 years are dying because of a shortage of safe drinking water (Lamb et al., 2021). Projections unveil that by the year 2050, more than 50 % of the world's population will be under moderate water stress, among which 80 % will be living in developing countries (Simelane et al., 2020). In addition, along with the rapid development of cities in the world, specialists

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reveal that more than two-thirds of the world's population will be living in urban places in the near future (Kim and Kim, 2022). Many environmental challenges are to be faced due to different urbanized land cover patterns (Uitto and Biswas, 2000). This includes higher-order wastewater treatment to treat increasing pollution loads and then facilitate the demand globally. Therefore, the water quality is at a higher risk.

Water quality is always a concerning topic. The most important public health consideration in tropical regions is the increased number of cases of pathogenic microorganisms. Over-usage of water resources tends to have more water quality-related problems. Eutrophication, increment of breeding sites of water-borne diseases, and decrement of the assimilative capacity of regulated streams can be seen due to seasonal changes in urban water usage (Hung and Hsieh, 2021). Especially, the high average annual range for Biochemical Oxygen Demand (BOD), Total Coliform (TC), and low Dissolved Oxygen (DO) levels have been reported in South Asian countries due to urban discharges to natural rivers (Karn and Harada, 2001). 40 % of the global population has limited access to enough sanitary facilities due to untreated sewage contamination of freshwater resources (Liyanage and Yamada, 2017).

The balance of the hydrological cycle changes due to several factors such as changes in climate, land use, geography, and other anthropogenic activities. Therefore, hydrology and the quality of water are considered inherently related components and thus the water quality is significantly affected by the runoff. Unpolluted water is very important to properly structure and function the hydrology of healthy natural systems. Therefore, many hydrological models are capable of handling water quality of streamflows in watersheds (Chathuranika et al., 2022).

Concentrations of heavy metals and bacteria change with several hydrological variables; watershed area, basin slope, permeability, etc. Rostami et al. (2018) evaluated the water quality parameter changes due on precipitation and found that there is a significant dependence. According to Bastaraud et al. (2020), the water quality of the watersheds in Antananarivo, Madagascar has gradually been affected by the direct effects of rainfall events due to low-income urbanization. In addition, changes in water quality influence the infiltration rate and surface ponding/runoff (Tuffour and Abubakari, 2015). More importantly water quality impacts the human life. Qasemi et al. (2019) revealed that infants and children are at a higher risk to suffer from water-borne diseases compared to adults due to higher concentrations of Fluoride and Nitrate in drinking water in Western Khorasan Razavi, Iran.

Therefore, proper planning is highly essential in any water supply system. Water quality requires multi-sectorial concerns. Therefore, this directly relates to integrated water resources management (Hassing et al., 2009). Discharge standards of waste load allocations and water pollution control policies are some of the factors taken into account when categorizing water quality standards. A set of objectives should be identidied for the proper management of a water pollution control program and the interations of the objectives has to clearly understood. Individual or regional treatment options have to be evaluated based on a collective approach satisfying the technical, economic, and administrative objectives and their viability. In addition, the water quality objectives, discharge standards, monitoring systems, and other important aspects can be used to get an idea of the standards of water management programs. These types of programs should be offered by a proper legal foundation as well as a stable institutional infrastructure (Food and Agriculture Organization of the United Nations, 2021).

However, the sustainability of these systems in developing countries is still a challenge. Bhutan has to manage its ample water resources properly due to these issues (Tariq et al., 2021). Among many other countries, it has one of the highest per capita water resource availability (94,500 m^3/capita/annum). Nevertheless, only 1 % of this amount is used due to ill water resources management depending on situations and certain geographical conditions (Tariq et al., 2021). However, the demand for water in the last decade in Bhutan has increased due to increased population, behavioral changes in people, and standardization of the economic state. By 2019, about 41.61 % of the total population was living in urban areas. This showcases an increment in the urban population of 22.35 % from 2009 to 2019. However, the economic condition of many are not up to the standard values. Thus, many lived under lowered living conditions with less infrastructure. Thereby, households adopt different strategies to obtain clean drinking water (Rahut et al., 2016). Therefore, more people suffer from water-borne and water-related diseases such as diarrhea, typhoid, skin infections, conjunctivitis, dengue, and malaria (Tsheten et al., 2021). Diarrhea and Dysentery were reported in 51,373 and 12,678 cases across the country in 2014 (Dorji, 2016). Thus the number of deaths per annum has been increased (Rahut et al., 2016).

National Environment Commission, Bhutan (National Environment Commission, 2023) states in which that there is a goal to improve local water quality standards while providing safe drinking water and sanitation. Water supply legislation was accelerated by the government of Bhutan considering human health and environmental needs. Drinking water quality programs depend on legislation that functions on sufficient and suitable regulatory standards and codes. These legislations examine the amount of supplied water to the consumer and procedures of treatment and distribution which should be followed when using water resources. The Water Act of Bhutan (2011) aims to protect water resources in the country by practicing conservation and management in an economically efficient and environmentally sustainable manner. Related studies conducted in 2013, reveal upstream and downstream water deterioration due to the increment of waste disposal at Thimphu City (Gawel and Ahsan, 2014). These facts reveal how urbanization affected badly on Bhutan's quality of water resources.

Assessment of available water resources and their quality is essential for Bhutan. However, there is no comprehensive assessment of the water resources in Bhutan in the literature. Identifying this research gap, this study discusses the state-of-the-art of drinking water quality standards, issues, water treatment technologies, monitoring, and adaptation strategies under rapid urbanization in cities and rural areas of Bhutan. The review was carried out under several sub-topics including, the importance of safe drinking water, drinking water sources, availability and Bhutan's stand, water quality depletion in Bhutan, water treatment in urban and rural areas in Bhutan, and implementation of sustainable drinking water accessibility with the population growth. Therefore, with the vast and comprehensive review, this study will open up a healthier discussion along with an enhanced literature review on future water resource availability in Bhutan.

