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Volume 3

Groundwater

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Groundwater

The UNESCO-IHP Regional Steering Committee for Asia and the Pacific

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March 2024

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Preface

It is our great pleasure to present the third volume of the Catalogue of Hydrologic Analysis for Asia and the Pacific. This volume focuses on groundwater for addressing water scarcity and quality in Asia and the Pacific, which contains 15 documents from Indonesia, Iran, Japan, Kazakhstan, Republic of Kiribati, Republic of Korea, Malaysia, Mongolia, Nepal, Philippine, Sri Lanka, Thailand, Timor Leste, and Viet Nam. It is the outcome of the international co-operation of the countries which form the Regional Steering Committee for Asia and the Pacific (RSC) under the auspices of the UNESCO International Hydrological Program Phase IX (IHP-IX, 2022-2029), which follows the publication of the Catalogue of Hydrologic Analysis (CHA) Volume 2.

The objectives of the publication of the Catalogue of Hydrologic Analysis are:

- To promote mutual understanding of hydrology and water resources of the region and of the neighboring countries.
- To promote information exchange among different organizations in each country.
- To share information on water-related issues such as disaster preparedness, water environment conservation, and water resources management in Asia and the Pacific.

In the Asia and the Pacific region, various hydrologic analysis methods have been applied for designing hydraulic structures and river improvement works for rainfall-runoff predictions, flood inundation mapping and other purposes. These hydrologic analysis methods and experiences have different characteristics in terms of climate, topography, and development history of the catchments. Developing a platform to share these experiences and hydrologic analysis methods would help improve the ability for risk estimation and water-related hazard damage reduction; especially for some of researchers and engineers in certain countries and sectors in the region who have limited knowledge and experiences with these hydrologic analysis methods.

To improve this situation and enhance risk estimation ability in research and engineering communities, meetings of the IHP Regional Steering Committee for Asia and the Pacific (RSC-AP) has discussed the formation of a research team and the development of a hydro-informatics platform in Asia and the Pacific with the objective of realizing hydro-hazard resilient Asia. With the objective enhancing regional capacity for evaluating water-related disaster risks, the RSC-AP decided to develop a Catalogue of Hydrologic Analysis (CHA) through collaboration among researchers and engineers in Asia and the Pacific. The Catalogue collects documents including various experiences and hydrologic analysis methods from practical use to advanced studies for short-term rainfall prediction, rainfall-runoff prediction, flood inundation mapping, hydrologic frequency analysis, eco-hydrology, and more.

In this volume, we focused on groundwater in Asia and the Pacific. Groundwater is available year-round and has been used as a high-quality water resource together with surface water since ancient times. However, excessive groundwater pumping causes problems such as land subsidence and destroys the healthy water cycle in the region. An appropriate balance between groundwater uses and conservation is essential to enable sustainable human activities and environmental preservation. As the hydrologic cycle is changing due to climate change, sustainable and inclusive water resource management is a critical issue. This report summarizes groundwater management in Asia and the Pacific.

By developing and sharing knowledge through CHA, RSC-AP provides a platform to improve the ability for evaluating water-related disaster risks and to enhance the capacity for sustainable and inclusive water resource management, which in turn will strengthen cooperation among researchers, governmental agencies and private sectors; serve to reduce the damage of water-related disasters; and stand as a regional contribution to achieve the targets of SDGs, UNESCO IHP-IX (2022-2029).

We would like herewith to express our sincere appreciation and due respect to all the individual contributors towards this volume from across the region. We also express our sincere gratitude to institutes, agencies and other organizations who have carried out the work reflected in its contents. In particular, we would like to thank the following organizations for providing the necessary support:

- UNESCO Office Jakarta
- The Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, which provides funds to support UNESCO IHP activities in Asia and the Pacific

The editors hope that this volume may serve in various ways to further fulfill related national and regional objectives. Finally, we invite readers to provide critical comments and ideas to improve future volumes of the Catalogue.

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Groundwater Issues and Management in Indonesia

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Abstract

Effective groundwater management is a critical issue in Indonesia, as it is extensively relied upon for a variety of purposes, including agriculture, industrial activities, and drinking water supply. Indonesia boasts a vast potential for groundwater resources, with a total of 421 basins stretching from Sumatra to Papua Island. However, at least 20 groundwater basins are currently vulnerable to critical conditions. The Jakarta groundwater basin, from the shallow to deep aquifer, is currently confronting significant challenges arising from excessive groundwater abstraction. Over-pumping and climate change are accelerating saline water intrusion into aquifers, thereby exacerbating water quality issues. As such, the Indonesian government is taking crucial steps to prevent groundwater damage and improve its condition. These steps include regulation enforcement, research, and innovation. This paper provides an in-depth analysis of the situation in the Jakarta groundwater basin while also offering general information on groundwater management and problems in Indonesia. It promotes sustainable groundwater management in Indonesia for current and future generations by integrating current understanding and policy perspectives.

Key Words: groundwater, basin, aquifer, hydrogeology, quality, conservation, Jakarta, Indonesia

1. Introduction

1.1. Terminology related to groundwater

Groundwater is an essential resource that can be found beneath the Earth's surface, held in permeable rock or sediment layers known as aquifers. These aquifers are responsible for transporting water that can be seen above ground in the form of wells, rivers, springs, and lakes. Aquifers are composed of various types of rocks and sediment, including sandstone, gravel, fractured limestone, and conglomerates, which may differ in composition. Aquifer systems are classified into three groups: unconfined, confined, and perched aquifers, as described by Tóth (1999) and Todd & Mays (2005).

An unconfined, also known as a water table or phreatic aquifer, is a type of groundwater source where the rock below is exposed directly to the earth's surface (Fig. 1a). Due to this, the water table remains at atmospheric pressure. This groundwater is mostly formed from precipitation that seeps through porous rocks, resulting in relatively young water that may be merely a few hours old. However, unconfined aquifers are more prone to surface contamination.

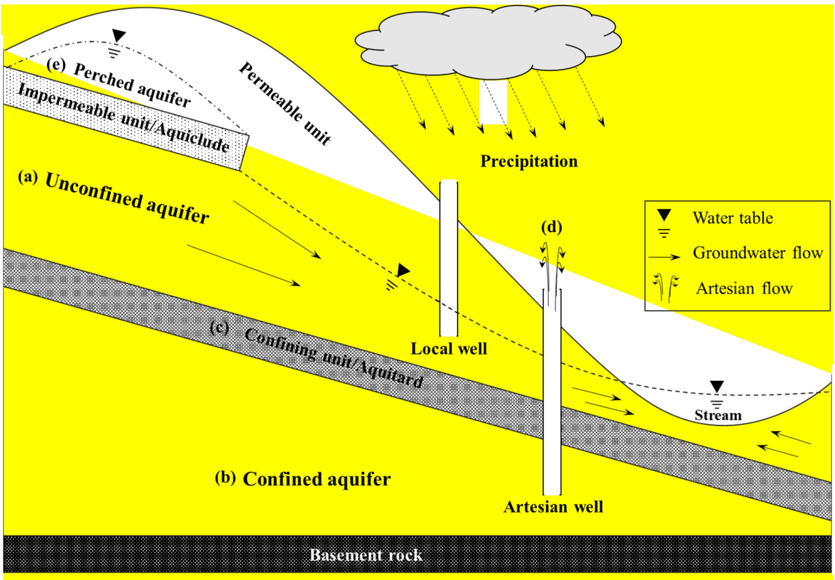

Figure 1. A visualization of the subsurface: schematic cross-section of aquifers system. The symbols (a), (b), (c), (d), and (e) are explained in the accompanying text.

Confined aquifers are distinct from unconfined aquifers in their geological composition. While unconfined aquifers are situated beneath a permeable layer, confined aquifers are ensconced by an impermeable rock or clay stratum known as a confining unit (**Figure 1c**). This confining unit is composed of materials such as clay, peat, and loam, which are impermeable and classified as an aquiclude or aquitard when nearly impermeable (Appelo, CAJ; Postma, 2005). Groundwater in confined aquifers is under greater pressure than atmospheric pressure, and in some cases, it can be artesian and flow independently (**Figure 1d**). Precipitation is the primary source of recharge for confined groundwater where water-bearing strata outcrops at the land surface. Consequently, the age of the water is typically protracted, measured in decades, and replenishment tends to occur slowly (Jalota *et al.*, 2018).

The perched aquifer is a type of unconfined aquifer that is situated above the saturation zone (**Figure 1e**). It is separated from the primary groundwater source by an impermeable layer, commonly referred to as an aquiclude. Compared to other aquifers, the perched aquifer has a smaller capacity and limited water availability, typically lasting only a few minutes (Todd & Mays, 2005; Salako & Adepelumi, 2018). A simplified illustration of the aquifer system and related terminology is presented in **Figure 1**.

1.2. The importance of groundwater management

Effective groundwater management is of utmost importance in Indonesia as it is heavily relied upon for diverse purposes such as agriculture, industrial activities, and drinking water supply. Several crucial factors must be considered to ensure proper management, including regulatory framework, permits and licensing, monitoring and assessment, determination of groundwater conservation zones, and research and development. Research and development are essential for maintaining groundwater sustainability, and some techniques that can aid in achieving this include developing artificial recharge techniques, an integrated water conservation strategy, and demand management. Furthermore, effective stakeholder engagement and collaboration are also vital.

Indonesia faces significant challenges when it comes to managing groundwater. These include drought, flood, land subsidence, landslides, and seawater intrusion. To tackle these issues, a comprehensive and adaptable approach is necessary. This approach should encompass a balance between groundwater extraction and recharge, improvements to water use efficiency, and the implementation of measures to safeguard the quality and quantity of groundwater. Effective governance, enforcement of regulations, and regular monitoring are essential to achieve sustainable groundwater management in Indonesia.

Research institutions and agencies in Indonesia play a crucial role in advancing groundwater management. They conduct studies on groundwater resources, hydrogeological mapping, and innovative approaches to promote sustainable groundwater use. The insights gained from their research findings are vital for evidence-based decision-making and developing effective management practices.

This chapter describes the hydrogeology system of groundwater in Indonesia and sheds light on the significant challenges currently facing the country. Using a relevant case study, we delve into these challenges and the steps being taken by the government to address them. This overview aims to understand comprehensively the complex issues surrounding Indonesian groundwater management.

2. Groundwater in the national water resources management of Indonesia

2.1. Groundwater basin in Indonesia

A groundwater basin is a designated region encompassing various hydrogeological processes such as groundwater recharge, flow, and discharge. The criteria that determine a groundwater basin, as recognized by Regulation No. 2 of the Minister of Energy and Mineral Resources of Indonesia (2016), are characterized by three key factors:

1. It has hydrogeological boundaries controlled by geological circumstances and/or groundwater hydraulic conditions.
2. It has recharge and groundwater discharge areas within the same groundwater–forming system.
3. It has a unified aquifer system.

Indonesia has 421 basins in total, stretching from Sumatra to Papua Island. These basins are divided into four classes based on the criteria. The first type is transboundary groundwater basins, comprising four basins. The second type encompasses across–province groundwater basins, of which there are 35 in total. The third type is across–district boundary groundwater basins, encompassing 176 basins. Lastly, the fourth type comprises intercity boundary groundwater basins, numbering 206 basins.

Indonesia's groundwater basins have diverse geological characteristics, including volcanic, alluvial, karst, and tertiary sedimentary regions. The total potential of these basins is over 300 billion m^3, with Timika–Merauke being the largest. This basin spans 131,609 km^2 and six regencies in Papua Province. Sumatra Island boasts the highest groundwater potential, accounting for more than 30% of the country's overall groundwater potential. Indonesia's groundwater basins offer significant potential for the country's water resources. Unfortunately, according to the Geological Agency of Indonesia, at least 20 groundwater basins are currently vulnerable to critical conditions.

The specific details of the vulnerable basins, however, remain limited to a few major urban areas, including Jakarta, Semarang, and Bandung (Onodera et al., 2008; Kagabu et al., 2011, 2012; Hasanuddin Z. Abidin et al., 2013; H. Z. Abidin et al., 2013; Tirtomihardjo, 2016; Taufiq et al., 2018; Lo et al., 2021, 2022). These three basins are currently facing significant challenges related to both quantity and quality. The reduction in quantity is mainly attributed to poor management of groundwater abstraction, resulting in a decline in groundwater levels. This decline has resulted in additional challenges, such as land subsidence and deterioration in groundwater quality. The latter issue is further exacerbated by subsurface accumulations of surface pollution caused by various human activities, including industrial, agricultural, household, and land use changes. Natural causes of groundwater contamination, such as minerals found in rocks, are also present, independent of anthropogenic activities.

2.2. Role of groundwater resources

Groundwater resources play a vital role in implementing the national water resources management plan in Indonesia. Careful management of groundwater is essential in ensuring the availability of water for various sectors, including agriculture, industry, and domestic use, as well as in maintaining ecological balance. In this regard, it is important to acknowledge the vital importance of groundwater resources and integrate them into the national water resources management plan. The key roles of groundwater resources are as follows:

a. *Water supply*
Groundwater is an important water supply source for various purposes, such as drinking, irrigation, and industrial processes, particularly in areas where surface water is either scarce or unreliable. The World Bank (2021) has reported that a significant proportion of domestic water demands, specifically 46%, are met through the utilization of groundwater resources.

b. *Drought resilience*
Groundwater resources provide a buffer during periods of drought or low rainfall. Groundwater storage is a reserve source that can be utilized during dry seasons or when surface water sources are inadequate.

c. *Surface water systems balance*
Groundwater naturally interacts with water systems on the surface, such as rivers, lakes, wetlands, and oceans. This interaction can help maintain river flow during dry periods or regulate water levels in lakes and wetlands. Understanding how these systems interact can lead to better management practices and ensure the overall health and sustainability of water systems.

d. *Land subsidence and saltwater intrusion mitigation*
   Over–extracting groundwater can lead to land subsidence and saltwater intrusion; therefore, it is important to manage groundwater usage responsibly. This means setting limits on extraction and using sustainable practices. Proper management can prevent flooding and seawater intrusion into coastal aquifers while preserving freshwater resources.

e. *Environmental conservation*
   Groundwater–dependent ecosystems, such as springs, wetlands, and underground rivers, maintain biodiversity and support unique ecological habitats. Groundwater management ensures these ecosystems are protected, and their water requirements are considered alongside other sectors' needs. This helps preserve ecological balance and supports sustainable development.

To effectively manage and conserve groundwater resources, it is essential to integrate their key roles into the national water resources management plan. This requires coordination among multiple stakeholders, including government agencies, water utilities, communities, and other relevant institutions.

2.3. Administrative and legal framework for groundwater management

Indonesia has established a framework for managing groundwater resources through a combination of regulations, policies, and institutions. This framework is designed to promote the sustainable use and protection of these resources. The key components of this administrative and legal framework include:

a. *Constitution and national policies*
   The Constitution of Indonesia in 1945 acknowledges water as a valuable national asset that ought to be handled for the optimum benefit of the people. Furthermore, the National Water Resources Management Strategy and other national policies provide a comprehensive outline for managing water resources, including groundwater.

b. *Law No. 17/2019 on Water Resources and Omnibus Law of Job Creation No. 11/2020*
   These laws are the primary legal basis for water resources management in Indonesia, setting the principles, objectives, and framework for groundwater management. It establishes the authority and responsibilities of the central government, regional governments, and users in managing water resources. Law No. 17/2019 on Water Resources stipulates that water resources are to be managed based on River Basin Territory (RBT), with priority given to the use of surface water over groundwater. However, this approach presents challenges, as it necessitates the consideration of complex factors and implementing appropriate measures to prevent water quality and quantity degradation.

c. *Permits and licensing*
   Groundwater extraction requires permits and licenses issued by relevant authorities to ensure sustainable groundwater abstraction and prevent over–exploitation. The Ministry of Energy and Mineral Resources and Local Governments are responsible for issuing these permits, which specify the conditions and limits for groundwater use.

d. *Groundwater basin organizations*
   Groundwater basin organizations are established at the basin level to manage and coordinate groundwater resources. These organizations facilitate stakeholder collaboration to implement

groundwater management plans and regulate groundwater abstraction. They also monitor and assess the groundwater resources within their respective basins.

e. *Groundwater conservation zones*
Groundwater conservation zones mark the boundary between protected and utilized areas in a basin. These zones are determined based on hydrogeological characteristics, vulnerability, and specific land uses. The groundwater protection zone denotes an area where specific regulations are implemented to safeguard the quality and quantity of groundwater. This zone is identified as a recharge area, where groundwater is replenished through natural processes. On the other hand, the groundwater utilization zone refers to an area where groundwater is extracted based on specific criteria that consider the level of potential damage. This area is classified as a discharge zone for groundwater. The groundwater conservation zones are represented on spatial maps and are important for regulating groundwater usage in a groundwater basin.

f. *Environmental Impact Assessment (EIA)*
Groundwater–related projects, such as large–scale groundwater abstraction or infrastructure development, require an EIA (AMDAL in Indonesian) to assess potential environmental impacts. The EIA process evaluates the project's potential effects on groundwater resources and proposes mitigation measures to protect the environment and groundwater quality.

g. *Monitoring and enforcement*
Various national, provincial, and local government agencies monitor and enforce groundwater management regulations. They monitor groundwater levels, quality, and land subsidence and take necessary actions to ensure compliance with regulations. Violations of groundwater extraction limits or failure to obtain permits can lead to penalties or sanctions.

h. *Research and technical support*
In Indonesia, research institutions focus on studying and developing sustainable approaches to groundwater management. They provide technical support and expertise to policymakers and stakeholders to ensure the effective use of resources.

It is important to recognize that the success of the administrative and legal framework for managing groundwater depends on its proper implementation, enforcement, and ongoing monitoring to overcome obstacles like over–extraction, land subsidence, and contamination.

3. Case Study: the groundwater issues in Jakarta's basin

3.1 Surface hydrology issue

Jakarta is the capital and the largest city in Indonesia. It spans an area of 662 km^2 along the northwest coast of Java and is officially known as the Special Capital City District of Jakarta or DKI Jakarta, with the same status as a province. The city is divided into five districts: Central, West, East, South, and North, with a total population of around 10 million people.

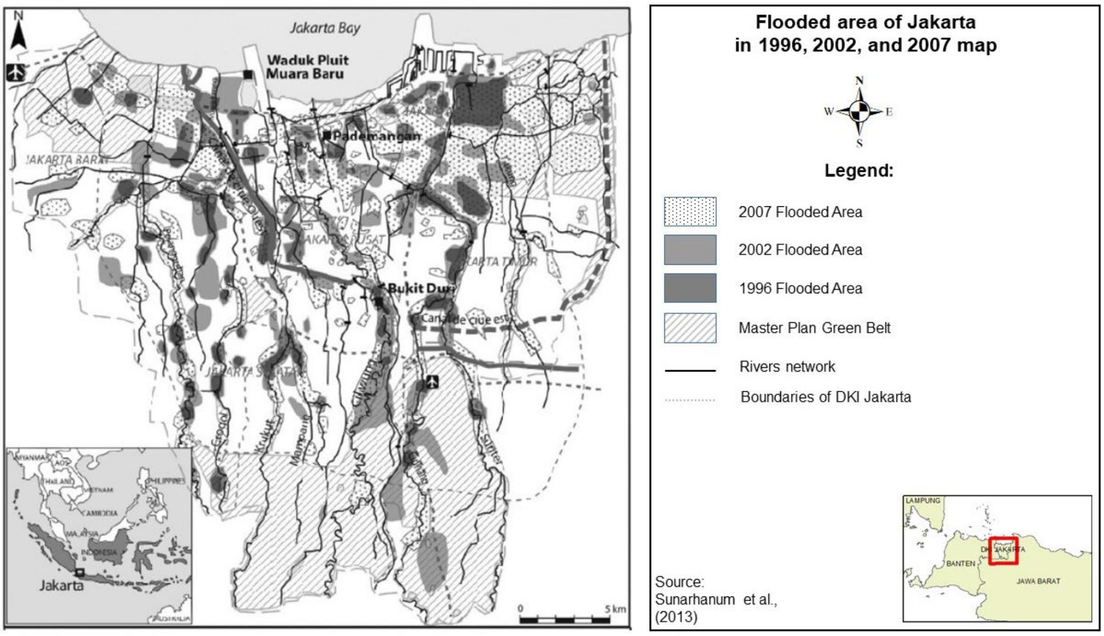

Figure 2. Jakarta flooded areas in 1996, 2002, and 2007. Modified from Sunarharum et al. (2013)

Jakarta has an average elevation of 8 meters above sea level, with a range of 2 to 50 meters. Approximately 40% of the city is situated below sea level, particularly in the northern region. The city is traversed by thirteen rivers, with the Ciliwung River being the largest. Nonetheless, Jakarta is susceptible to flooding due to inadequate drainage and heavy rainfall during the wet season, which spans from October to May. On average, the yearly rainfall is between 2000 and 2700 mm, with the monsoon season peaking in January and February. When the heaviest rainfall occurs, short but severe storms are prevalent in the area, with 60% to 80% of the precipitation taking place in the afternoon and evening.

Jakarta is prone to annual flooding, particularly severe incidents occurring in 1979, 1996, 2002, 2007, 2013, 2014, 2015, 2018, and 2020. During these events, nearly 40% of the city was submerged. **Figure 2** depicts the geographic extent of flooding related to the events in 1996, 2002, and 2007 (Sunarharum et al., 2013). The rising risk of flooding in Jakarta is largely attributable to population growth and land subsidence. The land subsidence itself is related to groundwater use, which is elaborated in the following subchapter of this chapter. In response to these issues, the government has implemented a program aimed at regulating groundwater overuse. This program represents a promising approach to mitigating flooding and preventing further land subsidence.

Jakarta's surface water is also facing a quality issue due to sewage from homes and businesses, industry, agriculture, solid waste, and septic tank leaks. According to Luo et al. (2019), there has been a decrease in Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) at most monitoring stations, but downstream stations are showing significant increases. The extreme values of BOD and TSS reach over 120 mg/L and 500 mg/L, respectively. Furthermore, although there is an increasing trend in Dissolved Oxygen (DO) at most stations, the DO levels are still below 5 mg/L. Despite some improvements, there is still a lot of work to be done to improve Jakarta's water quality. Sufficient Wastewater Treatment Plant (WWTP) capacity is required to deliver high–quality effluent to rivers, streams, and groundwater aquifers. Urbanization and population growth in the present and the future should be considered by WWTP.

3.2 Subsurface hydrology issue

Groundwater is one of the primary sources of clean water in Jakarta since only around 65 % of the 846 B m^3/year of clean water demands can be fulfilled by the government through a pipeline system (PDAM), with the remainder being met by groundwater or the purchase of bottled water. Since 1968, groundwater extraction for industries and residentials has increased. The groundwater abstraction increased by 70% between 1968 and 1994, from 10.3 M to 33.8 M m^3, followed by a nearly 90% growth in the number of registered producing wells (from 325 to 3018 wells) (Tirtomihardjo & Setiawan, 2013; Kagabu et al., 2012). The same data reveals that groundwater use declined in 1995 (32.1 M m^3) and notably in 1999 (16.4 M m^3) due to the national financial crisis of the time. In 2012, however, the amount of groundwater extracted grew dramatically to 45.6 M m^3 (Tirtomihardjo & Setiawan, 2013). Since only registered wells are included in the available data, the ultimate volume of groundwater extraction is estimated to be more significant. These inadequate data sets may hinder evaluation to comprehend and manage groundwater sources.

The continuous over–pumping has caused a substantial decline in groundwater levels. The historical records of groundwater wells in North Jakarta from 1874 to 1954 indicate a drop in the piezometric levels of wells, which have decreased by 150 meters beneath the ground. Similarly, in South Jakarta, well levels screened have also decreased to 8.0–15 meters above sea level (m.a.s.l) during 1903–1913. In the majority of Central Jakarta and the boundary between North and South Jakarta, the piezometric heads typically reach a height of 7.0 meters above sea level (m.a.s.l) (Tirtomihardjo & Setiawan, 2013). This value corresponds to the presence of positive artesian groundwater. However, some parts of the area of artesian groundwater have piezometric levels between 1.0 and 5.0 m above the ground surface. However, certain parts of the artesian groundwater area exhibit piezometric levels ranging from 1.0–5.0 m.a.sl.

Groundwater depletion can have severe consequences on ecosystems dependent on groundwater, such as wetlands and springs, and can lead to negative impacts on biodiversity and natural habitats. Groundwater depletion has also resulted in degradation of quality, seawater intrusion, land subsidence, and flooding. Further information regarding these issues can be found in the subchapter below.

3. 2. 1 Hydrogeology of the groundwater basin

The Jakarta groundwater basin is a transnational groundwater basin that covers an extensive geographical area located at 106°36'32.54"–107°04'04.78" E and 06°00'43.50"–06°26'58.23 S. This basin encompasses the provinces of Jakarta, West Java, and Banten, including the entirety of Jakarta Province, parts of West Java Province such as Bekasi Regency, Bekasi City, Depok City, and Bogor Regency, and Banten Province, including Tangerang City, Tangerang Regency, and South Tangerang City. The Jakarta groundwater basin, with an area of 1,439 km^2, is rapidly urbanizing, making it the most developed basin in Indonesia.

The basin generally comprises Quaternary deposits, primarily from alluvial deposits (swamps, rivers, and beach ridges) and local volcanic fan deposits, found in early to tertiary quarter–age rock units. As presented in **Figure 3**, the rocks of the study area are divided into nine rock units: (1) swamp deposits (Qsd), (ii) young river deposits (Qa), (iii) beach ridge deposits, (iv) tuffaceous sandstones and conglomerates, (v) shallow marine deposits (Qnd), (vi) young volcanic deposits (Qv), (vii) Banten tuff (QTvb), (viii) Sepong formation (Tpss), and (ix) Bojongmanik formation

(Tmb). Some rock units, namely Qa, Qbr, Qav, and Qv, are aquifers with high groundwater potential based on their lithology. (Tirtomihardjo & Setiawan, 2013).

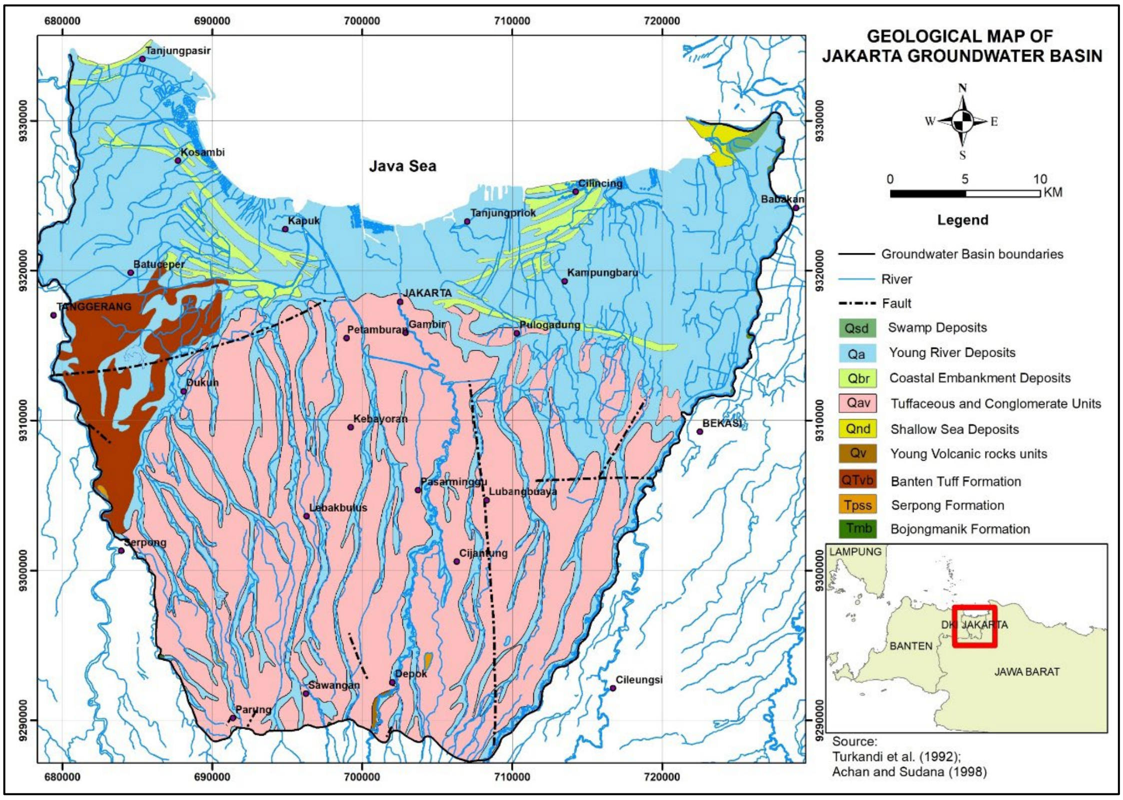

Figure 3. Groundwater basin of Jakarta: area and geology formation. Modified from: Achdan & Sudana (1998) and Turkandi (1992)

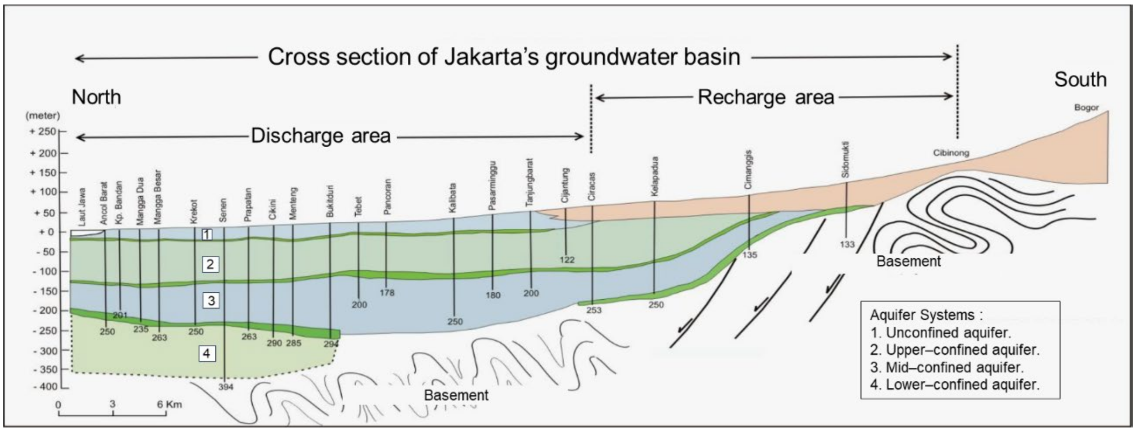

Figure 4. Hydrogeological cross–section of Jakarta groundwater basin. Modified from Kagabu (2011), Tirtomihardjo & Setiawan (2013)

The aquifer in the Jakarta groundwater basin is comprised of multi–layer aquifers, each with distinct hydraulic properties. As illustrated in **Figure 4**, these aquifers have been categorized into four systems according to their hydraulic characteristics (Soekardi, 1979; Kagabu et al., 2011), those are:

1. *Aquifer 1* is an unconfined aquifer with a depth of <40 m.b.s.l. (meter – below sea level).
2. *Aquifer 2* is an upper–confined aquifer with a 40 to 140 m.b.s.l depth.
3. *Aquifer 3* is a mid–confined aquifer with a 140 to 250 m.b.s.l depth.
4. *Aquifer 4* is a lower–confined aquifer with a depth of >250 m.b.s.l.

Aquifer 1 is a shallow aquifer that consists of sandstone, conglomerate, and sandstone. Meanwhile, aquifers 2 through 4 are considered deep aquifers of sandstone with breccias and claystone infixes. The thick marine clay layer of claystone with sand infixes in the aquiclude strata acts as a confining unit between the aquifers.

3. 2. 2 Deterioration of groundwater quality

Around 80% of Jakarta's groundwater basin, particularly in northern Jakarta, does not fulfill the health quality requirements defined in the Indonesian Minister of Health's Regulation No. 492 (2010). The most prevalent issues w are related to elevated contents of salinity (conductivity/EC, TDS, and Cl^-), dissolved metals (Fe^{2+}, Mn^{2+}, Pb), nitrogen (NO_3^-), and organic parameters (Onodera et al., 2008; Hosono et al., 2011; Kagabu et al., 2012). The hydrochemical studies revealed that mixing groundwater from unconfined and confined aquifers is another detrimental phenomenon due to groundwater abstraction (Onodera et al., 2008; Onodera, 2011; Kagabu et al., 2012).

Regarding the issue of salinity in groundwater, two maps (**Figures 5a and b**) have been created to show the distribution in 2011. The first map displays the salinity levels in an unconfined aquifer system (referred to as aquifer 1 system). Meanwhile, the second map shows the levels in an upper–confined aquifer system (referred to as aquifer 2 system). The salinity levels were determined by measuring Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Chloride ion (Cl^-) within the water. There are three distinct zones identified in the results. The first zone is an extensive area of fresh water (EC <1,500 µS/Cm, TDS <1,000 ppm, Cl^- <500 ppm) that mostly covers the southern part of Jakarta Plain. The second zone is an extensive area of slightly brackish water (EC = 1,500 – 5,000 µS/Cm, TDS = 1,000 – 3,000 ppm, Cl^- = 500 – 2,000 ppm), which covers most of the southern part of Jakarta Plain and extends up to 8 km from the coastline in North Jakarta and Central Jakarta. The third zone is a smaller area of brackish water (EC = 5,000 – 15,000 µS/cm, TDS = 3,000 – 10,000 ppm, Cl^- = 2,000 – 5,000 ppm) located in the Kapuk area (North Jakarta) with a maximum distance of 5 km from the coastline (Setiawan et al., 2011).

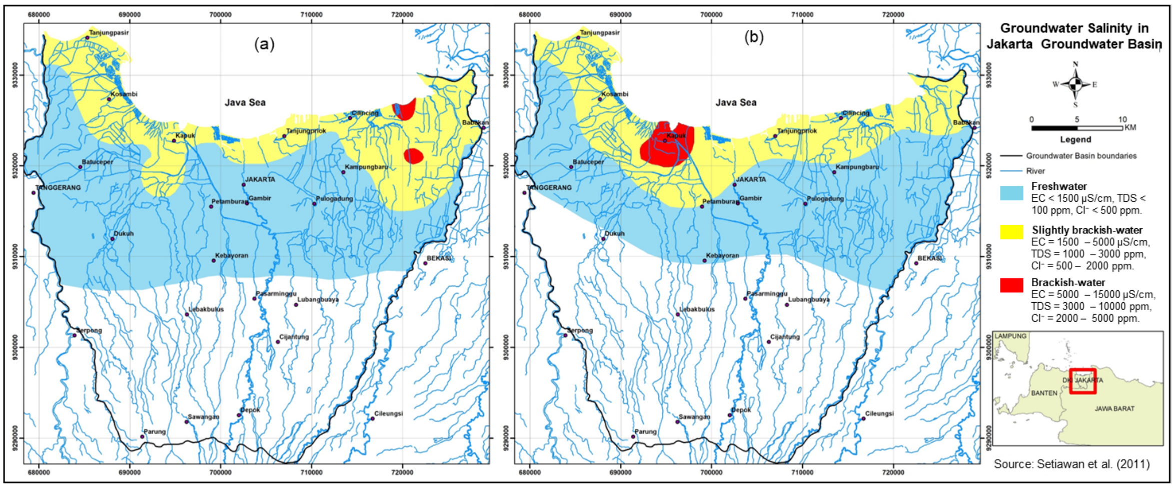

Figure 5. Spatial distribution of the groundwater salinity in the unconfined (a) and confined (b) aquifer systems of Jakarta groundwater basin. Modified from Setiawan et al. (2011)

The quality of groundwater in Jakarta's basin is affected by natural and human factors. According to Onodera (2011), the issue is complex, with human activities exacerbating natural attenuation. Onodera's model shows that the severity of contamination on the surface and subsurface impacts the susceptibility of groundwater to pollution. **Figure 6** illustrates that groundwater abstraction is only one of the many factors that influence groundwater quality.

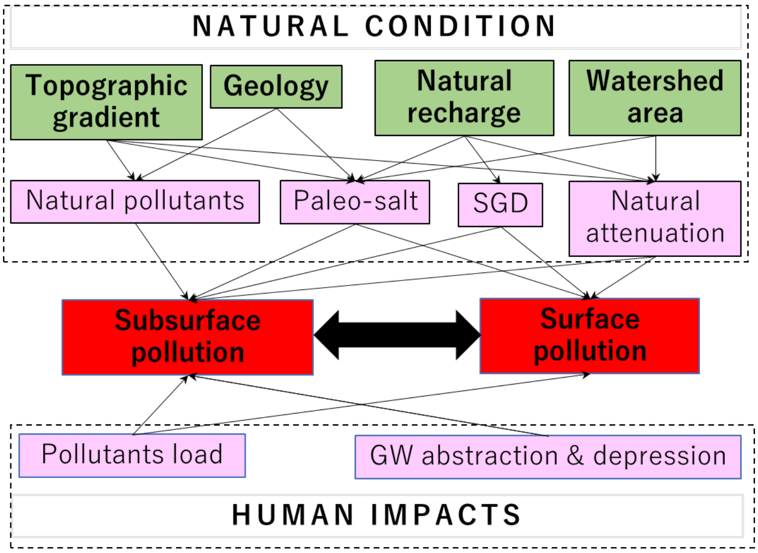

Figure 6. Controlling pollutant factors. The green color represents a natural situation that may have resulted in the presence of a pollutant, while the pink color represents contaminants that may enter the surface and subsurface (Onodera, 2011). SGD is submarine groundwater discharge

3. 2. 3 Land subsidence and flooding

The Jakarta groundwater basin is facing a major issue of land subsidence. This is caused by various factors such as natural compaction, excessive groundwater abstraction, settlement loading, and tectonic activity. The underlying aquifers have been compressed, leading to the sinking of the land above. As **Figure 7** illustrates, the northern part of Jakarta is particularly affected by this subsidence. This poses a significant risk as it increases vulnerability to flooding, damages infrastructure, and makes coastal areas more susceptible to seawater intrusion.

The rate of land subsidence for 2022 in unconfined and confined aquifers is shown in **Figures 7a** and **7b,** respectively, along with the groundwater level. The rate of land subsidence ranges from 0.04 to 6.3 cm/year based on the results of geodetic GNSS GPS observations from 2015–2022. The northern part of the Jakarta Groundwater Basin experiences a greater subsidence rate than the southern part. Settlement rates in the Jakarta Groundwater Basin vary spatially, meaning there is no clear relationship between the rate of land subsidence and location. This variation is due to various causal factors, such as natural soil consolidation and tectonics, as well as anthropogenic factors, like loading from buildings and uncontrolled extraction of groundwater.

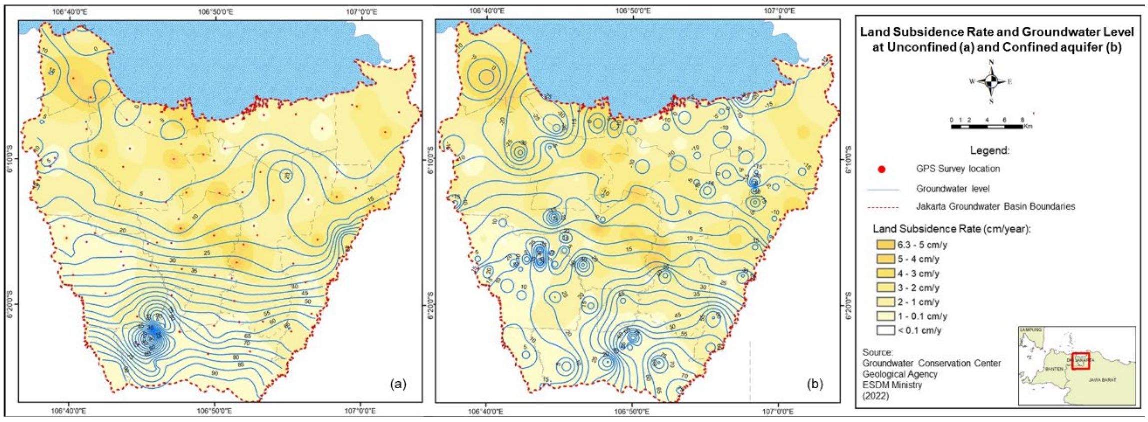

Figure 7. Subsidence rate in the Jakarta groundwater basin. From Abidin et al. (2011), Widodo et al. (2018)

The land subsidence resulting from excessive groundwater extraction has made Jakarta more vulnerable to flooding. As the city sinks, the capacity of drainage systems decreases, leading to reduced surface water runoff. This, combined with intense rainfall events, can cause severe flooding, particularly during the rainy season. This issue has also been discussed in the previous subchapter.

3.3 Groundwater conservation zone and regulations

The Indonesian government has taken steps to manage the groundwater in Jakarta by producing maps of groundwater conservation zones and groundwater usage regulations. The groundwater conservation zone is identified by the similarity of groundwater carrying capacity conditions, groundwater deterioration, and management in two aquifer systems: the upper–confined and mid–confined aquifers. Identification of groundwater conservation zones is carried out by determining protection and utilization zones.

The groundwater protection zone in Jakarta is a recharge or water catchment region that allows water to permeate groundwater basins naturally. The region is identified by the color green in **Figure 8**. Meanwhile, groundwater utilization zones are established to evaluate the level of quality and quantity deterioration of the groundwater. The criteria for water quality depend on five physical and chemical parameters; those are pH, total dissolved solids (TDS), chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-). The key groundwater quality parameters must be compared with the Indonesian government's drinking water quality standards (Tirtomihardjo & Setiawan, 2013). Good quality potential is determined when the parameters align with the standards, while poor quality potential results when they do not. Concerning quantity, the damage to groundwater in the aquifer system is assessed based on changes in the piezometric level of the upper–confined and mid–confined aquifers (**Figure8**).

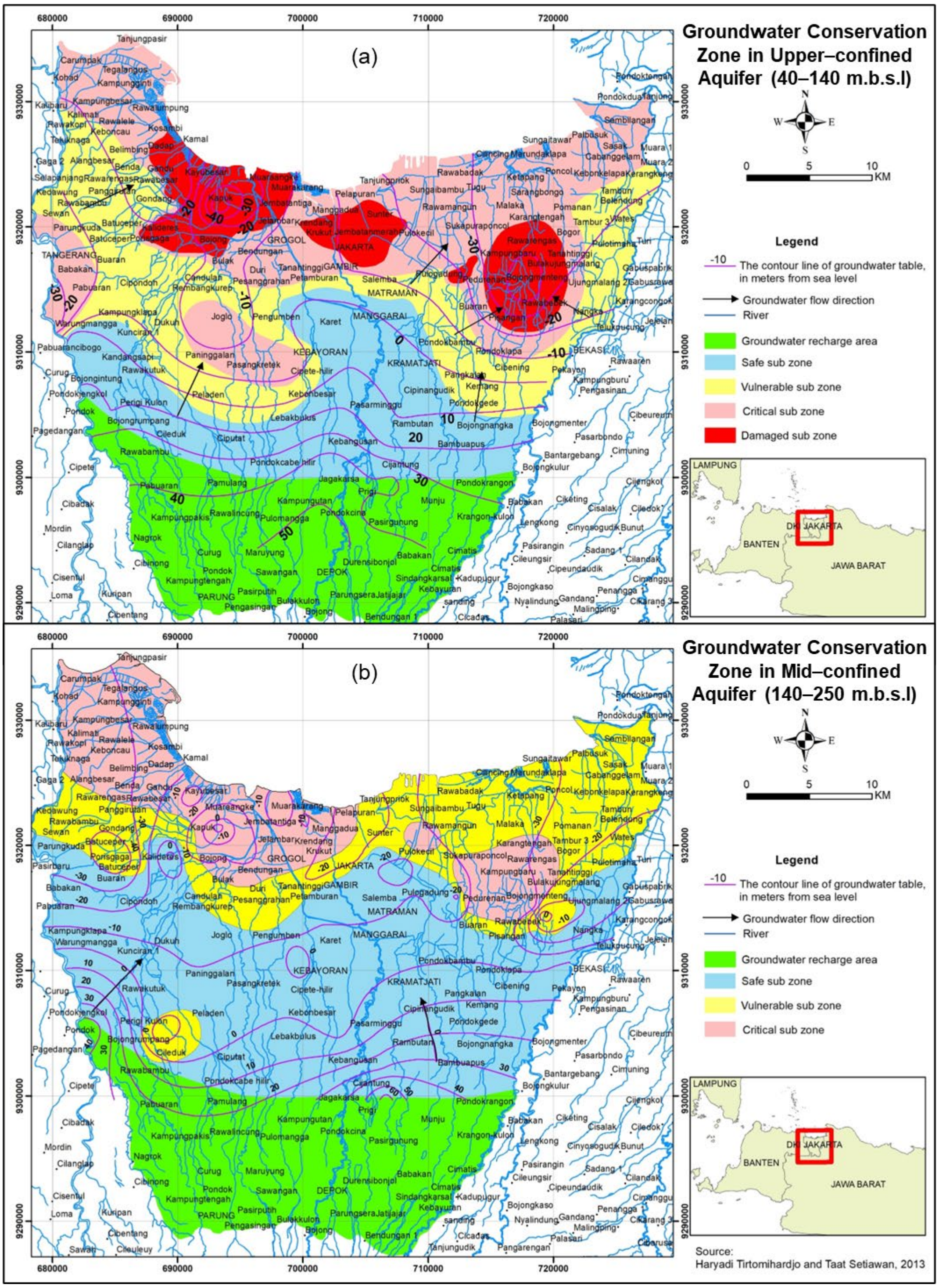

Figure 8. Groundwater deterioration level in the upper–confined (ab) and mid–confined aquifer systems of Jakarta groundwater basin determined by the percentage of piezometric decrease. Modified from Tirtomihardjo and Setiawan (2013)

According to the piezometric level, the groundwater can be divided into four different zones, which is indicated by a different color in **Figure 8**. The first zone, colored blue, is considered safe when there is a decrease in the piezometric level of less than 40% compared to the initial level. The second zone, colored yellow, is known as the vulnerable zone, and it occurs when the piezometric level decreases between 40–60%. The third zone, colored pink, is the critical zone, which occurs when there is a decrease in the piezometric level, ranging from 60–80%. Finally, the last zone, colored red, is the damage zone, which occurs when there is a decrease in the piezometric level by more than 80%. **Figure 8a** illustrates the four categories of groundwater deterioration in the upper–confined aquifer system, which are safe, vulnerable, critical, and damaged zones. On the other hand, **Figure 8b** shows the three levels of zones in the mid–aquifer, which are safe, vulnerable, and critical. The mid–aquifer has a better quantity of groundwater, with more than 70% of the safe zone.

In order to restore the piezometric level, the Indonesian government, through the Governor of Jakarta Regulation No. 94/2021, prohibits the extraction of groundwater in Jakarta by high–rise buildings. Buildings with an area of at least 5,000 m^2 and at least eight floors are prohibited from extracting groundwater. However, this regulation is restricted to the groundwater–free zone area.

4. Good Practice and Lesson Learned

The groundwater condition in Jakarta is a critical issue of concern in Indonesia and globally. To gain a comprehensive understanding of the groundwater situation in the Jakarta basin, it is imperative to consider not only the hydrological, geological, and environmental factors but also the social factors (Kooy et al., 2018; Batubara et al., 2023). A groundwater management strategy has been developed to address various issues in the Jakarta Groundwater basin. This strategy is based on several key aspects, which are listed below:

a. *Monitoring and assessment*
Regular monitoring of groundwater levels, quality, and land subsidence is crucial for effective management. Observation networks and monitoring wells gather data to understand the groundwater system and develop management plans.

b. *Regulatory measures*
Jakarta has regulations for responsible groundwater usage. Permits are required for extraction and there are pumping restrictions to prevent over-extraction and ensure sustainability.

c. *Demand Management*
Ensuring sustainable management of groundwater requires managing its demand effectively. This can be achieved through various methods such as promoting water conservation, enhancing water use efficiency, and exploring alternative water sources. To educate the public about the significance of sustainable water usage and the adverse effects of over-extraction, awareness campaigns and educational programs are conducted. The Ministry of Public Works and Housing has projected scenarios for groundwater usage from 2017 to 2080, considering factors such as extraction, recharge capacity, and injection wells. Among these scenarios, reducing groundwater extraction is the most critical factor that affects Jakarta's groundwater level fluctuations. By gradually reducing groundwater extraction until it reaches zero, the groundwater level can recover. However, if extraction continues to increase despite adding injection wells or recharge capacity, the groundwater level will continue to decline significantly, widening the cone of depression.

d. *Artificial Recharge*
Artificial recharge techniques are employed to replenish the depleted groundwater levels.

These techniques involve diverting surface water, such as rainwater or treated wastewater, into recharge basins or infiltration wells. By replenishing the aquifers, artificial recharge helps restore the natural balance of groundwater resources.

e. *Water Recycling and Reuse*
Promoting water recycling and reuse practices reduces the dependency on groundwater. Efforts are made to treat and reuse wastewater for non–potable purposes such as irrigation, industrial processes, and groundwater recharge. This reduces the demand for freshwater sources, including groundwater.

f. Integrated Water Resources Management
Groundwater management in the Jakarta groundwater basin is part of a larger integrated water resources management framework. This approach considers the interconnectedness of surface water and groundwater systems, considering factors like rainfall patterns, river flow, and the region's ecological health. It involves coordination among various stakeholders, including government agencies, local communities, and water utilities, to ensure a holistic and sustainable management approach. With the issuance of laws on Water Resources No. 17, 2019, the management of water resources is based on River Basin (WS) scale, taking into account the interrelation of the use of surface water and groundwater by prioritizing the utilization of surface water. Therefore, River basin organizations as water managers are now including conjunctive use as part of their strategies for future water management. As this concept integrates reliable water availability from all sources (surface water and groundwater are managed as a single resource at the basic catchment scale), thus sustainable water resources will be achieved and ready to encounter not just the Jakarta basin over–extraction issue thus the climate crisis and population growth issues in the future.

The groundwater conservation office (BKAT) under the Geological Agency of the Ministry of Energy and Mineral Resources in Indonesia has established basin-level management to conserve and coordinate groundwater resources. Government agencies, local communities, and stakeholders have collaborated to implement strategies for conservation. Over the past eight years, conservation efforts have resulted in rising piezometric levels in various locations in Jakarta, particularly in heavily industrialized areas like North Jakarta and Bekasi. As a result, data from 2017–2021 indicates an increase in groundwater levels (**Figures 9a and b**). Furthermore, the government is anticipated to accelerate piped water supply to all communities to protect groundwater resources. In addition to enforcing legislation, community engagement is crucial for groundwater protection. If the community recognizes the significance of groundwater and the threats that may arise if this resource is not maintained properly, groundwater use can be conducted responsibly (Lapworth et al., 2022).

Nowadays, water resources management in Jakarta has not yet integrated all its supporting components in a single system and with groundwater allocation as well. The availability of data support, simulation, and policy determination has not been integrated and operated in a real–time system. Efforts are needed to overcome these problems with integrated and real–time–based solutions. The Smart Water Management System (SWMS), which is currently being built as a prototype, is a solution that can be applied as a tool for sustainable water resources management.

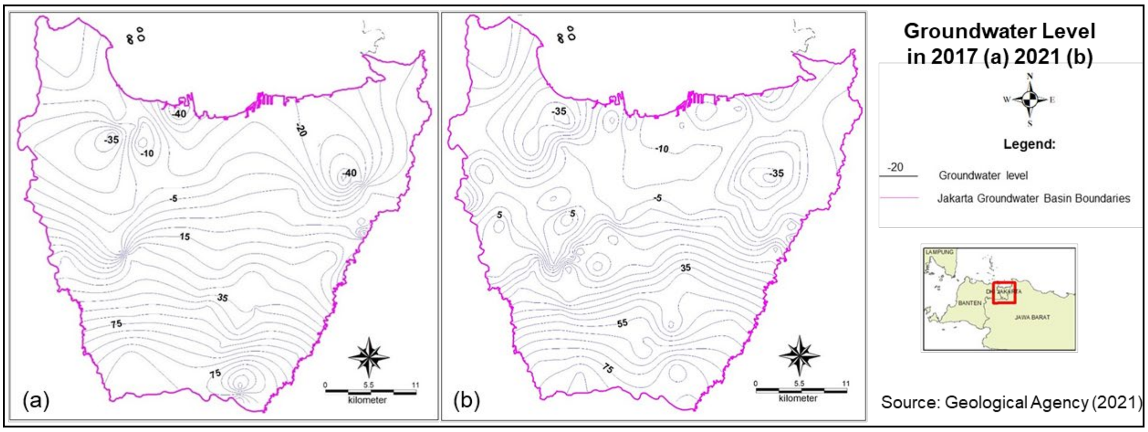

Figure 9. Groundwater level at several monitoring wells in the Jakarta groundwater basin area in 2017 (a) and 2021 (b). Modified from Geological Agency (2021)

5. Conclusion

Addressing groundwater management problems in Indonesia requires a comprehensive and multi–faceted approach to sustainable water resource management. It involves implementing sustainable groundwater extraction practices, promoting water conservation, preventing seawater intrusion, and managing land subsidence, and diversifying water sources using surface water and alternative water supply options. The ongoing issue with the Jakarta groundwater basin highlights the necessity for long–term solutions to ensure the sustainability of all groundwater basins in Indonesia. The government, industries, and the public must collaborate closely to address groundwater issues and environmental challenges.

Acknowledgement

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Contribution Statement

Apip, A.F. Rusydi, R.F. Lubis, N. Anatoly, and H. Tirtomihardjo are the main contributors to this paper, with support from T. Setiawan, A. Taufik, M. Syahidah, and M.I. Iman.

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Groundwater resources management in Iran through implementing the restoration plan

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Abstract

Management of groundwater resources plays an essential role in sustainable development, especially in drinking water supply. Over the last few centuries, groundwater resources in Iran were managed through the construction of qanat and water rights orders. In recent decades, population growth and health improvement along with access to advanced technologies led to the increased in number and depth of wells and consequently the increased in amount of groundwater extraction. On the other hand, precipitation has decreased compared to its long-term average due to climate change and greenhouse gases. The sustainable use of surface water resources is limited due to the climatic and geographical situation of Iran. Therefore, the increasing demand to supply water resources has led to groundwater resource extraction exceeding the annual renewable volume. Withdrawals exceeding the potential renewable have resulted in the intensified deficit of the reservoirs, the groundwater level declines, and the reduction in the aquifer yield. A large number of aquifers in the country have now reached a prohibited status. Other consequences include the reduction of water quality, water wells deepening, drying up of springs and aqueducts,

and land subsidence. This is because of the annual withdrawal of 54 billion cubic meters (BCM) from groundwater reserves and is affected by the significant increase in water wells. About 45% of these wells do not have a license to drill and operate, and the unauthorized extraction rate is about 15% compared to authorized wells. However, the majority of groundwater discharges are withdrawn by authorized agricultural wells. Since 1968 (i.e., Iran Water Law and Methods of Nationalization of Water), various measures have been taken to control the decline and create a balance between resources and consumption and to compensate for the deficit of aquifers, which did not have the necessary effectiveness. The groundwater resources restoration plan has been started since 2014 for the next 20 years. This plan consists of 15 different projects, among which is the plugging of unauthorized wells and controlling the withdrawal of authorized wells. The results of the implemented plan indicated that if the projects are not implemented simultaneously, there would be no reduction in water withdrawal from the aquifers. However, the results of the projects so far are clearly visible in the changes in the cumulative reservoir deficit of Iran's aquifers. Without the plan, it was expected that the cumulative volume of the reservoir's deficit would now reach 165 of which 20 billion cubic meters has been prevented by the implementation of the plan. Therefore, the implementation of the plan at the country scale and the measures taken have reduced the double pressure on the groundwater in the past decades. The progress of the expected projects has not been completed since the start of the plan. Therefore, measures have been taken to eliminate all illegal withdrawals and control overexploitation from wells to achieve the objectives of the plan by establishing integrated intelligent systems through the joint management of water and energy consumption in wells and creating a suitable structure for better groundwater governance.

Key Words: *Aquifer stress, Groundwater level decline, Iran, Restoration plan, Withdrawal control*

1. Introduction

United Nations Educational, Scientific and Cultural Organization (UNESCO) has defined 17 sustainable development goals (SDGs) by examining different social societies (General Assembly, 2015). The evidence shows that during the past decades, the development of the world community has been focused on groundwater resource extraction (Zektser and Everett, 2004).

Studies show that the sustainable and fair use and management of groundwater can directly contribute to achieving SDGs such as poverty eradication (SDG 1), food security (SDG 2), access to clean and safe water and sanitation (SDG 6), sustainable cities and communities (SDG 11), climate change adaptation (SDG 13) and environmental protection (SDG 15). On the other hand, the complete achievement of food security for the future decades requires the sustainable use of groundwater resources, which has already received much attention across the world (UN WWDR, 2022).

In order to coordinate between the SDGs and groundwater resource extraction, proper management, governance, and supervision should be applied, so that these strategic resources can be protected along with extraction. Groundwater sustainability means the development and exploitation of these resources in an infinite time period without harmful environmental, economic, or social effects (Alley, et al, 1999 and Samani, 2020).