2. Focused region

Bhutan (with an area of 38,394 km^2) is a kingdom trapped by the Chinese border to the North, the Indian border to most of the east, and the eastern Himalayan Mountain ranges to the south and east (refer to Fig. 1) (Asia and the Pacific Finance Ministers' Meeting Kingdom of Bhutan Country Overview, 2020). The population of the country is about 780,000 which has a lowered population density of 20 people per km^2 (Currinder, 2017). The country has a diversified climate due to its topographical variations. The northern parts of Bhutan are at an altitude exceeding 7000 m and the climate of these highest locations is similar to the arctic climate. In the lowland regions of Bhutan, particularly in the southern parts, temperatures can range from around 15 °C to 30 °C or higher during the summer months (Tariq et al., 2021). In the winter, temperatures in these areas can drop to around 5 °C or lower. At higher altitudes, temperature ranges are more extreme. Weather conditions have been changed rapidly in the past few years, with sudden shifts in temperature, wind speed, and precipitation (Mahagaonkar et al., 2017). Therefore, the country experiences five seasons; summer, monsoon, autumn, winter, and spring. Thus, it has good rainfall throughout the year with milder temperatures. The country recorded an annual rainfall of 1649.9 mm in 2018.

The total annual internal renewable surface water amount of Bhutan

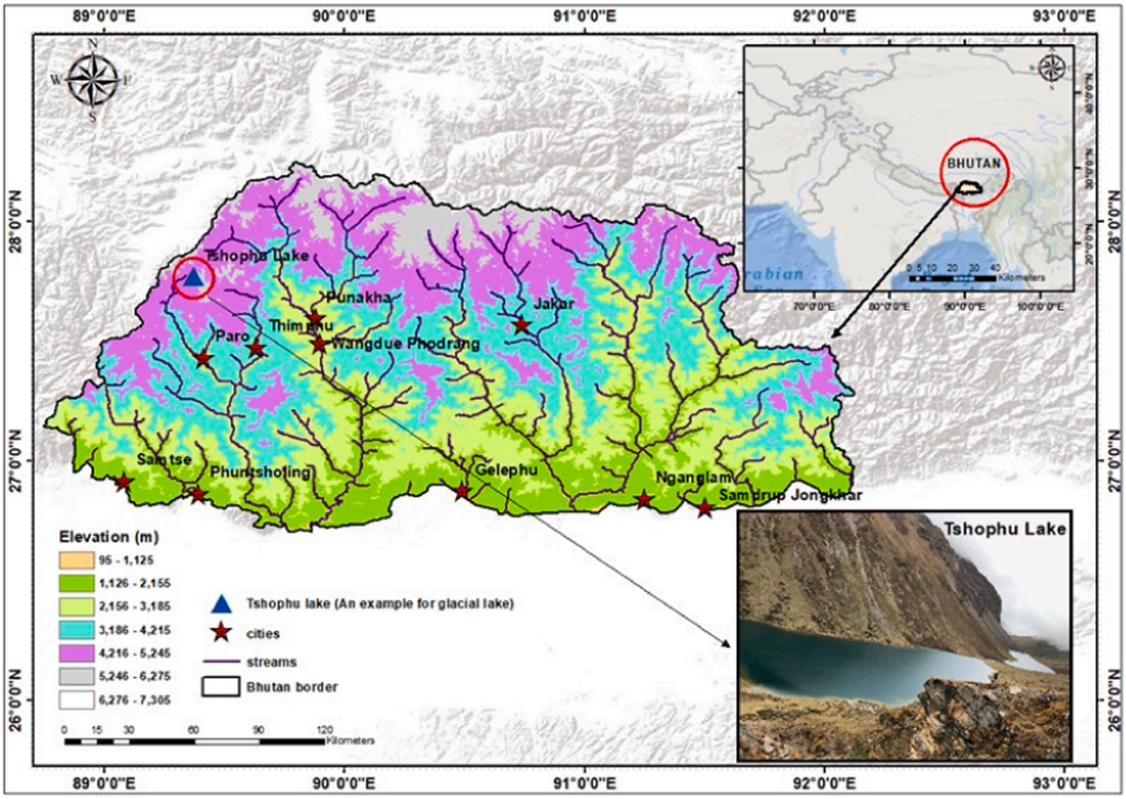

Fig. 1. Location of Bhutan and the Tshophu Lake, Bhutan, an example out of 2674 glacial lakes in Bhutan, topographical variation, river network, and populated cities in Bhutan. (Photo credit: Zam and Denkar).

is approximately 78,000 million m^3. There are 677 glaciers and 2674 glacial lakes at the highest altitudes in the upper part of Bhutan (refer to Fig. 1 for an example of the glacial lake - Tshophu Lake, Bhutan) and they are the initial sources of rivers, streams, lakes, and other natural water bodies (Dorji, 2016). Snow and glaciers are melting in some areas during the dry season resulting in increased stream flows. The process was enhanced due to the ongoing climate change in the area (Lhamo, 2015).

Most of the drinking water sources in Bhutan are natural streams and springs. In addition, groundwater extraction is witnessed for drinking water purposes due to rapid population growth in recent years (National Water Reference Laboratory, 2019). Several challenges in distributing water resources can be seen due to the mountainous nature of the terrain. The elevation range in Bhutan is between 95 and 7305 m above Mean Sea Level (MSL) which spreads from south to north. The flat areas where some people live are in river valleys between steep mountains (Walcott, 2009). Similar challenges can be observed in Nepal as stated by Dhital et al. (2022). Fig. 1 further showcases the topographical variation of Bhutan, its river network, and major cities in Bhutan.

3. Importance of safe drinking water

Surface and groundwater sources are used for water consumption in most countries (Herrera-Franco et al., 2022; Pradhan et al., 2022; Shyam et al., 2022). However, anthropogenic activities significantly impact the water quality of both resources (Redelinghuys, 2008). Groundwater is recharged from the surface while discharged naturally to the surface at springs and seeps. Groundwater is very precious for low-income countries to use as drinking water. It is more reliable than surface water because users can exploit it directly (Carrard et al., 2019).

Freshwater "scarcity" is considered a severe global environmental challenge at present (Durán-Sánchez et al., 2020). The global population is expected to rise to 9 billion in the year 2050, so it is a must to practice adaptation practices and mitigation of the over-use of fresh water (Srinivasan et al., 2012). People who did not have access to safe drinking water and basic sanitation in 2015 were a prominent environmental sustainability concern in Millennium Development Goal (MDG) 7 which has been followed up by the sustainable development goals 2030 (SDG 2030). This target was expected to cover 75 % of the population with access to improved water sources (Mohammed et al., 2013). Globally, the percentage of improved drinking water accessibility in urban areas is approximately 95 % and when comparing it with rural areas it is 73 %. Sub-Saharan Africa is a great example to reflect that there is a significant gap between urban and rural areas' safe drinking water accessibility (Mohammed et al., 2013). On the other hand, 52 % of people in Asia do not have access to improved sanitation facilities (Hutton and Haller, 2004). At present, 80 % of people who are living in cities have facilities to dispose of domestic wastewater via onsite sanitation systems (Dorji et al., 2019). Dorji et al. (2019) used 35 towns for one of their studies and revealed that only 22.8 % had sewage systems in Bhutan.