The sustainable management of groundwater resources in countries dependent on these resources has faced problems due to population growth, health improvement, and increasing demand for food and water supply. Consequently, overexploitation of groundwater has caused quantitative and qualitative changes in these water resources such as pollution and salinization as well as the occurrence of land subsidence (Khan, et al, 2015).

A major part of the agricultural products is the result of the overexploitation of groundwater resources and the reduction of its static part, and the continuation of this process and the failure to implement the policy and plan on the sound crop cultivation pattern cannot support sustainable agriculture and ensure the food security of the country. Optimizing the crop cultivation pattern is very vital to ensure sustainable food security and adapting to the challenging conditions of the future, and all programs related to agriculture must be prepared and implemented by taking the sustainable use of natural resources (i.e., water and land) into account (Soltani, et al, 2020).

On a global scale, the lack of continuous control and the lack of a plan to prevent overexploitation of groundwater resources lead to the instability of global food security, the growth of poverty and migration, the population imbalance of the cities, the failure of regional agreements, and environmental threats. So that now about 10% of food production is at risk. This threat mainly exists in 5 countries consisting of India, Pakistan, the United States, Iran, and China, whose groundwater resources are being extracted more than renewable water (Conti, et al, 2016). In addition to utilizing the sound crop cultivation pattern and the beneficial development of a food trade system (i.e., virtual water) for the sustainable optimization of the use of groundwater and achieving SDGs at national and international levels, much emphasis has been placed on the implementation of restoration plans compatible with climatic conditions (Mekonnen, et al, 2011).

Iran is located in a region whose dominant climate is arid to semi-arid. Studying the data and information on the withdrawals with respect to the amount of renewable water indicates that increased water consumption plays a major role in the reduction of groundwater reserves. Also, the reduction of precipitation is the second priority. Therefore, in order to define a comprehensive plan that can partially compensate for the high deficit and stabilize the annual decline rate, the groundwater resources management projects were investigated through the global experiences of some other countries so that all technical, managerial, legal, and social capital aspects can be utilized in the formulation of a single and sound plan, some of which are mentioned below.

In 1980, the state of Arizona passed the Groundwater Management Act (GMA) including three levels, 1. general management, 2. management of prohibited areas for agriculture, and 3. management of crisis areas (Jacobs and Holway, 2004). The most important policies of this state for the successful implementation of the restoration plan are the management of access to low-cost electricity, the non-integrated and generality of the GMA for the entire state of Arizona, the establishment of a faculty at Arizona State University to create scientific support for the formulation and implementation of policies and laws on the Arizona water management, the establishment of the Arizona Water Bank Authority (AWBA), updating the law to account for changes in climate and demographic conditions. Hence, the adoption of appropriate policies resulted in the successful implementation of balancing operations of aquifers in this state (Samani, 2020).

The Sustainable Groundwater Resources Management Act (SGMA) with the aim of sustainable groundwater management was approved in California in 2014 by taking awareness of climate change, population growth, environmental protection, cultivated land, and the reduced groundwater level. According to this law, executive agencies and organizations should prioritize and specify the areas with different criteria including severe groundwater level decline, overexploitation from wells, subsidence, reduction in the quality of groundwater, reduction in the volume of surface water, saltwater intrusion into the freshwater aquifers in coastal areas, dependence on groundwater and the negative environmental effects and stabilize groundwater resources by 2040 (Rogers, 2016 and Moir, et al, 2018). In the released act in which the adopted laws may be dynamically changed, the aquifers with the highest withdrawal rate and the most critical conditions have been prioritized for the implementation of plans (California Legislative Information, 2014). Investigations on the SGMA have shown that providing a platform for information transparency in an accessible database for water markets, informing about the problems of water shortage, and making the conditions concrete for local communities through animation and film in cooperation with Arizona Broadcasters Association and Arizona Education Association, modification, and repair of old equipment and facilities, using new tools and technologies, desalination of seawater, pricing of groundwater and implementation of artificial recharge projects are among that have been identified as effective and should be implemented (Derakhshan and Davary, 2018).

In India, a set of laws was enacted in order to stabilize groundwater resources and legalize water use in 2005 including mandatory registration of the well owners, the need to obtain permission to drill new wells, limitation on the depth of the well drilling, and to create protection zones around groundwater resources supplying the drinking water (Hamilton, 2012). The National Water Policy Law was approved in 2013, in which the pricing of groundwater resources, the gradual removal of water supply subsidies, rainwater storage, the implementation of artificial recharge projects, and investment in modern irrigation systems were emphasized (Suhag, 2016).

In Spain, with the announcement of a new law in 1985, groundwater which was previously a part of private property became a part of the country's public property, and water management was based on the river basin scale (Molinero, at al, 2011). After 15 years of the implementation of this law by 2000, the results show that the conditions of groundwater resources are still undesirable and this law has not had the necessary effectiveness. Because river basin organizations were not successful in attracting public participation in groundwater management, up-bottom management policies and imposing decisions on farmers did not have specific results (Fornés, et al, 2005). Therefore, in 2004, a reform plan was developed based on the European Union Water Framework Directive (WFD). This plan is based on the principle of strengthening the role of user associations, approving new laws related to the protection of groundwater resources, facilitating the administrative processes of the operators or users' affairs and the participation of self-governing organizations in these processes, trying to attract public participation, raising awareness about the effects of unauthorized or illegal withdrawals and increasing the water literacy of users and the public especially influential people on the management of aquifers and planning for drought management (Hernández-Mora, 2007).

The drought crisis management plans may include variable pricing in the groundwater resources extraction, expansion of the water market, virtual water management, desalination of seawater, improvement of productivity, and reduction of water consumption. In China, based on the studies e.g., Leng, et al, (2015), it was concluded that changing the irrigation method has a direct effect on groundwater resources. Therefore, some measures were taken in order to reduce aquifer withdrawals like using modern irrigation methods, saltwater desalination, and increasing recharge flow in susceptible areas. The monitoring of these measures is being done repeatedly through the control of groundwater storage (Cao, et al, 2013).

Studies e.g., Gesicki and Sindico (2014) conducted in Brazil show that the incompatibility between freshwater resources and places with high population density, along with the increasing risk of surface water pollution and extreme climatic events have led to water shortages in many places. So in Brazil, strategies including legislation, licensing, monitoring, and control over resources and uses were put on the agenda to promote water resources management (Patole, 2015).

Also, integrated management of surface and groundwater extraction was accomplished in areas with unequal distribution of water resources (Hirata and Conicelli, 2012). Synergy and coordination were made between ministries, national councils, and legislative entities in the implementation of plans with the aim of improving the effectiveness of national laws and ensuring the prevention of unauthorized exploitation and control of groundwater pollution, maintaining and improving groundwater measurement and monitoring networks with the aim of monitoring policymaking and implementing the established regulations. Some other solutions proposed at international and regional levels for stabilization and preservation of water sources include locating areas with artificial recharge potential to balance groundwater resources for semi-arid areas with increased withdrawals, encouraging the implementation of alternative plans such as the use of treated wastewater and desalination of salty waters taking the measures to increase the recharge of aquifers and prevent aquifer pollution into account, promoting knowledge on the potential of groundwater storage and management by utilizing the remote sensing and advanced mathematical modeling (Sahoo, et al, 2020), land use change (Patole, 2015), revision of the laws and regulations related to resource and consumption management (Gesicki and Sindico, 201), environmental education and public awareness of policies and plans through sources of academic institutions (Hirata and Conicelli, 2012) and increasing the import of water-intensive agricultural crops (Schreier and Pang, 2015).

Installing monitoring and measurement devices for groundwater resources alone cannot guarantee the management of water resources, and it is more important to create legal structures and entities that supervise the granting of licenses. Over the past 60 years, the use of recharge projects and replacement plans for withdrawals has increased 10 times, but this amount is still not sufficient, and it is necessary to increase the inflow volume to the aquifers or reduce the amount of withdrawals by changing the consumption pattern (UN WWDR, 2022).

Groundwater resources play a significant role in the economic, social, and cultural infrastructures of Iran. During the last decade, the protection and optimal use of these resources have been considered important. In this paper by presenting the groundwater resources restoration plan of Iran and evaluating the relevant measures taken, the following questions would be answered:

- Can the proposed plans and their continued implementation stop the process of reducing the reserves of groundwater resources?
- Have the weaknesses and strengths of plans and measures been diagnosed?
- Are the effects of the implementation of the plans currently observed?
- Has there been a replacement or revision in the implementation of plans?

2. Groundwater in the national water resources management (Iran)

2.1 The Role of groundwater resources in the national water resources management plan

In Iran, the first operational action to manage groundwater resources was approving the Iran Water Law and Methods of Nationalization of Water in 1964. In this law, it was mentioned that all unauthorized wells should be plugged without paying damages. In 1982, the Law of Fair Distribution of Water replaced the 1964 law. Article 45 of this law clearly states that anyone who digs an unauthorized well without complying with the provisions of this law must compensate for the damage caused to the aquifer while plugging it. Also, according to Article 4 of the law, it was approved to prohibit the development of extraction and issuance of extraction permissions in the plains with extraction rates exceeding the potential of renewable groundwater resources.

Therefore, in terms of laws and legislations on balancing, prohibiting the development of extraction in some aquifers and plugging unauthorized wells has been deemed necessary. In this regard, more than 75% of Iran's plains have been banned so far. Also, according to another law approved in 2005, the Ministry of Energy (MOE) was again obliged to consider the existing wells that were drilled without permission as illegal and take action to plug them. Therefore, with the increase of prohibited plains, a plan was started in 2005 with the aim of controlling the deficit of the cumulative reservoir (i.e., 65 BCM) through the establishment of patrol and inspection groups and the plugging of unauthorized wells and the design of measurement tools to control extraction. However, within 10 years, the results showed that it was not possible to control the over-exploitation of authorized wells and the number of unauthorized wells also increased. So, the expected progress was not achieved and the groundwater level actually continued to decline and the cumulative deficit of the reservoir reached 120 BCM by 2014. This caused the MOE to formulate a 20-year groundwater resources restoration plan with the aim of creating a balance between resources and consumption and compensating for the shortage of reservoirs. This plan was approved in September 2014 to be implemented in the plains with a negative balance. The restoration plan includes 15 different study, operational and executive projects. These projects have been prioritized by taking the main and influential components in project management into account (European Integration Office, 2011). Based on this, the projects have been divided into three sections: 1- completion, updating and verification of data and information, 2- water storage in aquifers, and 3- control and monitoring of extraction as presented in **Table 1**. Along with MOE which is responsible for 11 projects, 4 remaining projects must be implemented by Ministry of Agriculture, MOA (3 projects) and the Geological Survey and Mineral Explorations of Iran, GSI (1 project).

Table 1: The main projects of the groundwater resources restoration plan of Iran

Role and objective of the plan projects	Project title	Responsible organization
Completion, updating, and verification of data and information	Installing measuring equipment on water resources and piezometers and exploration wells	MOE
	Providing the online database and system for monitoring and controlling withdrawals from wells	MOE
	Providing a national inventory of water resources	MOE
	Updating the National Water Act in the areas of study based on cultivation pattern	MOA
Water storage in aquifers	Plugging the unauthorized wells and controlling and monitoring authorized wells	MOE
	Installing smart water and electricity meter	MOE
	Implementing artificial recharge projects and spreading flood in the forbidden plains	MOE
	Purchasing low-yielding agricultural wells	MOE
	Studying and implementing the watershed management projects	MOA
	Replacing treated wastewater with agricultural wells in forbidden plains	MOE
Control and monitoring of extraction	Establishing patrol and inspection groups	MOE
	Organizing drilling companies	MOE
	Establishment of a local water market	MOE
	Establishing water users associations and giving them financial and technical support	MOA
	Zoning and assessment of risks caused by land subsidence	GSI

As could be seen in **Table 2**, the responsibility for the implementation of 3 projects has been assigned to the MOA. Because the largest water consumer in Iran is the agricultural sector, carrying out these projects would help to improve water efficiency. These projects are mostly in the midst of ongoing studies, and no official report on the effects of the restoration plan has been published yet to be exploited. Also, a project entitled Zoning and Assessment of Risks Caused by Land Subsidence was defined in the plan. The GSI should study the effects of the implementation of the plan in the plains. According to the latest report, Geological survey and mineral exploration of Iran (2022), land subsidence has been announced in 359 study areas. In this plan, the global experiences of sustainable management of groundwater resources in achieving desirable conditions with less time and cost have been investigated, and the useful experiences of other countries have been localized for implementation in Iran through the formulation of 8 relevant guidelines (**Table 2**).

Table 2: The guidelines for the groundwater resources restoration plan of Iran

No.	Guideline title
1	Development of joint management of water resources
2	Information, education, and culture developing
3	Implementation of the regulation on the optimal use of water in the agriculture sector and the law on determining the assignment of water wells without an operation license
4	Establishment of groups for the protection and monitoring of exploitation of water resources and channels
5	Plugging the unauthorized wells and preventing the overexploitation of water resources
6	Installing and operating smart meters (volume, water, and electricity)
7	How to purchase low-yielding agricultural wells for balancing the aquifer
8	Replacing treated wastewater with water from agricultural wells in forbidden plains

2.2 Administrative and legal framework for groundwater management

Energy management (water and electricity) in Iran's governance structure is the responsibility of the MOE as the representative of the government to provide water and electricity services throughout the country. The MOE is divided into two major departments of water and electricity, and the management of water resources is managed by IWRMC at the river basin level. Therefore, the structure of IWRMC is divided into 9 river basins covering Iran. In each river basin office, there is a department on protection, exploitation, and social affairs, which controls and oversees the operational plans developed in order to maintain, monitor and exploit groundwater resources. The policy implementation agent at the provincial level is the regional water authority (RWA) located in the capital of 31 provinces of the country. Also, RWA has a water department in the cities belonging to each province that is responsible for providing services to users and carrying out field operations related to the policies and plans in the field of surface water, groundwater, and joint management of water resources.

3. Case Study: Groundwater Status in the Islamic Republic of Iran

Iran is one of the arid and semi-arid countries in the world, whose average annual rainfall is less than 250 mm per year (about one-third of the global average). In the center, south, and east of Iran, the average rainfall is less than 100 mm per year, and mainly in the north and west of Iran, the rainfall is higher. On the other hand, in less than 10% of the area of Iran, the average annual rainfall is more than 500 mm. Based on the results of studies on the balance of water resources and uses in a 45-year period ending in 2011, the total annual volume of renewable water is equal to 114 BCM, which is produced from the volume of rainfall equivalent to 396 BCM. This shows that the volume of renewable water is less than 30% of the total volume of precipitation, and the rest of the precipitation is lost due to losses and climatic conditions like evapotranspiration.

In Iran, about 98 BCM of water is distributed among different uses every year. 45% of it is supplied from surface water and another 55% from groundwater resources. 89%, 8% and, 3% of all available water are consumed in the agriculture, drinking and, industry sectors, respectively (Dezab Consulting Engineering Company, 2021).

In the groundwater sector, Iran has 609 study areas that include about 660 large and small alluvial aquifers. These alluvial aquifers, along with the karst aquifers form the whole groundwater reserves of Iran. Approximately 54 BCM of groundwater per year is withdrawn by about 825,000 wells and 40,000 qanats. The share of qanats is about 5% and the largest amount of extraction belongs to wells. All wells in Iran do not have legal permission to drill and operate, so about 45% of wells can be considered unauthorized due to insufficient supervision and legal gaps. On the other hand, according to the national water census, the ratio of extraction of unauthorized to authorized wells with operating licenses is about 15%. Hence, the majority of water (i.e., 43 MCM) is still withdrawn by authorized wells across the country. Similar to many countries, the water consumed in the agriculture sector is close to 85% which is highly dependent on groundwater resources. Therefore, the management of authorized agricultural wells plays a significant role in balancing groundwater resources.

According to the latest data and information recorded in the database belonging to the MOE (i.e., Integrated System for the Protection and Exploitation of Water Resources and Subscribers Affairs, SAMAB in Persian), the number of authorized wells for various consumptions in Iran is estimated 500,000 of which more than 416,000 wells are agricultural ones. More than 220,000 agricultural wells (equivalent to 53%) are electrified. The extraction volume from electrified agricultural wells is more than 25 BCM which is equivalent to 70% of the total discharge of agricultural wells.

The annual reservoir deficit of Iran's aquifers is calculated through the results of drilling exploratory wells and monthly measurements of the observation wells network, the number of which is about 12,500 wells. The amount of this index is a criterion that determines the degree of imbalance of groundwater sources and uses. The results show that the average annual deficit of 660 alluvial aquifers is equal to 4.9 BCM within the Iranian water year (23 September 2021 to 22 September 2022). Cumulatively, the deficit of the reservoir has reached 146 BCM.

Some researchers consider the amount of renewable water per capita of countries as an index to determine water stress. In order to determine the amount of access to water in different societies, Falkenmark's indicator (Falkenmark, et al, 1989) is used. This criterion accounts for only the amount of water available in countries and does not account for the amount of consumption. According to this criterion which is 1381 cubic meters per capita per year, Iran is exposed to water stress (Dezab Consulting Engineering Company, 2020).

Some other researchers have chosen the ratio of water consumption to total renewable water resources as the water stress index. These researchers use the Smakhtin criterion to determine the level of water stress (Smakhtin, et al, 2004). According to this definition, countries that consume more of their renewable water resources, so they experience higher water stress. As this criterion, accounts for the sources and uses of water at the same time, it provides a more acceptable description of water stress compared to the Falkenmark indicator. According to this criterion which is 86% for Iran, the country is exposed to water shortage (Dezab Consulting Engineering Company, 2020). Also, according to international guidelines, e.g. Smakhtin, et al (2004) if less than 40% of renewable water resources are used, the water resources situation is considered sustainable. Moreover, if the amount of renewable water use is more than 40%, the region is in a critical situation in terms of water resources. In Iran, the total amount of water withdrawn from aquifers is about 20% more than the natural yield capacity of these sources. For this reason, the water level in Iran's aquifers is decreasing every year compared to the previous year and the salinity is also increasing. The continuation of this process, which means the depletion of Iran's aquifers causes irreparable damage in a major part of agricultural lands and endangers the survival of the communities living in large parts of the dry and water-scarce land of Iran in terms of economic, infrastructural and social.

4. Good practice, Lesson learned

In this section, only measures are presented corresponding to the 11 projects (as presented in Table 1) for which MOE is responsible.

4.1 Providing the online database and system for monitoring and controlling withdrawals from wells

In the first step, creating a data and information system as the first and main system was put on the agenda with the aim of creating a database and clarifying data exchange in the data and information sector, and facilitating the implementation and control of the groundwater resources restoration plan. The main system as a database of Iran's water resources is the SAMAB system. This system, in addition to updating the data and information of resources and uses, has been developed and upgraded in order to implement all the stages and processes of issuing licenses to achieve a unified procedure in the electronic making and storage of user documents. It is also possible to exchange user information between departments through the web service. The electronic steps of this system have already been completed. The system will become smart in the next steps.

The second launched system (i.e., patrol and inspection system, SAMGASHT in Persian) is associated with recording data and information at the location of the wells and comparing those data with the ones of the issued licenses. Through this system, unauthorized withdrawals from water resources are identified and dealt with legally. The purpose of this system is to identify possible violations. The transparency resulting from the registration of the violation handling cycle can guarantee the prevention of unauthorized withdrawals and reduce the possibility of cooperation of the groups having the role of monitoring exploitation. All the processes of this system have not yet been fully utilized due to the weakness in the supply of infrastructure equipment and the completion of the human resources structure.

The third system monitors the project control activities of the plan. As explained, the plan has different projects, each of which has a different weight and influence in the plan. In order to annually monitor all the different actions and functions that are defined and planned under the projects, the project management and control system is based on the multi-criteria decision-making (MCDM) model (Torno, 1988) widely used in water resources issues. The MCDM has been designed and it measures the performance desirability based on the calculation of the distance from the ideal point. The performance measurement indicators and the related decision tree have been developed in a working group consisting of managers and experts of the MOE and the project consultant. The MCDM system is currently being used. So, all actions and functions performed across the country should be registered, reviewed, and approved in this online system. Validation of actions is carried out in both ways including office and field. In Iran, periodical progress reports of the plan are prepared by this system and it is also possible to provide the necessary information in the provincial divisions, river basins, and study areas.

The fourth system that was recently designed and is being launched and completed is related to the online monitoring of authorized electric agricultural wells equipped with electricity meters with visibility and controllability. In this system, the smart management of wells is carried out through monthly electricity consumption and comparison with the allowable electricity use, and action is taken to identify the delinquent users. Therefore, a notice is sent to those users to comply with the consumption pattern, and if they do not comply with the warnings, the electricity of these wells will be cut off. In the development stages of this system, it will be possible to communicate and exchange processes and information between SAMAB and SAMGASHT systems to simultaneously manage water and electricity in these wells.

4.2 Plugging the unauthorized wells and controlling and monitoring authorized wells

This project is the most operational and challenging one in the restoration plan. So, the implementation of this project in some aquifers helps in balancing and compensating for the reservoir deficit. In the first step, in order to identify and organize unauthorized wells and their role in the plan, aquifers were prioritized through groundwater stress (IGRAC, 2021) and an operational plan was prepared for each aquifer. Groundwater stress determines the ratio of groundwater extraction to its recharge rate for each aquifer whose equation is as follows:

$$Groundwater\ Stress = \frac{\mathrm{W(x)\ or\ U(x)\ -\ RF(x)}}{\mathrm{R(x)\ -\ E(x)}}$$

Where W(x) or U(x) is groundwater withdrawal or use, RF(x) is return flow from the agriculture sector, R(x) is the groundwater recharge, and E(x) is the groundwater environmental discharge. Values greater than one indicate the presence of stress in the aquifer. This index was used by the World Resources Institute (WRI) in the Aqueduct 2 project (Lou, et al, 2015).

In most of the studies, the main basis for the definition of the "Aquifer Stress Index, ASI" is the amount of withdrawal and the annual groundwater level decline in the aquifer. The higher the decline, the higher the ASI. In Iran, in order to determine the condition of the country's aquifers, the ASI index is calculated taking into account the indicators presented in other similar studies and considering the experiences of Iranian experts familiar with the conditions of the country's aquifers in terms of the variation in thickness and the dependence of drinking water supply on groundwater. The ASI index is defined as follows:

$$ASI = -WT_{a.a.d} \cdot C_1 \cdot C_2 \cdot C_3$$

Where

ASI is the Aquifer Stress Index, $WT_{a,a.d}$ is the average annual groundwater level decline, and C1 to C3 are modified coefficients for aquifer restorability ratio, aquifer damage ratio, and drinking water supply ratio, respectively. Values of these coefficients for Iran are presented in **Table 3** obtained based on numerous statistical investigations and understanding of aquifers.

Table 3: The values of modified coefficients for aquifers of Iran

Parameter	**Ratio**	**Coefficient value**
Aquifer restorability ratio	Less than 5%	1.2
	Between 5 and 10%	1.1
	Greater than 20%	1.0
Aquifer damage ratio	Less than 70%	1.2
	Between 70 and 85%	1.1
	Greater than 85%	1.0
Drinking water supply	Greater than 50%	1.6
	Between 20 and 50%	1.3
	Less than 20%	1.0

The aquifer damage ratio defines the ratio of the current aquifer reserves to its initial volume. The initial volume of the aquifer is the total volume of the non-renewable reserves of the aquifer before the water level began to decline in recent decades. Similar ratios are presented in some studies e.g., Richey, et al (2015) and Vaux (2011). The smaller the value of this ratio shows the aquifer of interest has lost a larger part of its non-renewable reserves.

The aquifer restorability ratio is calculated by dividing the annual renewable volume of the aquifer by its initial volume. This concept has been developed by the International Groundwater Resources Assessment Centre (2021) and has been localized and utilized according to the conditions of the country's aquifers. This ratio is expressed by the Groundwater Development Stress (GDS) and is defined as follows:

$$GDS=\frac{A}{R}*100$$

Where GDS is the percentage of the annual groundwater extraction (A) over the annual natural groundwater recharge. This index shows to what extent the current groundwater extraction has changed or will change the primary groundwater regimes. The smaller the aquifer restorability ratio, the aquifer of interest needs more time to restore its lost reserves.

In case the aquifer of interest has a significant role in supplying drinking water, another modified coefficient is also considered to consider this sensitivity (i.e., the importance coefficient of the aquifer in supplying drinking water". The coefficient of "drinking water supply ratio" represents the share of drinking water with respect to the total volume of water withdrawn from the aquifer.

From the viewpoint of the ASI and for the priority of project implementation, Iran's aquifers are divided into 4 classes as presented in **Table 4**. Worth noting that, the plains that do not face a decline in the aquifer water level were not considered damaged. So, they were not included in this classification. **Figure 1** also shows the distribution of the ASI values for the plains of the country.

Table 4: The classification of Iran aquifers based on the degree of aquifer damage

Degree of aquifer damage	**ASI value**
Very high	Greater than 1.0
High	Between 0.6 and 1.0
Moderate	Between 0.3 and 0.6
Low	Less than 0.3

As evidenced in **Figure 1**, 17% of Iran (i.e., 102 plains) have very high damage. These plains are mostly located in the provinces of Khorasan Razavi, Kerman, Fars, and Tehran. However, in general, the number of very highly damaged aquifers is higher around the center of Iran (i.e., south of the Alborz Mountain range and east of the Zagros Mountain range). The amount of water withdrawn from these aquifers is estimated 40% of Iran's groundwater consumption.

On the other hand, in order to determine the control of withdrawals from aquifers located in the study areas, the amount of groundwater that can be planned was determined based on the available data and information. Indeed, this amount is the sustainable withdrawal from groundwater resources for various uses (i.e., drinking, agriculture, industry, and green spaces) according to the volume of renewable water. When this amount was calculated for 609 study areas of Iran, it emphasized the necessity of stopping the groundwater level decline and compensating for the cumulative deficit of each aquifer. On a national basis, the current withdrawal from wells (authorized and unauthorized) is estimated 54% more than the planned groundwater. This indicates that groundwater withdrawal should be significantly decreased. **Figure 2** shows the ratio of withdrawal to planned groundwater at the provincial level, which varies between 11% and 192%.

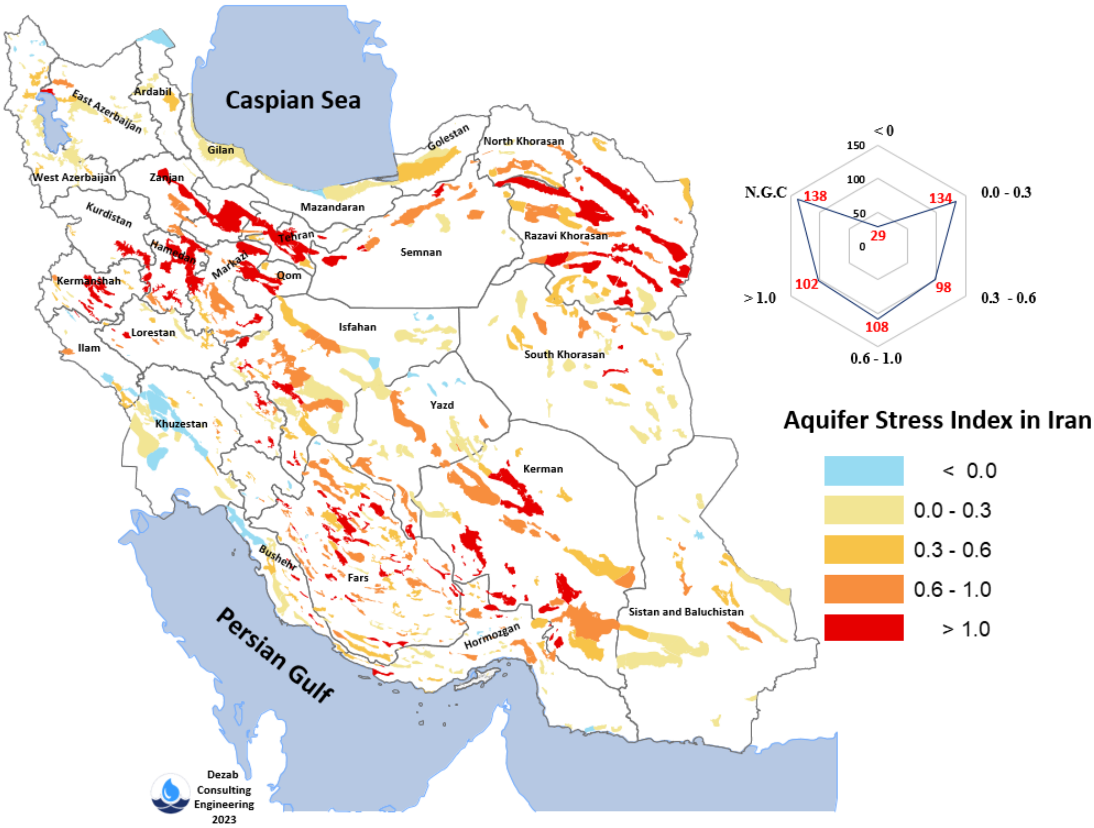

Figure 1: ASI value for aquifers of Iran (DCEC, 2023)

Legend: Red areas have the highest water stress, orange and yellow areas have moderate stress, and blue areas have low water stress. N.G.C. is the number of plains with negligible groundwater capacity.

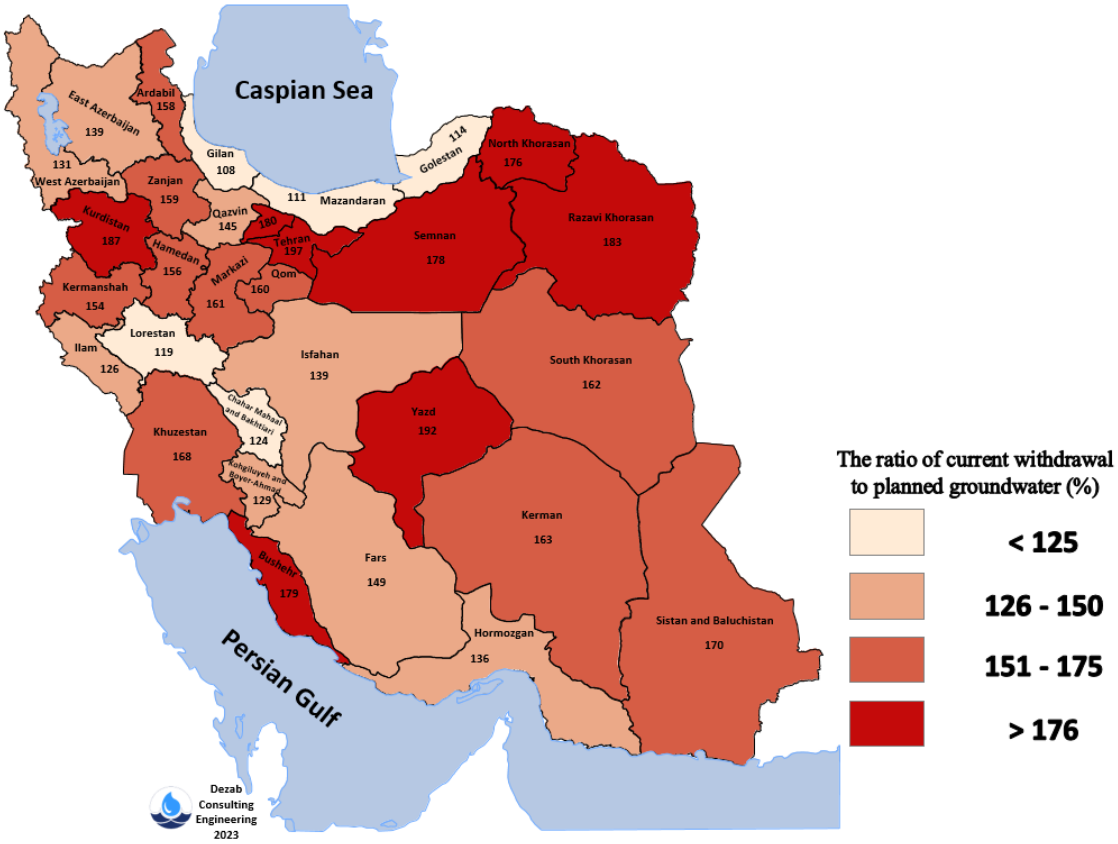

Figure 2: The ratio of current withdrawal to planned groundwater in provinces of Iran (DCEC, 2023)

According to **Figure 2**, the darker the areas, the more the withdrawals from wells than the planned groundwater, so groundwater extraction should be reduced. Authorized and unauthorized withdrawals are significant for agriculture in Iran. Hence, planned groundwater for the agriculture sector was highlighted in the preparation process of the operational plan for the plains. Moreover, in some plains, it was observed that even with the complete removal of unauthorized wells and the control of over-exploitation of authorized wells, it is still not possible to compensate for the annual deficit and its cumulative amount due to the over-exploitation from the aquifers in the past years. Another reason is the total number of permits issued for authorized wells which is more than the groundwater planned for the agriculture sector. This issue is shown in **Figure 3** in light green color.

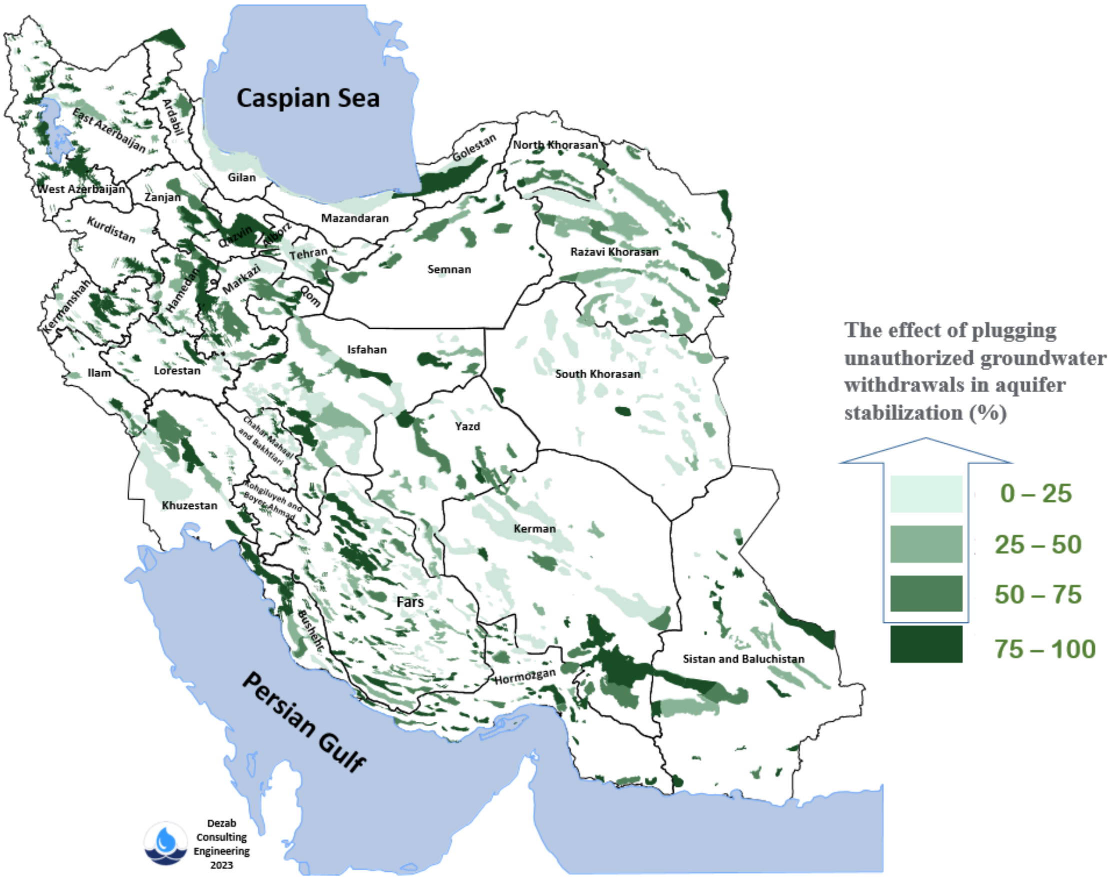

Figure 3: Mapping of dependence of deficit compensation of the aquifer by removing unauthorized withdrawals (DCEC, 2023)

In **Figure 3**, dark green areas indicate full deficit compensation through removing unauthorized withdrawals and controlling the authorized over-exploitation. The brighter the green color, the ratio of plugging and controlling the authorized over-exploitation is decreased. In this case, other joint measures such as revision and reduction of extraction from the authorized wells are needed. According to **Figure 3**, for the whole of Iran, the control of all unauthorized withdrawals achieves an average of only 30% objectives of the restoration plan, and the other 24% must be compensated in another way (the darker the green color, the more compensable). These values are variable in each of the plains of Iran as distributed in **Figure 3**. In this case and due to climatic restrictions, failure to implement the artificial recharge project, and failure to supply the financial resources required for the other projects, reduction of withdrawals from authorized wells has been determined as the only management solution.

Therefore, the process of revising the issued exploitation licenses is underway in 438 study areas for 236,000 authorized agricultural wells. On the other hand, controlling unauthorized withdrawals from aquifers with a history of half a century is not an easy task. The total number of plugged unauthorized wells in the past years is more than 118,000 of which 87% is related to the implementation of the restoration plan (103,000 wells after 2014). Therefore, the plan has a direct effect on the number of unauthorized wells in such a way that after the implementation of the plan, the increasing trend has almost stopped. The results of the recent nationwide census on water resources show that the number of unauthorized wells has decreased in several provinces (e.g., Kerman, Isfahan, Tehran, and Fars).

About 55% of the remaining unauthorized wells are less than 20 meters deep. A group of these wells are located in the area of irrigation networks (e.g., Isfahan, East Azerbaijan, and Khuzestan provinces) and are practically recharged by surface water sources and have no interactions with groundwater tables. A number of the others have been drilled in the rainy areas (e.g., Gilan, Mazandaran, and Golestan provinces), where the groundwater resources are not under much stress and their level is close to the ground level. Unauthorized water wells in these areas are mostly used for supplementary irrigation when sufficient rainfall does not meet all the farm demand. Therefore, the plugging of these shallow wells, although they are not ineffective, does not play a major role in the process of destroying groundwater tables. On the other hand, unauthorized wells deeper than 20 meters, mostly in Fars, Kerman, Hamedan, and Tehran provinces withdraw about 80% of the total unauthorized amount. The number of these unauthorized wells reaches 110,000. The continued operation of these wells can cause irreparable damage to Iran's groundwater resources. Hence, within the upcoming operational plans, it is planned to plug them in as soon as possible due to the time-consuming judicial process.

4.3 Installing smart water and electricity meter

According to the law, the owners of water well extraction licenses in Iran are obliged to observe the extraction according to the license. Due to the pattern of cultivation of water-intensive crops, multi-cultivation, and the development of land, consequently producing more crops and generating more income, they have the desire to increase the extraction rate or the working hours beyond the set limit, which leads to over-exploitation. The best and most practical implementation solution to determine, control, and prevent the over-exploitation of such wells is to install a meter with the ability to control and stop exploitation when it exceeds the valid permission. In this regard, it was tried to use up-to-date and efficient technologies in accordance with the existing and preferably indigenous infrastructures in equipping the wells with meters by starting the restoration plan. Hence, the use of remote monitoring and control systems (preferably online) was also put on the agenda. The objective was to obtain a high-quality product with an error of less than 5% so that at least 10 years can be used for the wells and the total extraction from the wells can be calculated at any time. Three sets of meters have been installed on Iran's water wells so far.

These sets consist of 1) water and electricity meters that convert electricity consumption into water withdrawal through relationships. 2) smart volume meters in two electromagnetic and WOLTMAN, and 3) mechanical volume meters that are initially for all wells and now are installed for wells having the up to 2-inch pipes. The total number of installed meters including all the aforementioned models on water wells is less than 110,000.

Therefore, it was decided to protect groundwater resources from 2023 until the installation of volume smart meters on water wells with the combined management of water and electricity and through new generation electricity meters that have capabilities such as visibility, control, and planning.

4.4 Establishing patrol and inspection groups

The patrol and inspection groups have been established and strengthened with the aim of using non-governmental capacities and entrusting protection and exploitation affairs to operators and local organizations to monitor and strengthen supervision and prevent violations of water resources. Constant monitoring in the plains has almost prevented the increased number of unauthorized wells. Currently, according to the number of existing wells, there are more than 800 patrol and inspection groups. However, these groups are faced some challenges including non-recognition by the people and governmental organizations and the lack of necessary training and empowering them to perform their duties.

4.5 Replacing treated wastewater with agricultural wells in forbidden plains

Planning for the collection, treatment, and use of wastewater in Iran has been highlighted after the beginning of the restoration plan and taking into account the decreasing trend of renewable water resources and the upcoming challenges in water supply, especially for drinking and industry sectors. The main approach of this project is to recycle and reuse treated wastewater while preserving the environment and preventing the pollution of existing water sources.

At the moment, this project is being implemented in some cities having wastewater treatment plants. However, there is a low willingness to use treated wastewater due to the lack of transfer of wastewater between basins, and the high cost of wastewater compared to the tariff of ground and surface water resources. Therefore, it is necessary to provide proper culture development and capacity building on the benefits of water recycling and create incentive facilities. Otherwise, this project will not be welcomed by the operators of agricultural wells for handing over or plugging water wells.

It is not possible to completely replace the wastewater with the water resources available to the agricultural sector due to the need to periodically wash the soil with raw water withdrawn by wells. So, part of the raw water must be provided to the farmers. Therefore, this project requires detailed studies for the following points:

- The reuse of returned water and wastewater while complying with the environmental regulations
- Presenting the temporal-spatial distribution of wastewater produced in the cities and assessing the consumption needs
- Carrying out a study to understand the hydrogeological and geological conditions of the aquifer in order to analyze the behavior of the aquifer and the feasibility of storing wastewater in the aquifer.
- Investigating the possibility of creating underground dams in order to store wastewater in aquifers
- Investigating the standards of wastewater application in Iran and the world and revising them (if necessary)

Although there is another point of view that before the implementation of wastewater recycling, the wastewater volume will recharge the aquifers, through considering the newly defined uses and functions of the wastewater, this benefit will be lost so that it will work against the objectives of the restoration plan and cause aggravation in the deficit of groundwater reservoirs.

4.6 Purchasing low-yielding agricultural wells

One of the solutions proposed in the plan in order to balance the water tables and compensate for the deficit of Iran's aquifers is the project of acquiring and plugging the agricultural wells that are active and licensed to operate. This project may be fruitful at the local scale. Currently, this project is not implemented in Iran.

4.7 Establishment of a local water market

This project is in the study phase. However, two main actions have been carried out including 1- conducting the studies in three aquifers (Qazvin, Khaf in Khorasan Razavi, and Semnan) as a pilot and defining the implementation tasks based on the establishment of a system and 2- the establishment of an executive agent for water exchanges. In the implementation of the water market, there should be no quantitative or qualitative damage to the aquifer, and on the other hand, water efficiency should also be improved. One of the most important challenges facing the establishment of the local water market is the lack of separation of water exploitation rights from land ownership rights. Therefore, the liberalization of water exchange should be recognized by neglecting the lands under the primary water well, which requires the establishment of a new law. In this regard, some measures have been taken for this issue and currently, it is possible to change agricultural consumption to other uses. On the other hand, due to the fact that the problems of the water market in Iran are unknown, especially in the field of the correct definition of water rights, allocations, licenses, and permits issued, as well as the procedure of participation and cooperation between the governmental organization and users, it is expected that there will be many disputes resulting from water exchanges. Moreover, the lack of control supervision and legal weaknesses double the problems. Therefore, this project may be implemented carefully by using the opinions of scientific experts and international experiences.

4.8 Implementing artificial recharge projects and spreading flood in the forbidden plains

Surveys show that in some areas of the United States (e.g., Orlando, Arizona, and California) and the Persian Gulf countries, the main method for restoring the aquifers is the implementation of artificial recharge projects. However, in Iran, due to the lack of rainfall and its uneven distribution, and the priority of dam construction to control surface runoff, the implementation of this type of project has not been effective. On the other hand, after a while, due to the lack of repair and maintenance of the constructed structures, the drainage volume and effective infiltration into the aquifer are greatly reduced. Currently, in Iran, 318 artificial recharge projects are in operation of which 306 projects are active. The total nominal storage capacity of these projects is about 700 million cubic meters (MCM). The average volume infiltrated through the ponds is between 40 and 45% of the aforementioned nominal capacity. According to the available data and information, through these projects, a total of 1200 MCM have been infiltrated into Iran's aquifers from 2018 to 2020. The annual average of 1.3 MCM for each active project is a small amount compared to the average annual and cumulative deficit of Iran's groundwater reserves.

Currently, there are 28 other artificial recharge projects implemented with an average physical progress of about 55% for which the recharge volume is estimated at 107 MCM. If these artificial recharge projects are completed and put into operation, the capacity of using these projects in Iran will increase by about 15%. On the other hand, 68 other projects are under study, and the nominal capacity of these projects is estimated at 138 MCM with an average progress of around 75%.
Due to the need for high investment in artificial recharge projects and their limited effectiveness, efficient monitoring systems should be established for the performance control of these projects. In order to preserve groundwater resources, it is tried to carry out other management planning based on fair, comprehensive, and sustainable extraction, which can be considered as allowing the withdrawals up to the maximum planned groundwater in the current conditions of Iran.

4.9 Providing a national inventory of water resources

So far, two national data collection periods have been carried out in Iran in 2004 and 2008 in each of which, every water source is visited and monitored in the field. According to the identified weak points, efforts have been made in the third data collection period (i.e., 2018) to review the data and information concerning the withdrawals from sources and evaluate their unauthorized status with respect to the issued licenses. All the field measures have been done for all the aquifers, but the office checks and summarizing the results are in progress. This information is of particular importance in studying the balance of water resources and uses, especially in the groundwater sector, so that upon finalizing the studies and publishing the relevant results, the effectiveness of all projects implemented in the restoration plan can be analyzed.

4.10 Installing measuring equipment on water resources and piezometers and exploration wells

About 12,500 observation or exploration wells have been drilled in the plains of Iran to monitor the groundwater level decline. Another 3500 exploration wells are needed for optimal coverage of groundwater resources and aquifers. On the other hand, in order to monitor the changes in the groundwater level online in the important proxy plains, 1500 data loggers were installed in the observation wells. However, this amount needs to be increased to 4000 data loggers. Currently, the quantitative changes in Iran's groundwater resources are evaluated and analyzed based on the existing monitoring networks.

4.11 Organizing drilling companies

Drilling companies having authorized drilling devices have been organized and monitored with the aim of preventing the drilling of unauthorized wells or water well deepening of authorized wells to extract more than the issued permission. Currently, all the devices are equipped with trackers and the device must be moved in the plains with the permission issued by the water authorities. After being installed in a certain place, these devices are sealed and monitored through the relevant system until the next mission. Hence, currently drilling deep wells through authorized companies is highly unlikely. Although, there are also unauthorized devices made by hand in Iran, many of them are discovered, seized, and destroyed every month through public reports or patrol and inspection groups.

5. Discussion

The main and most effective operational projects of interest in the groundwater resources restoration plan of Iran are the installation of meters on authorized wells and the plugging the unauthorized wells. Under the current situation, due to the decreased groundwater yield capacity, many of the authorized wells have faced a decrease in the water yield, and the withdrawal amounts are less than the amounts stated in the extraction license. Therefore, based on the operational planning of the plan, at the same time as the unauthorized wells are plugged, the operating permission of the authorized wells must be revised based on the planned groundwater, and the amount of their withdrawal must be managed and controlled by installing a meter. This measure is effective when the farmers can implement the policy on the crop cultivation pattern.

Plugging the unauthorized wells will lead to a reduction in water withdrawal and the gradual restoration of the lost capacity of the aquifer. In such a situation, the water level of the authorized wells will improve and the operators or users will be able to sustainably extract to the limit of the amounts mentioned in the updated extraction permission. The results of the implemented plan have shown that if these projects are not carried out simultaneously, there will be no reduction in water withdrawal from the aquifer and its negative balance will not be compensated. On the other hand, prolonging the time period for either plugging unauthorized wells or installing meters on authorized wells, will delay the achievement of the objectives of the plan in terms of reducing water withdrawal from the aquifer. The achievements of the projects that have been implemented so far in the restoration plan are as follows (DCEC, 2023):

- Plugging of about 100,000 unauthorized wells with a volume of over 2.5 BCM
- Preventing over-exploitation of authorized wells with a volume of nearly 1 BCM
- Installation of about 70,000 meters on agricultural wells to prevent the over-exploitation
- Revision of permissions issued based on planned groundwater and reduction of 4 BCM in the extended permissions
- Establishment and permanent presence of more than 800 patrol and inspection groups in the entire plains of Iran

It is worth noting that, unlike surface water resources having pretty fast interactions, it would not be expected for the positive effects of the implementation of the plan on Iran's groundwater resources, which have to reduce water withdrawal, to become increasingly apparent. Global experiences have also shown that the positive effects on groundwater resources are gradual, and it should not be expected that the problems arisen for these resources over half a century will be solved in the short term by taking urgent and privative measures. It is necessary to gradually solve the upcoming challenges with the continuation of projects and measures, along with culture development and cooperative management of users. Otherwise, the lack of attention to groundwater resources will cause migration from different regions, creating local conflicts and crises in the supply of drinking water in megacities and ultimately having irreparable consequences.

Also, some experiences have shown that despite the wide and increasing application of "integrated water resources management" models, Iran's groundwater resources management does not follow such rules and is mostly subject to specific management considerations that are appropriate to local and regional conditions. One of the main reasons is the existence of contradictions in the laws and policies related to water and food security. For example, the implementation of the irrigation plan for sloping lands means more water consumption which reduces the water sources recharging the aquifers, or increasing the areas of gardens means increasing pumping time and extraction rate exceeding the groundwater yield capacity. These cases mean failure to comply with the consumption up to the maximum planned groundwater. Therefore, the date corresponding to the cultivation area, production, harvest, and consumption volumes are always in conflict between the water and agriculture sectors so they have never reached the necessary operational coordination in the country. On the other hand, with the implementation of the restoration plan, the extraction amount will be decreased, and if the cultivation pattern does not change and the equipment and wells are not replaced with new tools, the area under cultivation and the per capita income of the operators will be decreased. Consequently, the livelihood of the unauthorized operators faces problems with the plugging of their wells.

The main law related to groundwater resources (i.e., the Law of Fair Distribution of Water) has been approved in 1982. This law was formulated when Iran's water resources were much more than its uses. Therefore, according to the experiences obtained from the drought conditions of recent decades and the data and information collected from the aquifers, it needs to be revised and many of its articles should be modified according to the current conditions. Other subsequent complementary laws are also associated with violations and contradictions, to resolve them, a draft comprehensive water law was developed with cross-sectoral consensus. This draft has not yet been approved.

The expert opinions of cross-sectoral departments (e.g., trade unions, local authorities, and governors) have been used less in the process of developing the 8 guidelines of the restoration plan (as presented in **Table 2**) and other guidelines related to groundwater resources management. But this weakness was partially covered in the establishment of another plan called the National Water Scarcity Adaptation Plan which has most of the objectives related to the restoration plan in the provincial documents.

Another problem facing the basic implementation of the plan is the lack of human resources in the water resources protection sector. With the adoption of the policy of outsourcing government activities in Iran, the monitoring task of the water sector was assigned to the private sector to conduct the assigned tasks by using patrol and inspection groups. According to the law, the protection of groundwater resources is one of the government's duties and the outsourcing of duties has problems. Hence, the use of patrol and inspection personnel in unsupervised sectors has caused the annual objectives in controlling unauthorized withdrawals to be not achieved during the implementation of the plan. Providing financial resources for these personnel, who have now reached 2300 people, is also one of the challenges of implementing this plan.

As for replacing wastewater with agricultural wells in prohibited aquifers, experience has shown that this project can only be implemented in industrial sector wells. Since the standard of discharging wastewater to recharge aquifers in Iran is very strict and the culture of farmers has not adapted to this issue, this project has not been accepted so far. However, by carrying out the reforms process, the direction is to use the water resources released from the industries in the reallocation process to balance the aquifer and make them sustainable.

The implementation of artificial recharge projects has not been effective so the watershed management projects should be highlighted. Currently, watershed management projects are mostly implemented by constructing structures (e.g., check dam or retarding basin) upstream of dam reservoirs, which must be changed for flood-spreading projects downstream of dams. In addition, the implementation in upstream of dams has practically not led to an increase in the storage of aquifers, and they should be implemented in line with constructing sediment trap basins.

Regarding the establishment of a local water market in Iran, the law on not separating water extraction rights from land ownership rights, the liberalization of the water exchange from land, and realizing the water rights should be strongly reviewed. It is expected that if the existing processes are fully implemented and monitored, valuable results will be achieved, the most important of which is the real valuation of groundwater extraction.
The project of purchasing agricultural wells must be modified or removed from the list of projects expected to be effective in the plan due to the reasons aforementioned earlier.

Budget allocation for the implementation of various components of the groundwater restoration plan requires more attention and investment than in previous years. Investigations show that the current necessary credit to accomplish the plan in the remaining period is about 350 million USD.

Nevertheless, in order to know about the measures taken with regard to the few financial resources allocated so far as a result of the gradual effects of the plan, the cumulative change of groundwater deficit of Iran's aquifers was investigated. The trend of these changes for 665 alluvial aquifers of Iran during a 40-year period has been presented in **Figure 4**.

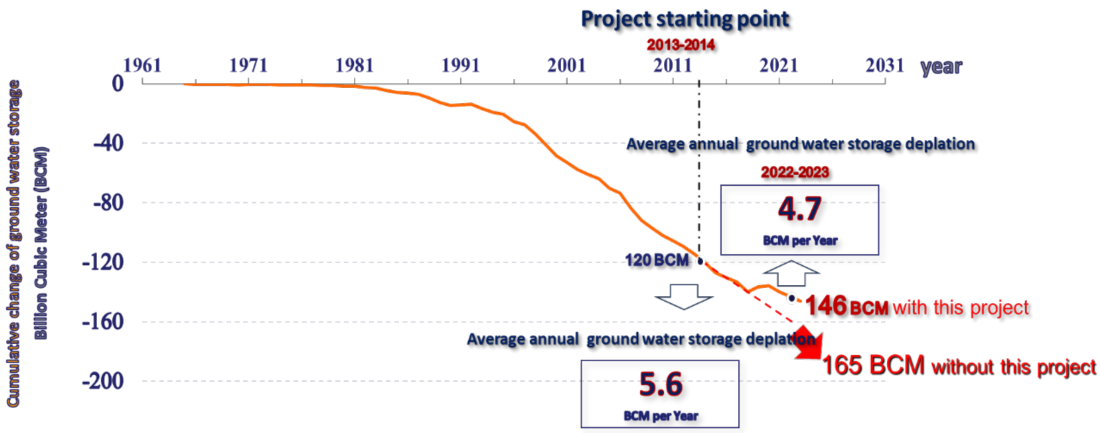

Figure 4: The trend of changes in the deficit of groundwater reservoirs in Iran and the effect of the plan implementation (DCEC, 2023)

Before the start of the plan, the average deficit of alluvial aquifers and the cumulative deficit were equal to 5.5 BCM and 120 BCM, respectively. From starting time of the plan until 2022, the cumulative deficit of aquifers has increased by only about 26 BCM (the average annual deficit of this period is 2.3 BCM). This decrease in the growth rate of the deficit (i.e., from 5.5 to 2.3 BCM per year) with the start of the plan confirms the positive effects of the planned and implemented projects of the plan. However, it is worth noting that part of the decrease in the reservoir deficit is related to the wet period that occurred in 2020 and 2021, and the other part is related to the reduction in the water capacity of aquifers and the decrease in the rate of groundwater level decline due to hydrogeological reasons. So, all decrease in the growth rate of the deficit cannot be attributed to the positive performance of the plan. Although it is not possible to calculate the exact contribution of each reason in the current situation, if the plan and the projects were not implemented as well as considering the same trend of the groundwater level decline as in the past, it should be expected that the cumulative volume of the reservoir deficit would reach 165 BCM of which about 20 BCM have been prevented, fortunately.

During the last decade (i.e., 2012-2022), Iran's average precipitation has reached 236 mm from 249 mm corresponding to the long-term period. Taking into account the 12% decrease in precipitation in the last ten years and the consequent decrease in aquifers recharging (2.5 BCM per year), it is clear that the implementation of the plan has reduced the double pressure of the past decades on groundwater resources (**Figure 5**).

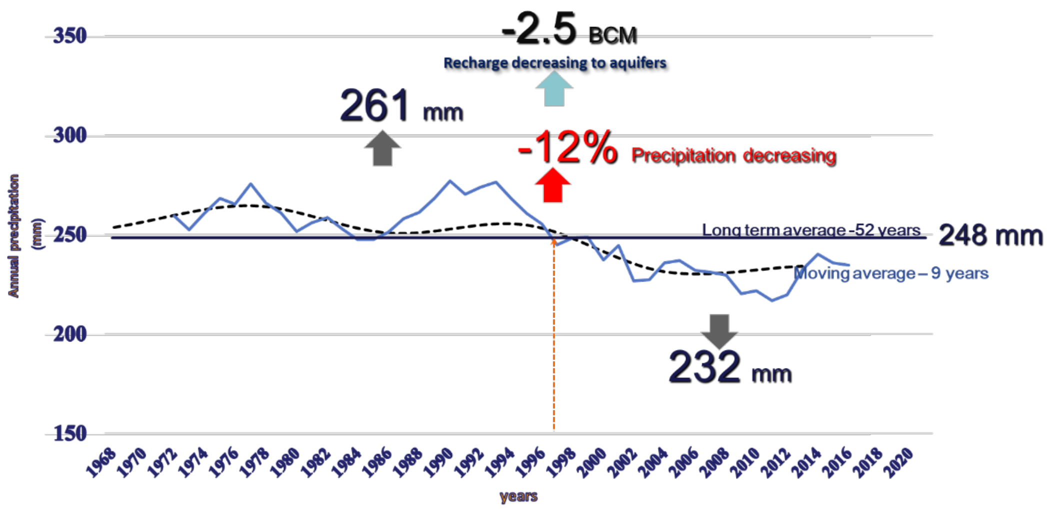

Figure 5: The decreasing trend of the average 9-year changes in precipitation and the relevant effects on recharging the groundwater sources in Iran (DCEC, 2023)

Because of some reasons such as the decrease in the natural supply of groundwater (i.e., due to climatic conditions including a decrease in precipitation and increase in temperature) and the increase in the cultivated area and the conversion of part of the pastures into agricultural lands and gardens and the lack of significant and extensive changes in the agricultural system of Iran, the values presented in **Figure 5** should be conservatively considered. Hence, it requires more verifications for which additional studies can be conducted in a number of selected plains of Iran.

6. Conclusions

Summarizing the findings and lessons learned from the implementation of the groundwater restoration plan of Iran led to the evaluation of the projects and actions implemented so far. These projects prevented or delayed half of the negative consequences of the cumulative deficit of groundwater reservoirs, while this issue has not been considered in the trends corresponding to the previous years before 2014. However, in some plains, due to the wrong behavior and neglect of groundwater resources by the operators, the interventions made by the local officials continue. Also, at the national level, there is not enough coordination and coherence in the groundwater resources management. For this reason, the plan has not been implemented well. But one should not ignore the definition and implementation of the plan. Therefore, it is very important to continue the implementation of the plan to restore and balance groundwater resources by making reforms in projects and by applying all technical, infrastructural, and human capacities.

Considering that more than 70% of groundwater resources are withdrawn by electrified wells, one of the important actions to reduce extraction in aquifers until the installation of smart water volume meters is the joint management of water and electricity through using new generation electricity meters that have capabilities such as visibility, control, and planning. At the same time, the policy of electrifying diesel wells, modifying and replacing installed devices, and using electro pumps with high efficiency in energy consumption should also be considered. This paradigm shift has tentatively been planned since early 2023 for a part of the operators.

Supplementary plans for synergy between SDGs and the exploitation of groundwater resources require the participation of operators as well as governmental measures through proper governance, management, and supervision so that these strategic resources can be protected by implementing control and preventive measures. According to the evaluation of the existing projects and in order to advance the restoration plan, the modification of the projects is underway. Some supplementary suggestions are stated below:

- Education and culture developing in the optimal and responsible use of groundwater resources and providing incentive plans through
    - Increasing awareness raising about the valuable role of groundwater in achieving SDG (SDG 6, in particular)
    - Providing facilities to the operators to improve the efficiency of water consumption and also helping to install measuring tools
- Governmental measures in order to increase optimal productivity and extraction control through
    - Synergy and alignment of laws and policies between the agriculture and water sectors
    - Appropriate pricing for water consumption used by the operators along with revisions in the provision of energy subsidies in order to pay attention to the real value of groundwater and reduce its inefficient use
    - Strengthening the approach of using virtual water, prioritizing and formulating the crop cultivation pattern, taking into account the vulnerability of the aquifer, local conditions, costs, and income, as well as the possible effects of the amount of water saved on the sustainability of groundwater resources
    - Promotion of greenhouse crops and development of cooperative management system for operators
    - Protection of natural recharge and discharge areas through flood-spreading as a cost-effective measure and preserve the ecosystem
    - Intensification of punishment for unauthorized use of water resources destroying

water quality

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Groundwater flow and governance in a rural area, Ono City, Fukui Prefecture, north-west Japan

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Abstract

Groundwater is one of the most important water resources worldwide. The surface water is a major water resource in Japan, however recent studies have focused on the importance of groundwater. The Basic Act on Water Cycle was amended in Japan in 2021, and the importance and responsibilities of groundwater management are described in the Act. Multiple local governments have constructed Water Cycle Policy Plans that focus on groundwater governance. Ono City, Fukui Prefecture, has a good groundwater governance practice. Ono City promotes artificial groundwater recharge through collaboration with multiple stakeholders, and the citizens participate in groundwater monitoring. The participation of multiple stakeholders is the key to the success of groundwater governance.

Key Words groundwater governance, stakeholder, participation

1. Introduction

The Japanese Basic Act on Water Cycle (enforced in 2014) was amended in 2021, in which the measures of sustainable groundwater conservation and use have been described and the responsibility of the local government with respect to groundwater management is clear. In addition, the Basic Plan on Water Cycle was modified in 2022 according to the Act revision, in which proper conservation and use of groundwater has been specified as a part of watershed management and the responsibility of multiple stakeholders with respect to groundwater is described. The series of above-mentioned measures should be remembered as milestones in the groundwater management policy of Japan.

Multiple local governments have constructed water cycle management plans (70 plans approved by the Secretariat of the Headquarters for Water Cycle Policy of the Cabinet Secretariat, Japanese Government, from 2016 to 2023), some of which focus on groundwater management. The focus of this section is on one of the good practices implemented in Ono City, Fukui Prefecture.

2. Groundwater in national water resources management (Japan)

2.1 Role of groundwater resources in the national water resources management plan

In Japan, the annual average precipitation is 660 billion m^3/y (1,733 mm/y), and approximately 35% of that evapotranspires; thus, the net available water resources are theoretically 430 billion m^3/y, of which 78.5 billion m^3 was consumed in 2019 for daily use (14.8 billion m^3/y), industrial use (10.3 billion m^3/y), and agricultural use (53.3 billion m^3/y) (Ministry of Land, Infrastructure and Tourism: MLIT, 2022). Water consumption is predominantly dependent on surface water (rivers and lakes); groundwater use is not dominant in Japan. Specifically, 89% of the total water use depends on surface water, and 11% is dependent on groundwater. The role of groundwater seemed to be not important for water resources in Japan; however, the importance of groundwater has increased recently because of its additional value, such as steadiness in quantity and quality, tourism resource, regional community asset, and symbol of human well-being.

2.2 Administrative and legal framework for groundwater management

The urban areas of Japan, especially Tokyo and Osaka, suffered from groundwater overexploitation and serious land subsidence in the 1960s (Tanaka, 2015). The Industrial Water Act of 1956 and Building Water Act of 1962 were established for groundwater conservation. These acts specified the target region and regulated groundwater exploitation; however, the regulation was limited, so the area of land subsidence expanded throughout Japan (Miyazaki, 2022). In parallel, local governments established ordinances to regulate groundwater pumping, and land subsidence diminished at the end of the 1970s.

Groundwater conservation and use are clearly described in the amended Basic Act on Water Cycle of 2021. One of the most important points in this amendment is that the monitoring, observation, data collection, analysis, and archiving of groundwater are specified in the Act, which is the general scientific process of groundwater hydrological research.

Recently, there has been a lot of focus on groundwater governance and management for better sustainable groundwater conservation and use. Groundwater governance and groundwater management sometimes have the same meaning; however, groundwater governance is defined as a process of groundwater conservation, management, and decision-making based on scientific understanding under collaboration in vertical and horizontal directions among multiple stakeholders (Chiba, 2020). The Secretariat of Headquarters for Water Policy published a "Manual of Groundwater Management" in 2019 and has promoted groundwater management.

3. Case Study: Groundwater status in Ono City, Fukui Prefecture, Japan

3.1 Water supply and demand of Ono City

The annual average precipitation in Ono City is 2,412 mm/y and the annual cumulative snowfall is 485 cm/y, which is a groundwater recharge source. The dominant water resource for daily, industrial, and agricultural use is groundwater, and the groundwater pumping rate was 8.34 million m^3/y in 2019. The spread ratio of waterworks was 38% and that of the sewage system was 85% in 2019 in Ono City because groundwater is the main water resource for daily use (Fig. 1).

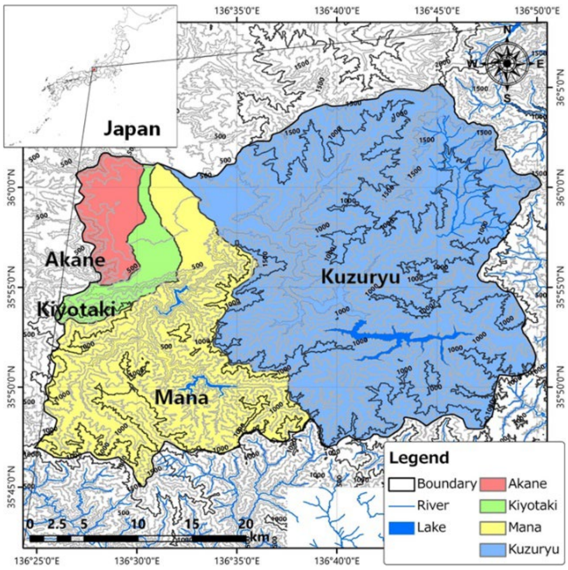

Fig. 1. Map of Ono Basin, Fukui Prefecture.

3.2 Hydrogeological setting of Ono City

Ono City (basin) is mainly underlain by sand and gravel, partly with clay as the main aquifer, with a thickness ranging from 40 m to 70 m and andesite and granite as the bedrock. The aquifer consists of alluvial deposits permeable in the west of the basin. Four rivers flow into the Ono Basin (Akane, Kiyotaki, Mana, and Kuzuryu Rivers from west to east), and the rivers interact with groundwater.

3.3 Groundwater and spring water use in Ono City

Ono City has a long history of groundwater and spring water use for daily life since the 1600s. The citizens conserve and use spring water, and they call the springs in the city "Sho-zu," in which "sho" means "clean" and "zu" means "water." However, Ono City suffered from serious groundwater table drawdowns due to over-pumping for thawing during the winter season from the 1970s to the mid-1980s. In addition, tetrachloroethylene was detected in groundwater in 2000. Ono City established the Regulation of Groundwater Conservation in 1977 and Management Plan of Groundwater Conservation in 2005, based on a comprehensive investigation of groundwater from 2001 to 2002.

4. Scientific investigation and policy of groundwater governance in Ono City

Figure 2 shows a spatial distribution of stable isotopic composition of ^{18}O in the river water and groundwater of Ono Basin. River Mana flows from south to north in the center of the basin, and there is a clear area with a lower ^{18}O value in the groundwater on the left side of River Mana (surrounded by the dotted line shown in red). This shows that groundwater on the left bank side of River Mana is dominantly recharged by River Mana water. Figure 3 shows a contour map of the groundwater table in the basin. The contour map also shows that the direction of groundwater flow is from east to west on the left bank of River Mana at the foot of the mountain in the southern area. This also means that River Mana water recharges the groundwater on the left bank of the river. There is a dam upstream of River Mana, and the Ono City Office and Dam Office perform artificial discharge from the dam during a certain period to enhance groundwater recharge from the river. The political performance of the artificial recharge is supported by the aforementioned scientific research outcomes.

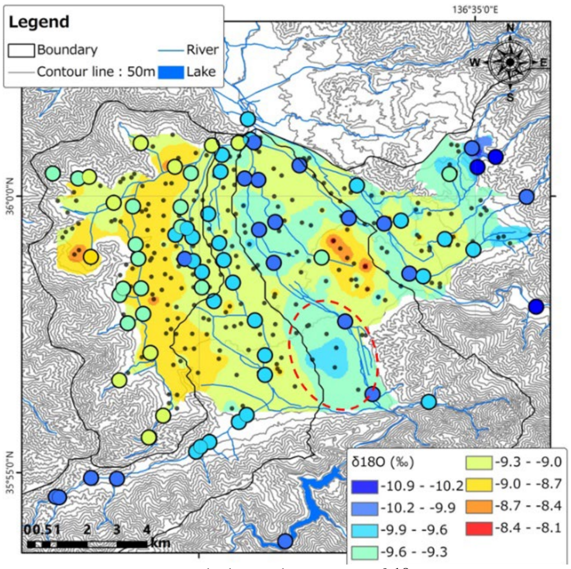

Fig. 2. Spatial distribution of ^{18}O in groundwater and river. (dotted line circle shows an area with lower ^{18}O value).

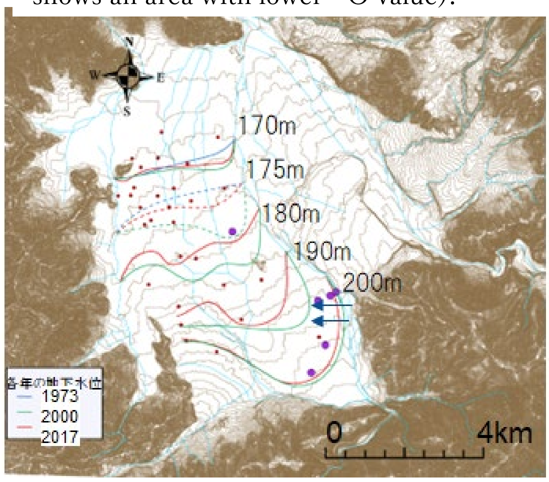

Fig. 3. Contour map of groundwater level observed in August 1973, 2000, and 2017. The arrows show direction of groundwater flow.

The monitoring system for the groundwater level by citizens was organized using 34 monitoring piezometers at 31 locations in Ono City. The citizens observe the groundwater level every day and report it to the city office. Citizen participation promotes concern for and recognition of groundwater conservation and use in Ono City.

Figure 4 shows the history of scientific research and governance of groundwater in Ono City. The policy of the Ono City Office is clearly supported by scientific research, and the multiple stakeholders–citizens, the agricultural sector, and companies–contribute to the political actions for groundwater and spring water conservation. The contribution of stakeholders and scientific data is key for the successful completion of the policy.

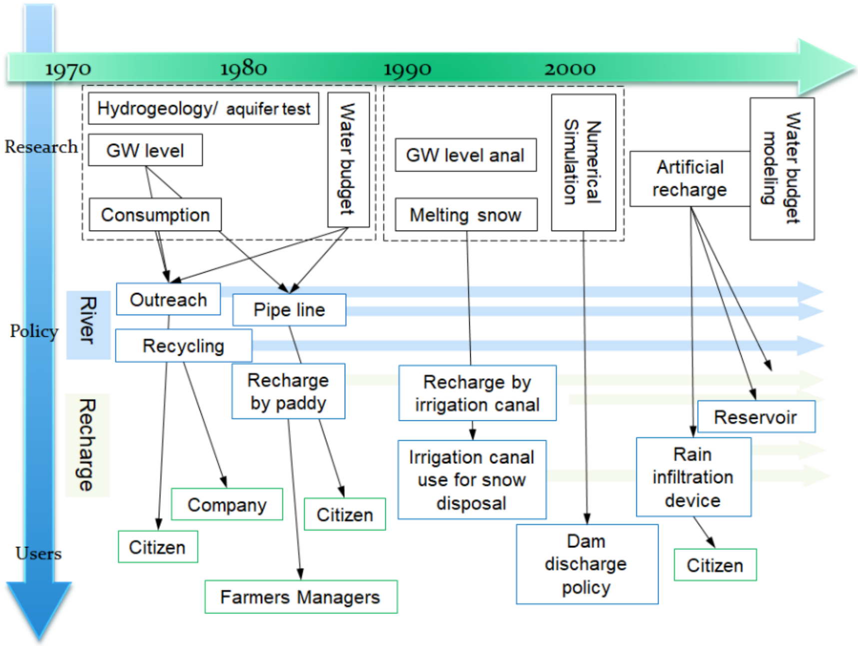

Fig. 4. History of groundwater policy and scientific investigation of groundwater in Ono City, Fukui Prefecture.

5. Conclusions

Japan suffered from over-pumping of groundwater and serious land subsidence in the 1960s and has overcome these issues. Groundwater governance is being recently promoted in Japan. Multiple local governments have constructed water cycle policy plans that focus on groundwater governance. Ono City, Fukui Prefecture, has a good groundwater governance practice. The Ono City Office promotes artificial groundwater recharge by using the discharge from the dam to the river in collaboration with multiple stakeholders, and the citizens participate in groundwater monitoring. The participation of multiple stakeholders is key to the success of groundwater governance.

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Groundwater management at Pretashkent Aquifer and Ecological disaster zone of the Aral Sea region (Kazakhstan)

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Abstract

The current article aims at presenting the current status of groundwaters in Kazakhstan, their use and challenges that arise in regard to this precious and valuable water source. The introductory chapter gives an overview of the availability of groundwater in the country, describes different factors that influence its use as well as provides data details on the distribution of groundwater reserves throughout the country and the demand for drinking water and its supply from groundwater. The following chapter gives an overview of the institutional framework in the country when it comes to the management of groundwaters as well as summarizes the legal basis for the regulation of groundwaters in Kazakhstan. The practical case studies are given to present current efforts to effectively manage the transboundary Pretashkent Aquifer and the Mynbulak Artesian Basin. The article is supplemented by key lessons learned identified in each chapter and by the conclusion at the very end of the article.

Key Words*: groundwater, management of groundwater, water supply, Pretashkent Aquifer, groundwater laws, Mynbulak Artesian Basin, Aral Sea*

1. Introduction

1.1 Overview

All water found beneath the ground surface in the saturated zone we can call groundwater. It is a valuable source of fresh water, widely used for domestic and drinking water supply, in industry, irrigation of agricultural land, for medical and other purposes. Therefore, for Kazakhstan, which is characterized by an arid, sharply continental, arid climate and limited surface runoff, groundwater is in many cases the only source of water supply. (Absametova et al., 2020)

As a result of climate change the volume of water resources generally in Central Asia, including Kazakhstan, is reduced. Climate change magnifies its consequence which results in a reduction in the availability of water in the region. The increase in droughts, floods, mudflows or other natural phenomena as well as an increase of the population´s demand for water hand in hand with economic activity have an impact on the water resources in a country. This demand is likely to increase as to compensate for the reduction of surface waters on the other hand. Hence, groundwater will play an important role in society and in the adaptation of the water sector to climate change.

Rational and efficient use of groundwater, taking into account measures that would protect it from depletion or pollution is therefore one of the key tasks for Kazakhstan. The current management practices in many regions of the country cannot cope with climate variability (Absametova et al., 2020). In this regard, integrated groundwater management might significantly help the country in its efforts towards the effective institutional management as well as towards legal regulation of groundwater.

1.2 Groundwater resources and their use in Kazakhstan

The arid climate of the vast majority of the territory of Kazakhstan is exhibited in high solar activity, low precipitation, often not exceeding 200 mm per year, low relative air humidity (less than 20% in summer), high evaporation from the surface of open water bodies and evapotranspiration, 1000 mm/year. In the context of climate change, an important factor in the formation of groundwater conditions is a change in the temperature regime of the territory. In recent years, there has been an increase in the average temperature on the territory of Kazakhstan - approximately 1.8 ° C per 100 years, which is more than 2 times higher than global values. Air temperature increase causes intensification of evaporation and reduces the amount of groundwater recharge, i.e. groundwater resources depletion.

These climatic factors, along with a relatively sparse river network, determine the difficult conditions for groundwater recharge. But at the same time, the geological and structural features of the surface layers of the earth's crust have predetermined the widespread distribution of underground reservoirs going hundreds and thousands of meters in depth and hundreds of square kilometers in area. Groundwater is confined mainly to the Quaternary, Neogene, Paleogene and Cretaceous aquifers; genesis differs as arrays of fissure waters, river valleys, artesian basins, alluvial fans.

Kazakhstan's groundwater resources are determined by a range of resources and reserves indicators. Natural resources are represented by the map of natural groundwater resources on the territory of the Republic of Kazakhstan on a scale of 1: 2,500,000. The authors proceeded from the fact that natural resources characterize the amount of groundwater recharge due to infiltration of atmospheric precipitation, absorption of river runoff and overflow from other aquifers, expressed in total flow rate. Natural groundwater resources are an indicator of groundwater replenishment, reflecting its main feature as a renewable nature's endowment, and characterize the upper limit of the possible withdrawal of groundwater over a long period without depletion. In the process of compiling a map of natural groundwater resources, the authors used data on the distribution of precipitation over the territory of the Republic of Kazakhstan, river runoff, the results of determining the natural groundwater resources during the exploration of large groundwater deposits. The value of natural resources in Kazakhstan as a whole equals to 105,046.45 thousand m^3/day, with an average modulus of -0.45 l/s per 1 km^2 (**Figure 1**)

The practical significance of the groundwater use is reflected in the work on the assessment of reserves, as well as a number of maps of the operational characteristics of groundwater deposits and on the territory of administrative regions and the main regions of Kazakhstan. According to official sources, the total amount of predicted groundwater resources in Kazakhstan is 176 million cubic meters per day, of which about 63% or 111 million cubic meters per day is fresh, which is about 40 cubic kilometers per year. For comparison: the amount of surface water resources available for use, with an average long-term runoff, in Kazakhstan as a whole reaches 46 cubic km per year, which indicates their comparability.

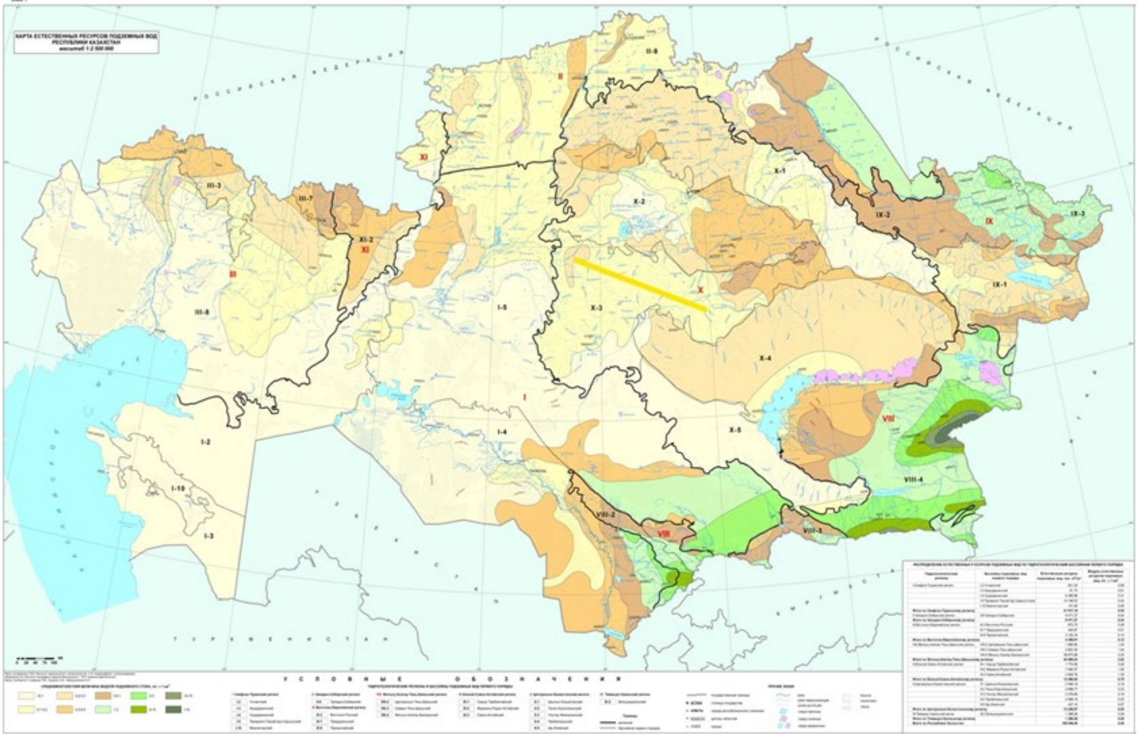

Figure 2. Hydrogeological map of Kazakhstan 1:2 500 000 (Achmedsafina et al., 2022)

As of 01.01.2022, 1510 groundwater deposits with various operational capabilities have been explored in Kazakhstan. The total value of operational groundwater reserves is 42,040.61 thousand m3/day (15.34 km3/year), or approximately 24% of predicted resources with salinity up to 10 g/l (176,105.5 thousand m3/day) and 38% of predicted resources with salinity up to 1 g/l (110,789.2 thousand m3/day). Among the operational reserves, fresh water is 36,127.23 thousand m3/day, or about 86% of their total amount (Absametova et al., 2020). This indicates a relatively high degree of groundwater exploration in Kazakhstan and, at the same time, significant potential opportunities for providing the country's population with groundwater, including for drinking purposes.

According to the intended purpose, the operational groundwater reserves are distributed as follows, thousand m3/day (km3/year): household and drinking water supply - 15,928.76 (5.81); industrial and technical water supply - 3,019.35 (1.10); land irrigation - 23050.88 (8.41); balneological purposes - 41.61 (0.015) (Absametova et al., 2020).

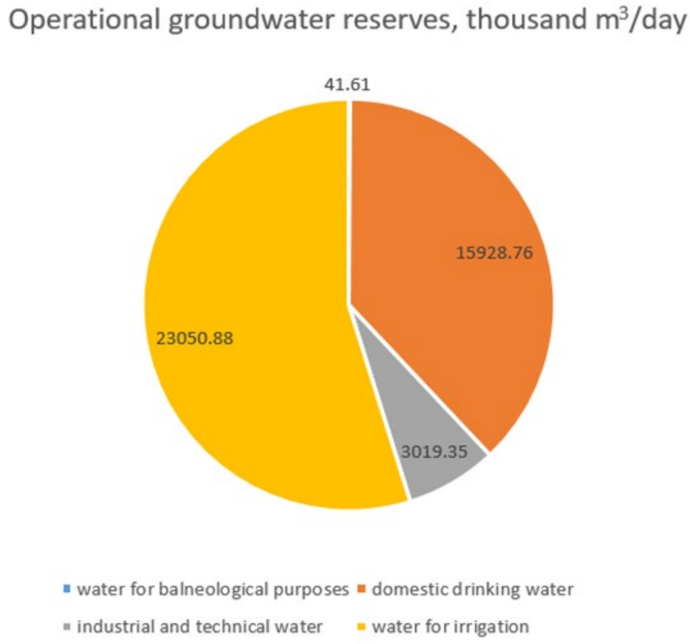

Figure 2. Operational groundwater reserves.

Taking into account the importance of the problem of providing the population with water of drinking quality, an assessment of the territories of administrative regions was carried out in order to determine the degree of their provision with fresh groundwater. The criterion for the degree of water supply of the administrative regions of Kazakhstan with groundwater for household and drinking purposes was the ratio of the needs of the regions in fresh water with the value of the predicted resources and operational reserves of groundwater with salinity up to 1 g/l. On this basis, the following territories were identified: reliably provided with groundwater for household and drinking purposes - K> 1.5; secured - K = 1.0–1.5; partially provided - K = 0.5–1.0; insufficiently provided - K <0.5 (Absametova et al., 2020).

As a result of assessing the degree of provision of the administrative regions of Kazakhstan with operational groundwater reserves for household and drinking purposes, Atyrau and North Kazakhstan regions are classified as insufficiently provided (K < 0.5), and Mangystau and Akmola - as partially provided (K = 0.5-1). The rest of the regions and the republic as a whole are classified as reliably supplied with proven reserves of groundwater for household and drinking purposes (K > 1.0) (Absametova et al., 2020).

Recent studies carried out by the Institute of Hydrogeology and Geoecology named after U.M. Ahmedsafin, devoted to the provision of the Republic of Kazakhstan with groundwater reserves for various purposes, showed the following picture of water availability at the present time and in the future for 2030.This research has been funded by the Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan (Grant No. BR10262555).

Table 1 Distribution of groundwater reserves in Kazakhstan as of 1.1.2020

Distribution of explored groundwater reserves of the Republic of Kazakhstan by administrative regions as of 01.01.2020								
№	**Administrative region**	**Number of deposits**	**Operational groundwater reserves, thousand m3/day**	**Distribution of deposits by purpose: explored reserves, thousand m3/day**			
				HPV	**PTV**	**ORZ**	**MIN**
Western Kazakhstan (Aktobe, Atyrau, West Kazakhstan, Mangistau regions)		836	2906,11	1556,472	673,746 4	796,0152	147,363 8
Southern Kazakhstan (Almaty, Zhambyl, Kyzylorda, Turkestan regions)		1328	25047,37	12540,83	3629,00 4	14562,05 6	3308,48 8
East Kazakhstan (East Kazakhstan region)		516	6482,055	2485,667	764,813	3310,814	0,940
Central Kazakhstan (Karaganda region)		417	2873,537	2230,279	308,610	422,250	1,066
Northern Kazakhstan (Akmola, Kostanay, Pavlodar, North Kazakhstan regions)		1337	5698,778	2554,907	1491,78 6	1049,088 1	1049,90 1

In order to increase the water supply of the population with groundwater, in 2002, the sectoral program "Drinking Water" was adopted, the implementation of which by 2010 was supposed to solve the problem of household and drinking water supply for the majority of the rural population. During the years of work on the program, the water supply of 3417 rural settlements has been improved. The number of residents using imported drinking water decreased from 445 to 83 thousand people. Meanwhile, in the implementation of the "Drinking Water" program and subsequent programs for 2010-2022 a number of shortcomings have been identified. The main ones include the lack of a systematic approach and proper interaction between the central and local executive bodies (Absametova et al., 2020).

The drinking water supply of the population of the republic was assessed based on two main sources: a demographic forecast of changes in the population of the regions of Kazakhstan from 2022 to 2030, as well as data on groundwater reserves, explored and approved by government agencies as of 01.01.2022. The results of the calculations showed the following picture: The population of the regions of Kazakhstan is provided with drinking water to varying degrees: by 2030, explored and approved in 2022 operational reserves with a security factor of 2-3 are reliably provided to Southern, Central and Eastern Kazakhstan, at the same time, Western and Northern with coefficients 1.2 - 1.5 are provided (**Table 2**). However, low share of groundwater abstraction for these needs should be noted.

Table 2 Demand for drinking water and its supply from groundwater in Kazakhstan 2022-2030

Demand for drinking water and its supply from groundwater in the Republic of Kazakhstan in 2022 and in the future for 2030.						
No. p / p	**Regions of Kazakhstan**	**Average annual headcount by regions (baseline) thousand people**		**Water demand (normative), m3/day**		**Operating reserves for cold water, m3/day**
		2022 y.	**2030 y.**	**2022 y.**	**2030 y.**	**As of 01.01.2022**
1	Western Kazakhstan	3051	3397	821320	722356	1095436
2	South Kazakhstan	9650	9567	2514722	2922004	7458639
3	Northern Kazakhstan	4236	4556	1268142	1411154	1955082
4	Central Kazakhstan	1356	1326	430736	424956	2368934
5	Eastern Kazakhstan	1343	1283	375630	368676	1004564
6	Total RK	19635	20129	5410550	5849146	13882655

2. Groundwater in the national water resources management (Kazakhstan)

2.1 Institutional Framework for groundwater management

State water management is based on the principles of recognizing the national and social importance of water resources, sustainable water use, separating the functions of state control and management, and basin management.

Groundwater management in Kazakhstan is carried out by the authorized body in agreement with the state body for geology and subsoil protection. It is currently implemented by the Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan (MEGNR).

Unfortunately, the management of groundwater resources in the Kazakhstan does not have its own separate body for control. It is always included in the general list of water resources, which is monitored by government agencies. However, the Strategy until 2050 ("Kazakhstan - 2050", 2012) notes that groundwater is an important strategic source for providing the population of the country with fresh water in a changing climate. And therefore, the increasing attention of scientists, international organizations to the issues of groundwater resources makes it possible to see the invisible and begin the rational and effective management of this resource.

By Decree No. 1359 of December 30, 1998, the regional committees for water resources were reorganized into republican state water enterprises, which are entrusted with the maintenance of hydroelectric facilities, main water pipelines, main networks, pumping stations, group water pipelines, i.e. provide consumers with water. The next stage of the reform was the transition in 2001-2002 of water management facilities (with the exception of objects of national importance) from state to communal ownership, as well as the empowerment of the local level with the authority to manage them. Separation of water resources management functions and improvement of water use regulation mechanisms allows taking into account the interests of water users both within the entire basin and in a certain territory. This also allows effective measures to be taken to protect basin waters from depletion. Under market conditions, the management system should ensure the conservation and reproduction of water resources, the proper timing of water use, the preservation of environmental sustainability within a particular catchment, basin and area (UNDP, 2004).

The result of the reforms was a **multi-level system of water resources management**, represented by intergovernmental, state, basin and territorial levels of management. These levels are interconnected and perform the following tasks:

At the intergovernmental level of water resources management, cooperation is envisaged for the joint use and protection of water resources. At this level, the following issues are considered, based on international practice: water resources management, reduction or prevention of negative impacts; prevention of water losses in the upper reaches and in parts of the basins by reducing evaporation losses from the surface; and cooperation in protecting water quality. At this level, water resources management is carried out through various interstate commissions for the use and protection of water resources of transboundary rivers (UNDP, 2004).

The Interstate Commission for Water Coordination of Central Asia (ICWC) is a regional organization that determines water policy, "taking into account all the needs of economic sectors, integrated and rational use of water resources, a long-term regional water supply program and measures for its implementation." » and approves water use limits (ICWC, 2023). Among the regional institutions are also the Interstate Council for the Aral Sea (IGAC), the Interstate Commission for Sustainable Development and the International Fund for Saving the Aral Sea (IFAS). It can be concluded that there are international and national institutions, and they can act as an initiating mechanism for transboundary cooperation. In the meantime, countries need to agree on specific rules for the use and protection of specific and individual groundwater aquifers (Kokimova, 2019).

At the governmental level, water resources management, including groundwater, is carried out by authorized bodies, whose activities are regulated by the Constitution of the Republic of Kazakhstan.

The State Committee for Water Resources under the Ministry of ecology, geology and water resources of the Republic of Kazakhstan is a main governmental organization, which is responsible for ensuring coordination on the implementation of state policy, the implementation of strategic, regulatory, implementation and control and supervisory functions in the field of water resources management. The State Committee is responsible for inter-sectoral and inter-provincial water allocation, as well as setting national policies for water quality and water resource protection. The structure and staff size of the Committee is approved by the Executive Secretary of the Ministry of ecology, geology and natural resources of the Republic of Kazakhstan after approval by the Minister itself (Committee for Water Resources, 2019).

Table 3 Functions of the State Committee for Water Resources of the Republic of Kazakhstan (Committee for Water Resources, 2019)

Functions of the State Committee for Water Resources of the Republic of Kazakhstan
1) exercises state control over compliance with the requirements for the regime of economic activity in water protection zones and strips within its competence; 2) establishes the volumes of environmental and sanitary-epidemiological passes for the basins of water bodies; 3) develop and approve water quality standards for surface water bodies; 4) creates, together with interested state bodies, a republican information and analytical system for the use of water resources; 5) creates an information database of water bodies and provides access to it for all interested persons; … 22) coordinate the use of groundwater of drinking quality for purposes not related to drinking and household water supply…

In general, at the governmental level, there are seven ministries and departments (in total, more than 17 departments within ministries) involved in the process of managing the water sector. The policy of the sector is currently being formed within the framework of various ministries: The Ministry of Regional Development is in charge of municipal water supply, the Ministry of Agriculture is in charge of water consumption in agriculture, the environmental policy is being formed in the Ministry of Environment and Water Resources.

At the basin level the water resources are managed by the local basin organizations (BWO). It oversees eight national water management organizations of river basins: the Aral-Syrdarya, Balkhash-Alakol, Irtysh, Ishim, Nura-Sarysu, Tobol-Turgay, Ural-Caspian and Chu-Talas BWOs.

Examples of activities at this level include: the construction of causeways, reservoirs, dams, centralized groundwater inlets, and pumping works; regulation of river flows and the work of major reservoirs; finding alternative sources of freshwater; reducing losses during water supply and distribution.

Management plans at these levels should be mostly based on realistic needs and consider current social and economic conditions in catchment basins. Management at the lower levels should correspond to general management plans and water policy should be oriented towards all levels of management (UNDP, 2004).

At the territorial level, technical maintenance of all state water bodies is carried out. This level is managed by Water user associations (WUAs). Work at this level is usually aimed at reducing water losses during transportation and distribution, delivering quality water in sufficient quantity and on time to various points, and establishing effective links between central and local organizations dealing with water resources in various areas. An important task here is to create an effective network of non-state services and private companies for the maintenance and repair of water supply facilities (UNDP, 2004).

Organic water management in the Republic of Kazakhstan is hampered by a lack of data, insufficient quality control and implementation of efficiency measures, and low levels of compliance. There is no integrated national database containing important data on the balance of water management and water consumption in various sectors. In addition, there is no unified electronic database on the state of water bodies (UNDP, 2004).

At the moment, according to many experts, there is a loss of consistency in the enforcement of water resources management, which generally leads to a deterioration in the situation at all levels of water management development. To resolve issues of sustainable water resources management in 2019, a Draft Concept of the State Program for the Management of Water Resources of Kazakhstan for 2020-2030 was developed. This concept provides for measures to manage water resources to increase the water supply of the natural and economic systems of Kazakhstan. These measures include the improvement of interstate water relations; assessment and forecast of the water resource potential of Kazakhstan, taking into account climate change and economic activity; development of explored groundwater reserves, taking into account their interaction with surface waters; prevention of the harmful effects of water and dangerous water-related phenomena; etc. (Draft Concept of the State Program of Water Resources Management of Kazakhstan for 2020-2030, 2019).

2.2 Legal Framework for groundwater management

Due to the growing water deficit in Kazakhstan, it is becoming more and more challenging to satisfy the population´s water needs. The groundwater, in particular, has become the main source of water not only for domestic uses but also to a significant extent for agricultural purposes (Yerkinbayeva et al., 2015). The role of groundwater is therefore very actual, taking into account the increasing influence of climate change and the unequal distribution of water resources across the territory of Kazakhstan.

In this context, the development of legislation in the field of groundwater is crucial and becoming relevant not only in Kazakhstan but also in other parts of the world. We should bear in mind that laws regulating the use and preservation of groundwater are still relatively new. Hence, the national policy-makers in many countries including Kazakhstan have to deal with some novelty when it comes to provisions on groundwater in national water or environmental laws.

To examine the current status of the legal framework for groundwater management in Kazakhstan, it is necessary to first look at the international law regulating groundwater, and subsequently at the national laws.

International law, in general, has so far given little attention to groundwater. The groundwater is mainly included in the scope of international legal instruments only if related, connected to surface waters or it is not mentioned at all. There are few such instruments which explicitly dedicate specific provisions to groundwater (Burchi et al., 2005). For instance, from international non-binding instruments - United Nations International Law Commission Resolution on Confined

Transboundary Groundwater (UN ILC, 1994), from non-governmental agreements - International Law Association Rules on International Groundwaters (ILA, 1998).

When it comes to global conventions which contain provisions on groundwater, there is only one such convention Kazakhstan has ratified so far, mainly United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification (UN, 1994). Although Kazakhstan is not a party to the global UN Watercourses Convention (UN, 1997) which already in its Article 2 mentions groundwaters as part of the system constituting a watercourse, the country has ratified the UNECE Water Convention (1992) (UNECE, 1992). This multilateral treaty, for instance, in its Preamble refers to the UNECE Charter on Groundwater Management (UNECE, 1989), in its first provision on the term *"transboundary waters"* include the ground waters as well and the treaty also highlights specific requirements of groundwater to be taken into account for water quality objectives and criteria in its Annex III. From other legal instruments, we can mention the Draft Articles on the Law of the Transboundary Aquifers (DA) (UN, 2008) or UNECE Model Provisions on Transboundary Groundwaters (Model Provisions) (UNECE, 2012).

Despite the fact that DA are not legally binding, they are built on the provisions found in Watercourses Convention, they are more specific and serve as a model for further regulation of transboundary aquifers, incl. groundwaters. The Model Provisions reflect on the DA, expand them and provide interpretative guidelines for implementation of Water Convention with regard to groundwaters (Eckstein, 2017). In 2012, Workshop on Legal, Institutional and Technical Aspects of Managing Transboundary Groundwaters was held in Almaty, Kazakhstan, organised by the UNECE, OSCE Center in Astana, UNESCO, UNDP and other. During the workshop the Model Provisions were discussed and concluding part of the event recommended to promote awareness about DA in the region (ISARM, UNESCO IHP, 2012).

At the national level, groundwater is mentioned in Article 6 paragraph 3 of the Constitution of Kazakhstan, in relation to property regulation of groundwater: *"The state shall own the land and underground resources, waters, flora and fauna, and other natural resources"* (Constitution, 1995). In other cases, the groundwater is regulated by Kazakh legislation mainly in water- or subsoil-related laws.

The core law is the Water Code of the Republic of Kazakhstan (WC), defining the groundwater bodies in its Article 13 (Water Code, 2003). These include groundwater basins, deposits and sections of underground waters, aquifers and complexes, and natural outlet of groundwater on land (springs). In Article 1 the Code is classifying groundwater into 5 categories: household and drinking, mineral, industrial-technical, industrial and thermal groundwater.

The Code seeks to limit the use of *"drinking-quality groundwater"* on many occasions, most notably in Article 72 defining the responsibilities of water users. The article prevents the use of drinking-quality groundwater for purposes not related to drinking water supply. Similar provisions we can find, e.g. in Article 90 of the WC.

The groundwater which is not classified as *"drinking and mineral water, may be used for technical water supply and for other industrial needs under special water use conditions in compliance with environmental requirements"* (Water Code, 2003).

For the special use of water, including groundwater the WC requires permits. This is regulated by the Article 66 of the WC which defines certain structures and technical devices when such permits are necessary. For instance, these include irrigation, watering, drainage systems, spillway structures, absorption wells, etc. (Water Code, 2003).

The separate provision on peculiarities of protection of groundwater bodies can be found in Article 120. The article, for instance, emphasizes that *"individuals and legal entities, whose industrial activity may have an adverse impact on ground waters, are obliged to monitor ground waters and to take timely measures to prevent pollution and depletion of water resources and the harmful effects of waters."* The Article also prohibits irrigating lands with wastewater if it affects or may affect the status of ground waters (Water Code, 2003). Other protection measures are listed within the operations on subsoil use, within underground water intake during construction and operation of drainage systems, etc. (Water Code, 2003).

Another important aspect of the regulation of groundwater is its commercialization and transformation into a commodity. As was mentioned above according to the general rules, prescribed already in the Constitution of the country, the right of government ownership applies to all natural resources. However, this applies only as long as we are not talking about commodities. For instance, thermal waters are used for commercial purposes and the legislation is lacking regulation in this regard (Yerkinbayeva et al., 2015).

In the following years, will be, therefore, important to adopt new laws or new sections, and provisions to WC regulating the protection of groundwater, incl. thermal waters.

In Kazakhstan, the promising step forward might be a new Water Code, which is currently under development and should be submitted to parliament for consideration this year (Water Diplomat, 2022).

Similarly as with the water resources in the WC, the subsoils regulated by the Code on Subsoil and Subsoil Use of the Republic of Kazakhstan (CSS) are in exclusive ownership of the state. The CSS is classifying groundwater as a mineral resource, underlining the responsibilities of subsoil users to prevent the accumulation of industrial and domestic waste in catchment areas and in places where groundwater occurs, which is used for drinking or industrial water supply (Code on Subsoil and Subsoil Use, 2017). On other occasions, the CSS mentions groundwater when dealing, e.g. with the territories for the subsoil space use or within the mining processes.

Last but not least, it is important to mention the Ecological Code of the Republic of Kazakhstan (EC), devoting to groundwater relatively many provisions. The EC contains provisions dedicated to the protection of groundwater, for instance, in its Article 212 dealing with the protection of water bodies (Ecological Code, 2021). The general provision can be found also in Article 219: *"To prevent harmful anthropogenic impact on water bodies, the environmental legislation of the Republic of Kazakhstan establishes mandatory environmental requirements for the protection of surface and ground waters when carrying out activities"* (Ecological Code, 2021).

The EC underlines the impact on groundwater, in particular, when it comes to provisions on environmental impact assessment (Ecological Code, 2021). Other provisions include, for instance, the special use of water, incl. groundwater where the permit is required by either WC as well as by EC (Ecological Code, 2021).

Other laws explicitly or implicitly mentioning groundwater include, e.g.: Rules for the implementation of state monitoring of subsoil; Rules for maintaining state accounting of waters and their use, state and city monitoring of water bodies; General scheme for the use and protection of water resources; Rules for classifying a water body as a source of drinking water supply; SNiP RK 4.01-02-2009 "Water supply. External networks and facilities"; Sanitary and epidemiological requirements for water sources, places of drinking water supply, drinking water supply and places of cultural safety of water bodies, etc.

Table 4 International and National legal framework for groundwaters in Kazakhstan

International Level	National Level
Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification (1994)	Water Code of the Republic of Kazakhstan
UNECE Water Convention (1992)	Code on Subsoil and Subsoil Use of the Republic of Kazakhstan
	Ecological Code of the Republic of Kazakhstan
	Rules for the implementation of state monitoring of subsoil
	Rules for maintaining state accounting of waters and their use, state and city monitoring of water bodies
Draft Articles on the law of transboundary aquifers (2008)	General scheme for the use and protection of water resources
	Rules for classifying a water body as a source of drinking water supply
UNECE Model Provisions on Transboundary Groundwaters (2012)	SNiP RK 4.01-02-2009 "Water supply. External networks and facilities"
	Sanitary and epidemiological requirements for water sources, places of drinking water supply, drinking water supply and places of cultural safety of water bodies

By regulating the groundwater mainly within the water or subsoil laws, the current legislation does not allow for specific regulation of groundwater. A significant change might come with the new WC, giving the emphasis on the specificity of groundwaters, avoiding the general rules which define the legal regulation of the groundwater in Kazakhstan now.

3. Case Study: Groundwater status in the Pretashkent Aquifer

3.1 Introduction into the case study

The Pretashkent Aquifer, located in the territories of the Republics of Kazakhstan and Uzbekistan, is a significant transboundary deep-water aquifer that serves as a crucial source of artesian water. The aquifer's history dates back to 1947 when the first wells were drilled, and presently, the territory of Kazakhstan part of the Pretashkent Aquifer comprises 37 wells (UNESCO, 2016) (**Figure 3**).

During the early 1980s, a comprehensive reevaluation of the groundwater reserves of the Pretashkent Aquifer was conducted in the two Soviet Republics. This reevaluation resulted in the approval and division of reserves between the Republics, with Kazakhstan allocated 1,464 m3/day and Uzbekistan 2,044 m3/day (UNESCO, 2016). While this allocation agreement remained in effect until the dissolution of the Union of Soviet Socialist Republics, it became void following the independence of Kazakhstan and Uzbekistan, thereby halting joint management of the aquifer. Regrettably, the unresolved issue of cross-border management continues to persist between the two republics.

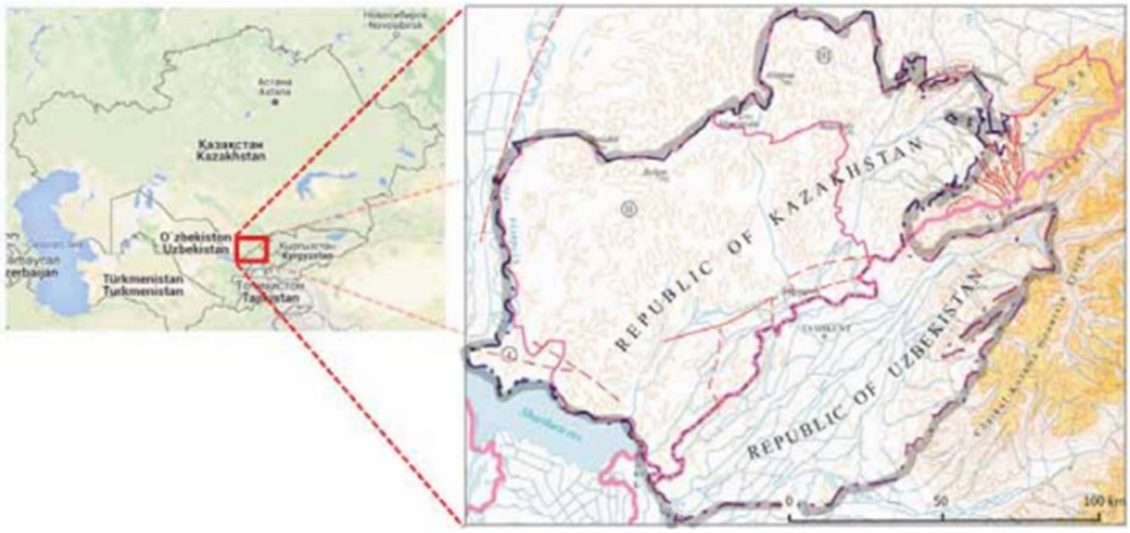

Figure 3 Location of the Pretashkent Aquifer (UNESCO, 2016)

Significant efforts have been accomplished by GGRETA Project - Governance of Groundwater Resources in Transboundary Aquifers within the Pretashkent Aquifer. Over the years, this project, funded by the Swiss Agency for Development and Cooperation and implemented by the UNESCO Intergovernmental Hydrological Programme (UNESCO-IHP), has facilitated collaboration between scientists from both countries and governmental stakeholders (e-link). Together, they have developed a mathematical model of the Pretashkent transboundary aquifer, serving as a fundamental tool for its joint management.

As a result of the project, a comprehensive concept of a Road map for the protection and sustainable use of the Pretashkent transboundary aquifer's groundwater resources has been formulated and approved by the relevant governmental bodies of both countries (e-link). This Road map establishes the wide range of activities aimed at ensuring the long-term viability of the aquifer, considering its significant role in the economies of both Kazakhstan and Uzbekistan.

The Pretashkent Aquifer holds vital importance for the economies of both countries due to its extensive utilization in various sectors, including tourism, balneological practices, agriculture, and mineral water bottling. Any modifications in the water quality of the aquifer resulting from a decline in the wellhead below the surface could have severe consequences. This includes the potential loss of employment in sanatoriums and resorts reliant on groundwater and water scarcity issues for agricultural purposes.

Effective management of the Pretashkent Aquifer is crucial to ensure the sustainable use of its water resources. Ongoing cooperation between Kazakhstan and Uzbekistan, implementing robust strategies, monitoring the aquifer's water quality, and promoting sustainable practices are essential to address the outstanding challenges associated with cross-border management and the long-term viability of this valuable transboundary resource benefiting both nations.

3.2 Water supply and demand of the Pretashkent Aquifer, South Kazakhstan

The Pretashkent Aquifer, situated in three administrative districts of southern Kazakhstan, is a crucial water source for agriculture, industry, and drinking water supply in the region. Within the Pretashkent Aquifer, water is sourced from both surface water and groundwater. The distribution of water sources varies depending on the sector and purpose of water supply, taking into account the specific quality requirements. In 2013, approximately 94.5% of the withdrawn water came from surface sources, while 5.1% originated from groundwater (Aral-Syrdarya Water Management Inspection, 2013).

The relatively high salinity of the Pretashkent horizon's water makes it suitable for specific purposes such as pastures watering, water supply for agricultural industries (such as cattle breeding complexes and poultry farms), bottling as therapeutic and table mineral water, and usage in medical health resorts and spas for balneological purposes. The distribution of water usage within the Pretashkent Aquifer reflects the diverse needs of the agricultural sector. In 2013, agriculture accounted for 21,345.1 thousand m3 of water withdrawal, representing 4% of the total water consumption for agricultural purposes. The majority of this water (72%) was used for supplying water to cattle breeding complexes and poultry farms, while the remaining portion (28%) was allocated for pasture watering and grazing (Aral-Syrdarya Water Management Inspection, 2013).

Table 5 Water Withdrawl from the Pretashkent Aquifer in 2013 (Aral-Syrdarya Water Management Inspection, 2013)

#	Type of use	Water withdrawal from Pretashkent Aquifer, thousand m3	Water withdrawal from surface sources, thousand m3	Percentage of water withdrawal from Pretashkent horizon in relation to surface sources, %
1	Water supply for agricultural industries	15345,1	3401,1	81.9
2	Pastures watering	6000,0	5696,8	50
3	Irrigation	-	479593,8	0
4	Industrial water supply	-	32,4	0

5	Domestic and drinking water supply	4629,3*	360,1	n/a
6	Bottling mineral water	264,7	-	100
	Total:	26239,1	489084,2	

**It is not well known how much water from Pretashkent Aquifer is used for domestic and drinking water supply. The given number is an indicator of consumption from all groundwater sources in the region including Pretashkent Aquifer.*

The Pretashkent Aquifer is also renowned for its mineral water reserves, which are exploited by over 10 industrial enterprises engaged in bottling. In 2013, these enterprises utilized 264.7 thousand m3 of water for bottling purposes, constituting 1% of the total water intake from the horizon (Aral-Syrdarya Water Management Inspection, 2013; see **Figure 4**).

Furthermore, a significant portion of water from the Pretashkent horizon is utilized for domestic and drinking water needs. Approximately 94 of the 152 settlements in the area rely on bareholes to meet their household and drinking water requirements (Inspection of the Aral-Syrdarya Department of Ecology in South Kazakhstan Oblast of the Republic of Kazakhstan, 2013; and Statistical Agency of the Republic of Kazakhstan, 2013).

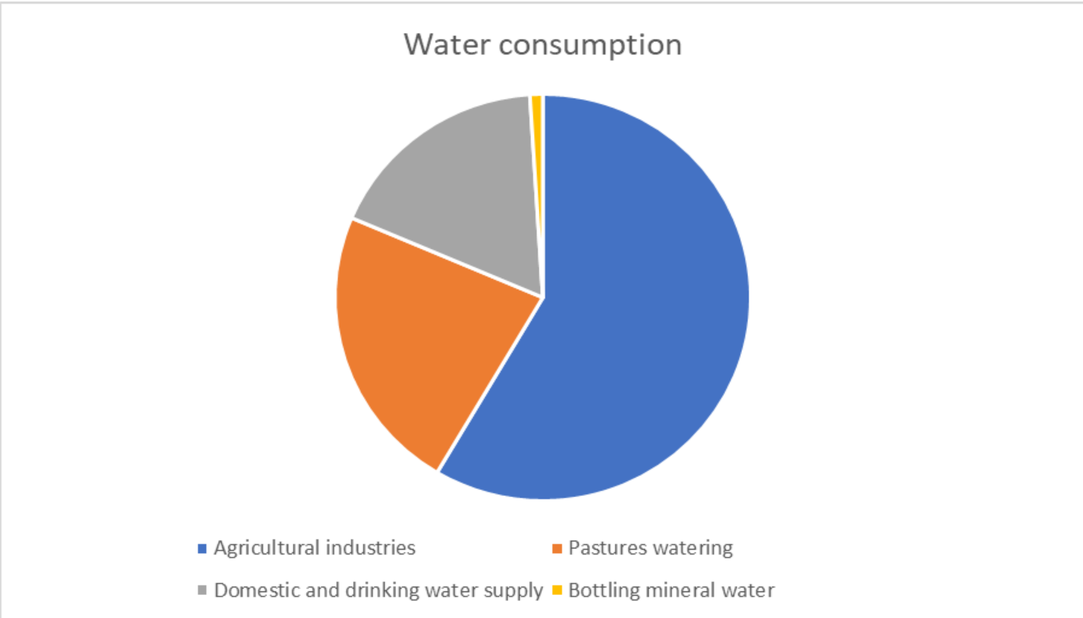

Figure 4. Distribution of water consumption targets from the Pretashkent Aquifer

The Pretashkent Aquifer plays a vital role in the agricultural water supply of the region. Its diverse usage spans from agricultural needs to bottling mineral water and catering to domestic and drinking water requirements. The proper management and sustainable use of this important water source are essential to ensure its long-term availability and support the various sectors relying on it.