The improved drinking water sources then have to be protected from outside contamination, especially from fecal matters (Cassivi et al., 2018) where the sanitation facilities are not up to date. Considering all these aspects, Sustainable Development Goal 6 (SDG 6) is expected to provide safe water and sanitation to all people in the world by the year 2030 (Andualem et al., 2021).

4. Drinking water sources, availability and Bhutan's stand

Ongoing climate change severely impacts the availability of water resources. Thus the water sources should be protected with additional care. Sources that are in the best condition in quality must be used for drinking water purposes. Usually, springs are cost-effective in terms of ease of water quality and maintenance. Users can accept spring water due to its coldness and fresh nature. But, the quality of water discharged from springs can vary hugely for several reasons, such as the quality of the water recharged by the aquifer and the constituents present in the colliding rocks. The flow rate and length of the flow path through the aquifer affect the time of contact with the rocks. Therefore, different types of minerals can dissolve in water. However, groundwater extraction and rainwater harvesting should conduct in the places where water shortages occurred (National Environment Commission, 2023).

Nevertheless, the quality of groundwater is sometimes questionable depending on the area. For example, RadFard et al. (2019) stated that Bardaskan villages in eastern Iran use groundwater as drinking water and this water contains higher values of Sulphate, Nitrate, total hardness, and Sodium compared to WHO and Iranian standards.

Many households practice rainwater harvesting in South Asia. However, the quality of the water is variable due to the cleanliness of the roof. Furthermore, ponds and lakes are other options for water. The users can have an intake and direct access to the water. However, small community ponds are easily vulnerable to contamination. These small community ponds in developing countries are usually not treated before consumption. Therefore, water-borne diseases are frequent in these small communities. Relevant authorities must take the necessary actions to do the required treatment before sending it to consumers. Nevertheless, streams and rivers are used abundantly for drinking water supplies and are one of the most used water resources in the world. Depending on the geographical locations the treatment strategies are different in surface water. Stream water is relatively less expensive; however, the real cost depends on various factors including treatment facilities, geographical location, and pumping. Usually, the streams at higher altitudes in forests are considered pure water which is exceptional for drinking purposes.

The National Environment Commission, Bhutan (National Environment Commission, 2023), states that each person has the right to consume a safe, affordable, and adequate amount of water. Even though Bhutan is rich in its surface water and groundwater resources, for a variety of reasons, some of the people of Bhutan are still unable to meet their safe drinking water needs. The continuous 24 h water supply is unavailable in some areas. Therefore, there are some proposals to improve the water supply system and provide Bhutanese with a continuous supply of water with standardized water quality. Potable water is defined as a common pool of natural resources that is responsible for everyone. This is highly vulnerable to pollution and contamination; therefore, potable water needs special care (Musingafi, 2013).

Dorji et al. (2020) have conducted a study based on rainwater supply for domestic uses in Zhemgang town in Bhutan and state that rainwater can be used as potable water to minimize water shortages (Hussain et al., 2019) due to minimal water availability in the lean season (March to mid-June) and problems in accessibility to natural water systems. The area receives significant rainfall during the rainy season (about 225 mm/month). Groundwater provides fairly good water quantity depending on the requirement of storage and community needs, but these are very expensive to implement in a large area. Tshachus, or hot springs, are widespread throughout Bhutan. These have been used by Bhutanese people since ancient times to cure their ailments (Banerjee and Bandopadhyay, 2016). Spring water is sometimes indicated by a tea color due to its abundance of red iron coloring and metals. Therefore, an indepth analysis is needed to look at the available resources, their quality and the reliatbility for Bhutan.

Water, sanitation, and hygiene (WASH) are considered the basics of human existence (Shrestha et al., 2017). Bhutan commenced the WASH program by collaborating with United Nations Children's Emergency Fund (UNICEF) in 1974. According to the Bhutan Living Standard Survey (BLSS) (NSB, 2022), the country has improved sanitation facilities to 99.1 % for households. In addition, it reports that there are 99.9 % of improved water sources in Bhutan, 57.2 % of households receive water through piped water into dwellings and 42.3 % get water from piped water in the compound. According to the Living Standard Survey from 2003 to 2012 from National Statistical Bureau for Bhutan, tap water usage in households was improved both in urban and rural areas. Pipe-borne water usage increased from 78.14 % (2003) to 87.2 % (2012) in urban areas. In the meantime, the usage of water from direct natural sources in urban households decreased from 1.03 % to 0.5 %. Hence, it is understood that urban areas in Bhutan are moving to safer drinking water. Economic progress in the country developed more infrastructure and facilities related to sanitation services, so the urban population got more access to treated water (Rahut et al., 2016).

However, as a whole, Joint Monitoring Program (JMP) 2019 declares that 36.2 % of people get access to safely managed drinking water with a pipe connection (Asia and the Pacific Finance Ministers' Meeting Kingdom of Bhutan Country Overview, 2020). Statistics further showcase that 43 % of Bhutan's total urban population is supplied with water 24 h a day, 46 %, 8 to 12 h, and 11 % less than 8 h (MoWHS, 2019). On the other hand, there is a significant gap in WASH facilities in Bhutan due to several factors such as inequalities related to income, gender, disability, and geographic conditions. 50 % of urban areas do not receive a continuous daily 6 to 12 h water supply. Sometimes, water quality is also not provided according to the required standards.

As it was stated in earlier sections, Bhutan has the highest water availability per capita value. But still, Bhutan is under water scarcity problems and floods due to poor water resources management (Hagg et al., 2021). Water accessibility is sometimes not available for essential moments is one of the main issues. Domestic needs have not been met in some places due to water accessibility problems. The main reason for the emergence of such accessibility problems is that the population is scattered on the mountain slopes. Bhutanese people live in mountainous areas because they do terrain farming by growing spices, rice, and vegetables, and also there are many sacred places in those areas. These scattered settlements have made the water supply more expensive. Since most regions of Bhutan are settled in narrow valleys, rivers and their tributaries in sloping areas flow into lower valleys below where people live. Due to this, water accessibility is economically inefficient for Bhutan. Furthermore, the lack of infrastructure especially pumps, storage tanks, reservoirs, and pipes enhances water accessibility problems (Tariq et al., 2021). The Paro and Dagana districts (dzongkhags) are the two most prone areas to water shortages in Bhutan, with occasional untreated and unmetered water supply (GNH, 2020). Therefore, people are sort of stressed. On the other hand, the per capita daily water consumption is approximately 148 liters in Thimphu, Bhutan. Therefore, the average water demand is 2.7 million m^3 in a year thus 7560 m^3 per day (Dorji, 2016).