3.3 Overview of the Pretashkent Aquifer, including hydrological and hydro chemical characteristics.

The Pretashkent Aquifer, part of the Upper Cretaceous Cenomanian complex, has been studied through pumping tests and geophysical investigations. It has a low hydraulic conductivity ranging from 5 to 35 m^2/day and is a confined aquifer with a water table/piezometric level above the ground surface. As of 2010, the average piezometric level is around 459.5 meters above sea level. The aquifer depth varies across locations, with surface outcrops found in foothill zones and depths ranging from 362 to 1900 meters in other areas of Kazakhstan. The aquifer has a total thickness ranging from 41 to 254 meters, with an average of 179 meters, and an effective thickness of approximately 90 meters. The Pretashkent Aquifer is mainly isolated within its territory, with surface outcrops covering an area of 185.7 km^2, and it is well separated from overlying aquifers based on analysis of various data sources. (UNESCO, 2016)

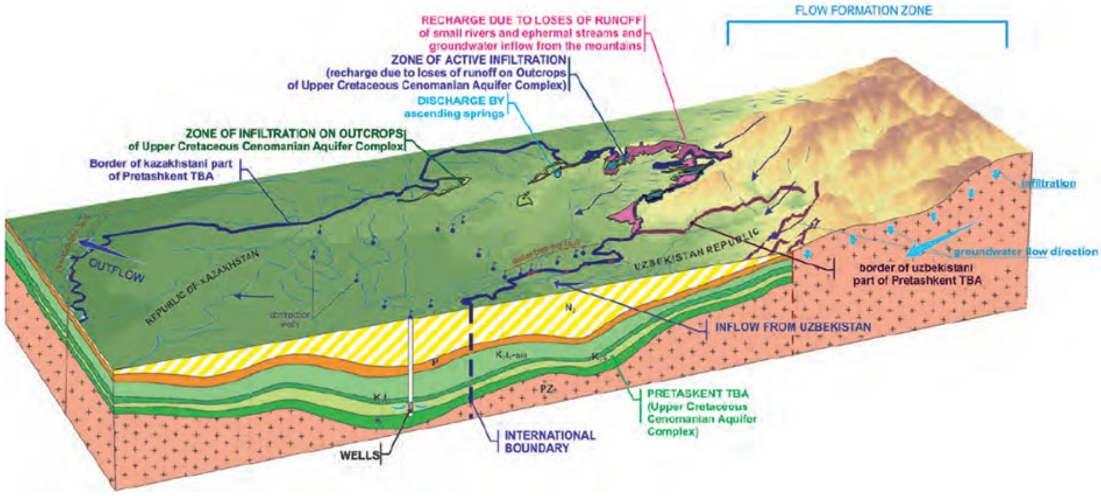

Figure 5. Conceptual model of the Pretashkent Aquifer (UNESCO, 2016)

The recharge of the Pretashkent groundwater has not been extensively studied, but field research conducted in 1981-1982 identified four natural recharge zones for the Upper Cretaceous Cenomanian aquifer. These zones include outcrops of the aquifer where recharge occurs through precipitation infiltration, losses from small rivers and temporary streams, lateral flow and partial recharge from overlying aquifers, and recharge zones along tectonic faults. A reassessment of exploitable reserves in 1983 estimated the cumulative recharge for the first three zones to be 41.65 liters per second, with an additional 8.8 liters per second from recharge along faults. The total recharge volume for Kazakhstan is 50.45 liters per second, with some inflow originating from Uzbekistan. Isotopic studies revealed that the discharged groundwater from the Saryagash region is approximately 6,000 years old, classifying the Pretashkent Aquifer as a non-renewable resource without the need for artificial replenishment methods. (UNESCO, 2016)

The mechanism of natural discharge was determined through mathematical modeling. Two discharge zones were identified: groundwater outflow beyond the boundaries of the Pretashkent (into the Kyzylkum artesian basin) and discharge through springs (**Figure 5**). Field research conducted in 1980-1981, along with calibration of the analog model using steady-state solutions, indicated a spring discharge rate of 19.2 liters per second. (UNESCO, 2016)

The total volume of groundwater in the Kazakhstani part of the Pretashkent, calculated by multiplying the aquifer area (10,840 km^2) by its effective thickness (90 m) and specific yield (0.1), is 97.6 km^3. The values for effective thickness and specific yield were obtained from previous studies, and the area was derived from the hydrogeological map. However, it is important to note that the average depth of the aquifer is 1064 m, and the average piezometric head is 26 m above the ground surface, resulting in an average piezometric head of 1090 m. Therefore, the elastic storage of the Upper Cretaceous Cenomanian aquifer over its area (10,840 km^2), with an average specific yield (4.36 x 10^-4) and average hydrostatic head (1090 m), amounts to 5.15 km^3. This parameter is crucial for evaluating deep aquifers, as these reserves are primarily utilized during groundwater exploitation. (UNESCO, 2016)

The Pretashkent Aquifer, belonging to the Upper Cretaceous Cenomanian complex, exhibits characteristics of a confined aquifer with low hydraulic conductivity and a water table/piezometric level above the ground surface. Regarding recharge and discharge, although the recharge of the Pretashkent groundwater has not been extensively studied, four natural recharge zones have been identified, including precipitation infiltration, losses from rivers and streams, lateral flow, and recharge along faults. The reassessment of exploitable reserves estimated the cumulative recharge volume for the aquifer, and isotopic studies revealed its non-renewable nature. The aquifer undergoes natural discharge through groundwater outflow beyond its boundaries and spring discharge.

Water quality

Groundwater in the Pretashkent has a mineralization ranging from 0.4 to 1.5 g/L. It displays diverse chemical compositions, including hydrocarbonate-chloride calcium-magnesium, hydrocarbonate-chloride sodium, hydrocarbonate sodium, hydrocarbonate-sulfate sodium, and sulfate-chloride sodium waters with higher silicon dioxide levels (14-20 mg/L). Trace elements such as phosphorus (0.05-0.1 mg/L), iodine (0.01-0.05 mg/L), fluorine (0.4-2.5 mg/L), boron (1-2.6 mg/L), and manganese (13-71 mg/L) are also present. The dominant gases in the water are nitrogen and oxygen. Groundwater temperature at the wellhead is 30°C, and no contamination has been observed. Hydrocarbonate-chloride calcium-magnesium waters are located in the northeastern part of the basin, south of the Baganalinsky uplift, with a composition of HCO3 45, Cl 36, SO4 19, Ca 45, Mg 43, and (Na+K) 12, and a mineralization range of 0.4-0.67 g/L. Hydrocarbonate-chloride sodium waters (from wells 3ts, 4ts, 506d, 7ts) have a composition of HCO3 47, Cl 25, SO4 5-23, (Na+K) 55-95, Ca 2-24, Mg 1-20, and a mineralization range of 0.58-1.5 g/L. Hydrocarbonate sodium waters (from wells 3md, 496, 607, 620) are widespread in most of the Pretashkent and characterized by HCO3 50-77, Cl 16-24, SO4 1-25, (Na+K) 97, Ca 2-5, Mg 1-5, and a mineralization range of 0.8-1.2 g/L. Studies have demonstrated the efficacy of groundwater in treating various conditions like gastrointestinal disorders, cardiovascular diseases, hypertension, polyarthritis, and radiculitis. Monitoring data, including mineralization graphs and maps, indicate that 46% of the Pretashkent Aquifer area does not meet the drinking water quality standards set by the Republic of Kazakhstan, which require a maximum mineralization of 1.0 g/L. (UNESCO, 2016).

3.4 Existing and potential problems associated to groundwater management and governance

Groundwater management

Under the current groundwater abstraction regime, groundwater storage depletion is inevitable due to excessive abstraction rates that cannot be compensated by recharge or natural discharge reduction. Consequently, the Pretashkent Aquifer behaves as a non-renewable aquifer, where abstraction mainly depletes groundwater storage. The predominant method of groundwater abstraction is through free-flowing (artesian) wells, but the declining groundwater levels pose challenges as water is released through elastic decompression. Collaborative efforts are needed among government authorities and stakeholders to determine the optimal path for depletion, considering increasing water demands and long-term sustainability. (UNESCO, 2016)

Water quality

While demographic and economic development drive the rising water demands in the region, various measures can mitigate the water demand from the Pretashkent Aquifer, including abstracting brackish and saline groundwater from overlying aquifers, implementing demand management strategies, improving water supply networks, promoting water-saving techniques among the public, and establishing regulations and incentives for water-saving practices in enterprises. Groundwater quality degradation within the Pretashkent Aquifer is not an immediate concern, except in localized recharge zones, but it may become problematic in the future when hydraulic heads decline and poor-quality groundwater flows from overlying aquifers. However, the pollution risks in shallow aquifers within the Pretashkent Aquifer area should not be disregarded, as they could pressure the Pretashkent Aquifer to substitute the corresponding volumes of water if the shallow aquifers become unsuitable for current uses. Both depletion and water quality issues have transboundary implications. Changes in pressure within the confined Pretashkent Aquifer can quickly propagate laterally, potentially affecting groundwater fluxes across international boundaries. (UNESCO, 2016)

Groundwater governance

Inadequate data sharing among Kazakhstani state organizations further contributes to the groundwater governance. The enhancement of monitoring networks, practices, and cooperation between state organizations could improve the governance. Specific needs for improving groundwater governance include developing legislation and regulations to promote conjunctive use and protection of water resources, raising public awareness about the consequences of irrational groundwater abstraction and pollution, enhancing the capacity of relevant agencies in groundwater resources management, and establishing transboundary cooperation between Kazakhstan and Uzbekistan for the Pretashkent Aquifer, which would be a significant advancement in groundwater governance. (UNESCO, 2016)

4. Case Study: Mynbulak Artesian Basin and its Use for Water Supply to the Population in the Ecological Disaster Zone of the Aral Sea.

4.1 Introduction to Topic Study

The Aral Sea, once the fourth largest inland body of water, has suffered the largest environmental catastrophe on a global scale. Its drying up has led to water supply problems for five Central Asian countries. Numerous valuable species of commercial fish and wildlife, including the Turan tiger, cheetah, swans, flamingos, and egrets, have vanished from the region. In the exposed areas of the Aral Sea, vast salt deserts spanning over 5.5 million hectares have emerged. These deserts become sources of destructive dust storms, carrying tons of toxic dust and salts over thousands of kilometres, devastating vegetation. Ecological catastrophe affected the lives and health of millions of people, with a noticeable rise in the larynx and esophageal cancer cases, as well as respiratory, eye, and other diseases. The Aral Sea itself can never be restored to its former state, but the local population requires protection and help. In recognition of this environmental crisis, the 75th session of the UN General Assembly adopted a resolution to support initiatives aimed at improving the environmental, social, economic, and demographic conditions in the Aral Sea region. In Kazakhstan, the Kyzylorda region in South Kazakhstan falls within the ecological disaster zone. The majority of the region's territory is located within the East Aral and North Kyzylkum artesian basins, while the northern part is occupied by the North Aral artesian basin. Additionally, small areas in the northeastern part encompass the Turgai and Chu-Sarysu artesian basins, as well as the northeastern part of the Karatau fissure water basin. In terms of water management division, the region is classified under the Aral-Syrdarya water management basin. The underground water sources in this region are found in various lithological-genetic rock complexes, spanning from the Paleozoic and Triassic-Jurassic periods to modern Quaternary deposits. Hydrodynamic conditions for groundwater formation in the region are significantly influenced by anthropogenic factors, including groundwater extraction, uncontrolled discharge of groundwater from wells, irrigation of agricultural land, and regulation of the river flow, particularly the retreat of the Aral Sea.

As of January 1, 2022, the Kyzylorda region has a total of 209 deposits, encompassing 244 areas of fresh and brackish groundwater. The operational reserves of groundwater amount to 1,478.1 thousand m3/day, as recorded in the balance sheet.

These include domestic drinking water (DDW) - 76%, industrial and technical water (ITW) - 11%, and water for land irrigation (LIW) - 13% (See **Figure 6**).

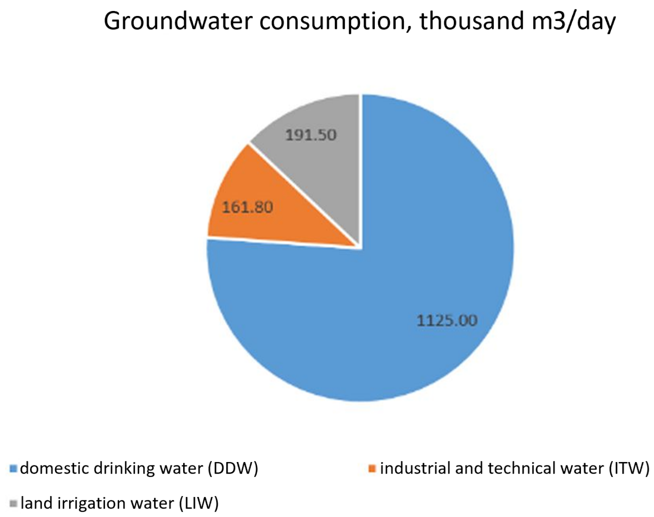

Figure 6. Underground water consumption

4.2. Use of Mynbulak Groundwater Deposit for Drinking Water Supply

The region has potential sources of water supply, including the significant **Mynbulak** groundwater deposit. This water source is also at risk of oil pollution. Developing this deposit offers an opportunity for a centralized water supply, providing high-quality drinking water to the population of Kyzylorda and rural settlements, independent of the quality of river flow, such as the Syrdarya and transboundary water issues. The Mynbulak deposit, located 160 km northeast of the village Zhosaly, is both extensive in scale and unique in terms of its quality. It possesses balance reserves of 250,000 m3/day with a mineralization level of 0.6-0.8 g/L.

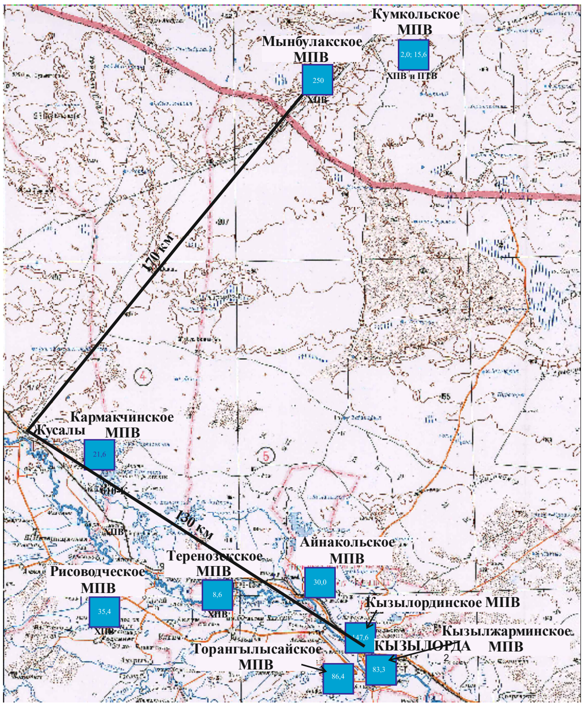

Figure 7 Location of the Mynbulak groundwater deposit and the route of water conduit for DDW supply

The Mynbulak deposit has remained unused since 1987. As the reserves approval period expired in 2015 after 27 years, additional exploration is necessary to reassess the deposit's reserves. This includes developing a Detailed Design for constructing a water intake, main water pipeline, and well operations. The process of developing, coordinating, and approving the contract for subsoil use, specifically for the extraction of groundwater from the Mynbulak deposit, along with all relevant approvals and reviews, will take at least 2 years.

Presently, issues regarding water pollution are escalating. For instance, the water in the Syrdarya region near the village of Kokbulak (a border point with Uzbekistan) exhibits nitrite and phenol levels reaching four times the Maximum Permissible Concentration (MPC). Iron and oil products also exceed the average annual MPC. Nitrite content exceeds the norm in most analyzed samples, and significant pesticide contamination is observed during the vegetation season.

The solution to the problem of providing a centralized water supply with high-quality drinking water to the population of Kyzylorda and rural settlements lies in the development of the Mynbulak groundwater deposit, independent of the quality of river flow, such as the Syrdarya and transboundary water issues.

Simultaneously, 9 settlements in Zhalagash district, 18 settlements in Karmakshy district, and 15 settlements in Syrdarya district are facing a severe shortage of drinking water. (**Figure 7**) The number of water consumers is projected to increase from 828 thousand in 2022 to 897 thousand by 2030. Consequently, the demand for water will rise from 201.4 thousand cubic meters per day to 220.6 thousand cubic meters per day.

The use of groundwater from the Mynbulak deposit will meet the projected demand and provide fresh water to the cities of Kyzylorda, Baikonyr, and 83 rural settlements in the Zhalagash, Karmakshy, and Syrdarya districts.

Field studies conducted by the Institute of Hydrogeology and Geoecology in 2022 revealed that several exploratory wells have been discharging water onto the surface for 35 years, forming lakes and streams that eventually dissipate into the sands. Remarkably, the water's quality remains suitable for drinking, with a mineralization range of 0.64 g/L to 1.07 g/L, composed of hydrocarbonates and sodium sulfate. It is concerning, however, that traces of oil products were identified in water samples.

Preliminary calculations indicate that the cost of engineering, survey work, and the construction of water supply systems, including a 300 km primary water pipeline (170 km from the Mynbulak deposit in Zhusaly settlement and 130 km from Zhusaly to Kyzylorda), will range from 47 to 114 billion tenge (based on 2018 prices).
The consideration of these groundwater deposits, alongside others located in the country's oil region, necessitates a special and meticulous approach in addressing state issues related to energy and the environmental challenges of the country's sustainable development.

4.3. Overview of hydrogeological conditions of the Mynbulak deposit

In terms of orography and hydrography, the deposit is situated in the northern part of the Baikonur River, with the upper reaches of the Karasuir tract and the Kalmakkyrgan river located to the south. The climate in the region is markedly continental, characterized by an average annual precipitation of 100-124 mm.

Geologically, the deposit encompasses Paleozoic and Meso-Cenozoic sandy-clay formations from the Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary systems.

Regarding hydrogeological conditions, the Mynbulak deposit is situated within the North Kyzylkum formation water basin and is confined to the aquifers of the Conacian-Campanian, Turonian, and Cenomanian Upper Cretaceous deposits. The Conacian-Campanian aquifer is accessed at depths ranging from 100 to 115 meters The water in this aquifer is fresh, with a mineralization level of 0.6-0.7 g/L. The Turonian aquifer is accessed at depths of 294-302 meters. The water in this aquifer is fresh, with a mineralization range of 0.64-1.12 g/L, averaging at 0.8 g/L. The Cenomanian aquifer is accessed at depths of 472-480 meters. The water in this aquifer is slightly brackish, with a mineralization range of 0.93-1.28 g/L, averaging at 1.0 g/L.

The macro component composition of the water includes bicarbonates at 161.7 mg/dm3, chlorides at 191.5 mg/dm3, sulfates at 317.8 mg/dm3, sodium at 368.3 mg/dm3, potassium at 2.6 mg/dm3, calcium at 4.0 mg/dm3, and magnesium at 3.0 mg/dm3.

4.4. Existing and Potential Problems Related to Groundwater Management

Groundwater Management

The development of the Mynbulak groundwater deposit, independent of the quality of river flow, such as the Syrdarya and transboundary water issues, will provide a solution to centralized water supply challenges, ensuring high-quality drinking water for the population of Kyzylorda and rural settlements. However, it is important to note that the deposit has remained unused since 1987. As the reserves approval period expired in 2015 after 27 years, additional exploration is necessary to reassess the deposit's reserves. This reassessment should involve design, approval, and expert review. It will also involve the development of a Detailed Design for the construction of a water intake, main water supply, and well operations. The process of developing, coordinating, and approving the Contract for subsoil use, specifically for the Extraction of groundwater from the Mynbulak deposit, along with all relevant approvals and reviews, will take at least 2 years.

Water quality

Presently, issues regarding water pollution are escalating. For instance, the water in the Syrdarya region near the village of Kokbulak (a border point with Uzbekistan) exhibits nitrite and phenol levels reaching four times the Maximum Permissible Concentration (MPC). Iron and oil products also exceed the average annual MPC. Nitrite content exceeds the norm in most analyzed samples, and significant pesticide contamination is observed during the vegetation season.
The use of groundwater from the Mynbulak deposit will provide high-quality drinking water to the population of Kyzylorda and rural settlements.

Groundwater Management

To ensure the effective management of the country's water resources, it is essential to follow the water legislation and relevant regulations. This entails taking specific actions that include:

- Substantiating the socio-economic necessity for utilizing the Mynbulak groundwater deposit.
- Reassessing the reserves of groundwater within the targeted deposit.
- Approving the project proposal with relevant state authorities.
- Developing and implementing a Detailed Design for constructing a water intake and main water pipeline.

5. Good practice, Lesson learned

Water resources management, including groundwater and the general availability of drinking water, are relatively difficult issues in many regions in Kazakhstan. This is caused by many factors, such as the uneven distribution of water resources, their extensive use in some sectors e.g. economy, population growth and probably most notably by climate change. Groundwater, as an important strategic resource for water security and the sustainable development of any country, is becoming the main source of household and drinking water for urban areas and agriculture, with decreasing surface water in Kazakhstan. (Absametov et al., 2023)

The interesting lessons on the current state of groundwaters in Kazakhstan are summarized in the following paragraphs.

Lesson 1: Current water management practices in many regions need to be improved and if not within the following years, the measures in Kazakhstan might not be strong enough to deal with climate change in the future. Adaptation to climate change will be necessary and groundwater will play an important role in society, as it would be the only source of drinking water for some of the regions in Kazakhstan. Adaptation measures must focus on the effective management of groundwater as well as its preservation.

Lesson 2: It will be important to reinstitute the Department of Hydrology under the Committee of Geology of the relevant ministry and its territorial subdivisions. The Department should be given the licensing functions such as issuing permits for the special use of water, incl.

groundwater. When it comes to Committee, among its competencies should be introduced conducting prospecting and exploration work on groundwater for water supply to settlements. In general, the state monitoring has to be strengthened. For the development of state programs, it would be important to take into account official recommendations from the Ministry of Economy as well as the sources coming from the Committee.

Lessons 3: For better legal regulation of groundwaters in Kazakhstan, it would be important to adopt new provisions to WC or adapt the existing ones and give special attention to the protection of groundwater, incl. thermal waters. Therefore, the development of a new WC seems to be a promising move of local policymakers. It would be important to avoid general wording or limited regulation of groundwater only within the water- and subsoil-related laws.

Lesson 4: The Pretashkent Aquifer as a significant transboundary deep-water reserve was divided between Kazakhstan and Uzbekistan in the early 1980s. However, after a while, this allocation agreement became void and the joint management of this crucial source has become challenging. The change came with the GGRETA Project. Within the project, the mathematical model was developed as a fundamental tool for the joint management of the Pretashkent Aquifer. Moreover, a comprehensive Roadmap has been formulated and approved by the local governments. The Roadmap envisages a range of activities aiming at the protection and sustainable use of the aquifer. Ongoing cooperation between the two countries must continue, the monitoring of the water quality should be conducted regularly, and finally sustainable practices need to be used by all relevant bodies as to ensure the effective management of the Pretashkent Aquifer also in the future.

Lesson 5: The environmental catastrophe of the Aral Sea is well known worldwide, and it is undeniable that this water body will never be restored to its former state. However, there are attempts to help this region, incl. recognition of the UN General Assembly. The region has water supplies potential for drinking purposes. One of those is the Mynbulak groundwater deposit which can provide high-quality drinking water to the population of Kyzylorda as well as surrounding rural settlements. Despite the fact that this deposit was not used for many years, its water quality remains relatively well. Now, the important step forward will be the development of the Mynbulak groundwater deposit and its further exploration.

6. Conclusions

The territory of Kazakhstan is distinguished by a variety of natural-climatic and geological-hydrogeological conditions; therefore, the quality of groundwater varies over a very wide range. The highest values of modules of predicted groundwater resources, mainly with low salinity, are typical for the southern regions of Kazakhstan, where the main groundwater resources are concentrated in the foothill zone. The central, northern, and western regions are characterized by a low value of predicted resources and increased mineralization of groundwater, and in deep troughs - the presence of strong brines.

One of the key features of the groundwater regime in Kazakhstan is the decrease in the average long-term value of the pre-spring and spring maximum water levels. In most groundwater bodies, after the water level stabilized as a result of a decrease in water intake, there was a decrease in water levels caused by dry years.

In most regions of Kazakhstan, groundwater is the main source of water supply for domestic and drinking needs. Groundwater resources are distributed over the territory of Kazakhstan extremely unevenly.

As a result of assessing the degree of provision of the administrative regions of Kazakhstan with operational groundwater reserves for household and drinking purposes, Atyrau and North Kazakhstan regions are classified as insufficiently provided (K < 0.5), and Mangystau and Akmola - as partially provided (K = 0.5-1). The rest of the regions and the republic as a whole are classified as reliably supplied with proven reserves of groundwater for household and drinking purposes (K > 1.0).

Judging by the size of the exploitable reserves of fresh groundwater (36,127 thousand m3/day), the population of Kazakhstan is fully provided with drinking water today and in the future for 2030. However, the provision of underground water resources for rural and urban areas is not equivalent, which causes a future shortage of water for domestic and drinking water supply in some regions of the country.

Monitoring and studying the potential of groundwater is an important strategic goal for Kazakhstan, which is confirmed by many strategies and programs for the development of the Republic. Due to the rapidly growing population of the country and the deterioration in the quality and decrease in the amount of surface water, in the foreseeable future, the countries of Central Asia, including Kazakhstan, will experience an acute shortage of clean drinking water, which in turn can lead to conflicts between the population and decline in economic growth. For the sustainable development of the country, there is a need to improve the groundwater management system and increase the potential for scientific research in this area.

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Sustainable Groundwater Management in Malaysia: Progress and Challenges

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Abstract

Groundwater has become crucial in addressing the increasing water demand and scarcity in Malaysia. Integrating groundwater into the national water resources management plan has been vital for ensuring water security and sustainability. However, the absence of a national groundwater policy impedes its sustainable use. Although existing legislation like the National Water Resources Policy provides a framework for water management, a specific groundwater policy is necessary. A case study in Terengganu's coastal zone highlights the threat of saltwater intrusion on groundwater quality and unregulated private wells. Addressing saltwater intrusion, and improving education and outreach efforts are essential for preserving freshwater resources and the environment. Thus, establishing a comprehensive groundwater policy and adopting sustainable practices can secure Malaysia's water future for the benefit of its citizens and the natural ecosystem.

Key Words: **water security, policy, saltwater intrusion, Terengganu**

1. Introduction

Malaysia boasts abundant water resources, including surface water from rivers, lakes, and reservoirs, as well as groundwater sources. The country receives substantial annual rainfall of around 2,500mm, contributing significantly to its water supply. Access to water supply in both urban and rural areas is relatively high, with rates of 97.07% and 97.03%, respectively, as of 2022 (Ahmad, 2023 and Wan 2023). However, despite these positive indicators, Malaysia's progress towards achieving Sustainable Development Goal 6 (SDG 6) on clean water and sanitation has shown stagnation, as highlighted in the Sustainable Development Report 2022. One of the main challenges is ensuring safe drinking water for all, particularly in underserved rural areas, which calls for improved water treatment and distribution systems. Furthermore, environmental degradation around rivers and catchment areas poses a significant issue, attributed to unsustainable land use practices, deforestation, urbanization, and encroachment into sensitive ecosystems, leading to reduced water quality and quantity in many river basins (Abdullah, 2021 and FAO, 2001). Climate change also presents significant challenges to the water sector, profoundly impacting the hydrological cycle and water availability. Alterations in precipitation patterns result in more intense and frequent rainfall in some regions, while extended droughts plague others (Voon, et atl, 2022). These changes disrupt the natural replenishment of surface water and groundwater, leading to water scarcity and distribution challenges (Ahmed, et al, 2014; and Daria and Norlaili, 2023).

Groundwater has emerged as an alternative water resource in Malaysia due to increasing demand, water scarcity in certain regions, and the need to diversify water sources for enhanced security (Khalid, 2018). Sustainable groundwater management practices are recognized as vital to ensure responsible utilization and complement the existing surface water supply. Private groundwater wells have gained popularity among households for domestic and agricultural needs, underscoring the resource's reliability. Moreover, specific regions, particularly the eastern states and coastal areas, make extensive use of groundwater by tapping into this vital resource. Additionally, the strategic construction of groundwater tube wells aids in fire prevention in peat areas. Notably, Kelantan stands out as the sole region in Malaysia that relies on groundwater as its primary water supply. In other parts of the country, like Terengganu and Selangor, many households have taken the initiative to install private groundwater wells for their domestic and agricultural needs (Mridha, et al, 2018). This trend highlights the growing importance of groundwater as a reliable water source for both domestic and industrial purposes in Malaysia.

2. Groundwater in the national water resources management

2.1 The role of groundwater resources in the national water resources management plan

The 3rd Malaysia Plan played a crucial role in driving the country's water sector and overall development, with a focus on accelerating economic growth and improving the well-being of the population. Economic diversification, rural development, and poverty alleviation were essential objectives, alongside human resource development and infrastructure enhancement to support economic growth. Environmental conservation was also integrated into development projects, demonstrating the government's commitment to sustainable practices.

The plan's success was evident in substantial contributions to the water sector and the nation's overall progress, addressing economic, social, and environmental aspects. In parallel, the effective incorporation of groundwater into the national strategy became crucial for enhancing water security, sustainability, and resilience in Malaysia. Groundwater management emphasized sustainable utilization, equitable allocation, water quality protection, environmental conservation, and public participation. The Department of Mineral and Geoscience has played a vital and multifaceted role in groundwater management to meet the increasing demands for clean water (JMG, 2023).

These initiatives encompass the Groundwater Development Project (BAT), which seeks to harness groundwater sources in areas struggling with clean water supply. Additionally, the Water Treatment Plant Project (LRA) explores the usage of groundwater as an alternative water source in water treatment plants facing water scarcity. Moreover, the Assessment of National Groundwater Reserves for Groundwater Modeling (RAT) contributes valuable insights into understanding and managing groundwater resources effectively. The National Water Balance Project (NAWABS) aims to develop a comprehensive water balance model for national water resource management. Meanwhile, the Peatland Fire Project concentrates on preventing and monitoring high-risk fire areas, particularly addressing haze issues. Lastly, the Water Supply Development in Indigenous Villages in Peninsular Malaysia endeavors to improve clean water accessibility and living conditions in indigenous communities.

The Department of Mineral and Geoscience's comprehensive efforts in groundwater management have significantly contributed to maintaining the quality and quantity of water resources, ensuring sustainable and efficient utilization. These dedicated efforts in groundwater management reflect Malaysia's unwavering commitment to sustainable and efficient utilization, while actively safeguarding the environment and communities from potential water-related challenges. By effectively integrating groundwater into the national strategy, Malaysia is taking significant steps towards ensuring a secure and resilient water future for the nation.

However, Malaysia faces a significant setback in groundwater management due to the lack of a national groundwater policy. This absence severely hampers the sustainable utilization of this vital resource, directly impacting the country's economic well-being and development. The current limited usage of groundwater, just 3%, is a direct result of the absence of a comprehensive policy that would effectively guide both the government and private sectors in responsible groundwater development. To secure Malaysia's future growth, it is imperative to establish a clear and all-encompassing policy that empowers all stakeholders involved in groundwater development, ensuring its prudent and effective utilization.

2.2 Administrative and legal framework for groundwater management

The legislation of Malaysia constitutes a comprehensive framework guiding national development and promoting the sustainable management of natural resources, particularly water resources. Notably, a national groundwater policy to safeguard this vital resource is yet to be established (Loganathan, 2019, Jing, et al, 2019, and Mat, 2019). The current relatively modest utilization rate of groundwater, standing at approximately 3%, can likely be attributed to the absence of a comprehensive and cohesive policy framework governing its exploitation (Ahamd, 2023 and Loganathan, 2019). Implementing such a policy would greatly aid in guiding the actions of stakeholders involved in groundwater development, whether in the government or private sectors. (Ahmad, 2023 and Rahman, 2021).

The National Water Resources Policy 2012 serves as a pivotal cornerstone in Malaysia's commitment to groundwater management. This policy takes a holistic approach by integrating social, economic, and environmental factors to ensure responsible use and conservation of water resources. With an emphasis on water security, the policy aims to meet diverse needs in population, agriculture, industries, and the environment, ensuring a reliable and sufficient supply of clean water. It advocates for equitable water allocation, considering the requirements of all stakeholders while promoting fair distribution among different sectors and regions. The policy also prioritizes critical aspects such as water quality protection and ecosystem preservation, preventing pollution and degradation in water catchment areas. Additionally, it addresses the impacts of climate change, developing strategies to tackle challenges like droughts and floods. Encouraging public participation and stakeholder engagement underscores their significance in water resources planning and decision-making processes. The policy emphasizes institutional strengthening to empower water-related institutions for more effective water management, and research and innovation are promoted to advance water resource management practices.

Relevant legislations, such as The Geological Survey Act of 1974, support responsible resource management through geological surveys and geoscience activities (Jing, et al, 2019). State-level enactments concerning water resources also contribute to regulating water usage and conservation, with Selangor and Terengganu updating their focus on groundwater resources. Concerning water quality, the Environmental Quality Act of 1974 addresses environmental protection, pollution control, and conservation of vital natural resources. The Town and Country Planning Act of 1976, along with the Local Government Act of the same year, play pivotal roles in regulating urban and rural planning, land use zoning, development control, and establishing local government authorities. Moreover, the National Forestry Act of 1984 safeguards forest resources, forest reserves, and wildlife protection. The Water Services and Industry Act of 2006 effectively regulates water supply services and the water industry, supporting national water management efforts.

Despite the absence of a specific groundwater policy, Malaysia has made significant strides and advancements in groundwater legislation, reflecting the government's increased focus on resource management. To effectively progress in groundwater management, it is crucial to establish a clear and comprehensive policy that guides responsible groundwater development, ensuring prudent utilization for Malaysia's future growth.

3. Case Study: Groundwater status in the Coastal Zone of Terengganu

3.1 Coastal Groundwater Usage in Terengganu

Coastal freshwater resources are under severe threat from saltwater intrusion, making the water unsuitable for human consumption. This phenomenon, widely recognized as a critical factor impacting groundwater quality in coastal aquifers globally (Elewa, et al, 2023 and Aladejana, et al, 2021). Saltwater intrusion occurs when fresh groundwater flows towards the coast and encounters seawater along an upward-sloping boundary. The delicate balance of this boundary is influenced by both natural and human-induced factors, driven by the density difference between seawater and fresh groundwater, leading to the flow and movement of salt (Qu, et al., 2023 and Sabino, et al.). Consequently, sections of formerly freshwater aquifers become salinized, resulting in reduced availability of freshwater in coastal areas.

Terengganu, situated on the eastern coast of Peninsular Malaysia, faces challenges in accessing clean and fresh water despite being surrounded by water (Zolkiply, 2022 and Rosalinda, 2022). In response to this issue, private groundwater wells have become prevalent in the region, providing a reliable and cost-effective source of water, especially in areas where surface water sources may be limited or unreliable (Berita PAS Terengganu, 2021 and Bernama, 2021). These private wells serve various purposes beyond household use, supporting agricultural, industrial, and commercial irrigation. Based on site observation, most of the private wells are equipped with boring machines, bucket augers, or cable tools, these wells access the aquifer to extract groundwater. In rural areas, hand-dug wells are common for domestic purposes, reaching depths of up to 6 meters.

In addition, the lack of regulation and oversight of unregulated private wells is a cause for concern, particularly because shallow wells have the potential to pose health risks through non-point source pollution. Despite the seriousness of groundwater pollution, there is a wide variation in public awareness and understanding of groundwater quality. Research studies have consistently shown that only approximately 45-50% of private well owners take responsibility for testing, treating, and maintaining the quality of their water. This leaves a significant portion of the population unaware of the potential risks associated with groundwater contamination, and as a result, necessary protective measures are being neglected. Addressing this issue requires greater education and outreach efforts to raise awareness about the importance of groundwater quality and the critical need for regular testing and treatment of private wells to ensure the safety and well-being of communities.

To address these challenges, there is a pressing need for enhanced education and outreach efforts to raise awareness about the importance of groundwater quality and the necessity for regular testing and treatment of private wells. By empowering individuals and communities with knowledge, sustainable water management practices can be promoted to safeguard coastal freshwater resources. Effective regulation of groundwater extraction, along with proactive measures to address rising sea levels and conserve freshwater resources, are essential in ensuring a reliable and resilient water supply for the coastal communities of Terengganu and other vulnerable regions. Engaging communities in responsible water use will play a significant role in preserving the integrity of coastal aquifers for the benefit of future generations.

3.2 Overview of the aquifer, including hydrological and hydrochemical characteristics

Terengganu experiences a tropical climate characterized by two distinct monsoon seasons. The Northeast monsoon, occurring from November to March, brings a wet season, whereas the Southwest monsoon, from April to September, results in a dry season. Throughout the year, the temperature remains relatively consistent, ranging from 21°C to 35°C. The warmest month in Kuala Terengganu is May, with an average temperature of 28°C, while the coldest month is January, with a mean temperature of 25°C. From January to April, the weather is characterized by dry and warm conditions. Humidity levels remain consistently high, hovering around 80% during the daytime.

Groundwater monitoring program has been conducted at the coastal zone Terengganu (**Figure 1**). The aquifer is predominantly consists of Indo-Gangetic alluvium, with a lithological distribution comprising marine clay and silt, continental mud and clay, peat, humic clay and silt, and sand. The groundwater level in this region exhibits spatial variations, with typical fluctuations ranging from 0.2 meters to 0.8 meters between the pre-monsoon and post-monsoon seasons. Some areas have shallow aquifers ranging from 5 to 30 meters, making it relatively easy to access water for private purposes.

The hydrogeochemical analysis of coastal groundwater and river water in the study area revealed a diverse range of water types. Current study show that river water samples were generally categorized as saline, with a few areas classified as brackish or marginal water types. The downstream areas near the estuary exhibited higher salinity, while the upstream areas had lower salinity due to freshwater dilution. In addition, the comprehensive geochemical analysis utilized advanced techniques to determine major chemical constituents and trace elements present in the groundwater. The findings unveiled three distinct hydrogeochemical facies: alkali-HCO_3, Ca-Mg-HCO_3, and alkali-SO_4-Cl, providing valuable insights into the water's chemical nature.

Overall, the study highlighted the impact of saltwater intrusion on coastal groundwater and classified the Terengganu River Basin as intermediate vulnerable. Effective management strategies are crucial to mitigate this impact and safeguard freshwater resources in coastal areas. Further research and monitoring efforts are needed to understand the dynamics of saltwater intrusion and ensure sustainable water management and protection of coastal ecosystems.

3.3 Existing and Potential Problems Associated to Groundwater Extraction

Despite the significance of saltwater intrusion, limited research has been conducted on its threat to freshwater resources in Terengganu. However, Siang et al. (2022) reported that dry weather during the spring inter-monsoon resulted in coastal seawater being pushed inland, leading to slightly saline water at stations located 10.24 km and 9.43 km from the estuary mouth. In contrast, in 1999-2000, saltwater was only detected 5.27 km away. Saltwater intrusion is a growing concern not only in Terengganu but also in several other areas of Malaysia, such as the Klang Valley, Johor, and Kedah. Over-pumping of groundwater, high surface water abstraction rates, and sea-level rise contribute to this phenomenon, adversely affecting water resource quality, quantity, the environment, and economic activities in the affected regions. The lack of sufficient regulation and monitoring of groundwater usage in Malaysia exacerbates the unchecked depletion of groundwater resources, posing potential long-term consequences for water supply sustainability.

Addressing the challenge of saltwater intrusion requires a comprehensive approach involving sustainable groundwater management, increased research and monitoring efforts, and effective measures to conserve freshwater resources. Proactive steps to protect coastal aquifers and promote responsible water use are essential to ensure a reliable and secure water supply for coastal communities and ecosystems.

4. Conclusions

Groundwater has emerged as an important alternative water resource in Malaysia, especially in regions facing water scarcity and the need to diversify water sources. Environmental degradation around rivers and catchment areas, coupled with the impacts of climate change, also poses significant issues, leading to reduced water resources. The successful integration of groundwater into Malaysia's national water resources management strategy, coupled with the establishment of a comprehensive groundwater policy, holds the potential to lead the country towards a secure and resilient water future. By doing so, Malaysia can ensure a consistent and dependable water supply that meets the needs of its people and safeguards the environment. The implementation of sustainable groundwater management practices, along with responsible water use and conservation efforts, will play a pivotal role in effectively addressing water challenges and ultimately realizing the crucial objective of providing clean water and sanitation for all Malaysians. Through these concerted efforts, Malaysia can pave the way for a sustainable and thriving water ecosystem that caters to the well-being and prosperity of its citizens and the nation as a whole.

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Appendix

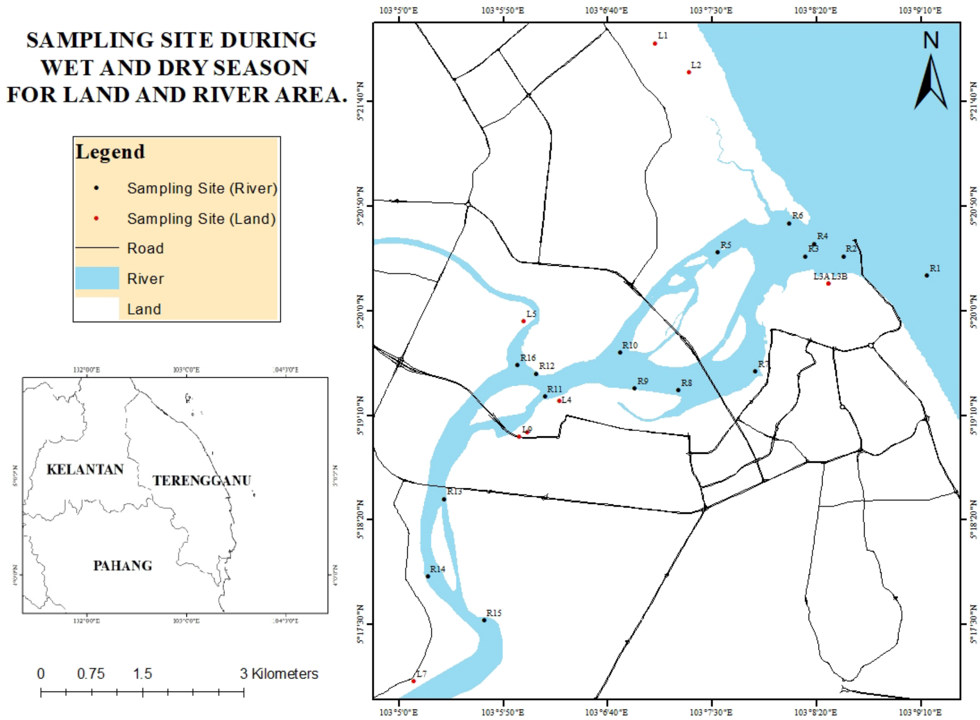

Figure 1: Map of sampling sites

Overview of Groundwater In Mongolia

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Groundwater is the main water sources for drinking and economic sectors especially in arid and semi-arid regions. Mongolia is an arid and semi-arid and landlocked country, where groundwater is the main water sources of fresh water. The total water resource of the country is around 564.8 million m^3, of which about 500 km^3 is lake water (Tsedensodnom, 2000), 19.4 km^3 is ice and glaciers (Davaa et al., 2012), and 34.6 km^3/year is river water (Ministry of Water Management, 1975), but only 10.79 km^3 consists of groundwater (Jadambaa, 2003). In other words, according to the results of the recent researches, about 2% of the total water resources of Mongolia is groundwater resource. However, the groundwater resources have not been determined accurately in the country.

Due to the geographical and climatic conditions of Mongolia, sustainable use of surface water is still problematic. Therefore, groundwater resource is very important and play vital role in the socio-economy of Mongolia. Because of very cold and long winter season, the soil freezes about 3 m from the land surface and almost every surface water (e.g., lakes, rivers and springs) freezes, making the surface water unusable. Therefore, more than 70% of water consumptions of the country are supplied by the both renewable and non-renewable aquifers.

Due to growing population and socio-economic development, water demand increased over the past decades in Mongolia. The country's water consumption in 2010, 2016, and 2021 was approximately 330, 490, and 594.8 million m^3, respectively. As of 2022, Mongolia's total water consumption was around 606.2 million m^3, and about 56% of the total water consumption was agricultural sectors (i.e., animal husbandry and irrigated agriculture), followed by 92.54, 86.38, 46.24 and 42.44 million m^3 water has been used for the mining, drinking water, energy including heat productions and industry including service's sectors, respectively (Boldbaatar, 2023).

Due to climate, geographical, geological and hydrogeological conditions, water resources of the country are distributed unevenly both in space and time. In the northern part of the country such as the Khangai, Khuvsgul and Khentii mountainous areas, the water resources are abundant comparing to the Gobi and Steppe regions.

In the northern part of the country, groundwaters of an alluvial floodplain is hydraulically linked with rivers. Therefore, the recharge rate is higher and residence time is relatively shorter than other aquifers in Gobi and steppe region southern Mongolia. On the other hand, age of the groundwater deposits in the Gobi and desert regions were determined between one hundred and nearly forty five thousand years (i.e., fossil groundwater) according to the isotope studies (Chinzorig and Janchivdorj, 2020). Therefore, groundwater in the southern regions is very poor rechargeable or non-renewable.

Based on the above facts, the groundwater in the Gobi provinces (i.e., Umnugobi, Dundgobi, Dornogobi and Sukhbaatar) is unsuitable to meet considerable water demand for economic sectors such as mining and industries in this region. Therefore, it is considered essential to determine an ecological limit/criteria for the appropriate extraction of these fossil and non-renewable groundwater in the Gobi region in order to supply water for mining industries, which play a vital role in the social and economic development of the country. Secondly, measures to regulate the uneven distribution of water resources is potential to plan, and to transfer part of the flow from the northern river basins to the Gobi region in order to supply sustainable water for economic sectors in the long term.

Groundwater monitoring is conducted by the Ministry of Environment and Tourism, Water Authority, National agency for meteorology and environmental monitoring, Institute of Geography and Geoecology of the Mongolian Academy of Sciences, Water Supply and Sewerage Authority (USUG), and some mining companies (State IWRMP, 2013). Currently, there are about 340 groundwater monitoring points in the country. Most of the monitoring points are measured groundwater level and temperature, while a few are monitored the level along with the water quality some parameters.

Generaly, quality of groundwater in the country has a spatial of increasing mineralization and hardness from the north to the south, the concentration of fluorine is low in the Khangai region and high in the Gobi region, which is related to the geological structure of aquifers. In addition, groundwater quality depends on the geographical and hydrogeological conditions, and the age of groundwater.

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Groundwater Management in Kathmandu Valley and Terai Plains of Nepal

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Abstract

Groundwater management in Nepal, particularly in the Kathmandu Valley and the plains, plays a crucial role in meeting various water demands. However, the availability, quality, and management of groundwater vary significantly across different regions of the country. This chapter provides a comprehensive overview of groundwater management in the Kathmandu Valley and the plains, focusing on three key components: groundwater aquifer, availability, and quality. The chapter explores the current state of knowledge of groundwater in the Kathmandu Valley and the plains, assesses existing management practices, and discusses the prospective future for groundwater therein. It highlights the position of groundwater across the relevant legal instruments – Policies (9), Strategies (2), Acts (13), Rules (8), and Guidelines/Directives/Manuals/Working Procedures (3) and their effectiveness in sustainable groundwater management. A case study on the groundwater status in the Kathmandu Valley sheds light on the increasing water demands, unsustainable extraction rates, and the impact of urbanisation on groundwater resources. It also examines the hydrological and hydrochemical characteristics of the aquifers in the valley, highlighting issues of pollution and depletion. The chapter concludes with insights on good practices and lessons learned, emphasising the importance of research, monitoring, and integrated management approaches for sustainable groundwater management.

Keywords: *Groundwater, Kathmandu Valley, Nepal, Sustainable groundwater management, Water supply and demand, Hydrochemical characteristics, Terai*

1. Introduction

Groundwater plays a crucial role as a water source in Nepal, particularly in the valleys and the southern plains of the Terai. In some areas, groundwater is confined to well-defined, often isolated, basins such as the Kathmandu Valley (the Valley), while in other areas, such as the Terai region, it constitutes a significant part of the extensive Indo-Gangetic plains. Groundwater is used for diverse purposes, including household needs, industrial activities, and irrigation. However, the extent of its utilisation has varied significantly, with the Kathmandu Valley witnessing large-scale exploitation, while the utilisation for irrigation purposes in the Terai remains relatively low, mainly due to energy constraints (Nepal *et al.*, 2021).

Groundwater in Nepal also has considerable variations in recharge mechanisms. In the Kathmandu Valley, the annual recharge is slow and limited due to urbanisation and the presence of fine sediments. In contrast, the Terai region is drained by large rivers with coarse sediment deposits, allowing for quick aquifer recharge (Kansakar, 2011). Additionally, groundwater quality exhibits wide variations due to chemical constituents, contamination, and pollution (Shrestha et al., 2018a). Consequently, the availability, quality, and status of groundwater exhibit significant variability throughout the country.

This chapter aims to provide a comprehensive overview of groundwater management in both the Kathmandu Valley and the Terai. The discussion is divided into three main components: groundwater aquifers, availability, and quality related to groundwater management. Specifically, a review of the current state of knowledge regarding groundwater is undertaken, both in Kathmandu Valley and the Terai. Furthermore, the chapter focuses on the groundwater management practice and future management strategies for the country.

2. National Water Resources Management for Groundwater in Nepal

Nepal has acknowledged the importance of water resources and has established several water-related institutions, formulated water policies, and developed legislation (Shrestha *et al.*, 2012). However, there is a lack of comprehensive regulation and regulatory bodies specifically dedicated to groundwater management (Poudel, 2021).

According to the Water Resources Act, 2049 (1992), all ownership of water resources, including surface water, underground water, or any other form, is vested in Nepal. Despite the absence of explicit mention of groundwater in cross-sectoral policies such as the Land Use Policy of 2015 and the National Agriculture Policy of 2004, it is noteworthy that more recent and directly related policies have considered groundwater (Annex 1). The most recent policy "National Water Resources Policy (2020) emphasises a focused approach to address the issues related to groundwater. The policy outlines a comprehensive plan, prioritising the conjunctive use of surface water and groundwater based on their potential and necessity. It underscores the importance of identifying groundwater recharge zones and urges measures to prevent the development of physical infrastructure, settlements, and harmful products in these crucial areas. Additionally, the policy aims to prevent over-exploitation of groundwater resources through the formulation and implementation of necessary guidelines. To counter the decline in groundwater levels, the policy advocates for the adoption of strategies or methods to focus on replenishing the groundwater aquifer, highlighting the importance of sustainable practices for the effective management of this vital water resource. Despite recognising groundwater as a crucial resource in certain policies, the country lacks effective and well-defined instruments for the implementation of these policies. For example, there is a lack of rules and regulations governing the construction of public and private wells, the primary means of extracting groundwater (Shrestha, 2017), thereby placing groundwater as an "unregulated resource" in Nepal (Kansakar, 2011). This gap is further accentuated by a dominant focus on surface water management in major legal instruments, relegating groundwater to the status of a cross-cutting issue in water resource-related projects. For instance, in projects like the Bheri Babai Diversion, which involves redirecting water from the Bheri River to the Babai River, inadequate attention to groundwater recharge emerges as a notable concern. Under the Environment Protection Rule 2076 (2019), certain requirements need to be fulfilled in Nepal for the development of groundwater resources. An Initial Environmental Examination (IEE) is mandated if the groundwater resource recharge development is estimated between 50% and 75% of the total aquifer. Additionally, an Environmental Impact Assessment (EIA) is required for a groundwater resource recharge development that exceeds 75% of the total aquifer. It is important to note that licensing requirements are currently absent for groundwater use, except for commercial purposes. Following the country's federal restructuring post-2015, the Local Government Operation Act of 2017 was anticipated to serve as a pivotal legal framework for advancing development initiatives. While a notable strength of this policy lies in empowering local authorities, it has resulted in contradictory developmental outcomes, raising concerns about the sustainability of natural resources as the prevailing understanding of development at the local government level often prioritises physical infrastructure, posing a significant threat to the existing status of groundwater resources.

Institutionally, the Water Resource Research and Development Centre (WRRDC) and Groundwater Resources Development Board (GWRDB), responsible for groundwater research and development, have been, discontinued recently in the Nepal government budget for the fiscal year 2023-2024. Both organisations used to operate under the Ministry of Energy, Water Resources and Irrigation (MoEWRI). The WRRDC focused on providing job-related training, conducting research and development, and offering laboratory facilities, while the GWRDB aimed to enhance groundwater study and investigation activities and identify potential areas for groundwater irrigation development. The GWRDB also managed a dashboard that provided groundwater level monitoring data from various parts of the country, although currently only available from Banke and Bardiya districts (https://gw-nepal.com/waterapp/). The discontinuation of these bodies could potentially hamper training and research activities related to groundwater in Nepal.

3. Groundwater in Nepal

3.1 Groundwater Aquifers

3.1.1 Groundwater Aquifers in the Kathmandu Valley

The aquifer in the Kathmandu Valley primarily consists of three types of sediments: Arenaceous sediments (sandy), Argillaceous sediments (clayey), and the intermediate sediments that lie between these two types (Shrestha *et al.*, 2018b). The distribution of these sediments has divided the Kathmandu Valley into three distinct groundwater districts (Figure1). These districts include the Northern Groundwater District (NGD), serving as the primary recharge zone, the Central Groundwater District (CGD), which encompasses both deep and shallow aquifers, and the Southern Groundwater District (SGD), characterised by limited aquifer developments (Table 1). Of the total watershed area of 650 km^2, very low, low, moderately low, moderately high, high, and very high recharge areas were 4.29%, 9.14%, 14.72%, 32.59%, 32.89%, and 7.37% respectively (Lamichane and Shakya, 2019). The groundwater in the Valley consists of multiple aquifers which can be classified into two categories: shallow and deep systems. The shallow aquifer is unconfined and exists between 0 to 10 meters below the surface, while the deep aquifer is confined and is found at depths ranging from 310 to 370 meters (Khadka, 1993). Sandy sediments exhibit higher permeability, facilitating faster groundwater flow and recharge rates, whereas clayey sediments have lower permeability, resulting in slower groundwater movement. The variations in sediment types across the groundwater districts contribute to the differences in aquifer development and groundwater availability within the Valley.

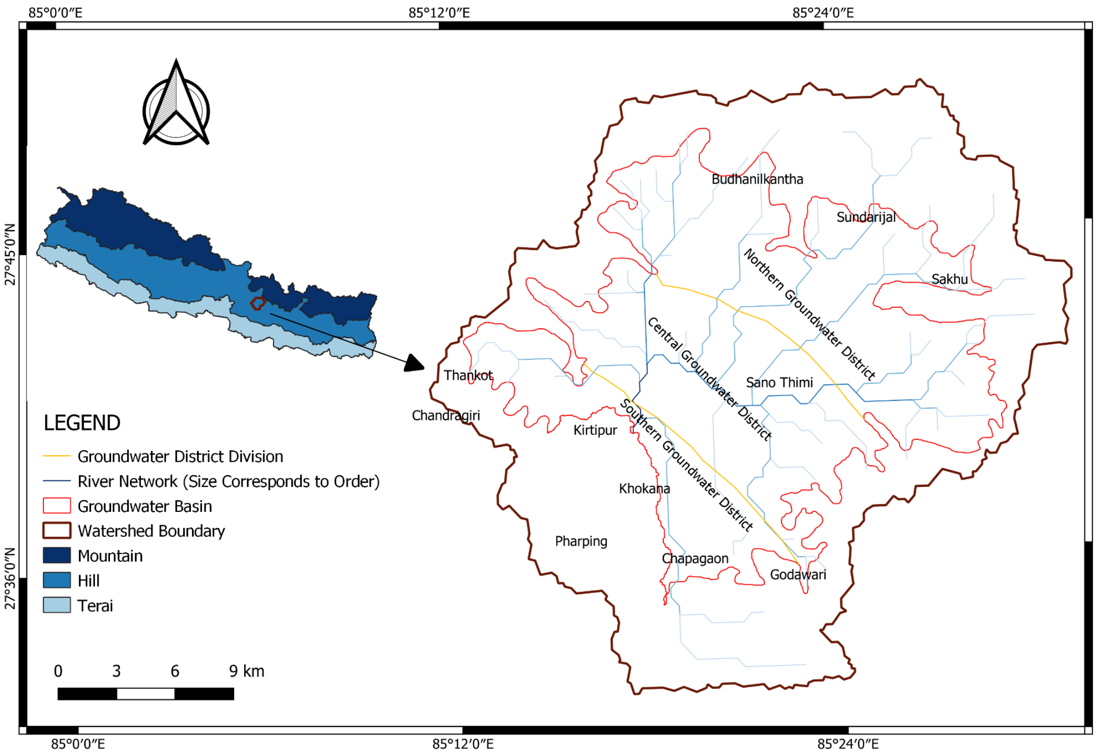

Figure 1: District-wise distribution of groundwater in the Kathmandu Valley

Table 1: A comparison of groundwater districts in the Kathmandu Valley (Chapagain et al., 2010; Shrestha et al., 2018; JICA, 1990)

Northern Groundwater District	**Central Groundwater District**	**Southern Groundwater District**
Features high transmissivity (83 – 1,963 m^2 per day)	Features low transmissivity (32 – 960 m^2 per day)	Features low transmissivity.
Main recharge zone	Consists of both deep and shallow aquifers.	Aquifers are not well developed.
Area coverage of 157 km^2	Area coverage of 114 km^2	Area coverage of 55 km^2
Consists of deposits of sand and gravel beds	Underlain with layers of thick impermeable clay - Kalimati and permeable coarse materials.	Underlain with carbonate rocks
Recharge area of 59 km^2	Recharge area of 6 km^2	Recharge area of 21 km^2
Budhanilkantha, Sundarijal, Sankhu lie in this region.	Kathmandu Core and Kirtipur lie in this region.	Pharping, Thankot lies in this region.

3.1.2 Groundwater Aquifers in the Terai

The aquifers in the Terai are found in two depositional zones, the Bhabar Zone and the Terai plains (Shrestha et al., 2018b). The Bhabar Zone, covering an area of 4,700 km^2 is the primary source of groundwater recharge in the Terai. It consists of an unconfined aquifer with a deep-water table. The Terai plains contain multiple layers of good aquifers at different depths, some are interconnected and some are not. The aquifer systems in the Terai plains comprise unconfined and semi-confined shallow aquifers, confined deep aquifers, and perched aquifers. The Terai plains have aquifers with transmissivity exceeding 0.1 million litres per day (MLD) and well yields ranging from 0.43 to 5.18 (MLD). The typology is characterised by a significantly higher proportion of finer alluvial sediments, with up to 20–30% silts and clays, as a result of the slightly lower energy of the fluvial systems that have deposited the alluvium stratigraphy (Bonsor et al., 2017).

3.2 Groundwater Availability and Supply

Traditionally, groundwater in the Kathmandu Valley has been extracted using traditional methods such as stone spouts and dug wells. However, due to the increasing population, changes in lifestyle, urbanisation, and industrialisation, there has been a shift towards more mechanised extraction methods to meet growing water demands (Shrestha et al., 2016). The rate of groundwater abstraction has been alarmingly high and has surpassed the rate of recharge since 1986. The sustainable extraction rate of groundwater in the Kathmandu Valley was assessed to be 26.3 MLD by Stanley et al. (1994), although there are varying estimates. However, the actual extraction rate in Kathmandu is around 143 MLD (Thapa *et al.*, 2019). The widespread drying of stone spouts in different parts of the Valley indicates the extensive use and high pressure on groundwater resources to fulfill water demands. In the Terai region, groundwater reserves of 8,800,000 million litres (ML) have been estimated by the GWRDB (https://gw-nepal.com/waterapp/meta-data). The extent of groundwater utilisation varies significantly, with the Kathmandu Valley witnessing large-scale exploitation, while the utilisation for irrigation purposes in the Terai remains relatively low, mainly due to energy constraints (Nepal et al., 2021).

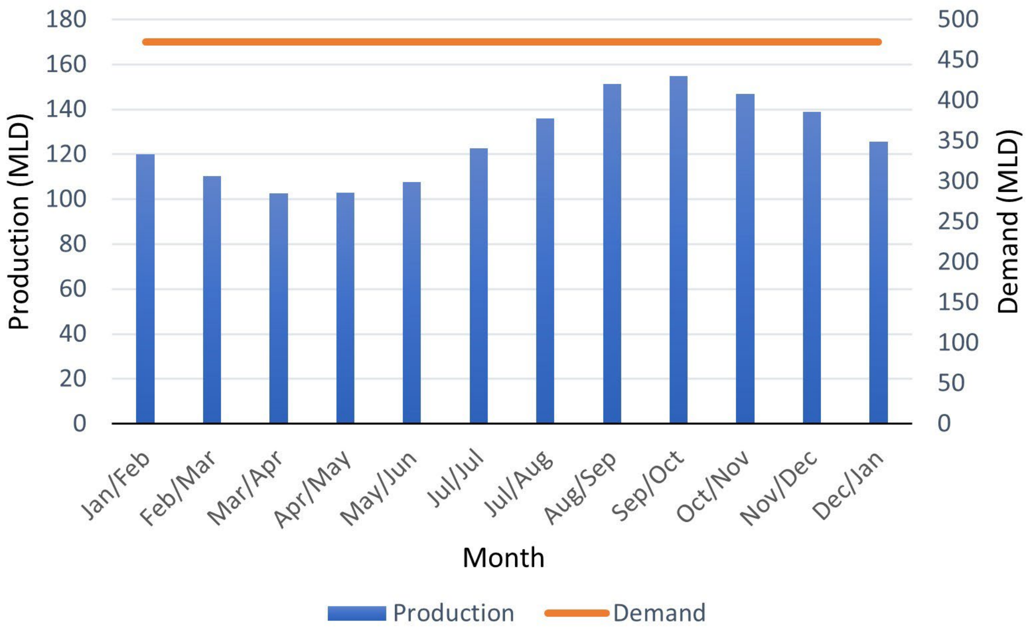

Figure 2: Water demand and average daily production in MLD in the year 2021/22 in different months. *Data source*: KUKL (2023)

To minimise the exploitation of groundwater, as well as to provide recharge to groundwater, and to meet the water supply demand in the Valley various surface water projects were introduced. The Melamchi Water Supply Project (MWSP, https://www.melamchiwater.gov.np/), which is one of Nepal's 24 pride projects (https://npc.gov.np/en/page/national_pride_projects), and one of three completed ones was envisioned as the best solution to meet the water demand of the Valley residents, aiming for a total water supply of 510 MLD in two phases - 170 MLD in the first phase and 340 MLD in the second phase. However, the project has faced multiple delays and is still incomplete. The first phase, providing 170 MLD, falls short of meeting the Valley's average water demand. Additionally, the 20% water loss between the source and the end distribution accumulates to a water deficit of over 370 MLD (KUKL, 2023). Kathmandu Upatyaka Khanepani Limited (KUKL), which serves as the main water supply utility in the Kathmandu Valley, presently can only meet 17.4% (dry season) and 26.2% (wet season) of the Valley's water demand (Figure 2). Out of this supply, 67% is sourced from surface water, while 33% relies on groundwater extracted through 104 deep tube-wells (KUKL, 2023). The gap in supply and demand is thus fulfilled by private groundwater extraction.

Increased urbanisation has led to the conversion of permeable land to non-permeable land, resulting in a decrease in the infiltration rate of 23.78 MLD between 2010 to 2020 (Shrestha et al., 2023). This decline is projected to further decrease by 20.67 MLD till 2030 (Shrestha et al., 2023). The decrease in infiltration not only results in a decline in groundwater recharge but also increases urban flooding. The northern part of the Kathmandu Valley consists of a large area of more permeable soils and generally experiences lower runoff rates (Dixit and Upadhya, 2005; Dahal et al., 2019). The ongoing construction of the Dhap dam in Sundarijal, the northern part of the Valley (Figure 3), could have a positive impact on enhancing groundwater recharge.

Sundarijal is one of the biggest reservoirs that supply drinking water to the Kathmandu Valley from rivers including the Bagmati, Bishnumati, Shyalmati, Nagmati, Chotte Khola, Baghmara Khola, Bounde, Bhandare, Alle, and Thulokhola. Roughly 30 million liters of water are drawn each day from these streams and captured in the Sundarijal, Maharajgunj, and Balaju reservoirs before being distributed throughout the Kathmandu Valley (Bhattarai, 2004). The Sundarijal reservoir is the largest among these reservoirs, receiving water from the Bagmati, Nagmati, and Shyalmati rivers. The majority of the Sundarijal region surrounding these reservoirs is contained inside the Shivapuri National Park's perimeter of protection. According to a study by Bhattarai (2004), the water quality of the Sundarijal reservoir and its feeder streams is suitable for drinking water.

Figure 3: Water storage in Dhap Dam.

Groundwater extraction in the Kathmandu Valley has reached unsustainable levels, leading to significant problems. According to Chinnasamy & Shrestha (2019), the current available storage capacity of the aquifer is approximately 246 billion litres of water in the aquifer. Furthermore, the rapid urbanisation of the Valley, one of the fastest in South Asia, has resulted in substantial changes in land use land cover (LULC). Projections indicate that approximately 6% of open land in the Kathmandu Valley is being converted into impervious areas every decade, accelerating the rate of groundwater depletion (Lamichhane and Shakya, 2019).

Moreover, Kathmandu Valley's excessive groundwater extraction has resulted in land subsidence, particularly in the north and northeast regions along the groundwater basin's periphery (Shrestha *et al.*, 2017). The primary factor contributing to the Valley's land subsidence is linked to deep aquifer compaction by excessive groundwater pumping (Bhattarai & Kondoh, 2015, Bhattarai et al., 2014, Ghorbanzadeh et al 2020). The estimated subsidence is also greatly affected by changes in the land cover in the recharge zones. The subsidence studies are mostly limited to using satellite data, for example, Interferometric Synthetic Aperture Radar (InSAR) (Krishnan and Kim, 2018). Further research is needed for a more comprehensive understanding of the issue. KVWSMB is currently monitoring the land subsidence using Differential Global Positioning System (DGPS) stations. They have not published the study results at present.

In the Terai, large-scale deforestation and mining in Chure and Bhabar, have increased the diminishing rate of groundwater as this region serves to recharge the groundwater in Terai. This is alarming because the region depends on groundwater for drinking water supply and agricultural activity. The section below discusses a case study of the Bhairahawa Lumbini Groundwater Irrigation Project to understand the groundwater supply and its use for the Terai for irrigation.

3.3 Case Study: Bhairahawa Lumbini Groundwater Irrigation Project

The Bhairahawa Lumbini Groundwater Irrigation Project (BLGWIP) aimed to utilise groundwater for irrigation purposes, covering an extensive area of over 20,309 hectares of land. The project was completed in three stages with the construction of 181 deep tube-wells; 68 in the first stage, 34 in the second stage, and 79 in the last stage. The project has increased crop intensity leading to productivity surpassing the national average which has had a positive impact on the economy and the living standards. Additionally, the project facilitated infrastructure development of electricity and motor roads to access markets for agricultural produce. The tube-wells used to operate with sufficient pressure flow to support irrigation activities, however, over time the efficiency of the tube-wells has declined due to groundwater depletion and a lack of maintenance. Currently, approximately 25% of the tube-wells are no longer functioning as expected.

The challenges faced by the BLGWIP highlight the importance of sustainable groundwater management practices. Adequate measures, such as monitoring groundwater levels, and implementing efficient water use techniques are crucial to prevent the depletion of groundwater resources and maintain the long-term success of irrigation projects.

Lessons learned from the BLGWIP case study emphasise the need for integrated management approaches, including careful planning, continuous monitoring, and regular maintenance of groundwater irrigation systems. Additionally, sustainable practices that take into account the limitations of groundwater availability and the depletion potential should be prioritised to ensure the long-term viability of similar projects in the future.

3.4 Groundwater Quality

The hydrochemical composition of an aquifer is influenced by various factors such as geological formations, land use practices, and anthropogenic activities. Gaining a comprehensive understanding of the hydrochemical characteristics of an aquifer system is essential for assessing groundwater quality, identifying potential sources of contamination, and implementing appropriate management strategies.

Groundwater quality in the Kathmandu Valley exhibits wide variations due to the presence of diverse chemical constituents and contamination sources (Shrestha et al., 2018b) and is influenced by both geogenic and anthropogenic factors (Shakya *et al.*, 2019). It exhibits a wide range of pH levels, varying from slightly acidic to alkaline, as indicated in Table 2. Studies have assessed the presence of elevated levels of nitrate and mercury in the groundwater (Khatiwada *et al.*, 2002). Deep wells have been found to contain high concentrations of ammonia, nitrate, iron, lead, arsenic and cadmium with some samples exceeding the World Health Organization (WHO) standards for drinking water (Chapagain *et al.*, 2010). Additionally, the presence of E. Coli bacteria has been observed in groundwater samples (Shrestha *et al.*, 2018a).

Due to the complexity, impracticality, and expense of remediating groundwater pollution, its prevention and control must be a priority (Shrestha et al., 2016). Haphazard and rapid urbanisation and industrialisation have caused an increase in anthropogenic and natural factors contributing to a rise in chemical and microbial contamination in groundwater (Pant 2009; Ghartimagar et al., 2020). Groundwater pollution hazards in the Kathmandu Valley are mainly due to anthropogenic causes and the extensive use of boreholes and wells (Ghartimagar et al., 2020). Along with this, point source pollution has been noted highlighting degrading conditions of groundwater (Shakya et al., 2019).

Table 2: Hydrochemical characteristics of groundwater in the Kathmandu Valley and the Terai plains along with the standards from National Drinking Water Quality Standards (NDWQS) and World Health Organization (WHO) (Bhandari *et al.*, 2020; Ghimire *et al.*, 2023; Gwachha *et al.*, 2020; Thapa *et al.*, 2019; Shrestha *et al.*, 2018; Pandey and Walraevens, 2019; Mahato et al., 2018)

Parameter*	**Unit***	**Kathmandu Valley**	**Terai**	**NDWQS (2005)**	**WHO Guidelines (2017)**
pH		6.0 - 11.6	4.78 - 9.32	6.5 - 8.5	6.5 - 8.5
TDS	mg/l	112 - 1,063	45 - 1001	1,000	1,000
EC	μS/cm	226 - 2,127	50 - 1,540	1,500	1,500

Total Coliform	MPN/100 ml	56 - 315	148 - 267	95% in sample	95% in sample
Turbidity	NTU	0.78 - 412	0-149	5(10)	-
Sodium	mg/l	13.9 - 79.8	0.4 - 118.2	-	-
Potassium	mg/l	0.27 - 50.3	0.01 - 14.04	-	-
Calcium	mg/l	38.47 - 389	24.32 - 61.36	200	100
Magnesium	mg/l	0.01 - 81.87	14.36 - 29.44	-	50
Total Hardness	mg/l	48.6 - 612	0 - 686.6	500	500
Chloride	mg/l	0 - 241.4	8.78 - 18.81	250	250
Bicarbonate	mg/l	15 - 450	171 - 256		300
Nitrate	mg/l	0 - 0.3	0.1 - 18.4	11.2	50
Ammonia	mg/l	0 - 0.99	0.01 - 3.34	1.2	1.5
Iron	mg/l	0 - 10.16	0.1 - 18	0.3	0.3
Phosphate	mg/l	0 - 3.65	0.1 - 3	-	1
Sulfate	mg/l	0.3 - 77.7	0 - 41	250	250
Arsenic	ppm	0.01 - 2.80	0 - 3.2	0.05	0.01
Zinc	mg/l	0.01 - 0.13		3	-
Copper	mg/l	0.01 - 0.29		1	2

( ) Values in parenthesis refer to the acceptable values only when an alternative is not available.
*pH: Potential of Hydrogen, TDS: Total Dissolved Solids, EC: Electrical Conductivity, mg/L: Milligram per litre, µS/cm: microSiemens per centimetre, MPN/100 ml: Most Probable Number per 100 millilitres, NTU: Nephelometric Turbidity Units, ppm: parts per million

3.5 Good Practices, Lesson Learned

The management of groundwater in the Kathmandu Valley has highlighted several good practices and valuable lessons for sustainable groundwater management.

- Research and monitoring: As famously stated by management guru Peter Drucker, effective management requires measurement. Research and monitoring play a crucial role in understanding and managing groundwater, and for observing changes in its status. Early works, such as the groundwater investigation program in various parts of the Terai region and the classification of different districts of the groundwater basin in the Kathmandu Valley by JICA (1990), laid the foundation of groundwater studies. Subsequent research projects, training programs, and annual events and symposiums further advanced groundwater knowledge, capacity building of early career professionals, and policy advocacy in the area; a few of these are listed in Appendix 2. Establishing a long-term monitoring network is vital for sustainable groundwater management. Citizen science can offer a potential solution to make monitoring large-scale and cost-effective (Prajapati, et al., 2021a; Prajapati, et al., 2021b).

- Promoting efficient use of water: Nepal faces challenges in implementing large-scale infrastructure projects due to political, financial, technical, and disaster risks, as evidenced by delays in projects such as the MWSP. Moreover, while MWSP has been proposed to lessen the water crisis in the Valley, it does not completely meet the water demand (Ayadi *et al.*, 2020). The Kathmandu Valley receives an average annual rainfall of 3,353 MLD (Shrestha, 2009), which is eight times the water demand of the valley. Despite this, a significant amount of water remains unused due to various factors. There are instances where efficient use of water resources is being promoted. For example, mobile applications like *Aakaashepani* are promoting rainwater harvesting in Nepal. These applications help users calculate the optimal tank size required for household needs, provide information on technical and financial aspects of rainwater harvesting systems, and map the nearest vendors for installation parts (APN, 2018).

- Integrated management: Land use and precipitation patterns have a substantial impact on groundwater levels, and these are expected to intensify in the future (Prajapati, et al., 2021b). Furthermore, water holds cultural and religious significance, which has been recognised in conservation and protection measures. This view promoted a harmonious coexistence with nature rather than viewing water solely as an economic asset (Nepali Times, 2020). However, integrated perspectives are often neglected, leading to mismanagement of groundwater resources. Thapa *et al.* (2018) suggested expanding the water distribution network to reach a greater population, particularly after the implementation of MWSP.

- Regulating groundwater use: Regulating groundwater use is crucial for its sustainable management. Effective policies and regulations are needed to control extraction rates, prevent over-exploitation, and ensure equitable distribution. Implementing permit systems, metering mechanisms, and enforcement strategies can help regulate groundwater use and mitigate the risks associated with excessive extraction. Ayadi *et al.*, (2020) emphasised the importance of improving the water tariff scheme in the Kathmandu Valley.

In summary, adopting good practices such as research and monitoring, promoting efficient water use, embracing integrated management approaches, and implementing effective regulations are essential for sustainable groundwater management in the Kathmandu Valley. By learning from past experiences and implementing appropriate measures, it is possible to safeguard and preserve this vital resource for future generations.

4. Conclusion

Groundwater management in Nepal, particularly in the Kathmandu Valley and Terai, faces various challenges and requires comprehensive strategies and policies. This chapter has provided an overview of groundwater management by examining data and research, discussing regulatory and policy aspects, as well as raising awareness and capacity building. The availability of groundwater in Nepal varies significantly across different regions. Varying sediment and geological formation significantly impact the behaviour and hydrochemical composition of the groundwater. Therefore, it is crucial to have a comprehensive understanding of these characteristics and implement effective management strategies to ensure sustainable utilisation of groundwater for the region. While the Kathmandu Valley witnesses high exploitation and groundwater depletion, the plains of the Terai have vast potential for groundwater irrigation due to the presence of large rivers and quick aquifer recharge.

The National Water Resources Management Plan has primarily focused on surface water, neglecting the importance of groundwater resources however the surface water accessible through rivers, rivulets and ponds degrading quality has added stress to the groundwater resources. Furthermore, the discontinuation of key organisations due to budget constraints and delay in major water supply projects responsible for groundwater management exacerbate the situation. Despite the establishment of water-related institutions and the formulation of policies and legislations, there is no holistic regulatory framework for groundwater management.

Despite these challenges, some good practices and lessons learned have emerged. The management of groundwater resources in Nepal requires urgent attention and comprehensive actions. It is crucial to establish a strong regulatory framework, enhance research and monitoring efforts, and implement sustainable management practices. By addressing the challenges and incorporating lessons learned, Nepal can ensure the long-term availability and quality of groundwater resources for various sectors and communities.

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Appendixes

Appendix 1: Legal Instruments Related to Groundwater in Nepal

Legal Instrument	**Key Provisions Related to Water Sector**
Policy	
Hydropower Development Policy, 1992	Not Mentioned
The Hydropower Development Policy, 2001	Not Mentioned
Climate Change Policy 2019	8.3 Water Resources and Energy Rainwater harvesting ponds will be constructed for groundwater recharge and their multiple-use Standards will be developed and implemented for the sustainable use of groundwater resources in urban areas.
Land Use Policy, 2015	Not Mentioned
Rural Water Supply and Sanitation National Policy, 2004	Not Mentioned
National Agriculture Policy, 2004	Not Mentioned
Irrigation Policy, 2013	Extensive irrigation services demand promoting the conjunctive use of groundwater and surface water irrigation systems; water reservoirs, rainwater harvesting, and groundwater resources shall be developed, conserved, promoted, and utilised as supplementary sources to the seasonal rainfall. Available groundwater resources shall be developed and utilised like the surface water reservoirs, and arrangements shall be made for conservation, promotion, and control of the quality. Proper measures shall be taken for the protection of groundwater resources for optimal use of that

	resource. Institutional reform programmes shall be conducted as prescribed by the water resources strategy in this regard. Special subsidy shall be provided on tariff for electricity used in groundwater and lift irrigation systems.
Water-induced Disaster Management Policy, 2015	Action Required
Draft Water Resources Policy	Action Required
Strategy	
Rural Water Supply and Sanitation National Strategy, 2004	No
Agriculture Development Strategy (2015-2035)	The APP period saw a dramatic improvement in rural road infrastructure, community forest, and horticulture. Irrigation expanded considerably even though it did not achieve the groundwater targets that were set by the APP. Activities related to Output 2.5 on Irrigation Area expanded equitably and viably, and improved Irrigation Efficiency and Management: Pilot construction of medium pond/recharge basins. These are basins that store water and recharge groundwater, for use by both irrigation and water supply. They may be linked with surface or non-conventional irrigation (e.g. sprinklers, drip systems). At present no agency is specifically concerned with multi-purpose water resource development, but the Groundwater Resources Development Board (GWRDB) may be appropriate. i. Identify an appropriate responsible agency and conduct a study to identify potential recharge basin sites based on farmers' need and estimated cost-benefit analysis. ii. Construct pilot recharge basins under ADS, and replicate based on impact assessment. Groundwater utilisation statistics are inaccurate, as changes in command area since construction and (for example) the breakdown of DTWs are not recorded.

	Major investment gaps are considered to be: Lack of sufficient budget for groundwater development. While the WRA requires licences for certain groundwater water uses, licences are neither sought nor issued.
Act	
Aquatic Protection Act, 2017	No
Civil Code, 2017	253. Property deemed to be immovable: (1) The following property shall be deemed to be an immovable property: 1. Natural water, surface water and underground water
Consumer Protection Act, 1999	No
Environment Protection Act, 1997	No
Soil and Watershed Conservation Act, 1982	Prohibited acts in land vulnerable or likely to be vulnerable to natural calamity: To block or collect in any way the water of any stream, canal, rill, lake or reservoir or groundwater or divert the blocked or collected water elsewhere or return the same through a ditch, diversion channel, drainage or in any other manner or use such water in any work by so blocking, collecting, diverting, returning or otherwise
Land Acquisition Act, 1977	No
Local Government Operation Act, 2017	Local water policies, laws, standards, planning, implementation, and funding mechanisms for operating and maintaining small surface and groundwater transportation systems, as well as managing service fees and data collection.
Natural Resource and Fiscal Commission, 2017	No
Nepal Water Supply Corporation Act, 1989	

Water Supply Management Board Act, 2006	The functions, duties and powers of the Kathmandu Valley Water Management Board, in addition to the functions, duties and powers set forth in Section 6, shall be as follows: Except as otherwise mentioned in the prevailing laws, to regulate, control or prohibit the extraction and use of water from groundwater resources within its geographical area, and, as per necessity, to give licence, as prescribed, to extract or use such water.
Water Supply Tariff Fixation Commission Act, 2006	No
Water Tax Act, 1966	No
Draft Water Resources Act	
Rules	
Drinking Water Rules, 1998	No
Drinking Water Service Charge (recovery) Rules, 1994	No
Environment Protection Rules, 1997	Proposals Requiring Initial environmental examination: Drinking water: Recharging of more than Fifty percent of the total aquifer for the development of underground water sources Over mining of biologically or chemically polluted point and nonpoint sources of underground water sources that may be affected by them.

Environment Protection Rules, 1997	Proposals Requiring Initial environmental examination: Drinking water: Recharging of more than Fifty percent of the total aquifer for the development of underground water sources Over mining of biologically or chemically polluted point and nonpoint sources of underground water sources that may be affected by them.
Irrigation Rule, 2000	Fifteen percent of total cost shall be borne by Users association for the deep tube wells under the groundwater. The entire amount shall be borne by Users Association for the construction of shallow tube wells.
Water Resources Rule, 1993	No
Pesticide Rule, 1994	No
Solid Waste Management Rules, 2013	No
Guidelines/Directives/Manuals/Working Procedure	
National EIA Guideline	The need for EIA was stressed in the Seventh Five-year Plan (1985-1990) which required preparation of EIA for all major development projects related to the sectors of tourism, water resources, transportation, urbanisation, agriculture, forestry, and industry
National Drinking Water Quality Standard, 2005	Parameters of NDWQS applicable for Rural Groundwater Supply System
Drinking Water Service Operation Directive, 2012	

Appendix 2: Different Efforts on Groundwater Management and Development

Activity/Event	Summary	Organisers
Groundwater Investigation Program (since 1970)	USAID was the first to conduct a primary groundwater investigation program in Nawalparasi, Rupandehi, Kapilvastu, Banke, Baridya, Kailali, and Kanchanpur districts through the construction of deep tube-wells. Afterward, with the help of UNDP, the Government of Nepal carried out a shallow aquifer investigation project covering whole districts of the Terai. From then onwards, GWRDP has been continuously conducting investigation programs by constructing deep and shallow tube-wells, and by carrying out geophysical survey, water level monitoring of existing tube-wells, and water quality analysis programs. The project also aims to start hydrogeological study of Kathmandu Valley, mountains, and the Karst aquifer of the surrounding area.	Ministry of Energy, Water Resources and Irrigation, Groundwater Resources Development Board
National Groundwater Symposium (since 2009)	The objectives of the groundwater symposium is to share research works and study related to Groundwater its issues and opportunities.	
Groundwater Expert Meeting (July 4-5, 2010)	The expert meeting discussed the current status of groundwater environment and identified the research and data gaps to be addressed in the future.	KVWSMB/CREEW/ UN-HABITAT
Graduate Course on Surface Water and Groundwater Interaction in Kathmandu (November 13-19, 2016)	The course aimed to educate graduate students, young researchers, and planners about the fundamental concepts of surface water, groundwater, and their interactions. Participants had the opportunity to share their research paper, working projects and proposals. Discussions were held on pressing water resource issues in Nepal, which also included groundwater contamination, and the lack of data and governance. A field excursion allowed participants to observe real-life examples of surface water and groundwater interaction and management in the southern part of the Kathmandu Valley.	The Small Earth Nepal (SEN), The Institute of Engineering, Tribhuvan University, University of Calgary, Canada and United States Geological Survey, USA.

Citizen Science Groundwater Level Monitoring in the Kathmandu Valley (since 2017)	Smartphone for Water (S4W) Nepal recruited Citizen Scientists (CS) for monitoring the monthly groundwater levels. They also assess the seasonal water quantity/quality of stone spouts and ponds of the Valley. Likewise, S4W-Nepal has been carrying out a stream-aquifer interaction study to understand the linkage between surface water and groundwater systems of the Valley.	S4W - Nepal
Restoration at Nigu Pukhu (Dui Pokhari) at Thimi, Bhaktapur (inaugurated on April 15, 2019)	The groundwater in the area had depleted severely for years, but after the pond was rebuilt, it started rising. After the Dui Pokhari was restored, the water levels rose in around 20 wells in the area	
Second Graduate Course on Hydrogeology (August 12-16, 2019)	The course focused on engaging the participants in hands-on exercises, group work, and poster presentations to enhance their understanding on the concepts of groundwater hydraulics and modelling, aquifer safe yield and sustainability considerations, water quality issues, water management, and water resources protection approaches. Participants showcased their technical approaches to groundwater issues in different parts of the country through poster presentations.	SEN, Fulbright Specialist Program, Asia Pacific Network for Global Change Research (APN), University of Rhode Island (URI), Tribhuvan University Alumni Association Nepal (TUAAN), Centre for Hydrology of University of Saskatchewan (C4H-Usask) and KVWSMB.
Seminar on Challenges of Sustainable Groundwater Development (August 18, 2019)	The seminar aimed to raise awareness about the importance of groundwater, issues of groundwater mining, and solutions for sustainable use and management of groundwater. The keynote presentation highlighted the traditional knowledge of water treatment technologies existing in Nepal and the experience of groundwater exploitation and management. A panel discussion emphasised on the need for urgent action to address groundwater depletion, pollution, and also looming water scarcity in urban areas of Nepal.	SEN, Fulbright Specialist Program, APN, URI, TUAAN, C4H-Usask, KVWSMB, and CREEW

Introduction Course to Groundwater Modelling with MODFLOW (22 October 2019)	The course was a combination of webinars, lectures, and hands-on-exercises to offer the major concepts and applications of groundwater flow modelling using the USGS MODFLOW family program.	SEN, Australian Water School (AWS), KVWSMB, the International Association of Hydrogeologists NSW (IAH NSW) branch, International Centre of Excellence in Water Resources Management (ICEWaRM)
Pilot Project on Recharge Kathmandu (February 18, 2020)	To replenish depleting groundwater in the city, Kathmandu Metropolitan City launched a pilot under which water is recharged by harvesting rainwater. Under the pilot, two 24-feet recharge wells have been dug on one *ropani* (5,476 m^2) of public land in the Gongabu Residential Area. Rainwater is first collected and then passed through a gutter and supplied to an underground tank. When the tank overflows, water then flows into the recharge wells that contain layers of boulders, aggregates, and sand.	Kathmandu Metropolitan City
Webinar on Groundwater Governance and Water Security Under Changing Environment (October 15, 2020)		SEN, in collaboration with the Central Department of Hydrology and Meteorology (CDHM), KVWSMB, Asian Institute of Technology (AIT), AIT Alumni Association of Nepal, Society of Hydrologists and Meteorologists – Nepal (SOHAM-Nepal), International Centre for Integrated Mountain Development (ICIMOD)

Rainwater Harvesting and Groundwater Recharge in Lalitpur Metropolitan City: Addressing Increased Water Demand (January 2020 - Feb 2021)	Project was implemented in Lagankhel, the highest point of Patan City, to enhance urban resilience through rainwater harvesting and groundwater recharge. 51 recharge wells along with 51 filter chambers were constructed within the Rajdal Barrack premises which has an annual water recharge potential of 51 million litres. Alongside, one rain garden has also been constructed to demonstrate the efficiency of such initiatives towards groundwater recharge. Furthermore, motivational and awareness programs on groundwater recharge were conducted in the wider communities involving local authorities, civil society organisations, and academic institutes.	Centre for Integrated Urban Development, WaterAid Nepal, and The Coca-Cola Foundation which was later handed over to Army Rajdal Barrack
Training on Groundwater Modelling using ModFlow and R-Programming (April 25 - 30, 2022)		Water Resources Research and Development Centre
Cluster-based Groundwater Development for Year-round irrigation: Potentials, Learnings and ways forward (July 28, 2022).		Nepal National Committee on Irrigation and Drainage (NENCID)
Webinar on Enhancing Sustainability of Groundwater Irrigation System through Clustering Approach (April 25, 2023)		NENCID

Groundwater Availability and Risk of Groundwater-Related Land Subsidence of Metro Manila

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Abstract

This paper is on groundwater resources of Metro Manila to address two issues: (1) is the water demand deficit of about 450 MLD in 2025 can be sourced from groundwater in the addition to the current extraction rate of 800 MLD; and, (2) is there a potential risk to land subsidence due to groundwater withdrawal. In this paper, groundwater model simulation studies were conducted to address the two issues. The simulation study shows that the additional of 450 MLD (or even more) can be sustainably extracted from groundwater in addition to current groundwater extraction rate of 800 MLD together with surface water sources to satisfy the Metro Manila's 2025 water demand. About the risk of land subsidence, the risk is relatively small at the groundwater current extraction rates and some additional future proposed groundwater withdrawals. It is suggested that optimal conjunctive use of surface water and groundwater sources should be adopted as a long-term operational strategy to meet future, increasing water demand of Metro Manila.

Key Words: *groundwater model simulations, sustainable groundwater pumping, land subsidence*

1. Introduction

The Philippines is endowed with abundant surface water and groundwater resources due to the large amounts of rainfall it receives annually. From water balance studies of the country, it is estimated that the average annual surface water available is 125,800 MCM (million m^3) while the available groundwater is estimated to be 20,200 MCM based on groundwater recharge studies (NEDA, 2021). This is a total of about 146,000 MCM freshwater available. However, based on water use permits issued by the country's National Water Resource Board (NWRB), only 86,000 MCM is allocated annually for various uses which is about 58% of the total freshwater available. For domestic and municipal water use, only 7,600 MCM is annually consumed by the country's population of 110 million people in which 5,600 MCM is from surface water sources and 2,000 MCM is from groundwater sources.

This paper in concern with the groundwater resources and use in Metro Manila. Currently, Metro Manila's water demand is approaching 5600 MLD in which 4500 MLD is sourced from surface waters such as the Angat Reservoir, Novaliches Reservoir and Laguna Lake and about 800 MLD is from groundwater. This is a deficit of about 300 MLD which is significantly felt during dry years that result in reduced amounts or hours of water deliveries in parts of Metro Manila especially during the months from March to May. It may be noted that groundwater as a source has become unreliable due to water quality issues and pollution problems so that its usage has been reduced to 800 MLD from about 1500 to 2000 MLD that was extracted in the 1980's as indicated by the groundwater permits during that period.

It is projected that Metro Manila's water demand will be increasing from 6950 MLD in 2025, 8300 MLD in 2035 and 10,000 MLD in 2045 (Tabios, 2023). By 2025, with the addition of new water sources (i.e., Wawa Upper Dam and Kaliwa Dam) which can add an additional of about 1200 MLD, there will still be a deficit of about 450 MLD (i.e., the current 300 MLD plus 150 MLD by 2025). In 2004, there was a moratorium of new groundwater permits and use in Metro Manila and apparently, there is some groundwater water storage recoveries in the last 20 years.

In view of the above, this paper presents a study to assess the groundwater availability of Metro Manila to investigate if the water demand deficit of about 450 MLD can be sourced from groundwater in the addition to the current extraction rate of 800 MLD. Also, this paper presents the risk of land subsidence due to groundwater withdrawal at certain, identified locations in Metro Manila to develop the additional groundwater wells.

2. Governance of groundwater utilization and management in the Philippines

A brief discussion of governance of groundwater utilization and management in the Philippines is given below.

The National Water Resources Board (NWRB) which is an attached agency of the Department of Environment and Natural Resources (DENR) manages and regulates all water resources and services in the Philippines. NWRB has three mandated functions: (1) policy formulation and coordination of development water sector programs, projects and activities within the framework of integrated water resources management (IWRM); (2) water resource regulation through the issuance of water permit and resolution of water use conflict; and, (3) regulation of water service providers by determining service standards and targets, tariff levels, monitoring and measuring company performance, enforcing compliance, and imposing sanctions. About groundwater resource allocation, NWRB's methodology to grant groundwater permits is based on regional groundwater volumetric rate availability studies conducted in the 1980's. If one applies for a groundwater permit, the amount granted is simply subtracted from this pre-determined volumetric rate available in that region until it is fully allocated. An appropriate method would have been to run a groundwater water balance simulation model to determine if the applied amount to be extracted and its location is sustainable in the long-term in terms of safe yield and potential well interference problems with the other existing groundwater extractions (permits) in that area or region.

The Mines and Geosciences Bureau (MGB) under its Groundwater Section appears to be another national agency of the country that manages the groundwater resources of the country. MGB is responsible for the administration and disposition of mineral lands and mineral resources and the conduct of geological, mining, metallurgical, hydrogeological, and other researches, as well as geological and mineral exploration surveys. It implements the DENR's mandate in relation to the conservation, management, development, and proper use of the State's mineral resources, including those in reservations, watershed areas, and lands of the public domain. This agency produces regional groundwater availability maps for the entire country. However, these maps are essentially potential groundwater availability since these are based on subsurface geologic information (i.e., geologic structure and configuration) of the region and may not provide actual groundwater available if not investigated through groundwater recharge and withdrawal balance studies.

3. Case Study: Groundwater Availability and Risk of Land-Subsidence due to Groundwater Pumping

The studies presented are in two parts: (1) to assess the long-term sustainability of additional groundwater extraction of about 450 MLD in Metro Manila from its current extraction rate of 800 MLD to compliment the surface water sources; and, (2) to investigate the potential risk of land subsidence due to groundwater withdrawals.

3.1 Groundwater simulation model utilized

The surface water model and groundwater flow model utilized in this study are described as below.

The surface water model employed is a continuous-time, distributed model consisting of various components: rainfall input, evaporation, surface detention, infiltration, overland flow, channel flow, river routing and soil-moisture accounting. This soil-moisture accounting model is the Sacramento soil-moisture model with watershed (overland) and river flow routing (Burnash, et al., 1973). This model essentially describes the natural surface water processes and generates the surface water recharge to the groundwater system from long-term historical rainfall data available in the study area. The computer model developed by Tabios et al (1986) is utilized here.

For the groundwater, the FEMWATER developed by Yeh et al (1992) is utilized which is a 3-dimensional, saturated-unsaturated, finite element groundwater flow model with advection-dispersion model for solute transport. Since the FEMWATER computer program does not explicitly model land subsidence, it was modified for purposes of this study as described below. In FEMWATER, the governing equation is given by:

$$\frac{\rho}{\rho_o} F \frac{\partial h}{\partial t} = \nabla \cdot \left[\mathbf{K} \cdot \left(\nabla h + \frac{\rho}{\rho_o} \nabla z \right) \right] + \frac{\rho^*}{\rho_o} q \tag{1}$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{dS}{dh} \tag{2}$$

where F is storage coefficient, t, is time, θ is moisture content, h is pressure head, α′ is compressibility of the medium, β′ is compressibility of the water, **K** is hydraulic conductivity tensor, n is porosity of the medium, z is potential head, S is degree saturation; ρ is mixture density (with solutes), ρ_o is water (reference) density, and ρ* is density of source/sink water.

As seen above, the storage coefficient F define by Eq. (2) distinguishes aquifer compressibility (compressibility of the medium) and compressibility of the water. The term in Eq. (2) that parameterizes land subsidence, also referred to as soil consolidation or displacement is:

$$\alpha' \frac{\theta}{n} \tag{3}$$

Following the development of Bear (1979), assuming vertical displacement only, the formula to calculate the total settlement δ of an aquifer of thickness B corresponds to the volume of water drained out of the column of unit horizontal area given by:

$$\delta = \frac{c_p B}{1 + e} [ph_t - ph_{t-1}] \tag{4}$$

where ph_t is the piezometric head at time *t* to a decreasing piezometric head ph_{t-1} at time t-1; c_p is the coefficient of compressibility of the soil matrix; and, *e* is the void ratio defined as $e = n/(1-n)$ where n is the soil porosity.

3.2 Groundwater model simulation for additional groundwater extraction

Shown in **Figure 1** are the location of existing groundwater permits in Metro Manila and vicinity issued by National Water Resources Board (NWRB). The total amount granted by NWRB is about 1340 MLD (about 15 CMS) but only around 800 MLD are around Metro Manila. From results of the 2004 study commissioned by NWRB to evaluate the status of groundwater resources in Metro Manila, NWRB has implemented a moratorium on issuing new groundwater permits in Metro Manila to allow its aquifer to recover the piezometric levels that has lowered 20 to 50 meters from its original levels due to excessive groundwater pumping or extraction.

Upon, comparing the observed piezometric levels in 2004 and 2012, it was found that there are already areas in Quezon City, San Juan and Makati that had regained their levels by 20 to 30 m. With this finding, the question is if it is possible to lift the moratorium on groundwater permitting in some selective areas in Metro Manila as source of domestic water supply.

In the groundwater model of Metro Manila, the groundwater three-dimensional subsurface geology or soil structure rendering of the groundwater aquifer is shown in **Figure 2**. This figure only shows geologic materials for layers 15 to -15 m, -15 to -45 m, -45 to -75 m, and -75 to -105m according to the nine (9) different soil types namely: tuff, basalt, limestone, Gabbro, sandstone, shale, gravel, clay, sand/clay. Each of these soil type would have different groundwater properties such as hydraulic conductivity, porosity, soil compressibility, storage coefficients, among others.

To assess the groundwater availability and assess the sustainability of additional groundwater withdrawal, the results of groundwater simulations conducted by Tabios (2023) are shown in **Figure 3** under two scenarios: (i) base case where the groundwater extraction rates are equal to the existing extraction rates granted in the groundwater permits; and, (ii) case with extraction rates are 1.5 times the existing groundwater extraction rates. In this study, daily model simulation over 40 years period was conducted and the bottom-line result is that is that there is no significant change in head in 2012 to 2055 thus it can be concluded that an additional of almost 450 MLD (or even more) can be safely extracted from the original 800 MLD or so which sums to a total of 1250 MLD.

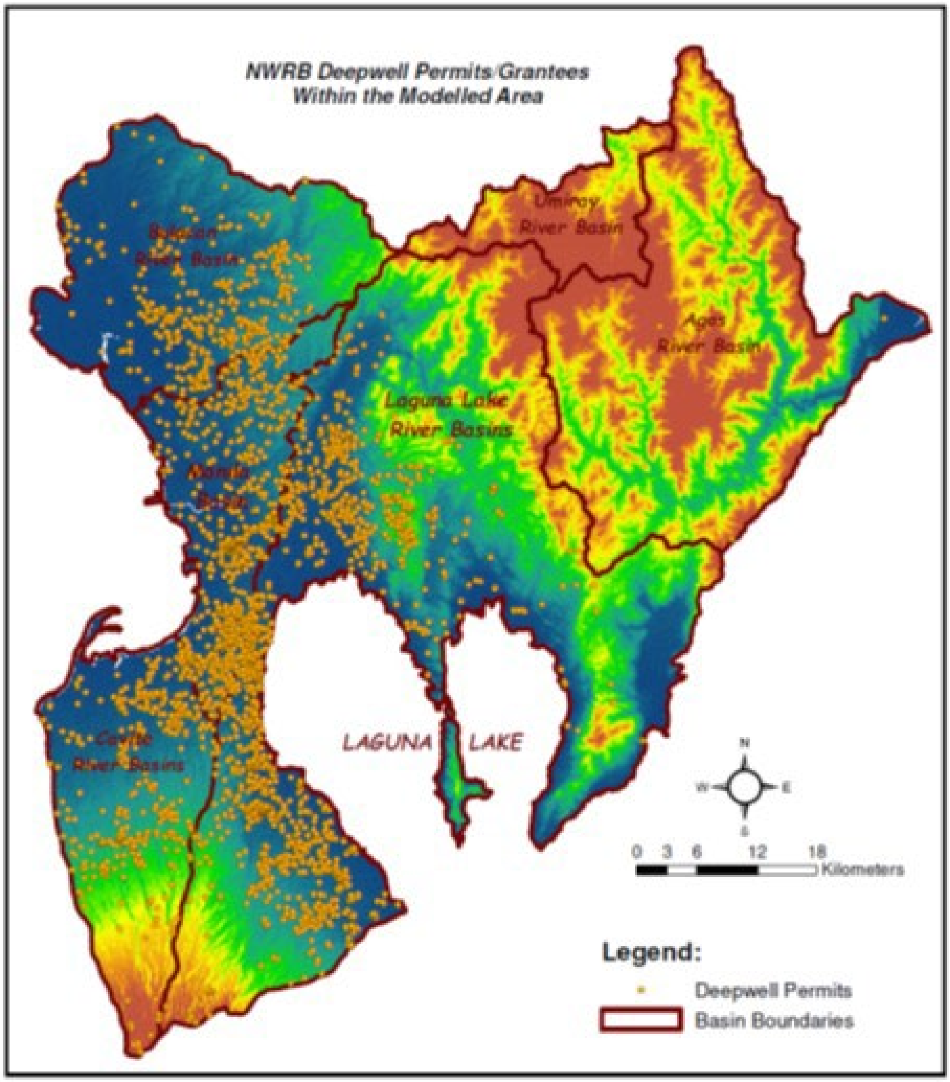

Figure 1: Location of existing groundwater permits issued by the National Water Resources Board (NWRB) as of 2012. (Taken from Tabios, 2016)

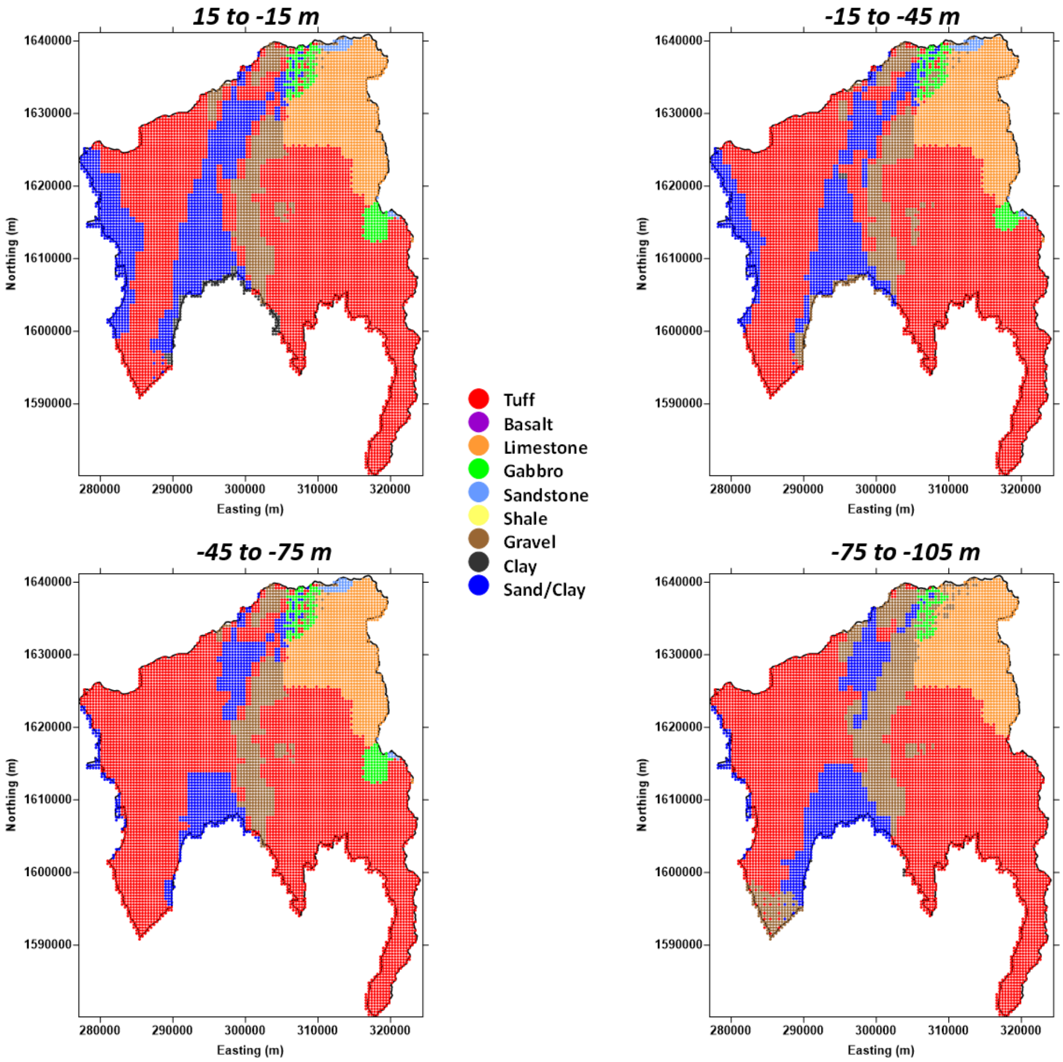

Figure 2: Groundwater three-dimensional subsurface geology or soil structure rendering of the groundwater aquifer of Metro Manila. This figure only shows the geologic materials for layers 15 to -15 m, -15 to -45 m, -45 to -75 m, and -75 to -105m according to the nine (9) different soil types namely: tuff, basalt, limestone, Gabbro, sandstone, shale, gravel, clay, sand/clay.

3.3 Model simulation to assess risk of land subsidence due to groundwater withdrawal

Ground subsidence is the slow lowering of ground surface. This phenomenon occurs in areas generally underlain by collapsible and expansive soils when natural and man-made stresses are imposed to the soil or substrate such as earthquakes, construction of heavy structures and withdrawal of groundwater to mention a few. These stresses squeeze out or removed the moisture or water in the pores of the soils supporting the soil. The removal of water support in particular results in ground lowering in the immediate vicinity of the source of stress, development of local basins, end ponds, tension cracks in soils and man-made structures, broken utility lines, tilting of buildings. However, the removal of water support due to groundwater pumping requires tremendously, excessive amount groundwater extraction.

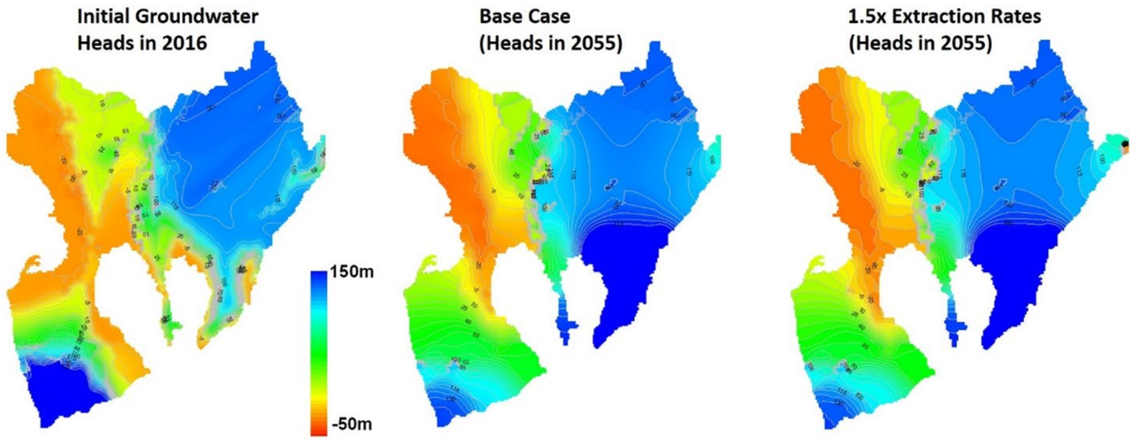

Figure 3: Groundwater heads in 2055 for base case (existing NWRB groundwater permits) and case with increased extraction rates (1.5 times base case extraction rates) from 3d groundwater model simulations. Initial heads in 2016 are also plotted. (Taken from Tabios, 2023)

Philippine Institute of Volcanology and Seismology (PHIVOLCS) published liquefaction hazard maps for Metro Manila and vicinity which is redrawn here as shown in **Figure 4**. These liquefaction hazard maps indicate the areas with highly compressible soils which collapse and cause damage to structures. The liquefaction hazard maps published by PHIVOLCS are mainly susceptibility to liquefaction and subsequently the land subsidence is attributed to earthquake and ground shaking since these areas are predominantly alluvial deposits. However, land subsidence without soil liquefaction can also occur due to large scale and excessive groundwater withdrawal or extraction. In any case, liquefaction hazard maps can provide guidance in identifying areas potential to land subsidence subjective to excessive groundwater extraction.

In Metro Manila and Rizal these are predisposed to ground subsidence such as in the Marikina Valley and Coastal Plain. These areas are underlain by alluvial deposits with extensive saturated and compressible fine soils and clays. Thus, these areas are the likely areas where ground subsidence may occur. Since these areas are near the so-called West Valley Fault in Metro Manila, it is likely that the risk of ground subsidence is greater due to earthquake or ground shaking compared to excessive groundwater removal since the latter can be easily regulated unlike earthquakes that cannot be controlled.

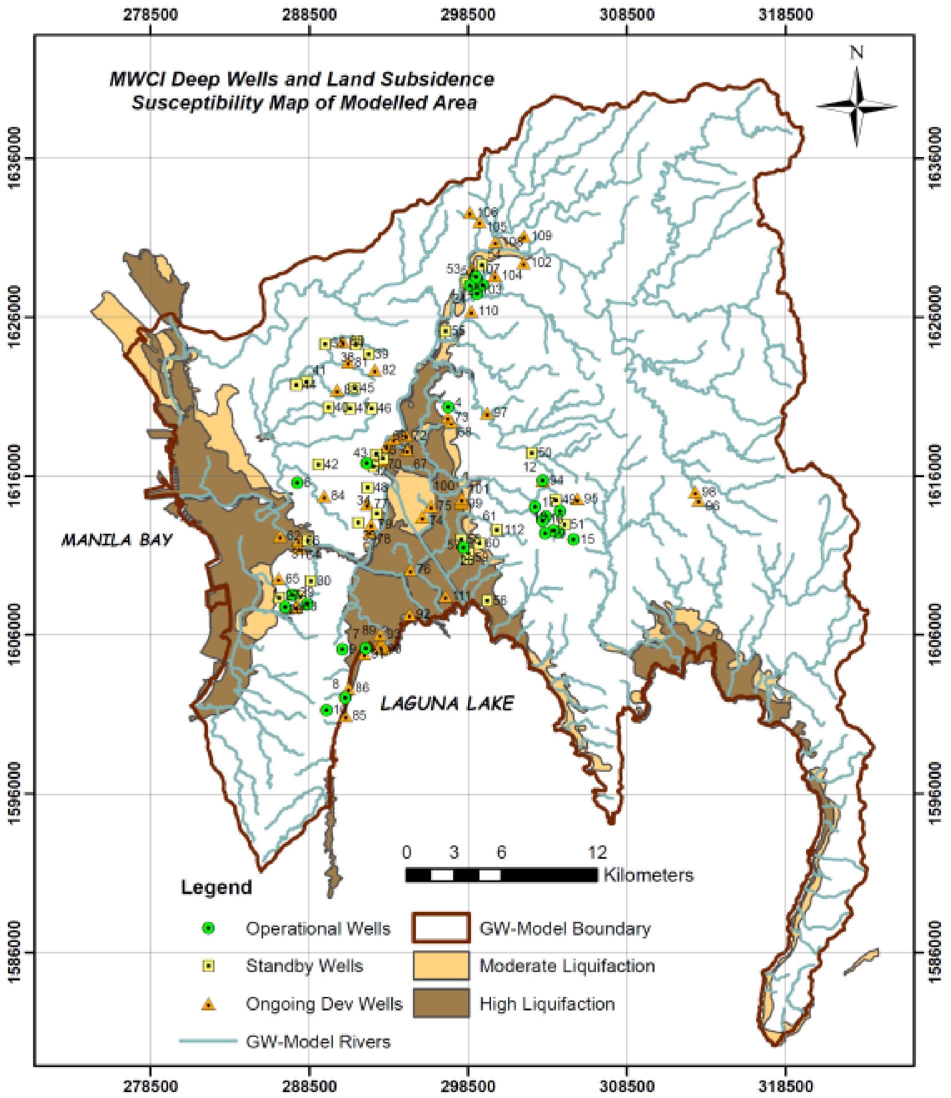

Figure 4: Groundwater susceptibility map of modeled area and location of groundwater deepwells from PHIVOLCS. (Source: Author's creation based on maps from PHIVOLCS website)

To study the risk or potential to groundwater-related land subsidence, a 10-year groundwater model simulation was conducted. In the simulation study, the pumping rates imposed are according to the water permits and certain groundwater wells were added at some strategic locations. A total of 483 groundwater wells are specified with pumping rates mostly ranging from 30 to 40 lps (liter per second) but the smallest is 2 lps and the highest 125 lps.

The resulting groundwater heads after 6 months, 1 year, 5 years and 10 years are shown in **Figure**

5. In the 10-year simulation, 43 (out of 483 groundwater wells) underwent wet/dry cycles and it is at these locations where there is potential risk to land subsidence or soil consolidation. In this wet/dry cycle, when the pumping well node becomes unsaturated (negative piezometric head), pumping is stopped at that location (i.e., wet-to-dry cycle) and when the node recovers (groundwater is recharged), pumping is resumed (i.e., dry-to-wet cycle). Over the study area as shown in **Figure 6**, the largest soil consolidation occurred in two (2) pumping wells of about 0.5 m. At these wells, the pumping rates are relatively high, both at about 110 lps which are located around the Calumpang area which are groundwater wells under the alluvial deposits of Marikina River. Seven (7) other pumping wells have maximum soil consolidations ranging from 0.06 to 0.3 m and the remaining thirty-four (34) wells with consolidation below 0.05 m.