District Development Councils (Dzongkhag Tshogdu) also contribute to developing the management strategies for drinking water (Tariq et al., 2021). Bhutan started to study the quality of water with the support of the Asian Development Bank (ADB) in 1997. Bhutan's drainage system, except for a few localized urban areas, has been reported to be highly oxygenated, marginally basic with low conductivity and no salinity (Tariq et al., 2021). Fig. 2 illustrates the condition of water sanitation

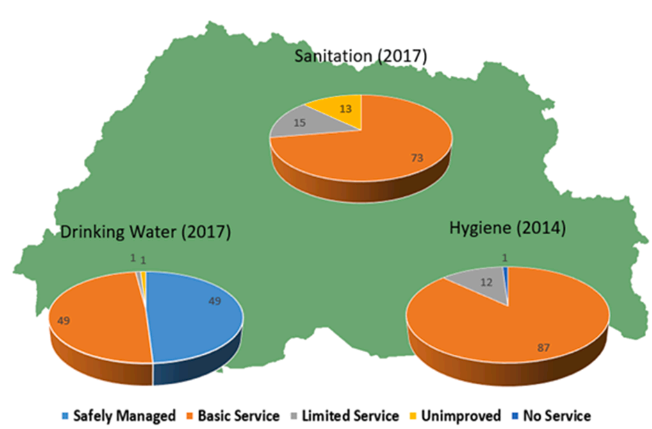

Fig. 2. Condition of WASH sector in urban areas of Bhutan (NSB, 2022).

and hygiene in urban areas of Bhutan. The drinking water condition represents a better status than sanitation in 2017. 49 % of people in urban areas received safely managed drinking water while another 49 % received drinking water under basic service. Only 2 % had unimproved and limited-service drinking water. Sanitation and hygiene were provided mainly under basic and limited services to urban people.

The main sources of drinking water are categorized as improved and unimproved in the Bhutan Living Standards Survey Report 2022 (NSB, 2022). Pipes in dwellings, pipes in the compound, public outdoor taps, protected well, protected springs, and rainwater collection are considered the improved water sources for Bhutan whereas unimproved water sources are unprotected springs, tanker trucks, surface water, and other sources (Ranaee et al., 2021). Table 1 illustrates the distribution of households as a percentage of the primary source of drinking water in urban , rural , and Bhutan. Both urban and rural areas show less than 1% accessibility to unimproved water sources (NSB, 2022). 99.9 % of households had access to improved water sources by 2022. However, only 83 % of households responded that they have access to drinking water 24 h a day through piped water in the compound (42.3 %) and piped water in dwellings (57.2 %) (NSB, 2022). Also, 83.5 % of urban households have access to piped water in dwellings compared to 39.5 % in rural areas.

The government of Bhutan has had to pay special attention to supplying safe drinking water due to the global COVID-19 pandemic since 2020 like other countries (UNICEF, 2021). The government has introduced new schemes to provide safe drinking water facilities to four cities and six districts with a population of 21,650 by December 2020. In addition, improved water facilities were provided to 47 healthcare centers around Bhutan. Furthermore, people are provided easy access to drinking water and sanitation purposes at bus terminals, markets, and taxi stations after initiating new water supplies by March 2020 (Ayana, 2019). In summary, Bhutan has to have a long-term drinking water master plan similar to most of the other countries in the world today. Bhutan's growing population and rapid urbanization showcase the importance of having sustainable drinking water distribution systems. In addition, several other determinant factors exhibit the importance of such a system, and they are education level, gender, age, economic status, access to the market, and location of the household.

Fig. 3 showcases a rapidly urbanized area closer to the natural water source in Bhutan. The water source can easily be polluted due to the nearby populated area. The people living in the cities and suburbs are tempted to consume safe drinking water because of their education level and employment background (Rahut et al., 2016). The number of residents within the service area, climate, economic structure, living standards, distance to the nearest water supply, public facility consumption, extent of sanitary equipment in the homes to be serviced, sewage disposal types, price of water, water quality and supply pressure are few factors to evaluate the drinking water demand quantitatively.

Table 1
Households' distribution by the primary source of drinking water accessibility for improved and un-improved water sources (NSB, 2022).

Improved Water Sources			
Source	Urban	Rural	Bhutan
Piped in dwelling	83.53	39.49	57.24
Pipe in compound but outside the dwelling	16.22	59.88	42.28
Public tap/standpipe	0.18	0.43	0.33
Protected dug well	0	0.03	0.02
Protected spring	0	0.07	0.04
Rainwater collection (Covered)	0	0.03	0.02
Unimproved Water Sources			
Source	Urban	Rural	Bhutan
Unprotected spring	0.05	0.03	0.04
Rainwater collection (Uncovered)	0	0.01	0.01
Tanker truck	0.01	0.02	0.02
Surface water	0.01	0.02	0.01

Fig. 3. Water source near an urbanized area (Photo credit: Zam and Denkar).

5. Water quality issues in Bhutan

Available water sources and community preferences are two important factors in water resources management. Therefore, the quality standards are varying among countries. However, the minimum quality threshold has to be maintained to ensure the usage of surface water as drinking water. Therefore, special care is needed to develop its quality. Anthropogenic activities like agriculture, economic expansions, and urban expansions are several key factors affecting the quality of water (Holden et al., 2015). Heavy usage of nitrogen, phosphorous, and potassium-based fertilizers and pesticides in agriculture washed into clean water bodies had significantly contributed to the decline of water quality around the world over the past few decades (Foley et al., 2005). Being the largest non-point source of decaying water quality, agriculture also releases lots of sediments into rivers through soil erosion (Gupta, 2016). Water quality decline had happened since ancient times in the world including in Bhutan. In the past, Bhutanese used rivers for burial purposes and they have added to the river water the ashes of dead people (Drivers of Deforestation and Forest Degradation in Bhutan, 2021). During the war periods, water sources were envenomed to kill enemies in case of military purposes (Drivers of Deforestation and Forest Degradation in Bhutan, 2021).

Deforestation is an impated issue to both water quantity and quality. During the period 2000–2005, Bhutan lost 116.67 km^2 of forest area due to agricultural work (Kadir et al., 2022). Deforestation results to reduce percolation and increase erosion by creating higher overland flows. Then the water quality in the natural and man-made drainage systems are tended to deteriorate (Somers and McKenzie, 2020). However, due to the strong policy on forests, Bhutan has not experienced much damage to its ecosystem. Therefore, deforestation has not significantly impacted the water quality in Bhutan.

Climatic variables including precipitation and temperature, and catastrophic events such as floods and drought influence water quality. Especially, high altitudes are prone to get higher temperatures compared to lowlands (Dorji, 2016). The Himalayan region's warming rate is higher compared to the global mean and therefore, Bhutan is more prone to climate-based risks (Chhogyel et al., 2020; Rai et al., 2022). Climate change hugely impacts water availability in Bhutan and seasonal water availability in rivers shows lots of fluctuations (Zam et al., 2021). According to Zam et al. (2021), the Wangchhu River basin in Bhutan would experience a temperature increase of 1.5 °C and 3.6 °C and a rainfall decrease of 1.9 % and 1.38 % under RCP 4.5 and RCP 8.5 emission scenarios compared to the reference period 1980–2005. Hence, the future river flow is expected to reduce by 5.77 % and 4.73 % under RCP 4.5 and RCP 8.5 climate scenarios with respect to the baseline period 1990–2005 (Zam et al., 2021). They also revealed that most of the discharge is projected to reduce in the dry season and increase in the wet season in the future. Therefore, low flows are expected in the dry season, and this results in reducing the amount of DO in the surface water. This also helps to settle fine sediments on the riverbeds. Changes in streamflow directly affect protected, endangered, and threatened living organisms and habitats. High flows in the wet season develop large sediment plumes in streams, tanks, and reservoirs, and therefore, the turbidity level rises. Geographic conditions change the water quality levels in the water resources systems (Desbureaux et al., 2019). Water temperature, pH value, oxygen content, erosion, deposition, runoff, total solids, pollution level, and BOD factors differ according to the topographical characteristics. Geographical features impact qualitatively both water resources at the surface and underground. Some people in Bhutan use spring water for household chores. When surface water is difficult to be obtained due to geographical conditions, Bhutanese tend to use groundwater, and this causes an increment in groundwater consumption and impacts the environment and water resources badly creating water scarcity problems in the urban areas. On the other hand, due to atmospheric temperature increment in Bhutan, glaciers at the hilltops, start to melt and make floods in the flat areas in the southern part. High flows adversely affect water quality and limit the amount of water that can be consumed. This situation is expected to develop further in the future under combined geographical and climate change conditions. Hills slopes and soil resistance to erosion affect hydrological conditions in different locations. Therefore, changes in geographical features can take an effect on water quality.

There is a strong link between economic development and water quality decline (Wang et al., 2008). Under economic factors in Bhutan, construction activities, industrial development, agricultural expansion, manufacturing, and transportation systems release lots of waste including chemical pollutants into water systems in the urban areas, and therefore, high mean annuals for BOD, and low DO conditions can be observed in the water systems (Liyanage and Yamada, 2017). As Bhutan, every country has a responsibility to ensure sustainable development, by minimizing damage to the natural environment and reducing water deterioration and degradation (International Decade for Action 'Water for Life' 2005–2015, 2015; Brouwer et al., 2020). Municipal development in the flat areas in the southern part of Bhutan causes to increase in the population, which makes water resources pollute significantly.

6. Water treatment approaches in urban and rural areas in Bhutan

With a constant increase in population, water quality standards become stricter throughout the world (Hossain et al., 2021; Tsaridou and Karabelas, 2021). The main objectives of the water treatment before it is used are to protect consumer's health (Rolston and Linnane, 2020) (removal of disease causing organisms) and to make it acceptable in an esthetic way (organoleptic aspects: color, odor, taste, and sight) or fulfill the certain requirement as such expected in food or beverage manufactures. The product of water treatment may be suitable for general domestic purposes or may be produced to higher standards such as those required for high-pressure steam, manufacture of food or beverages, and other specialized industrial purposes. The treatment of raw water may require complex processes depending on several parameters such as water source (groundwater, surface water, and ocean), the required quality of treated water, financial aspect for maintenance and operation, standards in effect in a country, and volume to treat (specific design of treatment plant according to the population). In order to be drinkable and fulfill requirements, it will be necessary to remove a certain number of pollutants that may contain in the raw water (Ramos et al., 2022). These polluted agents can be classified as physical, chemical, and microbiological (National Water Reference Laboratory, 2019). Wastewater treatment plants use more advanced and complex processes in water treatment compared to water treatment plants due to the poor water quality of the raw water. Typically, intake water for water treatment plants is taken from rivers, lakes, or wells and this water is considered clean compared to sewage water. Therefore, water treatment plants do a bit of cleaning and disinfection (What is the Difference Between Water Treatment and Wastewater Treatment? 2023). In addition, wastewater treatment facilities in rural areas of Bhutan are essential and these should be done in a small spatial coverage. The imported modular wastewater treatment method is used in only a limited number of towns (Dorji et al., 2019). The reason to implement such an expensive treatment technology is to limit the required space and cheaper waste stabilization ponds (Dorji et al., 2019).

According to the Sustainable Development Goal (SDG) 6, proportions of safely treated and collected wastewater flow percentages and volumes of wastewater generated for Bhutan for the year 2020 are given in Table 2. It can be noted that most of the wastewater is received through sewers and septic tanks. Sewers and Septic tanks generate 19.39 % and 68.02 % of wastewater respectively. Wastewater was collected from all sewers in Bhutan and 48.30 % of septic tanks. Furthermore, 40.99 % and 46.10 % of wastewater from domestic and septic tanks were safely treated.

It was found that the streams and springs are considered the main natural drinking water sources in Bhutan under the increased urban population (Mahmoud et al., 2018). There may be some contaminations in these stream and spring waters; however, levels should be identified by a detailed water quality analysis. If the concentrations of these contaminants are higher than the standard values, health problem may arise (National Guideline for Drinking Water Quality Surveillance, 2019).