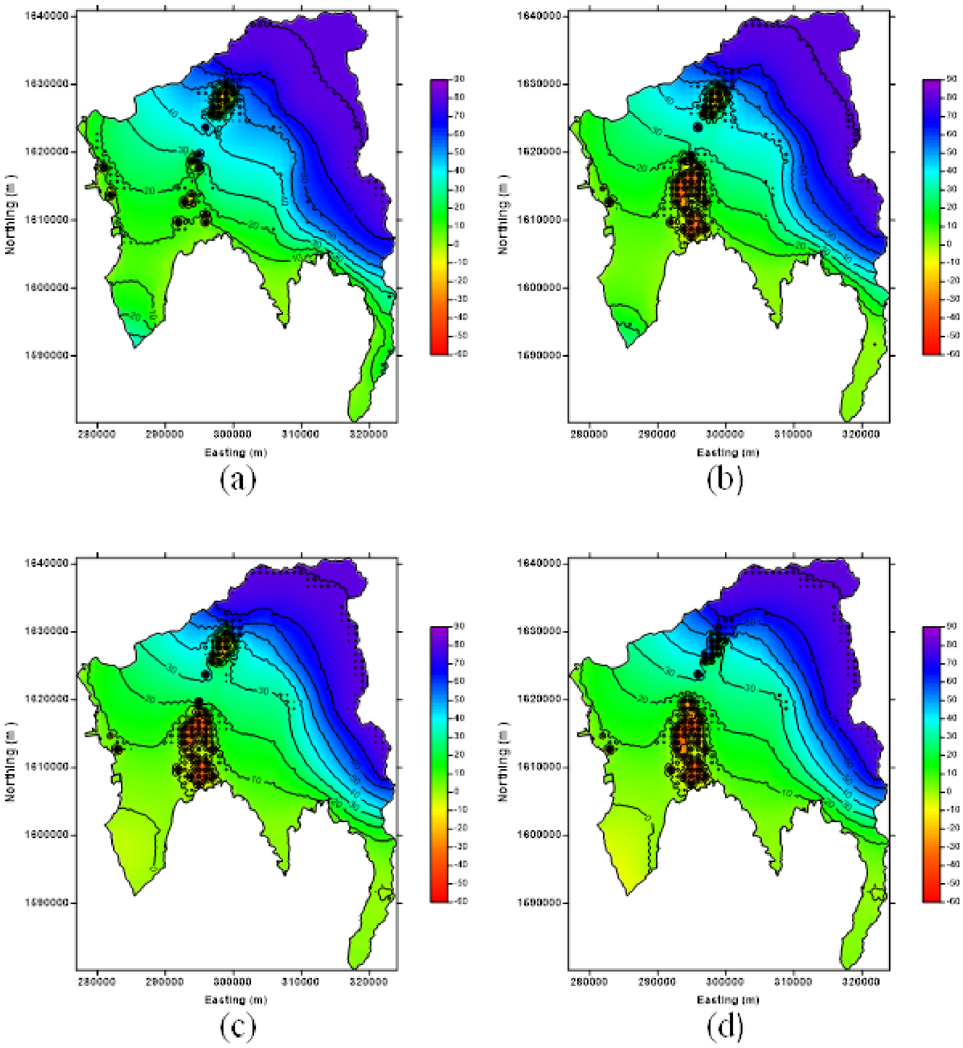

Figure 5: Contour maps of groundwater piezometric heads after (a) 6 months, (b) 1 year, (c) 5 years, and (d) 10 years over the 10-years simulation period.

Overall, it can be said that the risk of land subsidence over the entire study area is relatively small at the groundwater extraction rates imposed in the simulations here (based NWRB groundwater permits and the proposed groundwater well with associated extractions rates). It is suggested that at the groundwater locations that resulted in land subsidence as high as 0.5m, their pumping operation can be closely monitored and may be optimally operated (pumping schedule) to allow groundwater storage recovery even seasonally, to prevent the wet-to-dry cycles to occur. Since these wells are along alluvial deposits, groundwater recharge may be relatively fast on annual or even seasonal basis.

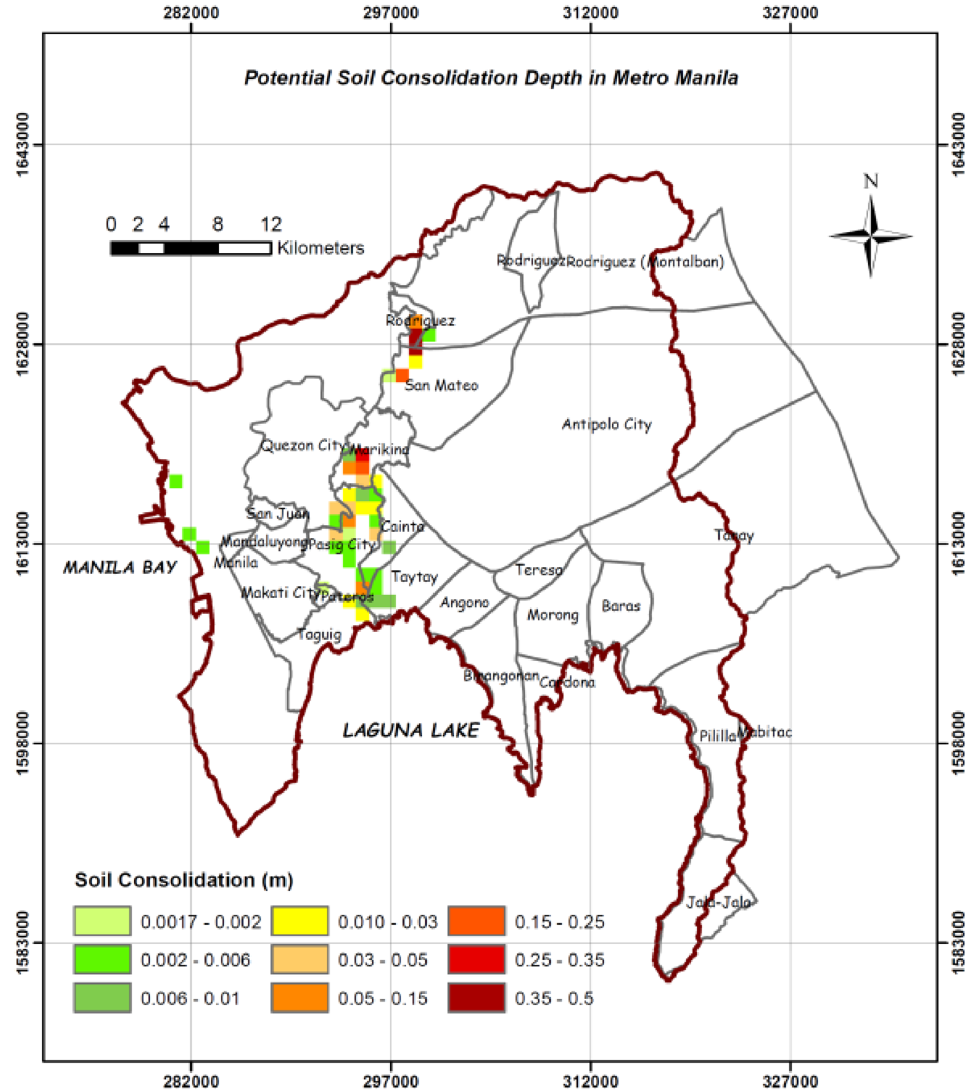

Figure 6: Map of potential soil consolidation depths (m) and their relative locations according to city and town boundaries.

4. Good practice, Lesson learned

The good practice that is advocated here is that groundwater modeling and simulation studies is vital and science-based approach to properly allocate and manage groundwater resources. In the Philippines, the NWRB which is the agency responsible for groundwater use permitting should utilize groundwater water balance model simulations to determine how much groundwater amounts can be permitted especially together with the existing groundwater permittees in an area according to long-term, sustainable groundwater withdrawal rates and without adverse impacts (e.g., creating well interference problems) to other existing groundwater wells with prior water rights. The groundwater modeling tools can likewise be utilized by MGB to produce groundwater availability maps instead of maps primarily based only on subsurface geologic structures. In may be noted that some local water service providers including some local governments use these groundwater availability maps to design and determining the capacity of their groundwater wells.

With regard to groundwater-related land subsidence studies, it is worthwhile to point out that when the aquifer undergoes consolidation or land subsidence, the porous medium (soil matrix) deforms and the porosity reduces resulting in a smaller elasticity or compressibility of the aquifer. In this study, with the maximum simulated consolidation of 0.5 m over the 30-meter aquifer thickness (per layer in the model), it can be shown that the coefficient of compressibility reduces to about 100 times. Thus, for the same maximum change of piezometric head that resulted in a consolidation of 0.5 m during a wet-to-dry cycle, the next time that a wet-to-dry cycle occurs for the same maximum change of piezometric head, at the same location, the soil matrix (aquifer) will consolidate only 0.005 m or 5mm (i.e., 0.5m divided 100). In other words, there is a limit and that the rate of soil consolidation or land subsidence exponentially decays.

5. Conclusions

The major concern of this paper is the groundwater resources of Metro Manila and to address two issues: (1) is the water demand deficit of about 450 MLD in 2025 can be sourced from groundwater in the addition to the current extraction rate of 800 MLD; and, (2) is there a potential risk to land subsidence due to groundwater withdrawal. These two issues are addressed by conducting groundwater model simulation studies.

To assess groundwater availability and address the water demand deficit, the groundwater model simulation was conducted over 40 years period on daily basis. The bottom-line result is that is that there is no significant change in head in 2012 to 2055 thus it can be concluded that an additional of almost 450 MLD (or even more) can be safely extracted from groundwater in addition to the original 800 MLD which sums to almost 1250 MLD.

With regards to the risk of land subsidence in Metro Manila, it can be concluded that risk of land subsidence is relatively small at the groundwater extraction rates imposed in the model simulations (based on current NWRB permittees and proposed, additional extractions rates). At the groundwater locations where as much as 0.5 m soil consolidation occurred, it is suggested that the pumping operation at these locations can be closely monitored and can be pumping can be optimally scheduled to allow groundwater storage recovery even seasonally, to prevent the wet-to-dry cycles to occur that causes soil consolidation. Anyway, since these wells are along alluvial deposits, groundwater recharge can be relatively fast on annual or even seasonal basis to allow for optimal withdrawal scheduling, timed with groundwater storage recovery.

Finally, optimal conjunctive use of surface water and groundwater sources should be adopted as a long-term operational strategy to meet future, increasing water demand of Metro Manila. Specifically, groundwater can be tapped as water source in the short-term and mainly for water supply augmentation especially during critical, dry periods (that lasts only for few months). Note that most studies conducted in the past, investigate surface water and groundwater resources separately – not conjunctively.

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Groundwater management in South Tarawa, Tarawa Atoll, the Republic of Kiribati

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Abstract

Shallow, fresh groundwater lenses in atoll islands are extremely vulnerable to changes in land use and water management, to development pressures and to climate variability and change. This chapter illustrates the complex issues involved in groundwater management in urban atolls with very limited land area and dense settlements by focusing on the urban area of Tarawa Atoll, the capital of the Republic of Kiribati in western equatorial Pacific. In Tarawa, groundwater has been the main freshwater source for over 1,000 years, however, the transition from subsistence to highly urban economies have challenged groundwater and land management. Demand for freshwater is poorly characterized but plausible estimates already exceed the assessed sustainable groundwater yield, which is currently contested. The groundwater aquifer consists of very permeable, heterogeneous, unconsolidated Holocene sand and gravel sediments, usually less than 25 m in depth, unconformably overlying karst Pleistocene limestone. Most of the freshwater resides in the Holocene sediments and freshwater lies on top of a saline transition zone grading to seawater below, mostly in the Pleistocene limestone. Tidal pressure signals are transmitted through the underlying karst limestone causing diurnal fluctuations of the water table and mechanical mixing the freshwater/seawater interface at the base of the groundwater lens, dispersively broadening the saline transition zone. Groundwater salinity is one of the main hydrochemical concerns and is regularly monitored using multi-level salinity boreholes and by tracking the salinity of pumped groundwater. The salinity of pumped groundwater increases during La Niña-related droughts and the fresh groundwater volume shrinks dramatically. To minimize upconing of salinity and drawdown of the water table, 300 m long infiltration galleries or skimming wells are used to extract groundwater from the fresher surface layers of the groundwater lens. The drawdown of the water table elevation in galleries is less than the diurnal tidal fluctuation of the water table. Another vital hydrochemical concern is anthropogenic pollution of the groundwater which, in Tarawa. Regulations which established groundwater reserves in 1977, restrict access to groundwater source areas. Lessons learnt in groundwater management in South Tarawa include: the fundamental importance of having reliable data on water demand, on hydrological and meteorological variables, on groundwater depth and salinity and on water quality; the value of infiltration galleries in minimizing water table drawdown and salinity upconing; the imperative to reduce water losses from the reticulation system; the necessity to legally protect groundwater source areas in atolls; the value in having multiple sources of freshwater; and the strength of legislation, regulations, community-supported policies and long-term plans. These lessons are transferable to other atoll and small island nations.

Key Words: Atoll fresh groundwater lens, salinity, infiltration galleries, monitoring, sustainable yield

1. Introduction

The past resilience of atoll communities to climate extremes and natural disasters is due in part to their ability to secure water from multiple sources such as shallow groundwater, rainwater harvesting, and in extreme situations using young coconuts for drinking and seawater for all no-potable uses. Shallow groundwater, however, has been the dominant freshwater source in most atoll islands across the Pacific for over 1,000 years (Falkland and White I, 2020).

The outcome statement 2014 United Nations (UN) third International Conference on Small Island Developing States held in Samoa reiterated the extreme vulnerability of water resources in small island countries to increasing development, population growth and highly variable and changing climate. The statement (UNGA, 2014) identified overexploitation of groundwater, saline intrusion, pollution, drought and water scarcity, projected changes in rainfall patterns and sea level rise as significant challenges to water supply in island countries. This is particularly so for shallow groundwater in low lying atolls (Falkland, 2022; White and Falkland, 2010; and Werner et. al, 2017).

These challenges are exemplified in the equatorial Pacific nation, the Republic of Kiribati (**Figure 1**) and especially so in South Tarawa, the population center on Tarawa Atoll (**Figure2**), the capital of the Republic of Kiribati.

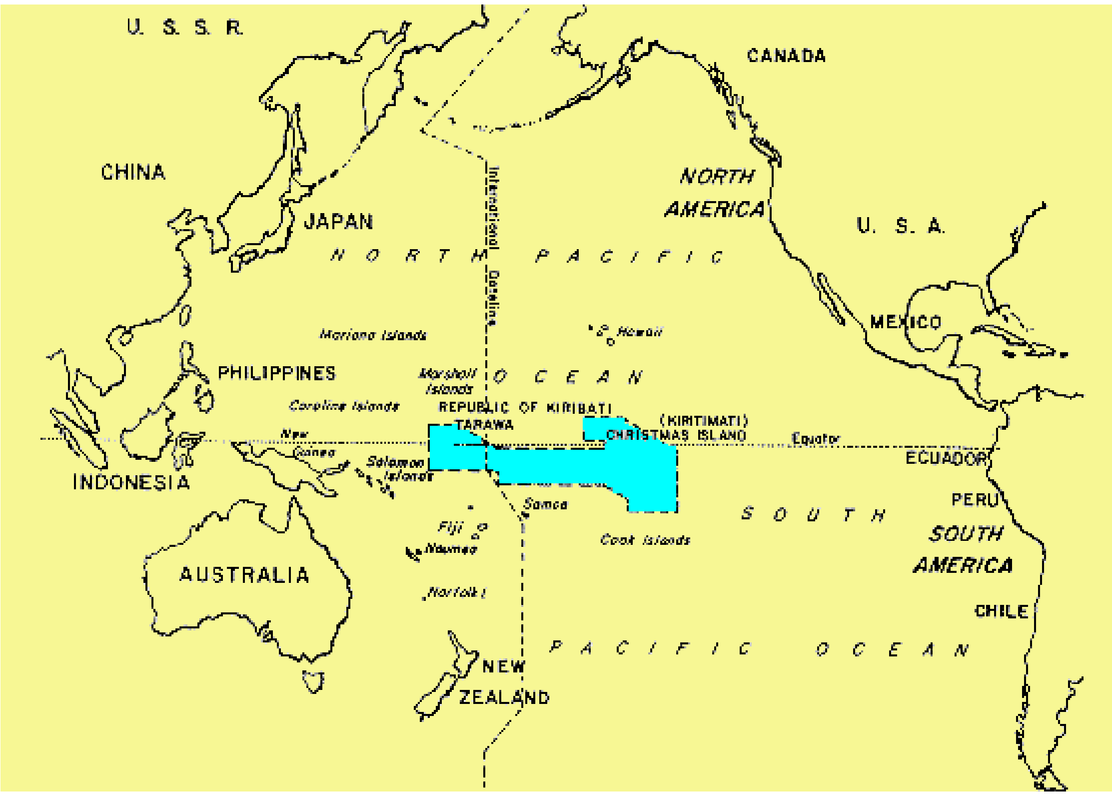

Figure 1: Location of the Republic of Kiribati (aqua shading) spanning about 3,500 km of the western to central equatorial Pacific Ocean. Tarawa Atoll lies on the western edge of the nation as indicated

In densely populated urban and peri-urban South Tarawa, demand has outstripped sustainable groundwater yield from the groundwater reserve islands of Bonriki and Buota (White, 2010) on the southeastern end of the atoll (**Figure** 2). Development and increasing population have led to the abandonment of public groundwater sources in most islands of South Tarawa due to groundwater contamination. Groundwater management in the remaining groundwater reserve islands is vital not just in the capital but in the Republic's 32 atolls and one raised limestone island.

I-Kiribati have always recognized that freshwater is a vital and limited resource (Talu et al., 1979). For over 1,000 years I-Kiribati have faced major natural challenges and have survived natural disasters and large interannual variations in climate with limited supplies of freshwater, predominately sourced from groundwater. Over the last 50 years, however, demographic, and socio-economic conditions have changed dramatically, particularly in urban South Tarawa. These have propelled residents in South Tarawa from a largely low-density, subsistence lifestyle to high-density, urban settings in which traditional adaptation strategies are ineffective in coping with the demands of a highly urbanized society with an extremely variable climate (Jones, 1997; White et. al, 1999; and White et. al, 2008).

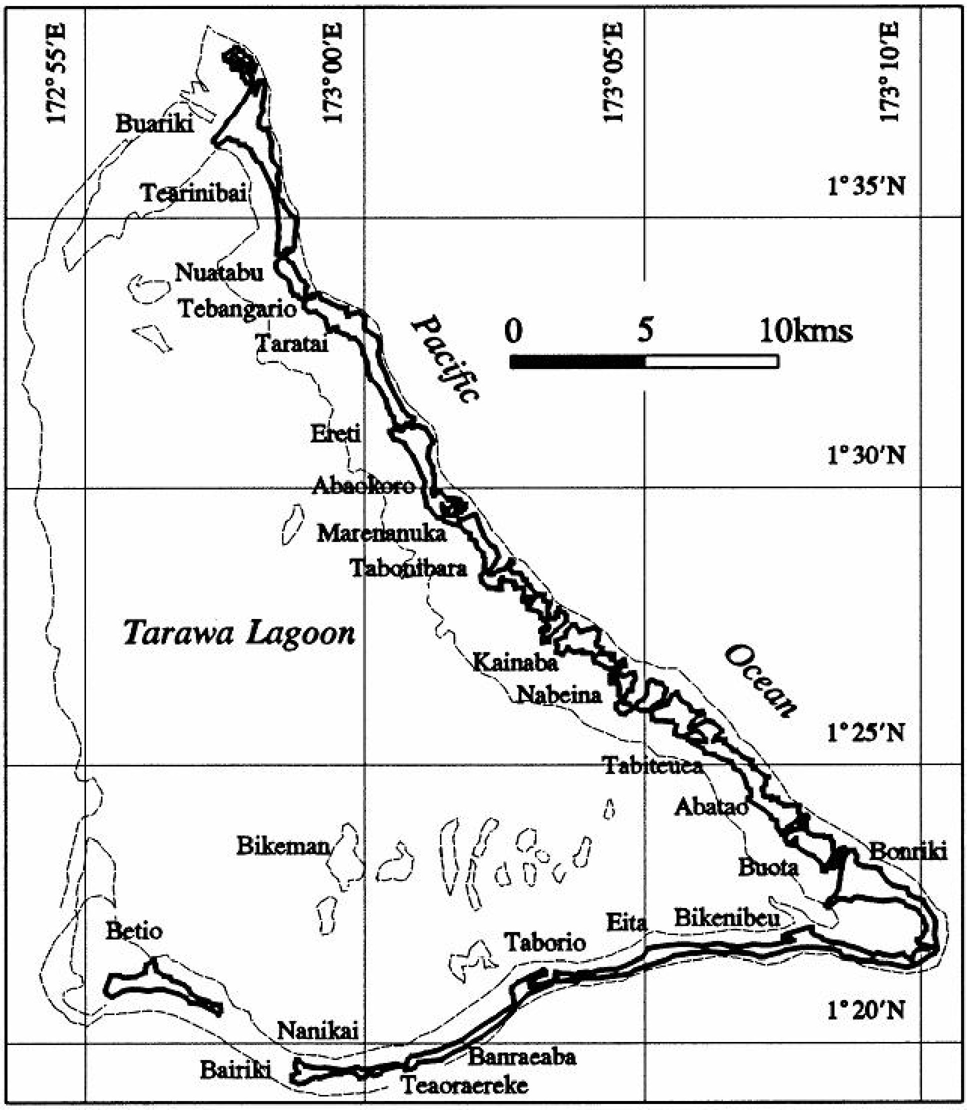

Figure 2: The islands of Tarawa Atoll, the national capital of Kiribati. South Tarawa extends from Betio in the west to Bonriki in the east. Groundwater for South Tarawa is sourced from the larger southeastern islands of Bonriki and Buota

The geographical, hydrologic, climatic, cultural, and current demographic and socio-economic factors in South Tarawa combine to make water issues amongst the most complex in the world (White et. al, 1999). Droughts related to La Niña events are common (White et. al, 1999) and safe freshwater is often scarce, so groundwater resources must be protected and used carefully. Increasing impacts of human settlement and particularly sanitation, the vulnerability of fresh groundwater sources in low, small islands to storm surges coupled to the links between development, poverty alleviation, health and safe water availability require continued leadership by government and commitment by government agencies and the community to protect, conserve and use wisely the nation's groundwater resources. The endorsement in January 2009 of the National Water Resources Policy (NWRP) and its accompanying 10-year National Water Resources Implementation Plan (NWRIP) by Cabinet of the Government of Kiribati (GoK) were important responses to wide-spread community concerns over freshwater availability and quality.

2. Groundwater in national water resources management (Kiribati))

2.1 The Role of groundwater resources in the national water resources policy and implementation plan

The Kiribati National Water Resources Policy (GoK, 2009) and National Water Resources Implementation Plan (GoK, 2009), approved by Cabinet of the Government of Kiribati on 14 January 2009 have three goals:

1. Provide safe, socially equitable, financially, technically, and environmentally sustainable water supplies to enhance the welfare and livelihood of I-Kiribati.
2. Protect and conserve freshwater sources for public water supplies.
3. Deliver freshwater efficiently and effectively.

Improved knowledge and management of groundwater is a central theme both in the Policy, where groundwater is mentioned 7 times, and in the Implementation Plan, in which groundwater has 57 references. The Implementation Plan has 7 strategic actions.

Strategy 1: Increase access to safe and reliable water supplies

Strategy 2: Achieve financially, technically, and environmentally sustainable water resource management

Strategy 3: Improve understanding of water resources and their use

Strategy 4: Improve protection of public water source areas

Strategy 5: Increase community awareness of and participation in water management and conservation

Strategy 6: Improve governance in the water and sanitation sector

Strategy 7: Decrease unaccounted for water losses, improve cost recovery, and explore alternate sources of freshwater

Because groundwater is the predominant source of freshwater throughout the 32 atolls and one raised island of Kiribati, these strategies are focused on groundwater. Planned activities include identification of suitable safe groundwater sources, determination of sustainable yields for all groundwater sources, protection of all groundwater sources, determining the quality of groundwater, documenting the impacts of groundwater extraction, and estimating the impacts of climate change on groundwater resources.

The Tarawa Water Master Plan: 2010-2030 (White, 2010) after a thorough examination of available groundwater information in the atoll made recommendations on 16 issues on sustainable groundwater management and other water resource issues:

1. Water Legislation
2. Whole-of-Government Approach to Water Management
3. Vision for Tarawa
4. Protection of Groundwater Reserves
5. Monitoring of Groundwater Resources
6. Payment of Land Rental in Groundwater Reserves
7. Committee for the Management and Protection of Groundwaters Reserves
8. Sustainable Groundwater Pumping Rates
9. Control of Water Losses
10. Demand Management
11. Cost Recovery
12. Drought Contingency Plan
13. Improved Rainwater Use
14. Safety of Household Wells
15. Behavioural Change
16 Training and Succession Planning

Some of these issues are now being addressed under the Government of Kiribati's current South Tarawa Water Supply Project (GoK, 2023).

2.2 Administrative and legal framework for groundwater management

The Public Utilities Ordinance, Cap 83,1 July 1977, established the Public Services Board (PUB) to supply electricity services from Beito, in South Tarawa to Nebeina in North Tarawa, water supply from Betio to Buota, and sewage disposal in major villages of Betio, Bairiki and Bikenibeu, with pump out services elsewhere. The Ordinance was amended in 2000 and on 1 August 2013 the PUB become a state-owned enterprise (SOE) under the SOE Act (PUB). The PUB is responsible for managing and operating the infiltration galleries for pumping groundwater on Bonriki and Buota islands, for water treatment of produced water, and for the public reticulation system. Water is supplied by metered connections, unmetered connections and by water tanker delivery trucks with water rationed on a two-day basis.

The 1977 Public Utilities Ordinance, vests responsibility for the protection and security of water resources in the Public Utilities Board and includes regulations for the protection of groundwater reserves. These regulations have caused major conflicts between the traditional owners of the groundwater reserves and the government resulting in on-going compensation payments (White, 1999).

The Directions Assigning Ministerial Responsibility (5 August 2003) specify line Ministry responsibilities in water:

- Minister for (the then) Public Works and Utilities – water management; sewerage systems
- Minister for Health and Medical Services – health inspectorate services and environmental health
- Minister for the Environment, Lands and Agricultural Development – environment and conservation; waste and pollution management

The Ministry of Public Works and Utilities was formed in 1999, was renamed the Ministry of Works and Energy in 2008 and became the Ministry of Infrastructure and Sustainable Energy (MISE) in 2017. The Water and Sanitation Engineering Unit (WSEU), a Department within MISE, is responsible for ensuring that the people of Kiribati have sufficient access to reliable, safe water supplies and safe sanitation facilities and practices. Its strategic objectives include (WSEU,2023):

- Consolidation and coordination of national water quality monitoring programs
- Implementation and enforcement of water protection and conservation measures
- Improved national planning plus enforcement and coordination mechanism in protecting water quality and quantity.

WSEU is responsible for monitoring the Bonriki and Buota groundwater sources, the salinity of pumped water supply, and the sustainability of groundwater pumping. WSEU is the water resources regulator in Kiribati.

The Public Health Ordinance of 1926, and Public Health Regulations of 1926, both provide for public health measures including microbiological water quality, sanitation, solid waste collection and drainage. The Land Planning Ordinance 1972 (amended 1973, 1974, 1977, 1979, 1980, 2000), applies controls over land use and developments within designated areas. The Local Government Act, 1984 empowers local government bodies to issue bylaws relating to environmental protection and (vii) Penal codes (Cap 76 1977) having some offences in the Code that are relevant to environmental protection. Finally, since frequent mostly ENSO-related droughts are a feature of the climate in South Tarawa. the Kiribati Meteorology Service is responsible for issuing three stage drought warnings: Stage 1 Drought watch, Stage 2 Drought warning, and Stage 3 Drought. Kiribati has not enacted the 1994 draft National Water Act.

3. Case Study: Groundwater status in South Tarawa

3.1 Water supply and demand of South Tarawa

3.1.1 Water sources in South Tarawa

The 2020 Census results (NSO,2021) provide recent information on the sources of water used for drinking and cooking by households in South Tarawa (**Table 1**)**.** The total of all sources exceeds the number of households in South Tarawa showing that most households use multiple water sources. **Table 1** shows that the predominant source of drinking water and cooking is groundwater. About 73% of households source groundwater for drinking from piped or trucked groundwater and 24% from domestic wells. For cooking, there was a higher reliance on domestic wells at 37% of total groundwater sources. The next most important source was rainwater harvesting being about 32% and 17% and of total groundwater sources for drinking and cooking, respectively. One of the reasons for households using multiple sources is the intermittent reticulated supply of pumped groundwater which is not equitably shared along South Tarawa (**Figure 2**)**.** Unfortunately, the Census provides no information on the quantity of water used by households, or the amount of water sourced by institutional, commercial, and industrial sectors.

3.1.2 Per Capita Demand Estimation

Table 1: Household (HH) sources of drinking and cooking water in South Tarawa in 2020 (NSO, 2021)

Water Source	**Number HH**	
	Drinking	**Cooking**
Piped into dwelling	510	499
Piped into compound or yard	4,041	4,339
Public tap/standpipe	1,565	1,445
Piped to neighbour	725	648
Protected well	969	1,439
Unprotected well	1,678	2,645
Rainwater tank, tap inside	479	297
Rainwater tank, tap outside	2,248	1,350
Communal rainwater tank	513	299
Tanker truck	115	75
Bottled water	388	118
Desalinated water	19	-
PUB water	401	-

Water Source	Number HH	
	Drinking	Cooking
Rainwater from neighbour	56	-
Other sources	47	61
Total	13,754	13,215
Total supplied by piped/trucked groundwater	7,357	7,006
Total supplied by domestic groundwater wells	2,647	4,084
Total supplied by groundwater	10,004	11,090
Total supplied by rainwater harvesting	3,240	1,946
Total Households South Tarawa	9,444	
Total Population South Tarawa	63,072	
Average HH Size (number persons)	6.7	

There are five main components to water demand in South Tarawa: household demand; institutional, commercial, and industrial (ICI) demands, and unaccounted for water losses from the groundwater reticulation system. Household demand depends on the number of people per household, and per capita demand. While the number of people, number of households and average household size in South Tarawa (**Table 1**) are available from the 2020 Census results (NSO, 2021) the per capita or household demands for water and ICI usage are not.

The ICI users in South Tarawa consist of:

- Schools
- Hospitals and clinics
- Government ministries and local government
- Maneabas (traditional meeting houses)
- Churches
- Hotels and guesthouses (tourism)
- Commercial premises
- Industries including agriculture and fisheries

There is very little information available on the quantities of water used by the ICI sector. Information was available on the average groundwater supply to Tungaru Central Hospital in South Tarawa, a priority for reliable water supply, over the period 2004-8 was estimated to be 39.2kL/day (White et. al, 2008). It is, however, clear from previous water supply projects that the largest components of freshwater use in Tarawa are household consumption and unaccounted for water losses.

It is very difficult to estimate the expected total freshwater demand in South Tarawa because of:

- minimal reliable data on the actual freshwater use by households
- very little quantitative data on use of household well water
- no information of quantities of rainwater collected and used
- the small number of metered connections to households
- almost no information on ICI water use including agricultural and stock use, and
- high leakage rates in the piped ground water distribution systems in South Tarawa.

Faced with these difficulties, the approach adopted by all groundwater supply projects over the last 50 years in South Tarawa has been to assume a design target of per capita daily demand consistent with estimates of minimum quantities required for consumption, cooking, and hygiene. Most of the previous estimations of per capita demand have been based on what the groundwater supply systems could supply rather than what the population needed.

It was recognised almost 50 years ago that the limited quantity of freshwater in South Tarawa meant that potable water could not be used for toilet flushing (AGDOW, 1973). Instead, systems were developed which flushed with seawater or local household well water (Falkland, 1992). This is still the case and demand estimates have always assumed that precious potable water is not used for toilet flushing in South Tarawa. In similar situations where there are no reliable demand estimates, estimates have been based on evaluations of the safe per capita water requirement needed for a range of criteria such as in **Figure 3** (WHO and WEDC, 2013).

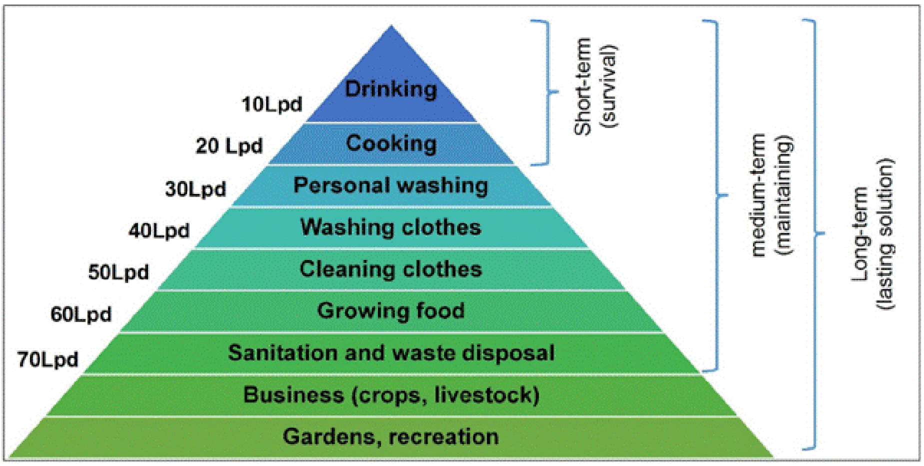

Figure 3: Hierarchy of per capita water requirements in litres/person/day (Lpd) modified (Falkland, 2020) from (WHO and WEDC, 2013)

The minimum safe per capita water requirement in **Figure 3** to satisfy essential health and hygiene needs in emergency situations is 20-30 Lpd while about 50 Lpd has been recommended as a base domestic water supply requirement (Howard, et. al, 2020 and WHO, 2017). Total per capita water requirements have then been estimated from assumed per capita demand together with a per capita allowance added for ICI water use together with a percentage added for estimated water losses from the system. **Table 2** provides a summary of past design estimates of the total per capita water demand in South Tarawa for treated groundwater. These range from about 10 to 102 Lpd. No allowance in these estimates has been made for crop production, livestock watering (mostly pigs) or toilet flushing. In South Tarawa, grey water is often used for modest domestic crop production and both grey water and household wells supply water for pigs. The total per capita demand estimate in the 2010 Tarawa Water Master Plan (White, 2010) in **Table 2** assumed groundwater losses from the reticulation system in South Tarawa were 50%. Later measurements of unaccounted for water found 92% losses (GHD, 2017). One of the reasons for the high losses is that water is supplied only intermittently so that households keep taps open to intercept spasmodic water supply.

If it is assumed in future that a modest per capita demand of 70 Lpd (**Figure 3**) is a more realistic design demand, that ICI demand will increase to 20% of per capita demand to allow for increased development, domestic crop production, and stock watering, and that unaccounted for water losses are reduced to 20% then the estimated total per capita demand is 101 Lpd, essentially identical to the value assumed in 2010 in **Table 2.**

Table 2: Previous estimates of the total per capita daily water demand in South Tarawa for treated groundwater supplied by the public reticulation system

Year	Total per Capita Demand (Lpd)	Reference
1973	18	AGDOW, 1973
1975	10-37	AGDHC, 1975
1978	14-27	RDI, 1978
1982	34-35	AGDHC,1982
1986	47	AGDHC, 1986
1992	30-50*	Shalev Z, 1992
1996	40†	Royds Consulting Limited,1996
2000	50†‡	OEC, 2000
2002	40†	Metutera, 2002
2003	40†	Falkland, 2003
2010	102¶	White, 2010

* Lower value for outer islands, upper value for urban areas

† Assumes only 80% of all households supplied with piped water

‡ Includes ICI demand and 30% assumed losses

¶ Includes 10% ICI demand, 50% assumed losses and 2 Lpd climate change increase

Currently, the South Tawara Water Supply Project (GoK, 2009) aims to install metered connections to all connections to the public water supply system so that in future there will be improved data on per capita water demand.

Here we select three total design per capita demands of 84 Lpd, which assumes 20% ICI demand and no water losses, 101 Lpd, which assumes the same ICI demand and losses of 20%, and 161 Lpd, which assumes losses are the recent 92%. To estimate the daily total demand in South Tarawa then requires information on the number of people in South Tarawa.

3.1.3 Population of South Tarawa and estimated total water demand

Figure 4 plots the rate of population growth in South Tarawa and that for the total population of Kiribati (NSO, 2021). Two key factors are clear in **Figure 4,** the consistent exponential growth rate of total Kiribati population at a rate of 1.83±0.02 %/year, and the ten times increase in percentage of the Kiribati population living in urban South Tarawa, from 5.3% in 1947 to 53% in 2020. This increase in urbanization is a result of inward migration from outer islands to the population center, common across the Pacific (Ward, 1999). For South Tarawa, the population growth rate has slowed to a linear increase of 1290±28 persons/year over the last three Censuses.

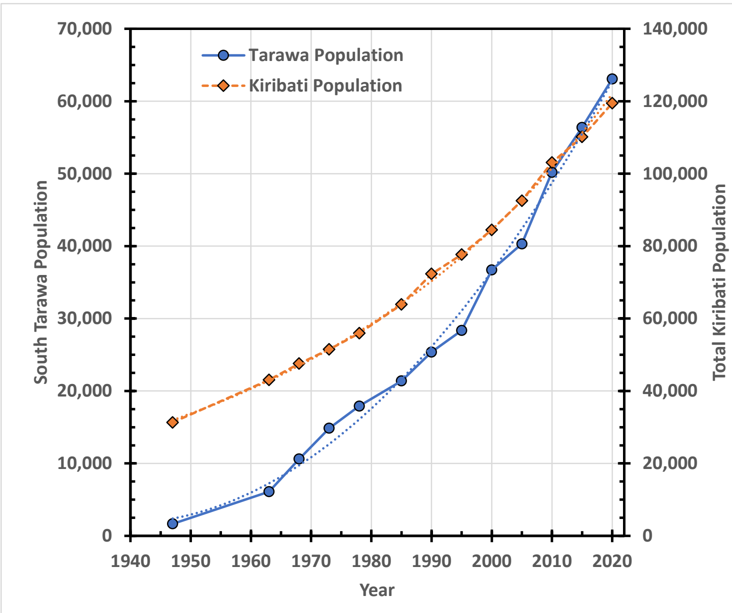

Figure 4: Population growth in South Tarawa and in Kiribati (White,2010). The data for Kiribati fits an exponential relation with a growth rate of 1.83±0.02%/year (R^2 = 0.9988). For South Tarawa, the Census results show a linear growth rate of 1290±28 persons/year (R^2 = 0.9995) since 2010

The population numbers for South Tarawa in **Figure 4,** together with the assumed linear growth rate of 1290 persons/year can now be used to estimate current and future total water demand under the three water loss assumptions, the estimates are listed in **Table 3**.

Table 3: Estimated total daily water demand for South Tarawa for three assumed water loss rates, zero, 20% and 92%, from the groundwater reticulation system for an assumed linear growth rate in population of 1,290 people/year from the 2020 Census count of 63072 persons.

Year	**Estimated Total Demand (m^3/d)**		
	Zero Losses	**20% Losses**	**92% Losses**
2020	5,298	6,370	10,281
2025	5,406	6,501	10,491
2030	5,515	6,631	10,701
2035	5,623	6,761	10,912
2040	5,731	6,891	11,122

If losses were zero, then total demand of South Tarawa out to the year 2040 will range from about 5,300 m^3/day to 5,700 m^3/y. For the more realistic target of 20% losses, total demand is estimated to be about 6,400 to 6,900 m^3/day. If the recent loss rate of 92% had continued, then total demand is estimated to increase from about 10,300 to 11,100 m^3/day, assuming South Tarawa's population continues to grow linearly. The current South Tarawa Water Supply Project (GoK, 2023) is addressing water losses through rehabilitation of the water supply network.

3.1.4 Estimated sustainable groundwater yield

The sensitivity of atoll aquifers to droughts, pumping regimes, and salinity intrusion means that estimation of the sustainable yield is a critical issue. The variety of methods used to estimate the sustainable yields of the Bonriki and Buota groundwater sources and estimated yields have been summarized by (Falkland, 1992; White and Falkland, 2010; and Werner et. Al, 2017) and the historic estimated yields are listed in **Table 4**. The most reliable are based water balance estimations of recharge using daily rainfall data and monthly estimates of actual evapotranspiration together with numerical models.

The combined estimated sustainable yield from both islands in **Table 4** varies from essentially zero (RDI, 1978) to 2,010 m^3/day which is the current groundwater pumping rate. Recent modelling has raised the concern that under the current pumping rate, the drawdown of the fresh groundwater lens at Bonriki is continuing over a multi-decadal time scale (Alam et. al, 2002 and Post et. al, 2019). This is somewhat surprising, given that the mean hydraulic residence time of the fresh groundwater lens at Bonriki is less than 10 years, even with pumping.

Table 4: Estimated sustainable yields of groundwater from Bonriki and Buota groundwater reserves (White and Falkland, 2010)

Year	Estimates of Sustainable Yield (m^3/day)			
	Bonriki	Buota	Combined	Reference
1973	110	-	110	Mather, 1973
1978	<85	<85	<170	RDI, 1978
1980	2,350	1,180	3,530	Harrison, 1980
1982	750	250	1,000	AGDH, 1982
1992	1,000	300	1,300	Falkland, 1992
2002	1,350	350	1,700	Alam, et al, 2002
2004	1,660	350	2,010	Falkland, 2004

The 2004 estimate of combined sustainable groundwater yield (**Table** 4) together with the 2020 population in South Tarawa (**Figure 4**) and its current linear growth rate can be used to estimate the average per capita water availability for the South Tarawa community assuming 0%, 20% and the historic high 92% water losses (**Figure 5**).

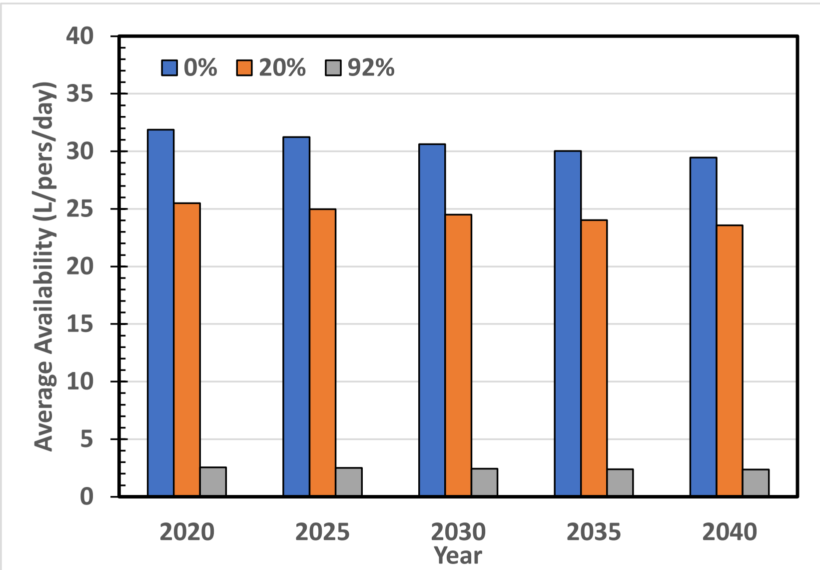

Figure 5. Estimated average per capita water availability in South Tarawa given the sustainable groundwater yield of Bonriki and Buota islands and the current and projected population of South Tarawa for three unaccounted for water loss rates, 0%,

20% and the historic 92%

Two things are evident from **Figure 5**. The first is that the average per capita water availability from groundwater is much less than the estimated per capita demand. The second is the imperative to control water losses from the reticulation system.

3.2 Overview of the aquifer

3.2.1 Hydrogeology

Specially constructed, multi-level salinity monitoring boreholes in the Bonriki groundwater reserve (**Figure 6a**) have provided information on both the geology of the aquifer and its groundwater salinity profiles (Falkland and Woodroffe, 2004; Falkland, 2004; Jacobson and Taylo, 1981; and Post, et al, 2018) The shallow phreatic aquifer (lying between 0.4 to 3.6 m below the land surface) consists of unconsolidated Holocene coral sediments lying generally unconformably over karst Pleistocene limestone. The limestone consists of skeletal wackestones and packstones, some of which are fractured (Jacobson and Taylor, 1981) and karstification occurred during the last glacial sea level lowstand when sea levels were about 100 m lower than present. Because of this, the Pleistocene surface is irregular with limestone occurring at depths varying from about 12 to 20 m below sea level (**Figure 6b**).

Radiocarbon dates of the Holocene sediments suggest that corals formed on the Pleistocene limestone and kept pace with rising sea levels following the end of the last ice age. Carbon 14 dating of these sediments indicated rapid accretion of sediments after 8,000 y B.P. at rates of up to 8 mm/y. Coral islands are thought to have formed about 3,500 y B.P. (Falkland and Woodroffe, 2004). The unconsolidated Holocene sediments are sand and gravels and contain cemented conglomerate called cay rock (Jacobson and Taylor, 1981). Sediments tend to be coarser on the ocean side of the island (Falkland and Woodroffe, 2004) which causes asymmetry in the fresh groundwater lens with the lens thicker on the lagoon side (**Figure 6b**). The Holocene sediments are heterogeneous as shown by the distribution of hydraulic conductivity in the surface layer of the aquifer determined from pump drawdown measurements (**Figure 7**).

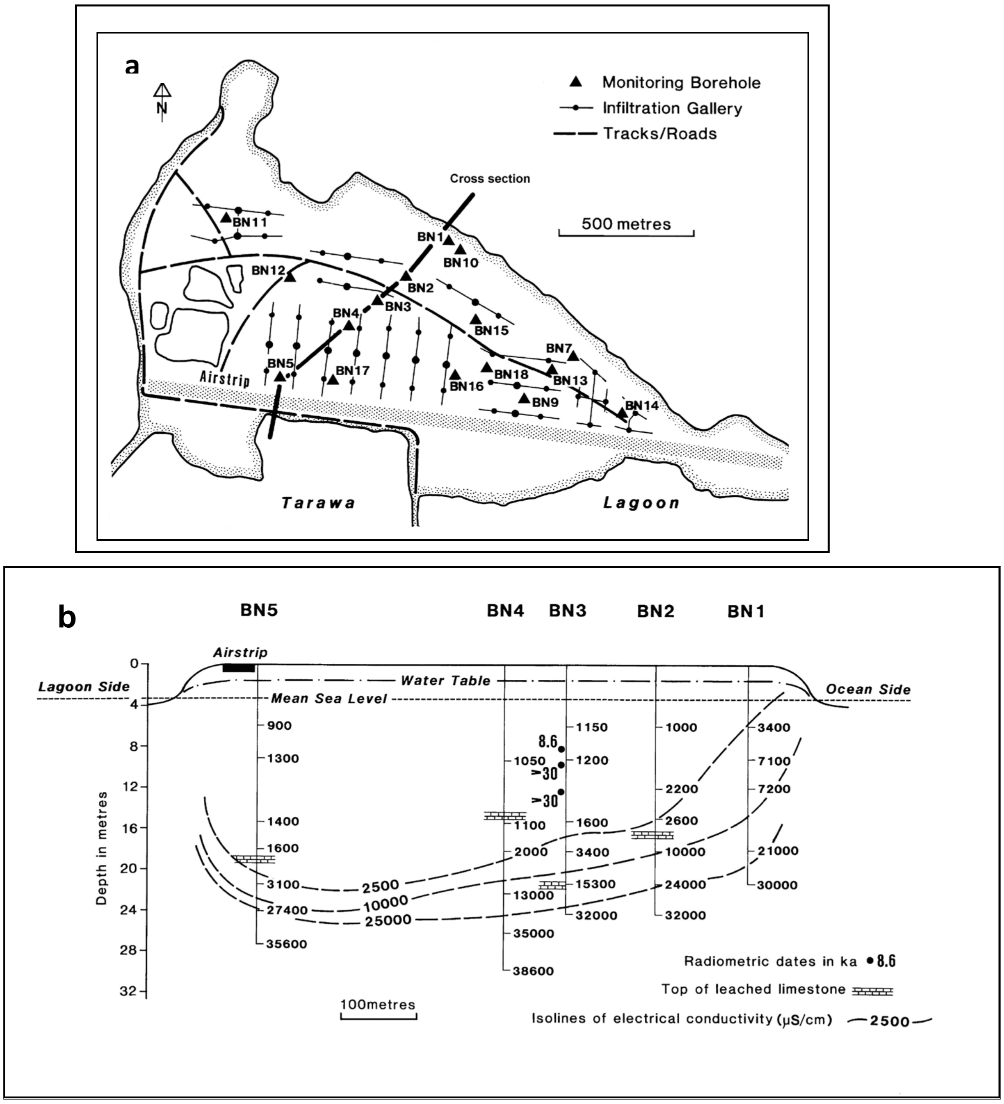

Figure 6: a) Bonriki groundwater reserve and the location of 300 m long horizontal infiltration galleries used to harvest groundwater and multi-depth salinity monitoring boreholes (BN), b) vertically exaggerated cross section through the groundwater reserve measured in May 1985 with isolines of salinity measured by electrical conductivity (EC). The EC 2,500 µS/cm contour is often considered the freshwater limit. Also shown is the top of the Pleistocene limestone encountered in the boreholes. Numbers beside dots in BN3 are the carbon 14 ages of sediments in millennia (Falkland and Woodroffe, 2004)

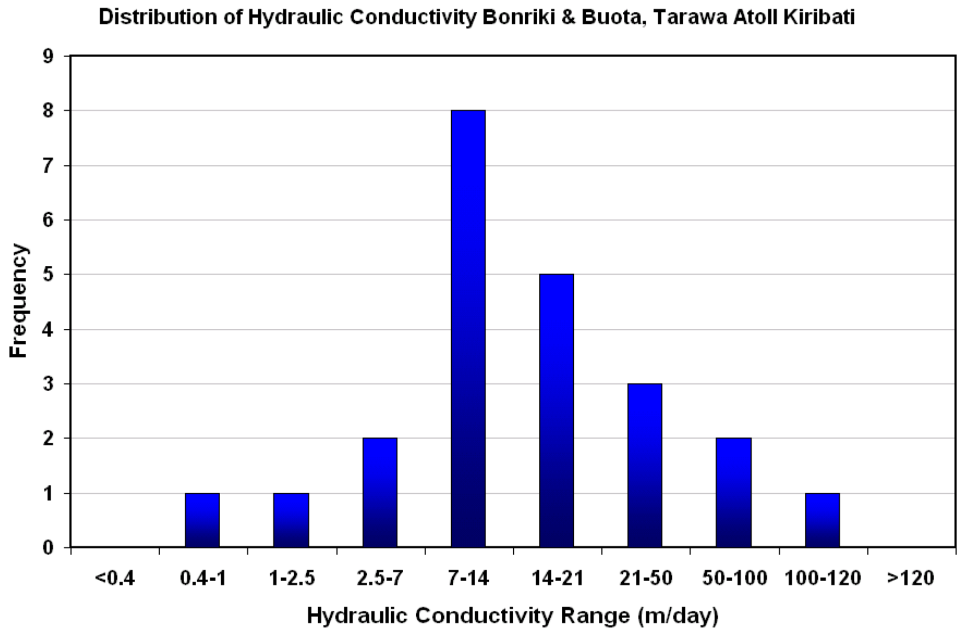

Figure 7. Distribution of hydraulic conductivity in the surface layers of the Bonriki and Buota aquifers determined through pump drawdown tests in infiltration galleries using pumping rates averaging 88 m^3/day (White and Falkland, 2010)

Most of the fresh groundwater resides in the Holocene sediments with some penetration of the Pleistocene limestone during wetter periods but which is mostly saturated with seawater (**Figure 6b**). This distribution of fresh groundwater predominately in the unconsolidated Holocene sediments overlying seawater in the karst Pleistocene limestone is predominantly due to the contrast between the hydraulic properties of the two units (Falkland and Woodroffe, 2004). Although spatially variable, the hydraulic conductivity of the Holocene sediments is of order 10 m/day -range 1 to 110 m/da- (White, et al, 2007) with a porosity of about 0.3. In contrast, hydraulic conductivity in the karst limestone is much higher and varies with depth from about 30 m/d to of order 1000 m/d (Falkland and Woodroffe, 2004; and Post, et al, 2018). The large hydraulic conductivity of the limestone unit means that tidal pressure signals are transmitted throughout the aquifer causing tidally influenced fluctuation of the shallow water table (Wheatcraft and Buddemeier, 1981) as shown in **Figure 8**. This occurs right across the island. Tidal fluctuations also cause mechanical mixing of the diffusive interface between fresh and salt water, producing a significant saline transition zone which moves downwards with recharge and upwards during dry times (**Figure 9**).

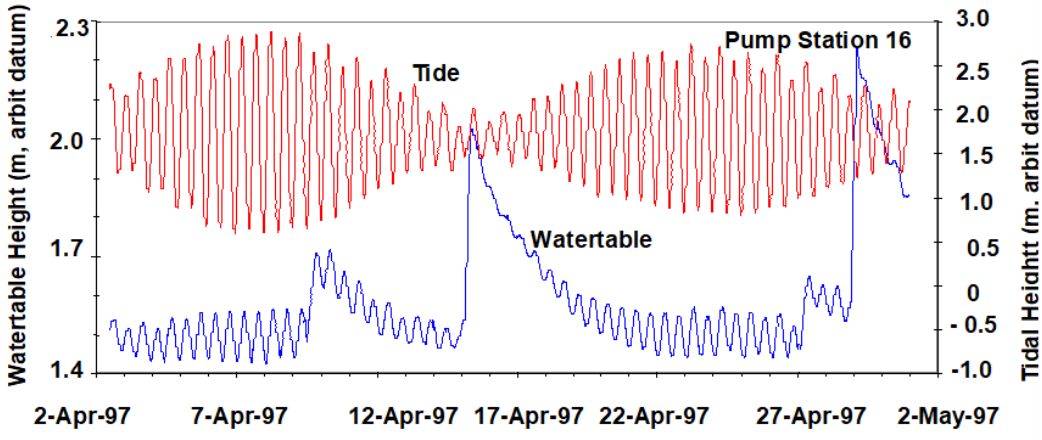

Figure 8: Tidal induced fluctuations of the shallow water table in an infiltration gallery pumping station (see **Figure 6a**) on Bonriki. Also shown are the rapid rises in water table due to rainfall recharge events and its slower decay as water recharges the aquifer (Jacobson and Taylor, 1981)

3.22 Hydrochemical characteristics

One of the main hydrochemical concerns in atolls is the salinity of pumped groundwater which can limit its use (Falkland, 1992). Salinity monitoring bores have been installed throughout both Bonriki (**Figure 6a)** and Buota groundwater reserves to measure salinity profiles in the aquifers (**Figure 9**). As another groundwater management strategy, the combined salinity of groundwater pumped from Bonriki and Buota is also monitored.

In fresh groundwater lenses in atolls, pumping from conventional vertical groundwater wells upcones the underlying salinity (Falkland, 1991) which can threaten the potability of abstracted water. To minimize upconing, 300 m long infiltration galleries or skimming wells (see **Figure 6a**) are used in Bonriki and Buota to abstract fresher water from the surface layers of the groundwater lens (White and Falkland, 2010).

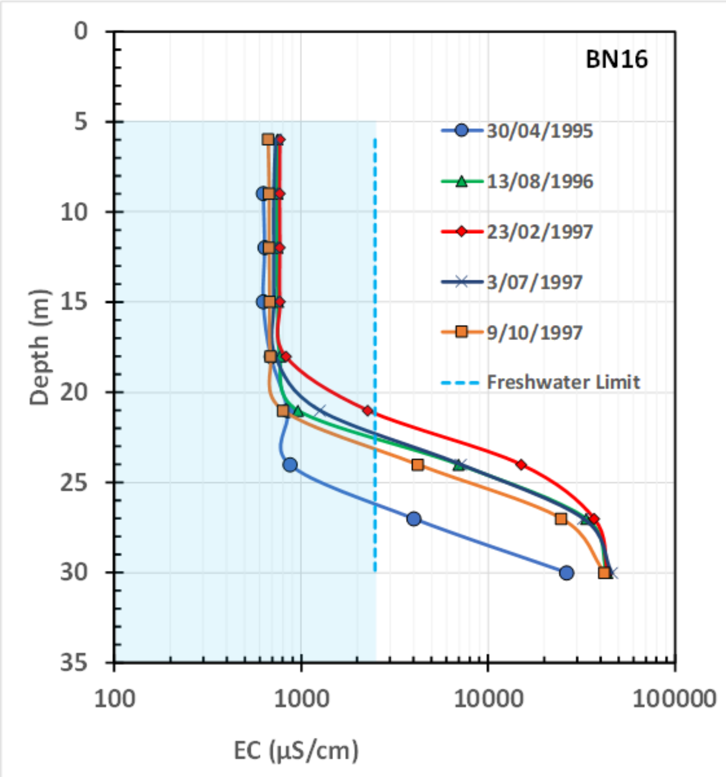

Figure 9: Profiles of salinity as measured by EC) in a salinity monitoring bore through the groundwater lens at Bonriki showing the upper freshwater layer and the saline transition layer overlying seawater. The pumping rate from the lens throughout the period was about 1300 m^3/day. The contraction of the freshwater zone from a significantly wet period in early 1995 to a drier period towards the end of 1997 is also apparent

The water table drawdowns caused by infiltration galleries on Bonriki are less than half the tidal fluctuations of the water table (**Figure 10**). Despite the minimal drawdown (and upconing) of infiltration galleries, the salinity of pumped groundwater increases (**Figure 11**) during major La Niña droughts as the lens contracts to less than half the depth in a wet period (**Figure 12**).