According to the Annual drinking water quality report 2019, currently Bhutan monitors two types of parameters which are physical (these parameters affect the physical appearance and characteristics of water (examples are turbidity, pH) and microbial (organisms such as viruses and bacteria receiving from sewage treatment plants, septic networks, farms, livestock systems, and natural ecosystems) (National Water Reference Laboratory, 2019). It is expensive to measure the direct pathogens and this process consumes a lot of time. Hence, when determining the quality of drinking water, it is needed to use an indicator organism such as Thermotolerant coliform. These indicator organisms can be used for urban water quality monitoring aiming to find out the probability of pathogens (National Water Reference Laboratory, 2019). Jungzhina and Bajo water treatment plants take raw water from the Jungzhina River and Baychu and their installed capacities are 6500 m^3/day (United Nations Sustainable Development Goal 6 on Water and Sanitation (SDG 6), 2022) and 2400 m^3/day (Dorji and Chhoden, 2016a) respectively. Both treatment plants measure turbidity, pH, and residual chlorine parameters before distributing them to the consumers. According to a 2014 report, the Jungzhina plant monitored 0–27.73 NTU for turbidity and 6.5–7.6 for pH for raw water. In the Bajo plant, the annual report in 2015 revealed that they received 1.5–217 NTU for turbidity and 6.5–8.5 for pH for raw water. After the treatment process, both plants managed to purify water until 0–4.56 NTU for turbidity and 6.5–7.5 for pH values were obtained. Treated water in the Jungzhina plant and Bajo plant reported a 1–2 mg/L and 0.2–0.8 mg/L value range for residual Chlorine (Dorji and Chhoden, 2016a, 2016b).

The urban water quality monitoring is carried out once a month and

Table 2
Wastewater treatment status in the Bhutan in 2020 (United Nations Sustainable Development Goal 6 on Water and Sanitation (SDG 6), 2022).

Indicator	Value
Proportion of wastewater flow (safely) treated %	
Domestic	40.99
Sewers	50
Septic tanks	46.1
Proportion of wastewater flow collected %	
Overall	52.2
Sewers	100
Septic tanks	48.3
Volume of wastewater generated (Million cubic metres (10^6 m^3))	
Total	24.39
Sewers	4.73
Septic tanks	16.59
Other	3.07

reporting is made through Water Quality Monitoring Information System (WaQMIS) in Bhutan (Osunla et al., 2021). Here, they especially consider parameters such as Thermotolerant coliform, Turbidity, pH, residual chlorine (wherever chlorination is carried out for disinfection), color, and odor (Osunla et al., 2021). Most of the water treatment plants in Bhutan use basic treatment methods with sand filters and sedimentation tanks (National Water Reference Laboratory, 2019). Chlorine in the form of Calcium Hypochlorite (bleaching powder) is used as a disinfectant but only in a few treatment plants (National Water Reference Laboratory, 2019). Few treatment plants (for example Gelephu treatment plant, the Chamgang water treatment plant, and the Trashigang water treatment plant) have more stages of treatment processes which include a combination of sand filters, pressure sand filters bio-ball filters, and disinfection by Chlorine). Fig. 4 presents the general water treatment process used in urban areas of Bhutan (National Water Reference Laboratory, 2019).

One of the most important requirements of drinking water is that it should be free from any microorganisms that could transmit disease or illness to the consumer (Hai et al., 2014). The treatment processes given in Fig. 4 reduce the bacterial content of water to some certain extent (He, 2022). Disinfection must be able to destroy particular pathogens at the concentration likely to occur and it should be effective in the normal range of environmental conditions (Ritter et al., 2020). The requirements for disinfection refer to indicator organisms, usually E.coli. Water entering the distribution system should be free from E-coli in a 100 mL sample (National Water Reference Laboratory, 2019). Chlorine is the most widely used disinfectant (Damalerio et al., 2019). It rapidly penetrates the microbial cell and kills microorganisms (Epelle et al., 2022). The other disinfectants which have found large-scale use are ozone and Chloramine (Berry et al., 2017; Kerry, 2007). A wide range of water treatment objectives can be achieved through gas transfer. Oxygen, either as a pure gas or in air, is often added to water to accelerate the oxidation of various inorganic ions.

Several different operations are combined to produce the overall removal of impurities by filtration (Gonzalez-Perez et al., 2018; Jamtsho, 2010). Rapid sand filters are widely used in Bhutan for the treatment of water supplies due to their greater adaptability to more turbid waters and smaller land requirements. Recently there have been some modifications in rapid sand filtration, these have necessitated a degree of operation technique and investment in initial and operating costs which are beyond the level of low-cost methods of water treatment. Rapid filtration generally implies a process, which includes coagulation, flocculation, clarification, and disinfection.

With the enactment of the Water Act of Bhutan in 2011, the Ministry of Health is in charge of maintaining the quality of drinking water in the country. The Royal Centre for Disease Control (RCDC) under the Ministry of Health is the leading institution to implement the testing and monitoring of drinking water quality. Further, the Water Act of Bhutan directs RCDC to serve as the national reference laboratory for testing and monitoring drinking water (Yoezer et al., 2018). Operational monitoring and compliance monitoring are required to be carried out by the water service providers and the surveillance agency respectively (Thu Minh et al., 2022). The quality of drinking water provided to consumers must comply with the maximum permissible values mentioned in the Bhutan Drinking Water Quality Standard, 2016 (Thu Minh et al., 2022). However, there is no dedicated laboratory for monitoring drinking water quality for the urban areas in the districts; therefore, the activity is carried out by the medical laboratories under the Regional Referral Hospital, District Hospital, and some Basic Health Unit I category facilities (BHU-I). The laboratories are responsible for conducting the test on a routine basis (monthly) and entering the data into Water Quality Monitoring Information System (WaQMIS).

In addition, the Water and Sanitation Division (Department of Engineering Services) looks after the provision of safe and affordable drinking water, the adoption of measures to combat the impacts of climate change on drinking water, protection of the environment and health by establishing sustainable wastewater and solid waste management systems in every Bhutanese town. The Urban Drinking Water Quality Monitoring System covers all the urban and some peri-urban towns where the drinking water is supplied by the Thromde (a second-level administrative division in Bhutan) or municipalities.

Dendup et al. (2022) have analyzed the water quality in the Kanglung locality area in Bhutan using a system consisting of three springs and two taps from October 2020 to April 2021 regarding drinking water from the springs. Table 3 provides the ranges taken from 86 no of samples considering the water quality including the relevant standards given by WHO. All water quality parameters were within the WHO water quality standards except turbidity and thermo-tolerant Coliform.

Table 3 also demonstrates the water quality results taken by Pradhan and Mandal (2015) for three rivers named Punatshang Chu in Punakha, Thimphu Chu in Thimphu, and Pa Chu in Paro. This study was conducted for five months from December to April, having 15 samples from the rivers. The results show that the water quality parameters for the three rivers are within the standard ranges and the water is suitable for drinking purposes. Due to rapid urbanization, pH, COD, phosphate, and heavy metal concentrations are growing with time. However, the values of water quality parameters can be further developed. Reasons to have different values for water quality parameters are, domestic effluents, soil types, dilution effect, expanded human settlements, agricultural runoff, overflow of septic tanks, and sewage from industries.

7. Implementation of sustainable drinking water accessibility with the population growth

The amount of water availability per person naturally decreases with the increasing population (Besseris, 2022). The main reason for this is the increase in water demand which requires great efforts to strengthen the national water supply. As the population increases anthropogenic activities cause harmful effects on the natural environment (Soares et al., 2022). The increment of the population with the increasing urbanization can be mainly seen in the flat areas in Bhutan, making the water quality decrement along with the degradation of natural resources. Especially, since a large amount of polluted water is released to city-based water systems through industries, the resulting water quality decline makes harmful impacts on water-based ecosystems, agriculture as well as the livelihood of people living in downstream areas (Dikshit

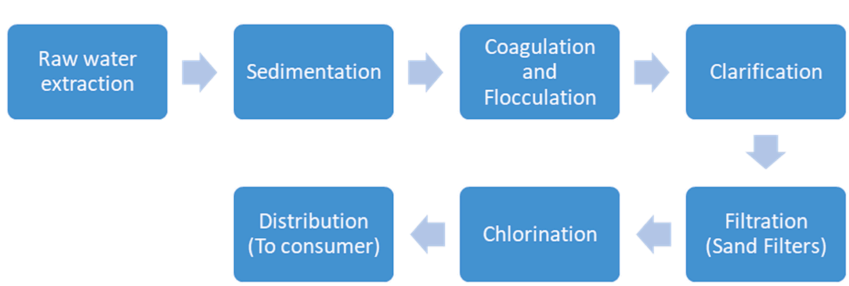

Fig. 4. General water treatment processes in urban areas in Bhutan.

Table 3
Results of different water quality parameters for Kanglung locality, Punatshang Chu, Thimphu Chu and Pa Chu; a: WHO Standard 2011 (WHO, 2011); b: WHO Standard 2017 (WHO, 2017); c: WHO Standard 2004 (WHO, 2004).

Parameter	Kanglung locality	Punatshang Chu	Thimphu Chu	Pa Chu	Recommended Level
Ca^{2+} (mg/L)	2.0 - 14.0	12.5	24.2	17.9	75[a]
Mg^{2+} (mg/L)	2.4 - 13.2	_	_	_	50[a]
Na^{+} (mg/L)	5.9 - 21.1	_	_	_	200[a]
K^{+} (mg/L)	4.2 - 5.4	0.5	0.45	0.5	12[a]
HCO_3^- (mg/L)	19.9 - 63.8	_	_	_	500[a]
Temperature (°C)	9.0 - 19.0	_	_	_	_
pH	6.3 –7.9	8.2	8.3	8.1	6.5–8.5[b]
Electrical Conductivity EC (μS/cm)	48.0- 231.0	102.8	167.7	151.5	1500[b]
TDS (mg/L)	30.7 - 147.8	_	_	_	1000[b]
Cl^- (mg/L)	8.9 - 26.6	0.41	0.31	0.29	250[b]
SO_4^{2-} (mg/L)	4.1 - 53.9	_	_	_	250[b]
Total Hardness (mg/L)	19.8 - 79.3	33.1	66.2	58.9	500[b]
Turbidity (NTU)	0 - 11.0	4.7	3.8	2.7	5[b]
Thermotolerant coliform (CFU/100 mL)	0 - 5.0	_	_	_	0[b]
Dissolved Oxygen DO (mg/L)	_	9.3	9.4	6.7	> 5[c]
Biological Oxygen Demand BOD (mg/L)	_	0.04	0.19	0.18	50
Chemical Oxygen Demand COD (mg/L)	_	7.6	7.2	3.94	250
PO_4^{3-} (mg/L)	_	9.3	14.2	12.8	< 5

et al., 2019). The challenge that Bhutan faces is prioritizing suitable development without harming the ecological environment. In this case, during the intake of water supply systems, it is needed to maintain the water quality. Also, water treatment methods should be conducted in a financially effective manner while securing natural resources.

The low capacity of water sanitization and accessibility and the increase in natural disasters in Bhutan mainly impact the sustainability of human settlements. These problematic scenarios affect human health, safety, natural resources, and finally the development of Bhutan. Floods, droughts, hurricanes, and landslides are the water-related natural disasters of Bhutan in the 21st century (Dikshit et al., 2020; Martínez-Retureta et al., 2021) (for example - the landslide in Gaza in the northern district on 16th June 2021). Several landslides and floods were reported in recent years (2019 and 2020) in Bhutan. In addition, the changes due to climate change and climate variability and the availability of water have changed the attention and redirected toward water management in Bhutan (Chathuranika et al., 2022; Tshering et al., 2020). In order to answer these problematic situations, the government of Bhutan has directed its attention towards integrating water resource management (IWRM) to maintain sustainable water resources along with the help of the Asian Development Bank (ADB).

IWRM is important for Bhutan because it provides a holistic, sustainable and adaptive way to managing water resources interms of water scarcity, population growth, urbanization and climate change challenges. It ensures that water resources are need to be used efficiently and equitably. The 2011 water act of Bhutan shows the IWRM approach to secure water systems and maintain economic, social, and environmental sustainability (Gain et al., 2017; Integrated Water Resource Management in Water and Sanitation Projects, 2023). The IWRM approach helped the country to look at the adaptation strategies for water and food safety under climate change. IWRM shows the efficient use, fair entries, compatible technologies, and extraction methods related to theories (Katusiime and Schütt, 2020; Taking a Sustainable and Holistic Approach to Water Resources Management, 2023). Bhutan should plan its IWRM according to its geography, area, politics, and development level. The national environmental commission, of Bhutan has called upon a technological advisory committee consisting of 15 high-ranking government officials, non-governmental parties, and civil servant groups to take action on critical areas of water management including the supply of safe drinking water and the necessary plans.