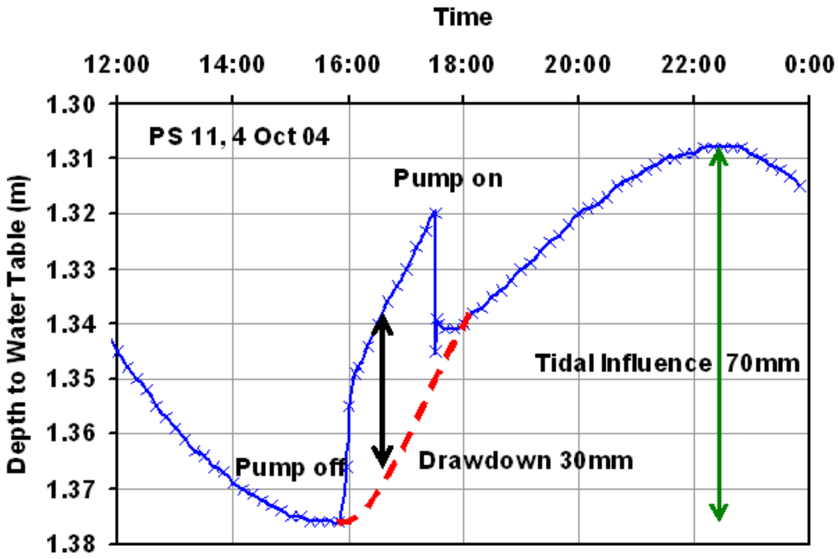

Figure 10. Drawdown of the water table in a Bonriki infiltration gallery shown by switching the pump off and on at a pumping rate of 112 m^3/day. The drawdown is superimposed on the tidal fluctuation of the water table (White, et al, 2007)

The principal natural hydrochemical processes occurring in the aquifer are the dissolution of calcium carbonate (Hem, 1992) in the unconsolidated Holocene sediments and the tidal mixing with underlying saline seawater. Profiles of relative ion concentrations (Ca/Na and HCO_3/Cl, in mEquiv/L) indicate that there is about twice as much bicarbonate than the concentration of calcium expected from the dissolution of calcium carbonate sediments (**Figure 13**). This excess bicarbonate may be due to respiration in the soil above the shallow water table (Stumm and Morgan, 1996).

Another significant hydrochemical concern in atoll groundwater is anthropogenic contamination of the surface groundwater (White and Falkland, 2010) due to the high hydraulic conductivity of the Holocene sediments (**Figure 7**) and the shallow water table. Although land use on the Bonriki and Buota groundwater reserve is regulated by law (White, et al, 1999), some potentially polluting land uses do occur. **Figure 14** shows the ratio of dissolved organic carbon to total dissolved nitrogen found in groundwater pumped from infiltration galleries on the Bonriki groundwater reserve. Areas with ratios significantly less than the Redfield ratio (Stumm and Morgan, 1996) correspond to areas of potential nitrogen contamination.

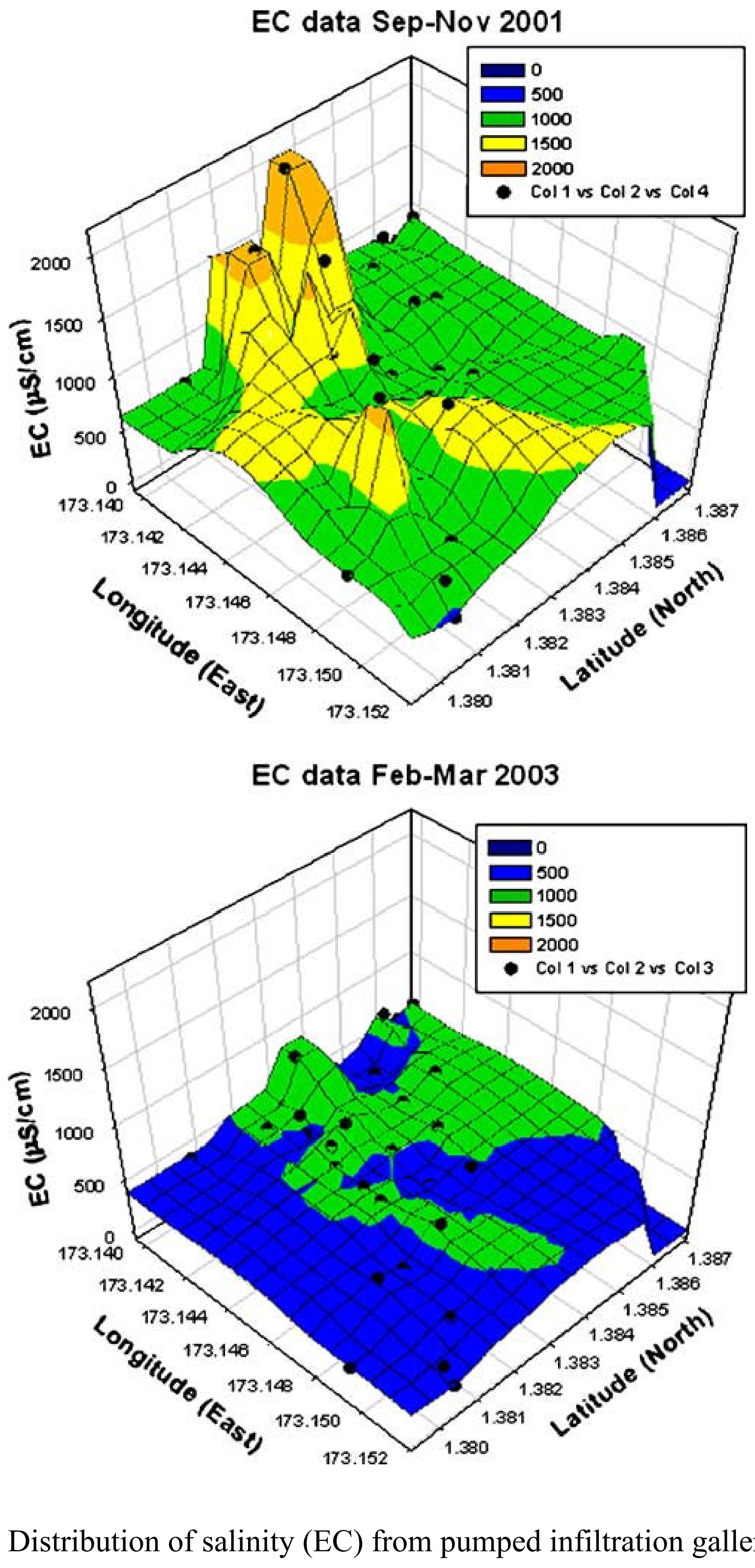

Figure 11: Distribution of salinity (EC) from pumped infiltration galleries across Bonriki island at the end of the severe 1998-2001 La Niña drought and following drought-breaking rain in 2003. Combined groundwater pumping rate was 1,300 m^3/day (White and Falkland, 2010)

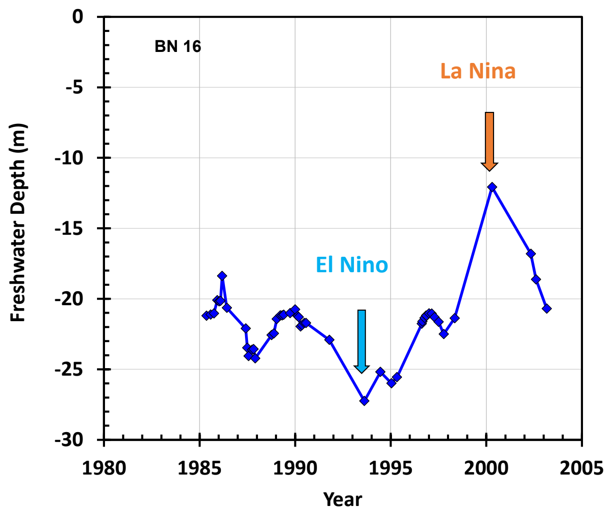

Figure 12. Change in the fresh groundwater depth in a salinity monitoring borehole between a wet El Niño period and a severe, triple La Niña drought

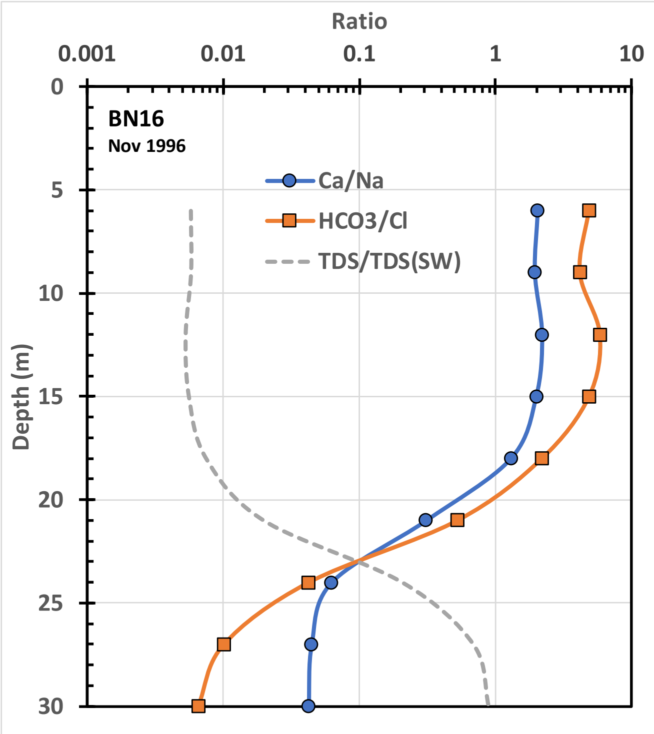

Figure 13. Depth distribution of the ratios of calcium to sodium and bicarbonate to chloride (all in mEquiv/L) in water a salinity monitoring borehole on Bonriki showing the dissolution of calcium carbonate in the Holocene sediments and the mixing with sodium chloride rich seawater in the Pleistocene sediments. The ratio of total dissolved solids (TDS) in the water samples to that in seawater (in mgm/L) is also plotted. All ratios approach those of local seawater at depth

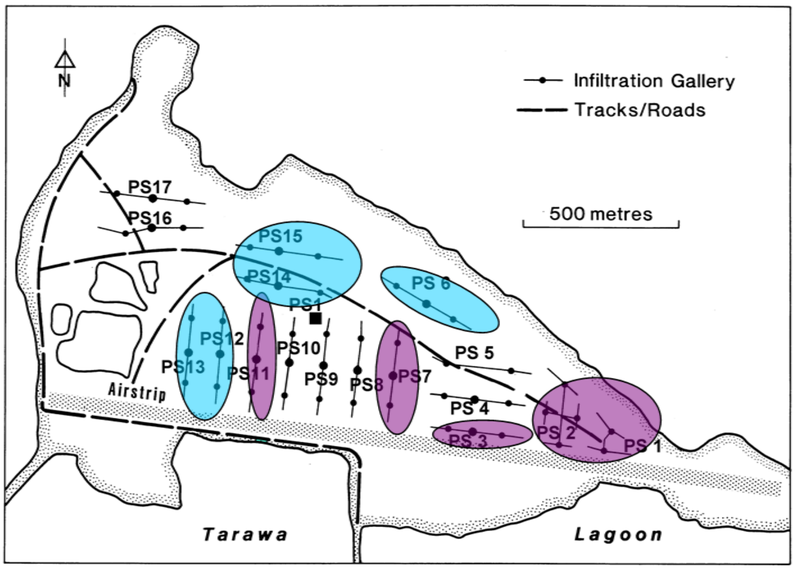

Figure 14: The ratio of dissolved organic carbon to total dissolved nitrogen in groundwater pumped from infiltration galleries on Bonriki island. Aqua coloured areas show pumps with the ratio close to the Redfield ratio (106/16) expected for micro-organisms (48). Purple coloured areas show regions where the ratio is significantly lower than the Redfield ratio (< 29/10) indicating sources of total dissolved nitrogen. Purple coloured areas correspond to land uses such as the raising of pigs, crop production and cemeteries (White and Falkland, 2010)

3.3 Existing and potential problems associated with groundwater extraction

As discussed above, the hydrogeology of atoll groundwater lenses means that atoll groundwater is vulnerable to salinisation during droughts or overextraction. Accurately determining the sustainable groundwater yield is, therefore, a critical factor in sustainable atoll groundwater management (White and Falkland, 2010). A three-dimensional, variable-density model of Bonriki water reserve (Post, et al, 2018) has suggested that even after 27.5 years, the pumping of the lens at 1,660 m^3/day continued to decrease the volume of the freshwater in the lens in proportion to the volume of water extracted. The claim is that the lens has not yet established a new equilibrium. This was found to be the case even when the pumping rate was reduced to 25% of the estimated sustainable yield (Post, et al, 2018). If extrapolated, the results suggest at the current pumping rate that the lens will be completely depleted by 2040.

Simple steady state estimates of the impact of pumping on the maximum thickness of freshwater in the lens (Volker, et al, 1985) suggest that pumping at the sustainable yield rate (1,660 m^3/day) should decrease the maximum thickness of freshwater by about 48% and pumping at 25% of the sustainable rate should decrease the thickness by about 8%. The steady state analysis, however can say nothing about the time to reach new equilibrium. While the hydraulic residence time of the lens is 5 to 10 years, there are many time scales associated with the lens recharge processes from hourly as shown by the recharge events in **Figure 8**, to monthly for evapotranspiration, to 3 to 7 years for ENSO events to about 17 years for the severe, triple La Niña droughts. Concerns about the depletion on the lens emphasise the importance of the continued monitoring of salinity profiles through the lens (**Figure 9**) as well as the combined salinity of pumped water. While the groundwater lenses in South Tarawa will always be an important source of freshwater, it is clear from **Tables 3 and 4** that demand there has outstripped the sustainable supply from the groundwater reserves. Because of that the GoK is installing two desalination plants under the South Tarawa Water Supply Project to meet demands (GoK, 2023).

A further concern over impacts of groundwater extraction was raised by villagers on Bonriki and Buota islands. They claimed that groundwater pumping has lowered water tables and has greatly impacted the production of swamp taro grown in the shallow water table. This was part of a claim for additional compensation for the use of their land for groundwater reserves (White, et al, 1999). Measurements of drawdown in infiltration gallery pumping stations in both islands (**Figure 10**) conclusively demonstrated that local drawdown was significantly less than the tidal fluctuation of the water table. It emerged that the decline in swamp taro production was due probably to an infestation of taro beetles.

4. Good practice, Lesson learned

The extreme sensitivity of shallow atoll groundwater lenses to changes in land and water management and the impacts of climate variability and change in South Tarawa highlights several examples of good practice and lessons learnt. Many of the lessons learnt are currently being implemented under the Government's current South Tarawa Water Supply Project (GoK, 2023)

4.1 Reliable data

This case study has revealed the critical importance of reliable data in managing fresh groundwater lenses and water supply in urban atolls. The valuable long-term Census data on households, their water sources (**Table 1**), and the increase in the number of people in South Tarawa (**Figure 4**) is essential for making first estimates of the total water demand in South Tarawa (**Table 3**), particularly in the absence of detailed data on sectoral water demands. Installation of water meters to all connections under the current South Tarawa Water supply Project (GoK, 2023) will provide detailed information on sectoral water demands. The historic estimates of sustainable yields (**Table 4**) were based on continuous daily records of rainfall and monthly estimates of evapotranspiration which are also essential for drought preparedness. The temporal change in salinity profiles through the lens (**Figure 9**) and records of the daily pumping rate and salinity are fundamentally important in determining the impact on pumping and climate on the amount of freshwater available (**Figures 11 and 12**). Water quality data is necessary to understand the hydrochemical processes occurring in the groundwater (**Figure 13**) and to identify pollution sources (**Figure 14**) to guarantee safe water supply.

4.2 Monitoring

The fragility of atoll freshwater lenses and their vulnerability to salinization through overextraction, in prolonged droughts or through wave overtopping means that regular, dedicated monitoring of the groundwater and the associated water supply system, including unaccounted for water, is essential for their management. Groundwater has been able to be pumped sustainably in South Tarawa for almost 50 years because of the investment in reliable, routine groundwater monitoring,

4.3 Infiltration galleries

The 300 m long infiltration galleries used to skim off the freshest water from the surface of the groundwater lens have meant that more water of lower salinity (Falkland, 1994) has been able to be supplied to communities in South Tarawa because of their small drawdown of the water table (**Figure 10**) and minimal upconing of underlying saline water.

4.4 Protection of groundwater source areas

The very limited land area on South Tarawa and the rapidly growing population since the 1990s means that there is always pressure to develop groundwater source areas. Indeed, some of the original groundwater source areas have been lost to development. The high hydraulic conductivity of the Holocene surface sediments (**Figure 7**) and the fact that the water table is usually within 2 m of the soil surface means that the groundwater is easily polluted by land developments. The

1977 regulations that established the water reserves have been instrumental in protecting the Bonriki and Buota groundwater reserves from development.

4.5 Reticulation system water losses

The large historic water losses from the groundwater reticulation system (GHD, 2017) have meant that extremely limited freshwater was available to people in South Tarawa (**Figure 5**). These losses were both economically and socially unacceptable. The Government of Kiribati and MISE through the South Tarawa Water Supply Project (GoK, 2009) is rehabilitating the water supply infrastructure to reduce losses.

4.6 Multiple water sources

The 2020 Census data in **Table 1** on household water sources for drinking and cooking reveal how households have made use of multiple sources of water to make up for the shortfall in supply from the groundwater reticulation system. One disturbing aspect is the high proportion of households in South Tarawa that continue to use local household wells for water supply. Groundwater in the highly urbanised South Tarawa is heavily polluted and its use has serious health risks. Because of the shortfall between sustainable yield of the groundwater in Bonriki and Buota islands, and concerns over the reliability of rainwater harvesting during droughts, the Government of Kiribati, as part of the South Tarawa Water Supply Project (GoK, 2023) is in the process of installing two large desalination systems in South Tarawa with a total drinking water capacity of 6,000 m^3/day.

4.7 Climate Change

One of the most significant threats to groundwater resources in low atolls is island overtopping or decrease in area because of climate change induced sea level rise. In South Tarawa, one estimate was that by 2020 sea level rise could cause a 20% reduction in sustainable yield (White, 2010). Measurements of 30 Pacific and Indian Ocean atolls including 709 islands (Duvat, 2018), reveals that, to date, no atoll lost land area and that 88.6% of islands were either stable or increased in area, while only 11.4% contracted. No island larger than 10 ha decreased in size. This suggests that shoreline forming processes in atolls are, at present, keeping pace with sea level rise. Another significant threat to atoll rainfall is the future frequency and intensity of ENSO events under climate change. Recent modelling (Cai, 2023) suggests that the frequency of intense ENSO events has increased since 1960s which appears due to greenhouse gas emissions. The strong correlation between rainfall in South Tarawa and ENSO events means that both rainfall harvesting and groundwater recharge may be significantly impacted by future changes to intense ENSO frequency.

4.8 Water Policy and Plans

In small island countries there are often several government ministries and agencies with shared responsibilities for water supply and management, so it is vital to have their roles clearly specified in policies and plans. In addition, it is fundamentally important to have those policies and plans supported not just by government agencies but by community groups which are key to social cohesion within the community. The Kiribati National Water Resources Policy and the Policy Implementation Plan were developed by a multi-agency-key community group committee the National Water and Sanitation Coordination Committee, to ensure that there was the strongest possible support for policy goals and plans (White and Falkland, 2012).

5. Conclusions

This chapter has attempted to show the complexities and challenges in managing vital, shallow groundwater resources in urban atolls and to draw lessons from the experiences in South Tawara, in the Republic of Kiribati. The dynamic nature of fresh groundwater lenses has been demonstrated in their diurnal tidal fluctuations, their rapid sub-hourly response to rainfall and how they shrink with prolonged droughts and with pumping. The ever-present threats of salinization and pollution because of their hydrogeology present significant management problems. Reliable data and routine monitoring through 50 years of rapid population growth and economic development, in which the population has increased by over 300%, have been two of the key factors in the sustainable management of these fragile groundwater systems. The long infiltration galleries which skim the freshest water from the surface of the groundwater lens were also very important because of their minimal drawdown of the water table and upconing of underlying salinity. A major factor in the sustainable management of the groundwater sources in Bonriki and Buota has been the creation and protection of groundwater reserves through the 1977 Ordinance which has largely protected the reserves from polluting developments. This emphasizes the importance of strong groundwater regulations and knowledge-based policies and plans supported by the community. The case study has revealed that managing groundwater sources is only one part of the task of supplying safe freshwater to atoll communities. Leakage from the water reticulation system can subvert efforts to supply adequate freshwater. The resilience of atoll communities over the last 1,000 years has been underpinned by their ability to use diverse sources of water. The current freshwater demands in South Tarawa have now outstripped the estimated sustainable yield of the groundwater supply system and the government is in the process of installing desalination plants to supplement water supply. Groundwater, however, will remain a valuable source of freshwater because it optimizes storage without requiring scarce land surface area, minimizes evaporation losses, is economically favorable and readily accessed. Many of the lessons from South Tarawa are transferable to other urban or peri-urban atolls and small islands, particularly in facing changing climate.

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National Groundwater Management Plan and National Groundwater Information Center of the Republic of Korea

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Abstract

Groundwater plays an important role in water resources management in South Korea. This article introduces the National Groundwater Management Plan of South Korea for the sustainable development as well as conservation of groundwater for the future generation facing global changes such as climate change and urbanization. This article also highlights the groundwater information management system (GIMS) that provide all groundwater information with the national-wide monitoring network. Despite the historic achievement in groundwater management, the NGMP need be improved considering climate change, sustainability, integrated groundwater management on a watershed scale, and information systems. In this regard, the latest NGDP (2022-2031) envisions "Healthy and Safe Groundwater for all" considering groundwater management based on a watershed, climate change adaptation, and smart management. The author expects that all the experience in groundwater management and policies will be shared with neighboring countries, fostering a promising and mutually beneficial relationship and contributing to the mutual development of groundwater management.

Key Words *National Groundwater Management Plan, National Groundwater Information Center, Groundwater Information Management Center, South Korea*

1. Introduction

1.1 Groundwater in South Korea

The characteristics of groundwater depend on the geographical, topological, and geological characteristics. South Korea, officially known as the Republic of Korea, is a country located in eastern Asia. It is situated on the southern portion of the Korean Peninsula and shares borders with North Korea to the north. The landscape of South Korea is predominantly mountainous, with about 70% of its land covered by mountains. The Taebaek Mountains run along the eastern edge of the country, while the Sobaek Mountains are located in the central region. The highest peak in South Korea is Mount Hallasan, standing at 1,950 meters (6,398 feet), located on Jeju Island. In terms of groundwater, recharge dominates on the eastern highlands, while discharge dominates in the western lowlands due to the topography and spatial hydro-geological characteristics.

1.2 National Groundwater Management Plan of South Korea

National Groundwater Management Plan (NGMP) is the highest level of national plans regarding groundwater development, conservation and management since 1996 when it was firstly established in the Republic of Korea. The scope of the groundwater management policy stems from the National Water Resources Management Plan (2021~2020), where it suggests its own vision of "Happy and Bountiful Life without Concerns for Water". The core objective of the NGMP is to promote groundwater development and conservation at the same time considering the future value of groundwater, which is reinforced by the Article 6 of the Groundwater Act. The plan is established every 10 years and can be revised every five years in-between the ten years of interval. Every plan has its own vision and focus area (See **Figure 1**). **Figure 1** shows that the earlier plans from 1996 focused on foundation and infrastructures for groundwater management such as monitoring and assessment system. On the contrary, the later plans focused on the balance of conservation and sustainable development of groundwater.

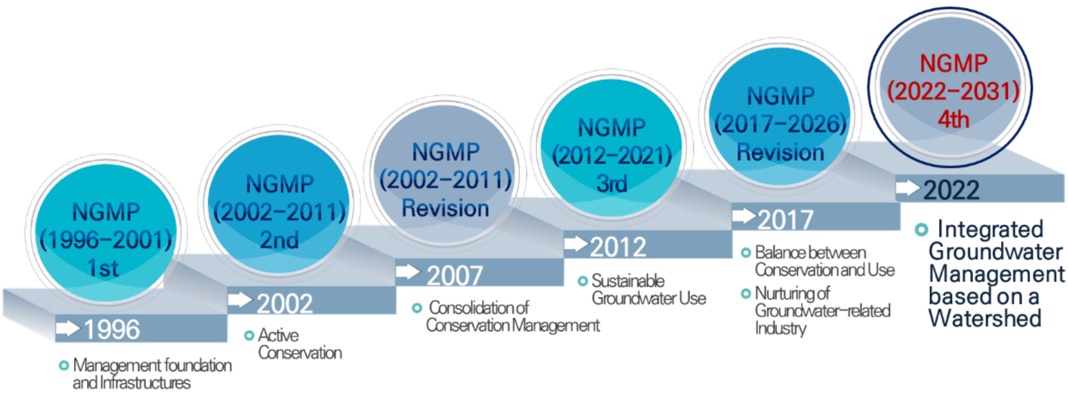

Figure 1: The National Groundwater Management Plan of South Korea and its proposed vision

The 4th NGMP is the most recent plan, which considers the impact of climate change as well as the integrated water resources management of South Korea (Ministry of Environment). It also proposed a new paradigm for groundwater management based on natural and socio-economic changes with advanced management for critical areas in terms of groundwater management. Based on the National Water Resources Management Plan, the 4th NGMP focuses on critical areas vulnerable to drought and employing groundwater as a key solution during the drought season. The 4th NGMP started from June 2021 where the opinions from professionals and related agencies and departments (five times) were collected until September 2022. Based on that the government held public hearing for the 4th NGMP in 2022 and additional opinions from local governments were brought together by the end of 2022.

2. Groundwater management in South Korea

2.1 Changes of groundwater assessed by the NGMP

The changes in groundwater recharge and available amounts are assessed based on basic survey and regional groundwater management plans. Table 1 shows the changes in groundwater recharge and available amounts assessed by the 3rd NGMP (2017) and the 4th NGMP (2022) and the changes between the two assessments. The annual precipitation is 1,299.7 mm per year, which was increased from the previous assessment 1,293.5 mm per year. The groundwater recharge and available amount were also slightly increased from the previous assessment by 1.1% and 4.6 %, respectively. The total available amount of groundwater is estimated to be 13.61×10^9 m^3/year, which was assessed in 2022.

Table 1: Changes in groundwater recharge and available amounts depending on assessment years from the National Groundwater Management Plan

Groundwater Availability	3rd Revision ('17. A)	4th NGMP ('22, B)	Changes compared to '17	
			Amount (B-A)	% change
Annual Precipitation (mm)	1,293.5	1,299.7	+6.2	+0.5
10-year drought (mm)	855.3	863.9	+8.6	+1.0
Recharge ratio (%)	14.9	15.0	+0.1	+0.7
Recharge (10^9 m^3/yr)	20.02	20.24	+0.2	+1.1
Availability (10^9 m^3/yr)	12.99	13.61	+0.6	+4.6

2.2 Groundwater use in South Korea

Most of the water resources use depends on surface water (88%) in South Korea and the lest of water resources use are originated from groundwater (12%). Among the total water use amount (or demand), agricultural water demand is the highest (58%), while municipal water demand (29%) is the second largest water demand. In contrast, industrial water demand is relatively small

(13%). However, the groundwater use pattern is quite different from it. In 2020, the total amount of groundwater use monitored in South Korea was 1,687,515 m^3, of which the municipal use amount was 834,086 m^3 (49%), agricultural use was 836,834 m^3 (50%) and industrial use was 13,508 m^3 (1%).

Table 2 shows the available groundwater and use assessed in the NGMP using the data collected from previous decades, where the percentage of groundwater usage compared with the available amount is 21.9% on average. The result shows that the most portion of the available groundwater is not developed and the percentage of use is low in South Korea. However, Table 2 also shows that the percentage of groundwater use varies greatly by regions depending on regional characteristics including population, area, hydro-geological features and so forth.

Table 2: Available groundwater and percent use by regions

Region	Availability (10^6 m^3/yr)	Use (10^6 m^3/yr)	% Use
Total	13,610.5	2,978.3	21.9
Seoul	60.5	17.8	29.4
Pusan	99.1	28.6	28.9
Daegu	90.8	22.0	24.2
Incheon	120.6	50.0	41.5
Gwangju	59.6	17.3	29.0
Daejeon	74.9	25.0	33.4
Ulsan	156.7	24.4	15.6
Sejong	58.8	22.2	37.8
Gyeonggi	1,405.7	413.9	29.4
Gangwon	2,218.3	190.6	8.6
Chungbuk	974.8	272.0	27.9
Chungnam	1,071.2	379.9	35.5
Jeonbuk	1,034.5	249.9	24.2
Jeonam	1,627.2	392.7	24.1
Gyeongbuk	2,282.2	341.0	14.9
Gyeongnam	1,486.6	294.9	19.8
Jeju	789.2	236.2	29.9

Table 3: Ratio of GW amount, which is not suitable for use based on Groundwater Act (2011-2020)

Year	National Monitoring Network				Auxiliary Network
	National Groundwater Monitoring (municipal use)	National Network		Rural Community Monitoring (municipal use)	Auxiliary Water Quality Monitoring
		Water Quality Monitoring (municipal use)	Contamination Monitoring		
2011	6.5	14.2	9.0	16.8	7.6
2012	6.4	12.8	7.7	14.4	5.4
2013	6.5	11.8	6.4	12.8	7.4
2014	6.4	13.0	6.3	12.6	5.8
2015	6.1	11.7	8.4	17.8	6.3
2016	7.2	14.4	7.1	13.6	6.4
2017	7.1	14.8	6.4	14.4	6.6
2018	9.9	14.3	7.9	15.4	6.2
2019	8.5	16.8	6.9	17.5	6.8
2020	6.7	7.9	6.4	16.7	6.8
Avg	**7.1**	**13.2**	**7.3**	**15.2**	**6.5**

Table 3 shows the percentage of available groundwater amount, which is not suitable for use based on the water use and water quality standards. The results shows that 6.5%~15.2% of groundwater is not suitable for use depending on the monitoring network. It is concerning that the amount of unsuitable groundwater in terms of water quality is not decreasing, which means that groundwater is vulnerable to constant contamination sources and countermeasures are quired to secure the groundwater quality.

2.3 Groundwater management infrastructures

Ministry of Environment is the top rank entity that supervises the national wide groundwater management. Ministry of Agriculture and Ministry of Internal Affair are also involved in groundwater management depending on specific groundwater uses such as agricultural water use and emergent water use in case of severe droughts. The actual groundwater use is approved by the local governments, where 31 out of 243 local governments have exclusive departments for groundwater (13%) and 76 local governments established the regional groundwater management plan (31%) as of 2020. Groundwater industry is also increasing for last 10 years that there are 3,850 groundwater development companies, 904 institutes of groundwater assessment in terms of both water quantity and quality, and 102 companies for groundwater purification purpose.

Ministry of Environment and Ministry of Agriculture are in charge of three information systems regarding groundwater management information. Under the Ministry of Environment, there are two systems, where National Groundwater Information System is operated by K-water and data collection started in 1997 using the national groundwater monitoring network. The national groundwater monitoring network is composed of total 2,577 monitoring wells. Among the total monitoring wells, 951 wells are operated by Ministry of Agriculture and the rest of the monitoring wells are managed by Ministry of Environment. The other information system, Soil-Groundwater Information System is managed by National Institute of Environmental Science and begun data collection from 2005. Ministry of Agriculture has its own Rural Groundwater Management System mainly focusing on groundwater wells for agricultural purpose and the monitoring data collected from 2003.

Table 4: Groundwater information management

Responsibility	System	Producing information	Data collection and management
Ministry of Environment	National Groundwater Information System	• National groundwater survey information • Groundwater use, water quality, local monitoring network and so forth • Additional research and monitoring information	Collected from 1997 by K-water
	Soil-Groundwater Information System	• Groundwater, soil, potable water and other information	Collected from 2005 by National Institute of Environmental Science
Ministry of Agriculture	Rural Groundwater Management System	• Rural groundwater monitoring network, seawater intrusion • Rural groundwater survey information • Groundwater monitoring well for agricultural use	Collected from 2003

2.4 Historical lessons and achievement in groundwater management

In terms of groundwater management, historical achievement during the last two decades in South Korea can be summarized as follows:

- Legislation of groundwater management and implementation: principles, support for the critical regions, industry, establishment of National Groundwater Information Center and so forth

- Integrated GW monitoring system and National Groundwater Information Center
- Sustainable GW development plans
- GW water quality monitoring and management
- Digitalized GW infrastructure management

Despite the achievement in groundwater management, still the plan should be improved based on the following historical lessons and limitations summarized below:

- Lack of consideration: climate change and carbon neutrality, IWRM based on a watershed, more focusing on critical regions, newly detected contaminants
- Lack of sufficient groundwater infrastructures: budgets and organization, groundwater industry support

2.5 The 4th National Groundwater Management Plan (2022-2031)

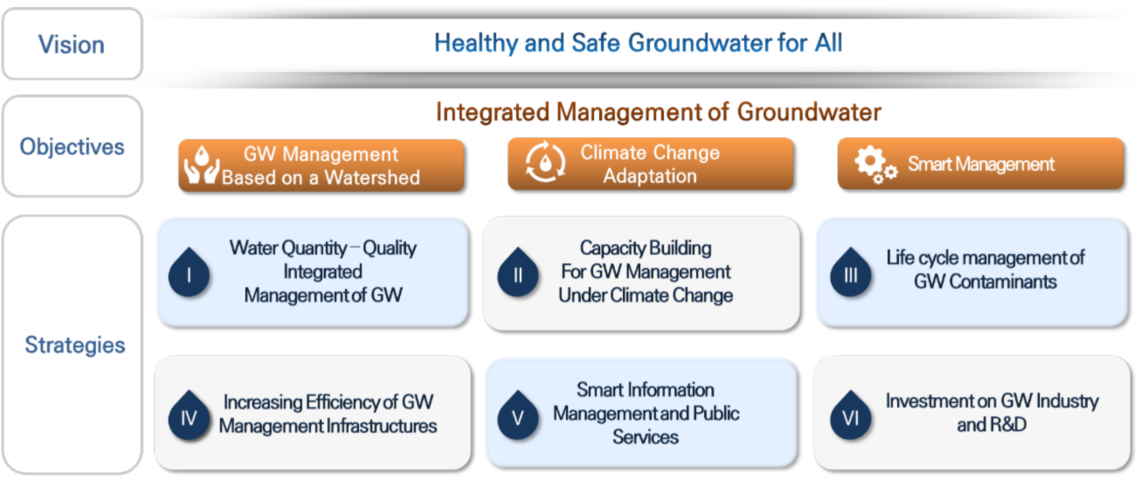

Figure 2: The 4th National Groundwater Management Plan (2022-2031)

The 4th National Groundwater Management Plan (2022-2031) envisions "Healthy and Safe Groundwater for all" and suggests three objectives for integrated management of groundwater: Groundwater management based on a watershed, climate change adaptation, smart management. For the purpose of groundwater management based on a watershed, the plan requires a long-term groundwater management planning, integrated groundwater management based on water circulation, and focus on groundwater contamination in critical regions. Similarly, for the climate change adaptation and carbon neutrality, the plan aims to diversify water resources and groundwater use and to increase value of groundwater. For the smart information services with innovation, the plan pictures a big data and AI-based open platform as well as increased groundwater information accessibility and availability. In order to accomplish these objectives, the new phase of the NGMP suggests six strategies as follows until 2031(**Figure 2**):

- Water Quantity – Quality Integrated Management of Groundwater
- Capacity Building for Groundwater Management Under Climate Change
- Life cycle management of Groundwater Contaminants
- Increasing Efficiency of Groundwater Management Infrastructures
- Smart Information Management and Public Services
- Investment on Groundwater Industry and R&D

Figure 3: Implementation strategies of the 4th National Groundwater Management Plan (2022-2031)

The 4th NGDP also adapted four implementation strategies for a consistent and effective planning as shown in **Figure 3**; the first one is adapting implementation-evaluation procedures and development of the next generation index for quantitative evaluation of implementation. The next one is consistency in national water resources planning such as with the National Water Resources Plan and other relating policies. The third one is cooperation of central and local government and related agencies by developing consultative group between them. The final strategy is the long-term financial planning that enables implantation of the NGMP by increasing budgets for initiatives (water welfare, climate change adaptation) and securing financial resources for local governments.

3. National Groundwater Information Center of South Korea (NGIC)

3.1 Introduction

National Groundwater Information Center of South Korea (NGIC) was established on November, 2003 by Ministry of Land and Transportation for the purpose of the comprehensive groundwater information management based on a legal basis from Groundwater Act Section 5(2) regarding National Groundwater Management Plan (**Figure 4**). The main role of the NGIC includes:

- Development and operation of groundwater information management system (GIMS) based on monitoring data, innovative technologies and researches
- Supporting groundwater management policy by collection, management and analysis of GW information
- Standardization of groundwater information
- Education, R&D, and dissemination of groundwater information technologies

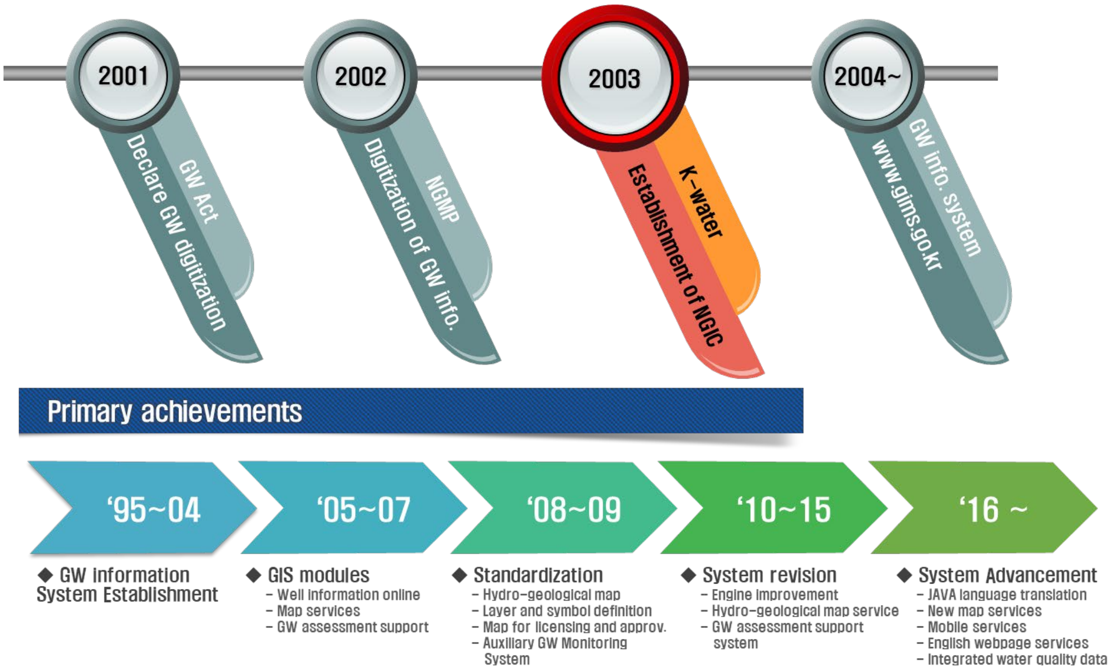

Figure 4: History of National Groundwater Information Center of South Korea (NGIC)

One of the most effective roles of the GIMS is providing groundwater information based on a GIS and map services that maximizes the end users' convenience. The end users can easily find all relevant information for their interests using the map services. The real-time monitoring data from national groundwater monitoring network including water surface elevation of the observation well, temperature, electronic conductivity is also provided by GIMS (http://www.gims.go.kr/).

3.2 Groundwater Information Management System (GIMS) based on map services

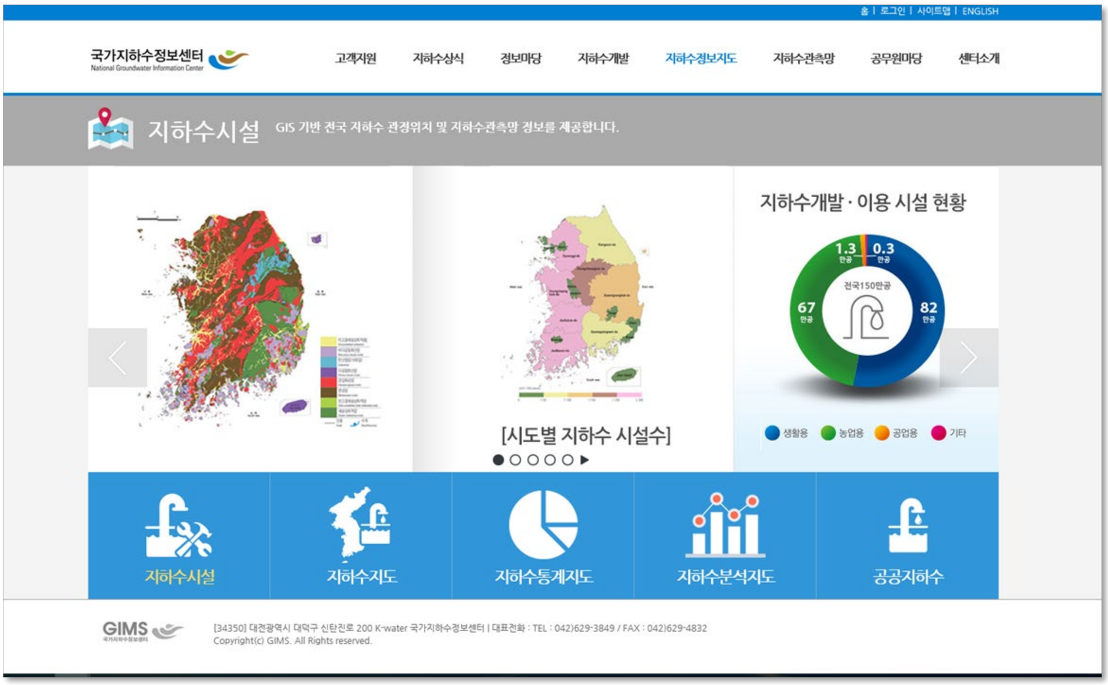

Figure 5: The webpage of NGIC and GIMS with groundwater information provided by map services (http://www.gims.go.kr/)

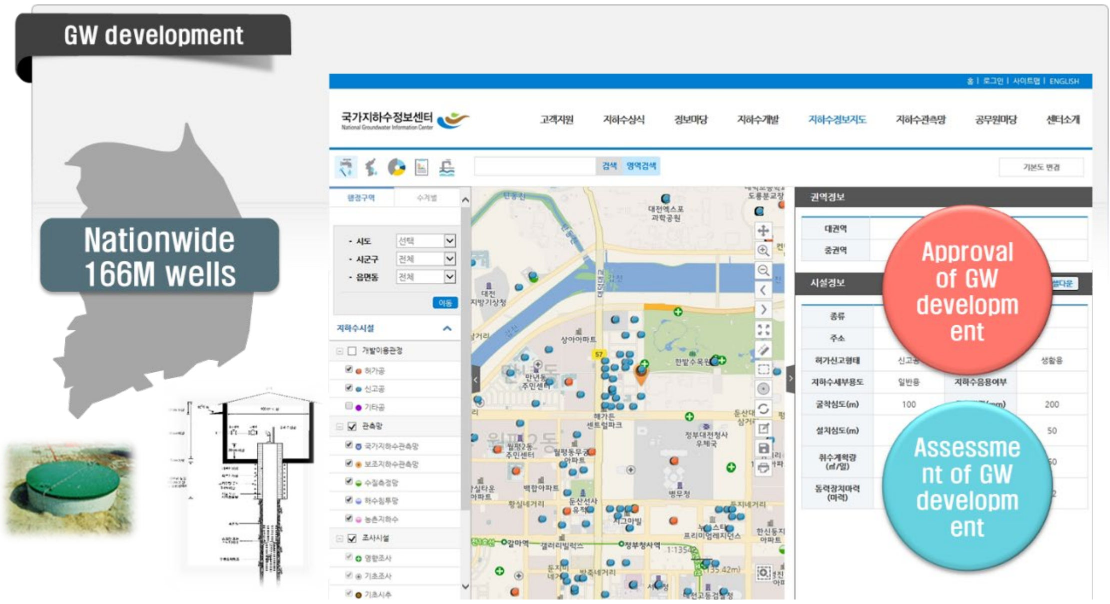

Figure 6: All groundwater information including approval and assessment provided by

the GIMS by map services

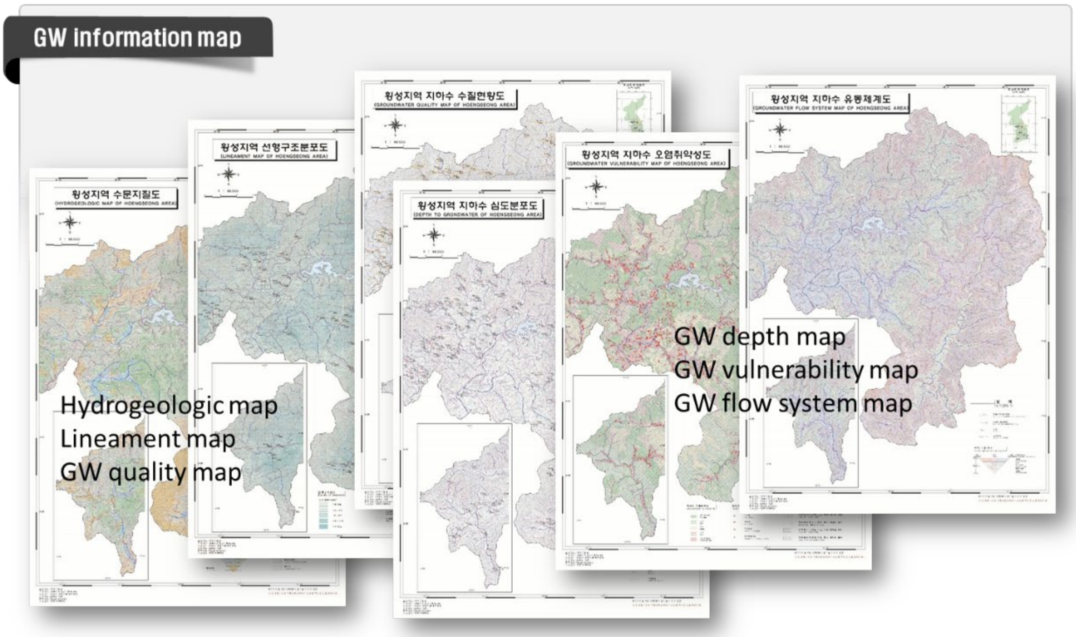

Figure 7: Groundwater maps provided by GIMS including hydrogeologic map, lineament map, groundwater quality map, groundwater depth map, vulnerability map, groundwater flow map and other groundwater subject maps

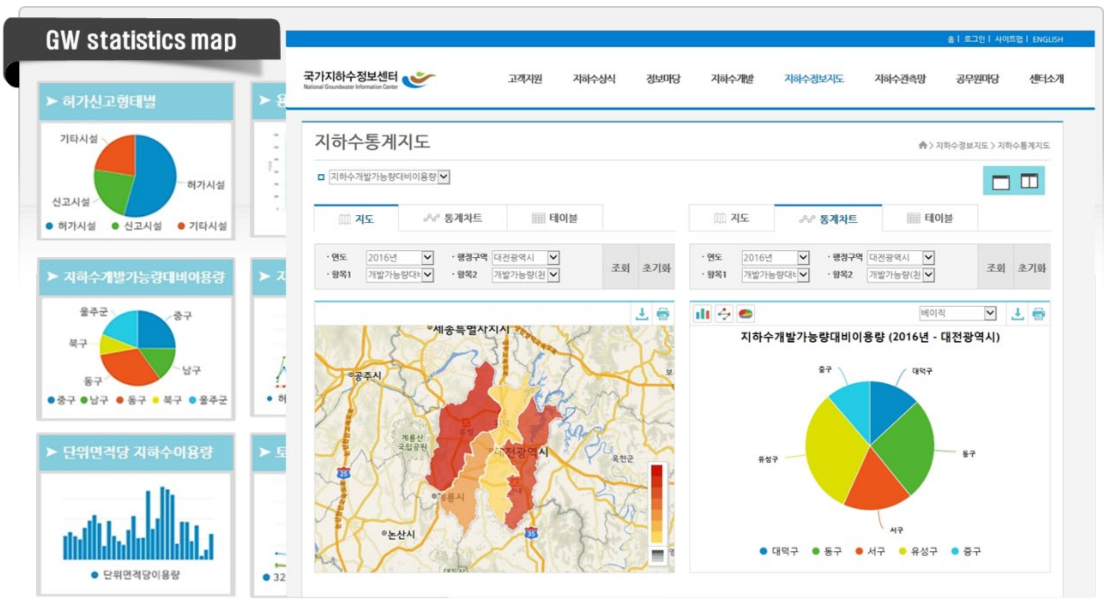

Figure 8: Groundwater statistics provided by GIMS based on map services including available amount and yearly changes, percent use, use amount per area and so forth

Figure 9: Groundwater well information provided by GIMS based on map services including address, purpose, managing authority, pump and well information, and other relevant information

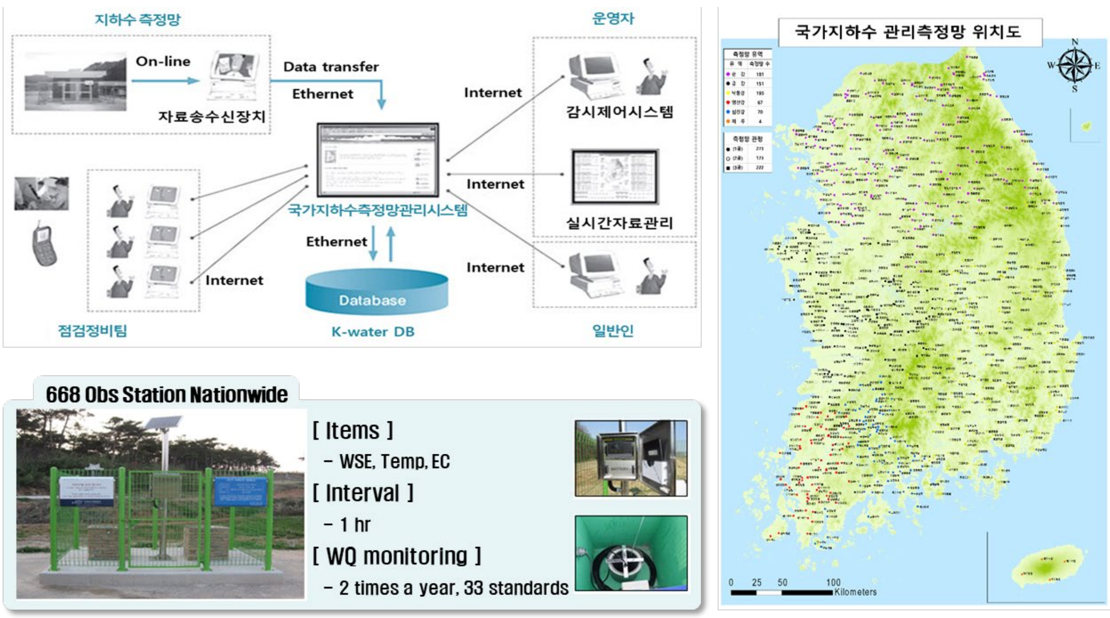

Figure 10: Realtime groundwater monitoring from national monitoring network (668 observation wells nationwide)

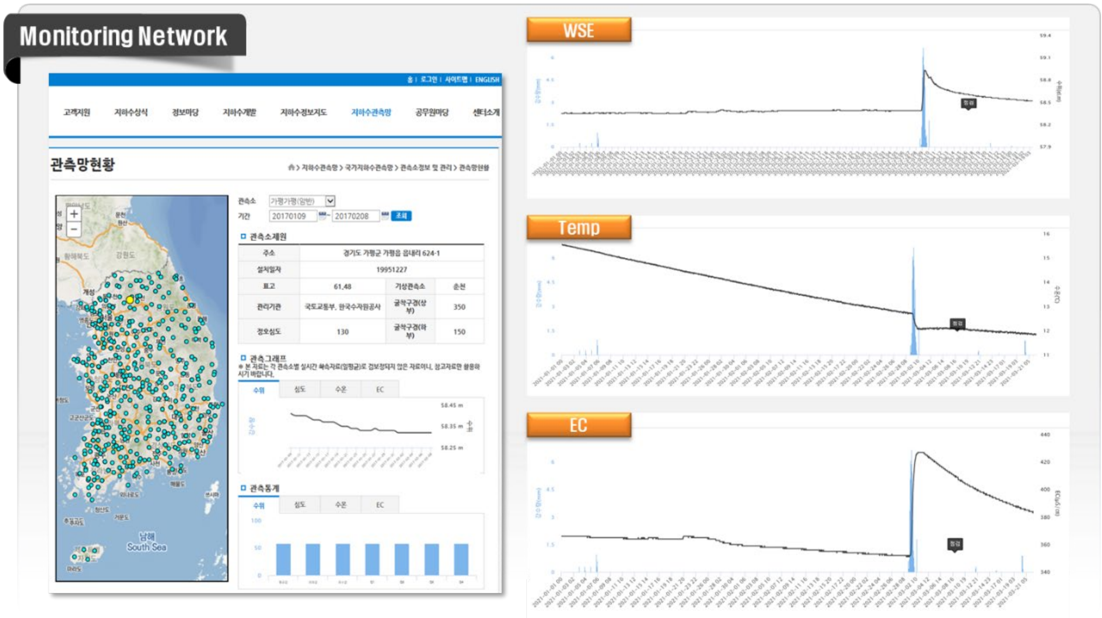

Figure 11: Realtime Groundwater well information provided by GIMS based on map services including water surface elevation, temperature, electronic conductivity time series of the observation wells

Figure 5 show the webpage of NGIC and GIMS with groundwater information provided by map services (http://www.gims.go.kr/). **Figure 6**, **Figure 7**, **Figure 8**, **Figure 9**, **Figure 10**, and Figure 11 show the information provided by the GIMS. **Figure 6** illustrates the groundwater approval and assessment information provided by the GIMS by map services. **Figure 7** depicts groundwater maps provided by GIMS including hydrogeologic map, lineament map, groundwater quality map, groundwater depth map, vulnerability map, groundwater flow map and other groundwater subject maps. **Figure 8** shows the groundwater statistics provided by GIMS based on map services including available amount and yearly changes, percent use, use amount per area and so forth **Figure 9** shows the well information provided by GIMS based on map services including address, purpose, managing authority, pump and well information, and other relevant information. **Figure 10** and **Figure 11** show the real-time groundwater well information from national groundwater monitoring network (668 monitoring wells) provided by GIMS based on map services including water surface elevation, temperature, electronic conductivity time series of the observation wells.

4. Conclusions

While the most of water use depends on surface water, groundwater is gaining more and more attention facing the impact from climate change, increasing drought severity, rapid development and urbanization in South Korea. Therefore, the groundwater policy tends to highlight conservation rather than development of groundwater in South Korea. This article introduced the National Groundwater Management Plan (NGMP), which is the most important national plan regarding groundwater development, conservation and management since 1996 and played the most important role in groundwater management development. This article also highlighted the groundwater information management system (GIMS) that provide all groundwater information with the national-wide monitoring network. Despite the historic achievement in groundwater management, the plan need be improved considering climate change, sustainability, integrated groundwater management on a watershed scale, and information systems. In this regard, the latest NGDP (2022-2031) envisions "Healthy and Safe Groundwater for all" considering groundwater management based on a watershed, climate change adaptation, and smart management. The author expects that all the experience in groundwater management and policies will be shared with neighboring countries, fostering a promising and mutually beneficial relationship and contributing to the mutual development of groundwater management.

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Appraisal of pumping tests on the infiltration gallery and the individual shallow tube wells constructed on the shallow sand dune aquifer (the lens aquifer) at Point Pedro area in Jaffna district of Sri Lanka.

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Abstract

Point Pedro in Jaffna peninsula of Sri Lanka has experienced significant shortage of fresh water due to climatologically condition. This area has comparatively very low annual precipitation and high evaporation and this results no any perennial streams on this terrain in order to develop the water supply necessities. With the expansion of resettlement and other developments activities in the north region, the demand for water supply has increased in the community. In this situation, groundwater has become the key component to cater the water supply necessities in the North region. In this context, National Water Supply and Drainage Board has played major role and taken the responsibility to develop the water supply schemes at the several main areas in Jaffna district. Under such activities, development of the water supply scheme (demand 4000m3 per day) at Point Pedro area has indicated significant hydrogoelogical importance. Because, this water supply scheme exploits the *shallow coastal sand dune aquifer* which could be easily affected by improper groundwater withdrawal. Therefore, it was constructed the *infiltration galleries* in order to exploit this *lens aquifer* with the minimum stress on it and to keep the *hydrogoelogical balance.* One of these *infiltration galleries* and four other individual shallow test tube wells on the same formation were used to perform the pumping tests to identify the aquifer behavior.

The *infiltration gallery* and the individual shallow tube wells were illustrated significant variations while pumping. Pumping of the individual tube wells created larger drawdown than the *infiltration gallery* under the low discharge rates i.e. 150 to 175 liters per minutes (l.p.m.). With such low pumping rates, it was unable to reach the reasonable value of the required demand. The discharge rate applied to the *infiltration gallery* was much higher than individual tube wells and it was 300 l.p.m. and it resulted comparatively very low drawdown of 0.15m. Therefore, *infiltration galleries* can use to skim water off the surface of the *lens* (thin aquifer formation), thus distributing the pumping over a wide area by

creating the possible minimum drawdown. Also, it allowed to access the hydrogeologically sensitive aquifer with safer manner to withdraw the large quantity of water that helps to cater the required demand up to successful extent.