The safe drinking water systems and the needed sanitizations and the orderly output of city-based trash are important factors in the journey of sustainable Bhutan. Thereby, the health, and safety of the citizens, as well as the ecosystems, are protected while lowering pandemic cautions. With the development of the economy, Bhutan's population increased demanding a higher water supply for many different users (Giri and Singh, 2013). However, the national integrated water resource management plan (NIWRMP) managed the water resources in the country with the aid of the collaboration of different parties in 2016. Also, it has tracked the development of the methods of the government toward water sustainability goals by developing the water security index of Bhutan (Giri and Singh, 2013).

Understanding water sustainability in Thimphu and Paro (highly urbanized areas) is very important. The Wangchhu basin is highly important in Bhutan and holds 12 % of the total area of Bhutan with Thimphu and Paro (Giri and Singh, 2013). Therefore, it is highly important to have a reliable and sustainable water plan for this basin. Therefore, the Wangchhu River basin management plan has been established to secure urban and rural drinking water supply and sanitization, farm development, and food protection. A water quality-related study done near Thimphu city in the Wangchhu river basin shows that in the period 1990–2008, the forest, scrub, and agricultural areas have been lessened due to the establishment of urban infrastructure. The water quality has also deteriorated due to these land-use changes (Dikshit et al., 2019). The temperature of the water, pH, conductivity, TDS, Turbidity, nitrate, phosphate, chloride, total coliform, and BOD decreased as the water quality parameters upstream and increased near the Thimphu urban area. It has been found that the DO concentration is higher in upstream areas and lower in Thimphu city (Giri and Singh, 2013). This study shows the importance of the purification of water near urban areas. In addition, the distribution of water to many citizens in the mountains is still a challenge. The government of Bhutan may need comparatively high funds to establish sustainable water supply systems in mountainous areas. Most of the time water resources management teams need to take difficult decisions to allocate water. In some cases, supplies need to decrease with growing demands. This condition grows mainly due to climate change and population growth. Hence planners need to manage water resources by referring to holistic approaches rather than referring to no longer valid traditional approaches.

However, many challenges are there in implementing the IWRM concept in sustainable water systems. Improper coordination, lack of funding, limited resources and human capacity, institutional barriers, laws, prices, and policies are some of these challenges. Fig. 5 provides the basic practical steps in IWRM.

Bhutan should analyze the urgent requirements related to water with all stakeholders. It is very important to increase the cost recovery rate to maintain water services sustainability. When recovering the costs, attention should be drawn to operations and management costs, capital costs, and expenses for future work. When considering the financial aspects, the Thimphu municipal cooperation (TMC) has shown a water

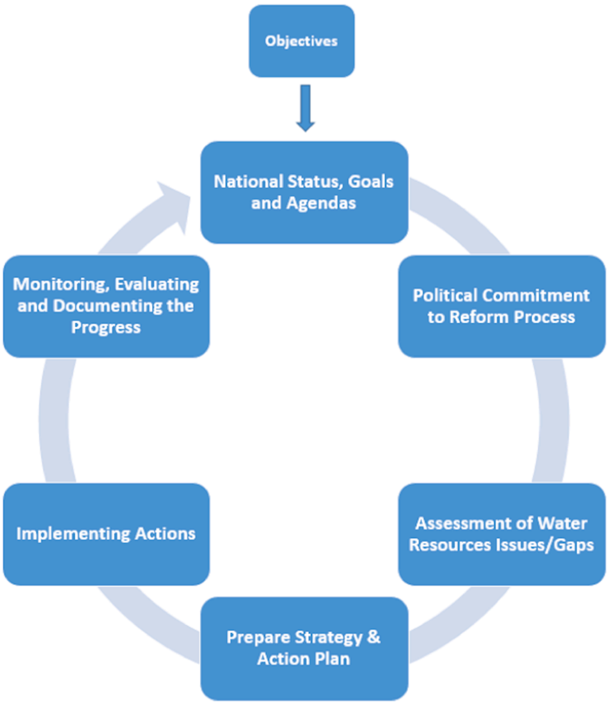

Fig. 5. Integrated water resources management (IWRM) process in practice.

billing system that proposes the sustainability of water supply and sanitization services caring for the financial side for July 1996. Here, a revenue collection has been made using satisfactory funds for proper operation and maintenance of water supply and sewerage systems. In the longer run, proper billing systems might be needed throughout the country.

8. Summary and recommendations

This paper presents the state-of-the-art of water resources in Bhutan for drinking water purposes. During the last decade, the urban population in Bhutan has increased by 22.35 %, and therefore waste disposal in the cities was significantly raised. This waste accumulated in the natural water systems and the water quality has been decreased. Higher levels of BOD, TC, and low DO levels have been reported in the rivers in urban areas. Eutrophication happened due to over-usage of polluted water and people who are living in urban areas are diagnosed with several waterborne diseases. Currently, some urbanized areas in Bhutan are facing a lack of accessibility to safe drinking water due to geographic changes, economic conditions, urban expansion, climate change, and agricultural work. In addition, land-use changes are happening due to city extension and therefore deforestation increases soil erosion and surface flows. Bhutan is highly vulnerable to climate change due to higher altitudes and this causes changes in seasonal flows in the rivers therefore, the water quality in the rivers is getting degraded. Continuous 24 h safe drinking water accessibility is a serious challenge due to this.

The government of Bhutan has already taken action to supply safe drinking water to people who changed their settlements in urban areas during the last two decades following the IWRM approach with the help of the Asian Development Bank. However, Bhutan needs a holistic master plan to manage its water resources. This plan should consider all stakeholders with relevant technical support. The genuine effort would increase reaching the sustainable solution to the rising issues in water resources. Water resources management is not straightforward in any country as it has multiple uses and multiple objectives. Therefore, sustaining everyone's requirements is a tedious task. However, if everyone can agree to one basic objective which is reaching water sustainability, the task is achievable.

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Status of water resources in urban and rural areas of Bhutan.

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CRediT authorship contribution statement

Imiya M. Chathuranika: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Visualization. **Erandi Sachinthanie:** Investigation, Data curation, Writing – original draft, Visualization. **Phub Zam:** Investigation, Resources. **Miyuru B. Gunathilake:** Validation, Writing – original draft. **Denkar Denkar:** Investigation, Resources. **Nitin Muttil:** Writing – review & editing. **Amila Abeynayaka:** Writing – review & editing. **Komali Kantamaneni:** Writing – review & editing. **Upaka Rathnayake:** Conceptualization, Supervision, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Further reading

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