Electrical Conductivity (EC) variation is the other most vital factor to be concerned under such aquifer condition. Because, EC of the lens aquifer has a higher possibility to increase due to the groundwater withdrawal activities. However, significant variation of the *EC* values was not indicated in the individual tube wells under the above mentioned drawdown conditions. The gradual increase of *EC* value and then stabilization of the *EC* values in that range was noted while pumping of the infiltration gallery. However, these variations do not give possible indication of salt water up conning or intrusion. These facts should be the priority matters to concern the technical method that appropriate to extract groundwater from the *shallow lens aquifer* and such significances evaluate applicability of the *infiltration gallery* for the hydrogeologically sensitive aquifer system in order to obtain the maximum benefits while withdrawing groundwater for the long term purposes. According to that, use of the infiltration gallery can cause to obtain the maximum benefits of groundwater extracting under the hydrogeologically limited aquifer condition, minimizing the possible negative impacts of shallow groundwater withdrawal from the sand dune formation at Point Pedro area.

1. Introduction

This water supply scheme was designed focusing the groundwater potential of the shallow costal sand dune aquifer of this area. This sand dune formation locates in between the sea and lagoon and occurrences of the fresh water aquifer has a high possibility to affect with salt water intrusion and upcoming. Therefore, exploitation of the large water quantities for long term proposes should be done under the special attention in order to maintain such sensitive hydrogeological setup. Under these limitations, new approach was made to withdraw groundwater by using infiltration galleries. Four infiltration galleries were established at the selected area of the sand dune formation. Prior to construct the infiltration galleries, four individual shallow tube wells were also constructed at the same area to identify the aquifer characteristics and hydrogeological behavior of the concerned formation. These both well types were used to perform the pumping test and special attention was made to identify the pumping significances in between the infiltration gallery and individual wells. This study was done in order to appraise such pumping significances including hydrogeological behavior of the concerned aquifer while withdrawing its water by using the Infiltration galleries and individual shallow tube wells.

Objectives of the study;

- Evaluation of pumping tests on the infiltration gallery and the individual tube wells constructed on the shallow sand dune aquifer (the lens aquifer) at Point Pedro area.
- Comparative assessment on the applicability of the infiltration galleries and individual wells to withdraw groundwater from the shallow coastal lens aquifer.

2. Groundwater in the national water resources management of Sri Lanka:

2.1 The Role of groundwater resources in the national water resources management plan

Unfortunately, the country does not practices a systematic natural resources management plan. Specially, groundwater resources in Sri Lanka have no proper owner ship or a responsible institutional authority to mutual access. Therefore, groundwater resources development and its usage in national level has less priority. This back ground has created negative impact on the rural communities which do not have proper water supply facilitate. Therefore, this invaluable resource has no proper management and protection on behalf of its users. Hence, in the absence of a policy, the users and mangers of groundwater take the liberty to exploit the resource in an unregulated manner.

2.2 Administrative and legal framework for groundwater management

The present climatic changes and pollution trends have created significant affect on the natural resources, especially the groundwater sources and similarly the challenges have been developed on the groundwater resources management due to the existing unorganized disseminated practices of it. Therefore, the need of systematic intervene on this matter is extremely high by increasing the level of service and be in the line with present environmental challenges and water sector development process of the government.

However, various groundwater development activities and projects have adopted different policies, utilized inconsistent strategies, and modes of use of groundwater resources in water supply and sanitation programmes. Therefore, it has become necessary now do develop a consistence policy for pumping test, in order to provide the better service and to achieve the institutional and government goals of present water supply by giving priority to establish the centralize mechanism through the specialize section for practicing aquifer and pumping test activities to face future endeavors of groundwater section of NWS&DB.

3. Case Study: Groundwater status in Point Pedro area

3.1 Water supply and demand of Point Pedro in Jaffna.

This areas has faced nearly 30 years of a civil war. This unrest situation causes significant depraved impacts specially, on the water supply developments. As a result, the community totally has depended on the scattered wells to use groundwater and such sources have been not incorporated systematic sanitary measures and extraction management and regulations. The forecasted water demand for this area is about 4000 m3 per day. In addition, his region has experienced significant shortage of fresh water due to climatologically condition. This area has comparatively very low annual precipitation and high evaporation and this results no any perennial streams on this terrain in order to develop the water supply necessities. With the expansion of resettlement and other developments activities after the unrest situation of the country specially, in the north region, the demand for water supply has increased in the community.

In this situation, groundwater has become the key component to cater the water supply necessities in the North region. In this context, National Water Supply and Drainage Board has played major role and taken the responsibility to develop the water supply schemes at the several main areas in Jaffna district. Under such activities, development of the water supply scheme (demand 4000m3 per day) at Point Pedro area has indicated significant hydrogoelogical importance. Because, this water supply scheme exploits the shallow coastal sand dune aquifer which could be easily affected by improper groundwater withdrawal.

3.2 Overview of the aquifer, including hydrological and hydrochemical characteristics

Investigated area is located at Vallipuram, Point Pedro in Jaffna peninsula (See **Figure 02**). The mean annual rain fall of this region is in the range of 1500 -1000 mm and it is in the range of 1250 -1000 at the investigated area (Department of Meteorology, Sri Lanka). The coastal belt of this area is formed with the sand dunes (See **Figure 03**). These sand dunes extend in the direction of NNW - SSE of the Eastern coastal belt of the peninsula. The maximum width of the sand dune formation at the investigated area is about 2-3 Km and it thins out at the southern coastal belt of the peninsula. This formation is located on the narrow land strip in between the lagoon and sea and totally underlain by Limestone rock and this formation was affected by Tsunami action in the year 2004 at the some locations. On this narrow land strip, fresh shallow groundwater can occur as the lance on the high dense water of the lagoon and sea (See **Figure 01**).

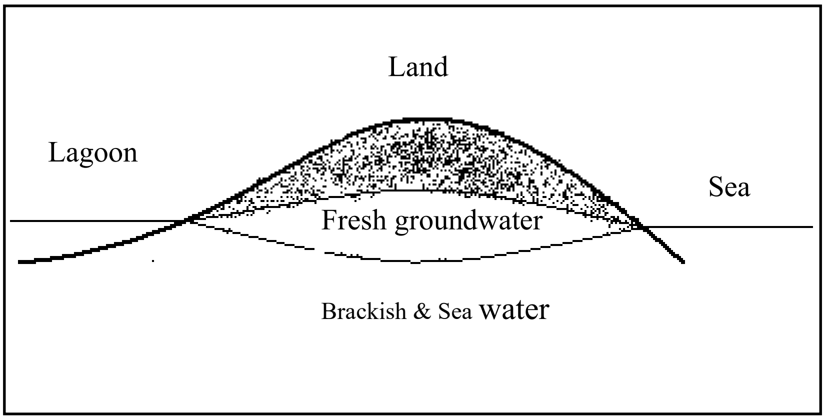

Figure 01: Typical cross-section of the freshwater lens on a sand dune formation

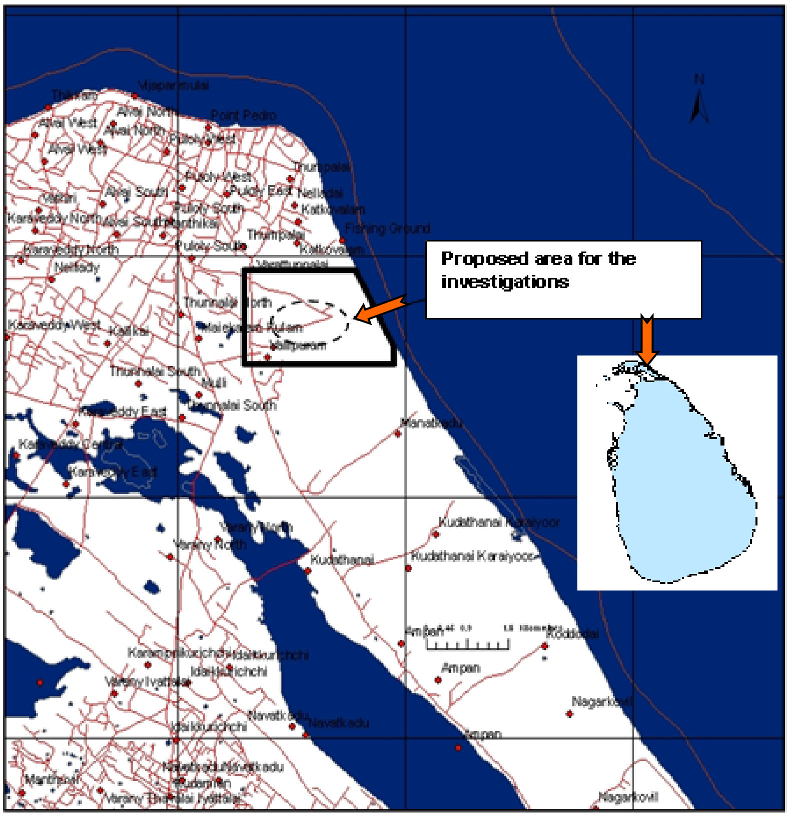

Figure 02: Investigated area with the index map of Sri Lanka

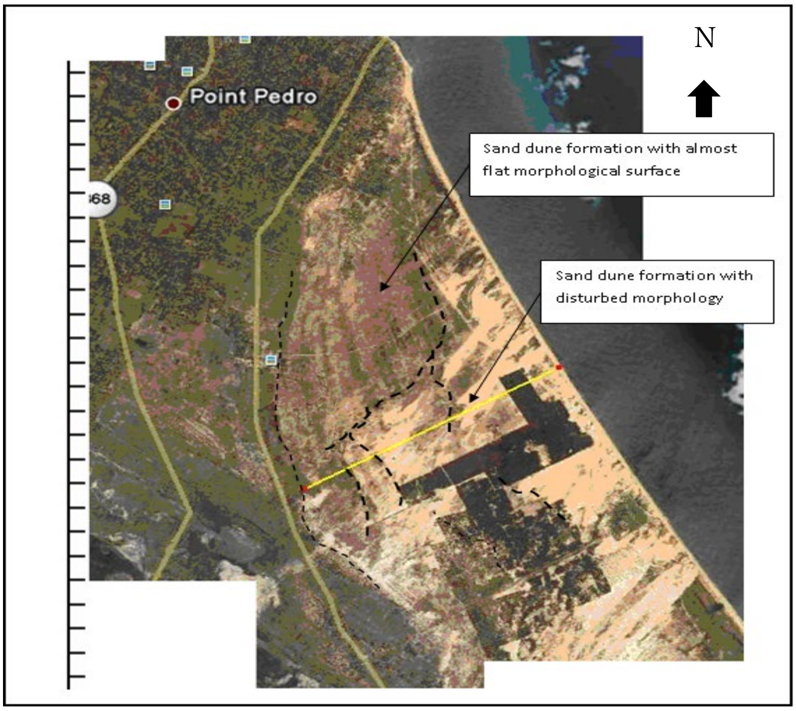

Figure 03: Distribution of the sand dunes at the study area of Vallipuran - Point Pedro in

Jaffna peninsula (Source: Google Earth)

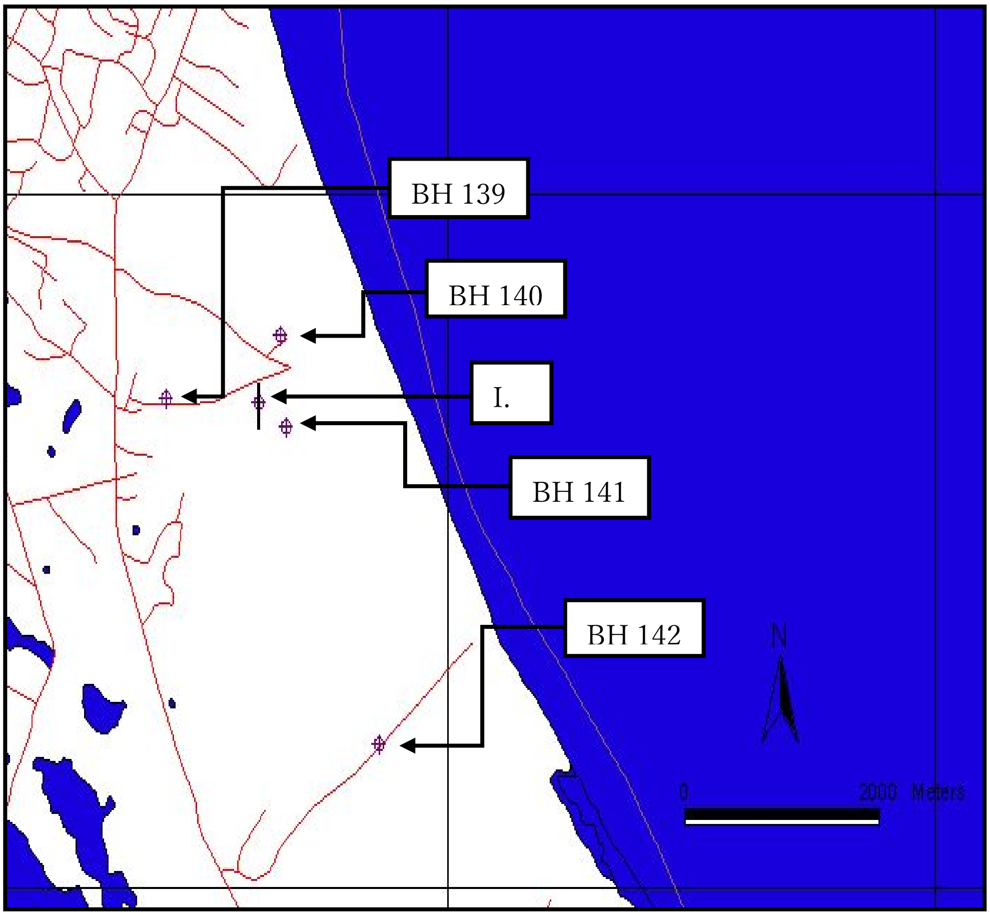

Figure 04: Locations of the individual tube wells (BH) & Infiltration Gallery (I.G)

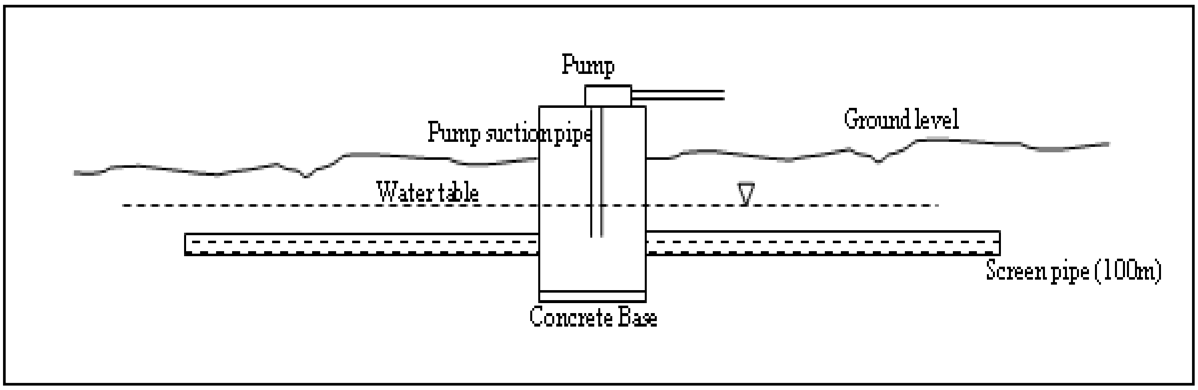

Figure. 05: A general sketch of the infiltration gallery

Methodology

Pumping tests were included with main two steps. These were step draw down and constant discharge tests. Initially step draw down test was conducted for selected each well and it consists with several numbers of steps. Discharge rates as well as drawdown values of each step and general information were noted. The constant discharge test was designed based on the result of this test. It was performed as the single well test. The procedure of this test was; water was pumped from tube well with constant discharge rate for certain time. The effect of this pumping on the water table *i.e.* drawdown rate was measured in the pumped well as well as observation wells. Similarly, the recovery rate was also recorded after the cessation of pumping. The drawdown/recovery data were then analyzed.

Table 01: Details of the wells of tested (*Duration of each step was 60 -100 minutes, **Duration of each test was 2880 minutes, l.p.m – liters per minute)

Well type	Well No.	Step Test Data*	Constant discharge rate test**
		Rates of pumping (l.p.m)	Rate of pumping (l.p.m)
Individual tube well	BH139	100, 150, 200, 250, 300	160
	BH140	50, 100, 150, 200, 250	150
	BH141	100, 150, 200	175
	BH142	-	300
Infiltration Gallery	No.01	200, 400, 600	300

Significant characteristics of the pumping tests

Drawdown and extractable water quantities

Drawdown values of the pumping tests indicated clear difference between the individual wells and infiltration Gallery. The individual wells indicated significantly higher drawdown values than the infiltration gallery for the same duration of pumping. The well BH 142 indicated impressively higher drawdown than the infiltration gallery under the same rate pumping (See Table 01 for pumping rates). Further, high drawdown values of the well number BH 139, 140 and 141 were resulted under the low pumping rates (See table 01) than the pumping rates of the infiltration gallery (See **Figure 06**). The well BH 142 and infiltration gallery indicate prominent drawdown difference under the same rate and period of pumping (i.e. 400 liters per minute).

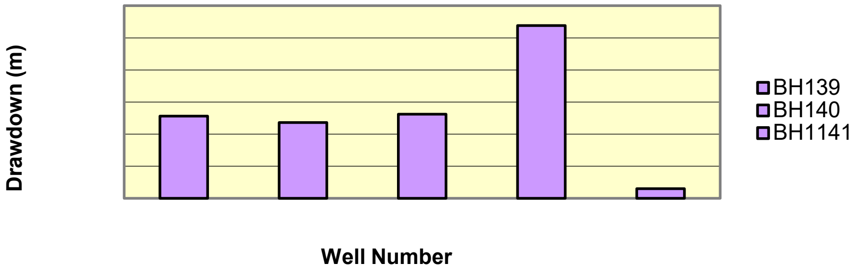

Figure 06. Variation of the drawdown values between individual tube wells & Infiltration gallery (For 24 hours of pupming)

It is clearly indicated that large water quantity can be pumped using infiltration gallery under the minimal drawdown condition. Three individual tube wells (BH 139, 140 &141) were applied with low pumping rates than infiltration gallery in order to control the high drawdown and resulted less pumping water quantities. The **Figure 06** and **Figure 07** have clearly illustrated these matters.

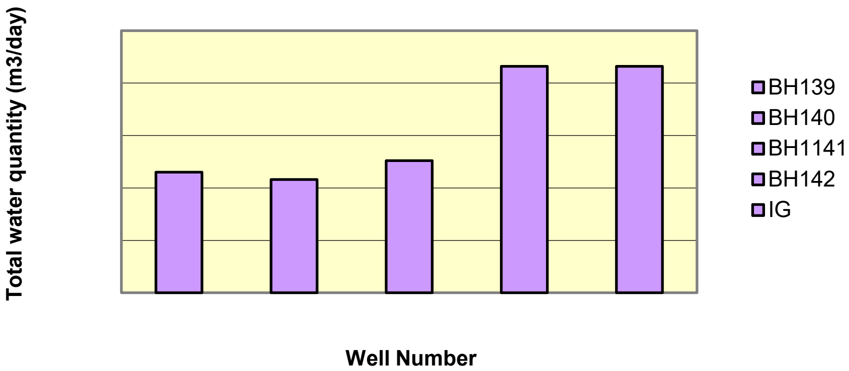

Figure 07. Variation of the total pumping water quantities (m3/day) between individual tube wells and infiltration gallery (For 24 hours of pumping)

Electrical Conductivity

Electrical Conductivity (EC) variation was measured at the field while pumping the individual tube wells and infiltration gallery for the period of 48 hours. However, significant EC variation was not observed in the both types of wells due to groundwater withdrawal and EC values of all pumped wells were adjusted in the range of 200 - 500µs/cm.

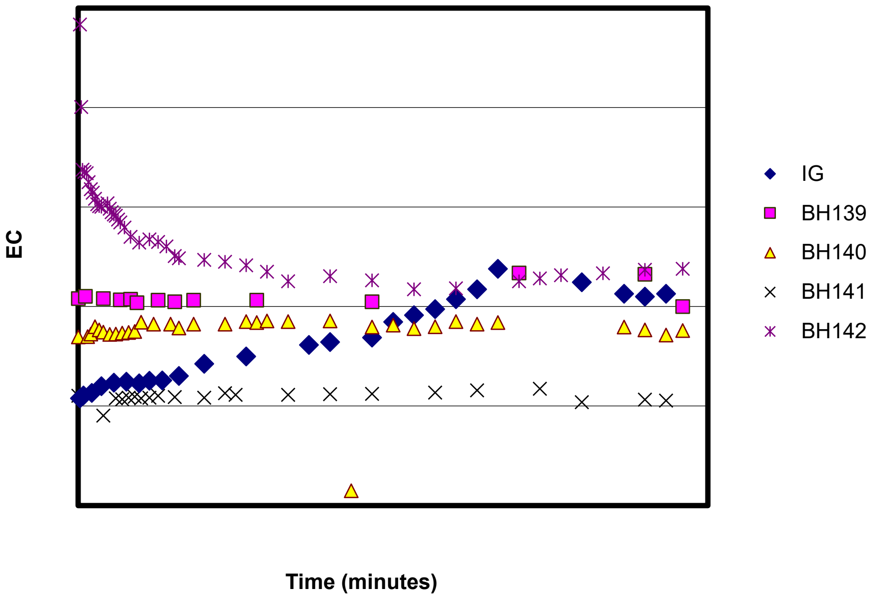

Figure 08. EC Variation between pumping of individual tube wells and infiltration gallery (For 48 hours of pupming)

3.3 existing and potential problems associated to groundwater extraction

This sand dune formation locates in between the sea and lagoon and occurrences of the fresh water aquifer has a high possibility to affect with salt water intrusion and upcoming. Also this area has no perennial surface water sources and the shallow groundwater system recharges from rain fall and the annual rain fall is comparatively very less than other areas of the country and represents semi-arid conditions. Therefore, exploitation of the large water quantities for long term proposes should be done under the special attention in order to maintain such sensitive hydrogeological setup.

4. Good practice, Lesson learned

In this scenario it is very important to practice proper monitoring system while extracting groundwater in this area. In order to maintain the sustainability of aquifer system, it should be adopted to strict groundwater management and regulation strategies. This will directly benefits to the all communities of this area and life style of them.

5. Conclusions

Construction of the infiltration galleries can give more benefits than use of individual boreholes for groundwater extracting for the productive scale long term proposes under the above mentioned aquifer conditions. Because, Infiltration galleries skim water off the surface of the lens (thin aquifer formation), thus distributing the pumping over a wide area. This distributed pumping cause to avoid the problems of excessive drawdown and create possible minimum stress to the aquifer and minimize consequent up-coning of saline water caused by localized pumping from individual wells. When the large quantity of water are required application of this method will allow to access limited aquifers in more safe manner and can yield large water quantities

Excessive drawdown of such lens aquifer can lead to initiate saltwater up coning and also lateral inflow by long term water usage. Therefore, drawdown can be considered as the most crucial hydrogeological factor that needs to control while extracting groundwater. This kind of distributed pumping system can apply to minimize such excessive drawdown based on the pumping test results discussed above.

However, application of this method i.e. infiltration gallery is more expensive than boreholes due to related construction coast and other required materials. Further, this method can be successfully applicable when pheritic surface is shallow i.e. less than about 4m depth. These can be considered as the main disadvantage of such application.

Considering all facts discussed, it should be the priority matter to concern the technical method that applicable to extract groundwater from the shallow lens aquifer of this area and application of the infiltration galleries under these conditions will leads to obtain more benefits.

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Acknowledgement

This paper on Appraisal of pumping tests on the infiltration gallery and the individual shallow tube wells constructed on the shallow sand dune aquifer (the lens aquifer) at Point Pedro area in Jaffna district of Sri Lanka is a product of specially, the field working experiences and desk activities, at the well field construction for water supply development under the Emergency North Rehabilitation Project for the benefit of the communities that has been affected by long unrest situation of that area. This task was handled by the Planning and Designing (P&D) section of the National Water Supply and Drainage Board (NWS&DB), I was informed to perform all hydrogeological activities of relevant. The main focus of this was to compile the all relevant hydrogeological and technical aspects those were used to develop water supply needs rather than a research basis study.

I am very grateful to the following persons for their invaluable contributions. Former Engineer Sajjan Jayasiriwardene the Deputy General Manager (DGM), P&D section, Chief Engineer Ms. A.S. Kaluarachchi (At present, the Deputy General Manager (Development) and a former Hydrogeologist, the Manager-(Groundwater Investigation Section) Mr. A. Perera for their supervision on this work. In addition, all the staff members of the Regional Support Center (Northern) and the all members of field investigation and testing crews of the Groundwater Investigation Section for their tired less field worked relevant to the task.

Groundwater Research for groundwater management in Central Plain, Thailand

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Abstracts

Bangkok and the Central Plain Basin of Thailand have high potential for social and economic development and rapid population growth. As a capital, water supply for public, commercial, and industrial uses is critical for socio-economic development infrastructure. Past over-pumping in urban areas like Bangkok caused land subsidence and induced considerable damage to city development. Then, in the central plain basin, irrigated areas had been developed for a long time and became high agricultural productivity areas, especially for rice cultivation. Due to water scarcity, groundwater took a partial role in the city water supply and in irrigation areas to compensate for the surface water irrigation deficit for summer rice in irrigation projects and at the regional scale.

Three case studies were selected to demonstrate how the groundwater research conducted and applied to help manage groundwater resources more suitably, i.e., land subsidence in Bangkok as city groundwater use, Thor Thong Daeng irrigation project (TTD) as groundwater use in an irrigation project, and the Upper Central Plain as regional groundwater use at the regional scale.

Groundwater models have been developed to simulate the groundwater flows in the study areas. A field study on groundwater use was conducted to understand the groundwater use pattern of the farmers in each water year. The water balance of the basin of both groundwater and surface water was explored from the groundwater model to set permissible water pumping for the area to control water pumping and reduce the impact of groundwater drawdown. The research results helped set suitable countermeasures to reduce land subsidence and control groundwater use in the irrigation project and the Upper Central Plain, representing lessons learned for groundwater management in other areas.

Keywords groundwater modeling, groundwater water balance, conjunctive use, Bangkok, irrigation, central plain, Thailand

1. Introduction

1.1 Groundwater issues in Asia, the world, and Thailand

In Asia, the problems of urban groundwater use and groundwater management practices reviewed in various cities have been explored, and technical tools that might help to deal with urban groundwater problems were presented. Urban groundwater is a renewable and efficient resource if wisely managed (Shinichiro, 2008).

From overall mapping, the groundwater sustainability of selected Asian cities can be rated as "medium sustainable to sustainable." In most of the studied cities, groundwater conditions are under risk because the groundwater level is declining, aquifer volumes are decreasing, and water quality is deteriorating. To cope with these situations, cities like Bangkok have taken measures to restrict groundwater exploitation such as the introduction of a licensing/permission system and a groundwater charging scheme. However, cities such as Chitwan, Ho Chi Minh, Hyderabad, Lahore, and Yangon lack such policies and their implementation. Therefore, higher priority must be given to formulating groundwater policies and regulations for achieving groundwater sustainability in these cities (Sangam Shrestha, 2016).

Groundwater has become a major source of freshwater for supporting socio-economic development in the rapidly urbanizing cities of the Greater Mekong Subregion (GMS). The findings reflected a lack of effective policies and low institutional capacity as the key challenges of groundwater management in the study area. Consequently, the way forward requires the consideration of collaborative strategies among key actors to strengthen groundwater governance in the rapidly urbanizing area to balance groundwater use, socio-economic development, and climate resilience. Furthermore, the capacity of groundwater governance should be enhanced at the local level beyond transboundary aquifer management to ensure sustainable groundwater extraction in the GMS region to respond to the sustainable development goals (Preeyaporn, 2022).

The UNESCO Groundwater Report described the challenges and opportunities associated with the development, management, and governance of groundwater across the world. The report aims to establish a clear understanding of the role that groundwater plays in daily life, of its interactions with people, and of the opportunities for optimizing its use to ensure the long-term sustainability of this largely available yet fragile resource. Unlocking the full potential of groundwater will require strong and concerted efforts to manage and use it sustainably. All of these efforts start by making the invisible visible (UNESCO, 2022).

In Thailand, surface water, groundwater, and pipe water are the three main sources of water supply for consumption and production. The demand for water has increased owing to urbanization and industrialization in Thailand during 1970–2000. Users could not access pipe water supply in the urban area. Manufacturing production could not access sources of surface water or pipe water in many areas. They therefore have to rely on groundwater supply as an immediate solution. Accordingly, the quantity of groundwater usage has rapidly increased. Many studies on groundwater control in the supply side control have been conducted to propose safe yield figures and pumping control measures (JICA, 1995; CU, 1999; KU 2004).

The general climate change trends were analyzed with a review of groundwater conditions in Thailand. The climate changes, hydrologic variability, and the impact of climate change on groundwater sustainability were discussed based on a national groundwater monitoring program. The impact of climate change on groundwater-dependent systems and sectors is also discussed according to certain case studies, such as saline water intrusion in coastal and inland areas. Managing aquifer recharge and other projects are examples of groundwater adaptation projects for the future (SRISUK, 2017).

With an already expected decline of groundwater head defined within this study throughout all of Northeast Thailand because of climate change, a continued intensification of groundwater extraction could lead to an increase in saltwater intrusion and eventually the unavailability of groundwater resources. This is especially true for those areas defined within this study to be the most severely affected. Given the importance of groundwater for the livelihood of the region during droughts, expanding groundwater use for irrigational purposes is not advised so that the resource can be kept available for domestic use as a safeguard throughout periods of extended water shortages (Wouter, 2019)

A study in a community area in Amphoe Ban Na, Nakorn Nayok Province recommended that groundwater quality should be closely monitored because of below-average quality based on its WQI (water quality index) map. Hence, decision-makers should plan a project for improving and managing groundwater in this region. Moreover, the study showed that the integration of GIS and the program R with the WQI can be an effective tool for evaluating groundwater quality and quantity (Pongpun, 2019).

A groundwater study in Phuket Province found that high recharge areas are located in the Southeastern part of Phuket and most areas of the island have moderate recharge rates. Some small areas on the island have low recharge rates. The recharge estimation from groundwater simulation in Phuket could help manage the future development of the groundwater system in Phuket Island as being a critical parameter of groundwater resources (Avirut, 2019)

Recent activities of groundwater management are on the issuing artificial recharging facilities standards (both well and pond types) and large-scale water supply systems via groundwater wells (linking more than three villages) and groundwater irrigation for agriculture to facilitate local groundwater users to recharge groundwater on their own, to provide water supply and high value-added agriculture in the no surface water source.
(Surin W., 2022, http://www.dgr.go.th/th/newsAll/124/5069,
http://www.dgr.go.th/en/newsAll/302/4475, http://www.dgr.go.th/en/newsAll/302/4473).

1.2 Groundwater Situations in Bangkok and Central Plain, Thailand

Groundwater has been commonly used for domestic and industrial use in the area of Greater Bangkok (covering the Bangkok Metropolitan Region and six nearby provinces of Nonthaburi, Samutprakarn, Pathumthani, Ayuthaya, Samutsongkran and Nakornprathom) in the last 40 years and caused serious water drawdown, saltwater intrusion, and land subsidence in the area. Many measures had been introduced to lessen the impacts of groundwater drawdown since 1983, e.g., critical zoning, pumping restrictions, and pumping fees, especially the strict policy on fee charging measures in 2003. The groundwater situation at present seemed to have gradually recovered due to these policies and measures. In 1983–2003, considerable groundwater had been pumped out from the aquifers to serve the socio-economic development in Greater Bangkok. This over-pumping had also caused serious physical and environmental problems such as land subsidence and salt intrusion. From the end of 2003, the Thai Government announced a strict groundwater conservation policy in the area that comprised groundwater pumping restrictions, groundwater conservative fees, and groundwater use fees. The groundwater situation at present seems to have gradually recovered due to the policies and measures. This present study reviewed the policies and measures imposed on this area to counter the over-pumping issue, and both supply and demand management schemes were reviewed and discussed (Sucharit, 2005).

The study gave an overview of the occurrence of land subsidence in Bangkok. The history, characteristics, identified causes, and measures for mitigation of land subsidence in the area were discussed. Efforts to alleviate the problems and studies that had been conducted to understand the problem were presented and analyzed (Mukand S., 2006).

The complex Bangkok coastal multilayered system has been tremendously exploited over the last several decades. The sustainable yield is then defined as "the maximal groundwater yield " that may be withdrawn so that the water levels in the third, fourth and fifth layer do not decrease by more than 25% of their current water levels (Dec, 2002) and/or that their chloride concentration stay beneath 250 mg/l." Hence, the sustainable yield in 2032 is 5x105 m3/d (Phatcharasak, 2006).

The groundwater age results revealed that groundwater age was highly distributed between 140 to 177,505 years with an average of 18,665 years due to the distribution of groundwater recharge and pumping in the basin. In addition, the average groundwater age with RCP 2.6, 4.5, and 8.5 was decreased to 17,217, 15,960, and 16,286 years from the base case (18,665 years), respectively, because the quantity of rainfall that contributed to the hydraulic head, hydraulic gradient, and velocity was changed. Hence, the groundwater sustainability in the Lower Chao Phraya Basin was consistent during this period because the groundwater age was decreased by rainfall. However, the old groundwater and non-renewable groundwater could be conservative due to the distribution of groundwater age being increased (Pinit, 2019).

For unconfined aquifer research in the basin, groundwater storage depends on both natural and anthropogenic processes. The results from this study provided the spatial distribution of groundwater storage change in unconfined aquifers based on GLDAS data. Further research to analyze the relative impact of each natural and anthropogenic factor needs to be carried out to identify key factors impacting groundwater storage change in each area (Phanith, 2022).

1.3 Approach of study

To manage groundwater use properly, the water balance of the aquifers must be understood, and the pumping control criteria via groundwater modeling should be set up accordingly. Both supply- and demand-side management measures have been introduced, which included the introduction of supply-sided (water resourcing, expansion of water supply service area from surface source, artificial recharge) and demand-sided (groundwater zoning, pumping restriction, water pricing, water 3R (reduce, reuse, recycle)) by various concerned authorities.

In this article, the permissible yields of the region, province, and district were proposed to set the appropriate countermeasures to control groundwater pumping and reduce the impact of groundwater drawdown. The definition of permissible yield is the volume of groundwater pumping, which will induce drawdown to the control level and will not create negative impacts from social and economic aspects.

2. Groundwater in the national water resources management, Thailand

2.1 Role of groundwater resources in the national water resources management plan

Based on the draft National Water Resources Masterplan (2023–2037), the groundwater resources role is assigned to (a) provide water supply via development and expansion, upgrade village water supply, and develop water supply to match with standards and provide affordable prices; (b) increase water security in the production sector, especially the area expansion in rainfed agriculture; and (c) to set management tools and establish water plans in each level (National Water Resources Master Plan (ONWR, 2023)).

The Groundwater Department Action Plan (2023–2027) sets targets under the department mission in the next five years to focus on the water supply shortage and improve farmer quality of life via (a) developing hydrogeological knowledge, drilling technology, and sustainable groundwater management to international standards and (b) supporting and regulating groundwater use and conserving and rehabilitating groundwater aquifers to prepare for security, critical periods, natural disasters, war, and climate change in the future.

Climate change tends to induce more extreme events and changes in seasonal rainfall patterns and durations, water shortages, and inadequate water storage risks, thereby impacting water supply and water for production sectors. The climate change impacts on groundwater may cover long-term storage reduction, more frequent and intensified floods and drought, and salt intrusion due to sea level rise. The impact will be high at the community level, which will need water storage. Other factors for increased groundwater demand are land use changes and increasingly dense populations (DGR, 2023).

The departmental action plan has four main targets: (a) to increase water storage to respond to water supply demand and production sectors (agriculture, industries, tourism, and services) including ecological systems; (b) to promote groundwater development and high-value agricultural production systems to response to economic growth; (c) to develop knowledge and information database systems to international standards, to conserve and rehabilitate groundwater aquifers; and (d) to strengthen management capacity via regulating and controlling groundwater business, to develop/improve groundwater laws to match with current status, to manage knowledge and train personnel and related parties, and to develop to be a high-performance organization.

2.2 Administrative and legal framework for groundwater management

The Ministry of Natural Resources and Environment was established in 2002 under the administrative reform for more unified and integrated management and was assigned to preserve, conserve, and rehabilitate natural resources and the environment, as well as conduct sustainable utilization management and other assignments. The Ministry set policies explicitly to preserve diversified natural resources in Thai society forever and make people live happily in a good quality environment (refer to https://www.mnre.go.th/th/about/content/3071).

The Department of Groundwater Resources is under the Ministry of Natural Resources and Environment and was also established in 2002 under the administrative reform by upgrading Groundwater Division under the Geology Department and moved to the Ministry of Natural Resources and Environment on October 3, 2002.

The Department of Groundwater Resources is responsible for (a) recommending policies, programs, and measures for management, development, conservation, and rehabilitation of groundwater resources; (b) controlling and regulating the monitoring of groundwater resources to comply with the Groundwater Act; (c) survey groundwater potential potentials, development, conservation, rehabilitation groundwater resources, including groundwater use promotion and groundwater resources management for maximum benefits; (d) monitoring, assessing, and inspecting groundwater resources and impacts due to groundwater development; (e) studying research and developing standards and new groundwater technologies for groundwater management, conservation, and rehabilitation; (f) being a groundwater information center; (g) inspecting and analyzing groundwater quality for domestic, agricultural, and industrial use; (h) implementing and supporting groundwater drilling and development to support water domestic supply, industry, agriculture in assigned areas, areas that need high-level hydrogeology, and areas affected by natural disasters; (i) preparing groundwater resources for emergency including correction and mitigation of natural disasters both drought and floods; and (j) other responsibilities assigned by the Department, the Ministry and the Cabinet.

At present, the central administration has six agencies, comprising the Bureau of Central Administration; the Bureau of Groundwater Control; the Bureau of Groundwater Development;

the Bureau of Groundwater Conservation and Restoration; the Groundwater Information Technology Center; and 1–12 regional offices. These agencies manage groundwater resources in the area to comply with the objectives and targets of departments, provinces, and related agencies; study surveys and assess groundwater potentials in the area; develop groundwater for maximum benefits for domestic, industrial, and agricultural use; promote and support the control and regulate to comply with the Groundwater Act; support the Royal-initiated Projects; help people affected by natural disaster; advise and transfer groundwater technologies for development and management to local administrations and people; support and promote people's participation and publicity; provide data and information of groundwater in the service area; and provide water quality analysis (refer to http://www.dgr.go.th/th/responsibilities).

Groundwater management in Thailand is governed by the Groundwater Act, which covers the content of the groundwater committee; license application and issuance of licenses for groundwater operations; duties of the licensee with respect to groundwater operations; competent officials; and amendment and revocation of a license, penalties, and transitional provisions.

Historically, the Groundwater Act has been periodically amended. In 1969, the land subsidence issue was given public attention and was considered a cause for floods in Bangkok and the vicinity. The Groundwater Act was enacted in 1997 but it started enforcing with a groundwater charging scheme in 1978. In 1983, "Cabinet Resolution on Mitigation of Groundwater Crisis and Land Subsidence in Bangkok Metropolis as a Critical groundwater usage region in Bangkok, Nonthaburi , Pathumthani and Samut Prakan" was announced. After major floods in 1992, the Groundwater Act, B.E. 2535 (1992) was amended from Groundwater Act, B.E. 2520 (1977). In 1994, a groundwater use fee was introduced, and in 1995, groundwater use fees were required for all provinces identified as groundwater use regions. In 1995, the critical groundwater usage regions were announced to be extended to seven provinces surrounding Bangkok. In 1997, the groundwater use charging scheme started. In 2003, Groundwater Act, B.E. 2546 (2003) was amended from Groundwater Act, B.E. 2520 (1977) to add groundwater conservation fees reflected from Cabinet Resolution on The Problem of Groundwater Use. In 2004, a groundwater conservation fee was imposed for private groundwater users in provinces around Bangkok. Starting in 2012, the groundwater fee in the Bangkok area was decreased due to the recovery of the groundwater level (Oranuj, et al., 2022).

With the recent development of groundwater artificial recharge, Onwipa (2019) revealed that rules, approaches, and conditions associated with the artificial recharge into the groundwater well have not been put in place. As a result, specific legal rules and measures to control the artificial recharge into the groundwater well should be established. Furthermore, the author recommends that a groundwater injection project should be organized throughout the country by integrating the use of all systems of surface water and groundwater for the sake of sustainable and highly efficient national water management.

3. Research Case Studies

Groundwater studies have been conducted to help alleviate groundwater over-pumping and set the appropriate countermeasures. Three case studies were selected to represent the urban case, irrigation cases, and the regional scale (see the study area in **Figure 1**).

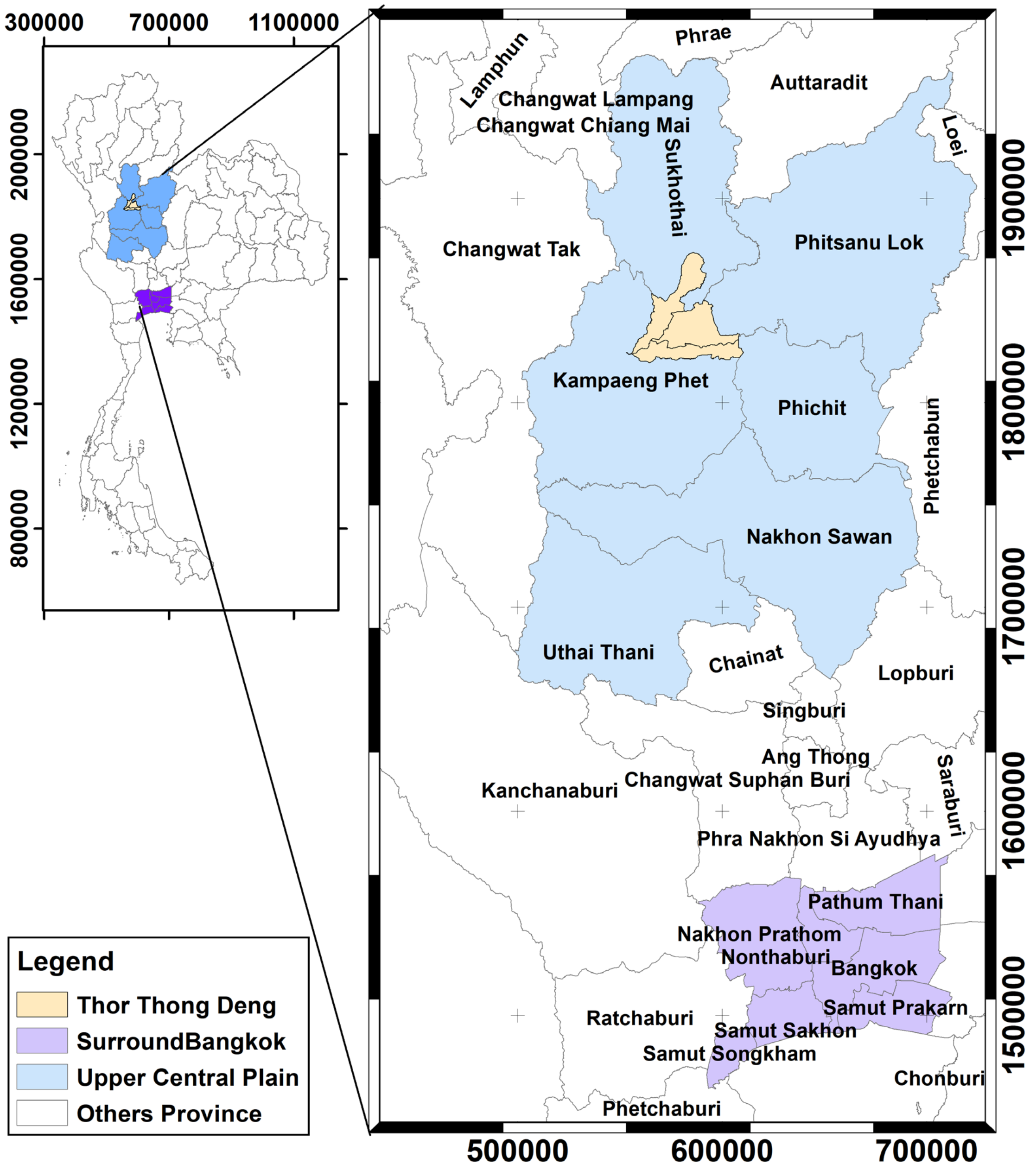

Figure 1 Locations of case study areas

3.1 Groundwater and land subsidence in Bangkok area

The land subsidence issue in the Bangkok area is a critical issue from both social and economic impacts due to fluent flooding. Considerable research on monitoring stations, groundwater modeling, and demand management has been conducted to estimate the pumping safe yield of the aquifer and to set appropriate countermeasures (CU, 1999: JICA 1995: Kasertsart, 2004: Sucharit, 2005: Juan Fornés, 2014: Sutasinee Intui, 2022: Phanith Kruy, 2022).

3.1.1 Land subsidence

Land subsidence was measured via the geological method with a sinking benchmark to monitor the surface level network done by the Royal Thai Survey Department during 1978–1981 under the groundwater crisis and land subsidence mitigation project. The annual subsidence rate was over 10 cm, and the subsidence area tended to expand to the west (Samutsakorn) and east (Ladkrabang) of Bangkok. In 1984, the department surveyed again the land subsidence after the groundwater pumping reduction countermeasures implemented. The accumulated land subsidence in the east part of Bangkok (Bang Kaen, Bung Kum, Bangkrapi, Prawet Districts) and Samutprakarn Province is more than 1 m during 1978–2008 (National Reform Assembly, 2015).

3.1.2 Permissible yield estimation

In 2000, the estimate methods of yield in Bangkok aquifers were reviewed, and a groundwater model was developed by applying the recharge study of Piyasena (1982) and soil consolidation via Quasi-3D-Hydrologic Mode and 1-D Consolidation Model by Premchitt (1978) and proposed the permissible yield in Bangkok aquifers to be 1.25 M m3/d with the acceptable land subsidence of 1.0 cm/year and groundwater table at 30 m. The subsidence rate in 2027 is estimated to gradually decrease to 1.07 and 0.86 cm/year if the groundwater pumping rates are controlled and set at 1.86 and 0.8 M m3/d, respectively (CU, 2008). The proposed permissible yield was then used to further design the groundwater pumping and land subsidence reduction measures (National Reform Assembly, 2015).

3.1.3 Countermeasures

Countermeasures for groundwater pumpage reduction in the study area and the historical development of measures implemented for both groundwater and surface water can be summarized in **Table 1**. Three main measures were set: zoning, pricing, and monitoring until reaching permissible yield (DGR 2006, 2007). Initially, in 1983, DGR started to announce the critical zone in the inner Bangkok area (classified into three types and considered from groundwater level drawdown speed and land subsidence rate in **Figure 2**) to control or restrict the pumpage permit, i.e., critical zone 1: no extension if tap water is available; zone 2: extension only year by year; and zone 3: careful consideration for permit). In 1985, DGR started to collect a groundwater usage fee of 1.0 Bath/m3. In 1995, DGR extended the critical zone to outer Bangkok and increased the usage fee to 3.5 Bath/m3 and 8.5 Bath/m3 in 2001. The drawdown conditions continued, and in 2003, DGR extended the critical zone to cover all of the Greater Bangkok area and added a conservation fee of 8.5 Bath/m3 to control groundwater use. In 2007, these measures were evaluated, and with the better situation in groundwater, the conservation fee was reduced to reduce to 4.5 Bath/m3 apart from a usage fee of 8.5 Bath/m3.

The water supply authorities also played an important role to cope with groundwater control by transferring the raw water source from groundwater to surface water and investing in the expansion of the service area after 1983. However, due to budget constraints, the expansion of water supply plants and water transfer were not aligned. Then, PWA decided to adopt the BOT scheme with private firms to increase water supply and distribution capacity in the Patumthani and Samutsakorn Provinces in 1998 and 2004, while MWA (Metropolitan Water Works) invested in the new pipeline network to deliver water from surface source to Samutprakarn Province also in 2004.

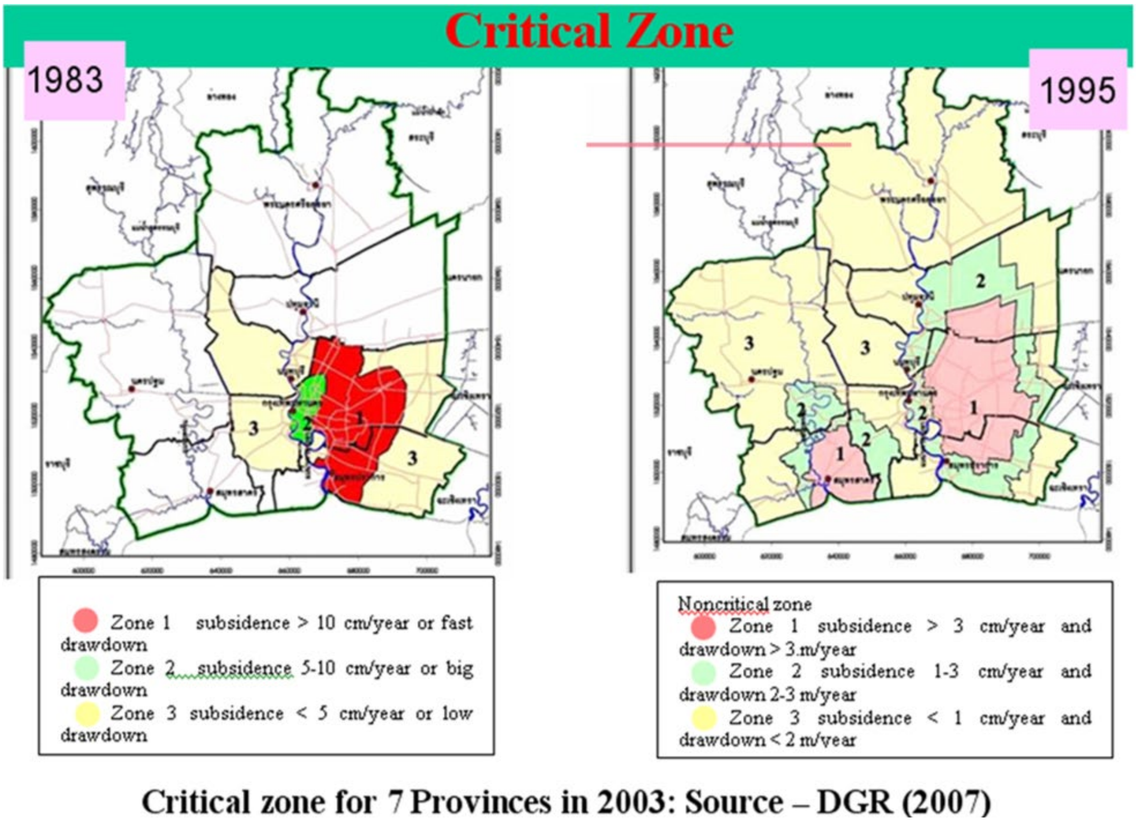

Figure 2 Historical groundwater critical zoning in Bangkok area

3.1.4 Results

With countermeasures implemented, the impacts can be evaluated via water level, pumpage, subsidence rate, and groundwater fees, as shown in **Table 2**. During 1978–1998, groundwater use fluctuated up and down based on socio-economic development in the Bangkok and its vicinity, e.g., growth in 1978–1984 (water level lower by 12 m), 1991–1997 (water level lower by 13 m), recession in 1985–1990 (water level up by 13 m), and 1998–2000 (water level up by 9 m). After the investment and charge fee in 1998 and 2004, with economic recovery, the groundwater use dropped drastically back to 1977 conditions in both water level in most of the area and total pumpage (Sucharit, 2009).

The land subsidence rate increased sharply together with the drawdown rate during 1978–1984 (9.72 cm/year) though the rate dropped in during 1985–2000 (1.5 cm/year), and after 2000, the rate maintained at 1.3–1.9 cm/year (Pawan, 2015) which is commonly accepted as a design rate of subsidence in Bangkok area. The groundwater fee was adjusted from 17.00 Bath/m3 in 1997 to 13.00 Bath/m3 after 2008.

Table 1 Historical development of related countermeasures

Year	Groundwater	Water Supply fee
1981		fee = 3.00 Bath/m3
1982		fee = 3.03 Bath/m3
1983	Groundwater Zoning – 1 (inner – 3 levels)	Promoted to transfer to use surface water
1985	usage fee = 1.0 Bath/m3	fee = 6.46 Bath/m3
1988		fee = 6.89 Bath/m3
1993		fee = 8.17 Bath/m3
1995	Groundwater Zoning – 2 (outer – 3 levels) usage fee = 3.5 Bath/m3	service area expansion scheme
1998		fee = 11.75 Bath/m3 new supply scheme – 1 (in Patumthani) with promotional scheme
2001	usage fee = 8.5 Bath/m3	
2003	Groundwater Zoning – 3 (7 Provinces)	Industrial Water Technology Institute setup (3R)
2004	usage + Cons. fee = 8.5+8.5 . Bath/m3	new supply scheme-2 (in Samutprakarn)
2007	measures assessment	fee = 15.28 Bath/m3
2008	usage + cons. fee = 8.5+4.5 Bath/m3	

3.1.5 Conclusions

From the ground survey of land subsidence, the subsidence rate was high, at more than 10 cm/year during 1978–1981 as the subsidence expanded to the south-west and east of Bangkok and groundwater level drawdown was more than 50 m from the ground surface. The total accumulated subsidence in the Bangkok and Samutprakarn Provinces was more than 1 m in 30 years (1978–2008). The aquifer permissible yield study was conducted with groundwater and land subsidence models. If the controls of land subsidence are under 1.0 cm/year and groundwater drawdown is at 30 m from ground level, the pumping should be decreased to 1.25 M m3/d.

On the basis of the permissible yield setup, the countermeasures of pumping control zoning, groundwater pricing, and severe monitoring were implemented to reduce groundwater pumping and land subsidence together with surface water supply service area expansion. Groundwater level and land subsidence recovered substantially in most of the Bangkok and the vicinity area with pumping under 0.8 M m3/d after the countermeasures were implemented.

The groundwater management scheme in Bangkok and the vicinity area could not be successful without good infrastructure in well monitoring networks, socio-economic data, and systematic studies done by various agencies during the past 40 years. The experiences in the area are hoped to be good experiences for other regions to manage invisible but valuable groundwater resources and also to counter land subsidence where a soft clay layer exists.

Table 2 Impacts of Groundwater measures against water level and land subsidence rate at selected stations (Bangkok inner area)

Phase	period	GROUNDWATER level (m)	Subsidence Rate (cm/year)	Pumpage (M m3/d)	zoning and fee
1	before 1977	approx 30	n/a	0.8	
2	1978-1984	40-52	9.72	1.0-1.4	Groundwater zoning-1
3	1985-1990	52-40	1.50	1.3-1.5	usage fee = 1 Bath/m3
4	1991-1997	40-53	1.50	1.4-2.0	Groundwater zoning-2 usage fee = 3.5 Bath/m3 (Economic crisis in 1997)
5	1998-2000	53-42	1.50	2.1-2.2	
6	2001-2004	42-38	1.30	1.8-2.5	groundwater zoning-3 Usage fee = 8.5 Bath/m3
7	2005-2007	38-30	1.00	1.2-1.7	Total fee = 17.0 Bath/m3

3.2 Groundwater in the Thor Thong Daeng Irrigation Project

3.2.1 Objectives and assumptions used

The study is to assess the permissible groundwater abstraction of the Thor Tong Daeng (TTD) irrigation area (divided into three irrigation zones) with an area of 61,400 ha in the Ping Basin of the Upper Central Plain of Thailand, under the influences of natural and permissible conditions. In terms of permissible conditions, a definition of permissible GWA is proposed to assess the amount of GWA that ensures the groundwater depth is not over 20 m below the ground surface. First, to understand the current situation of the groundwater system, carrying out a field survey is necessary to investigate the current status of groundwater consumption and groundwater issues in the irrigation area. Then, a series of numerical simulations was carried out to take into account hydrogeological data, artificial and natural discharges of shallow and deep wells, and boundary effects in the TTD irrigation area. The groundwater modeling is calibrated under the flow conditions of the transient state from 2010 to 2020 for 16 observation wells distributed in the study area.

3.2.2 Groundwater use and flows

The groundwater system in the TTD area is modeled into three layers, representing three aquifers in the study area: Flood Plain aquifer (Qfd), Young Terrace aquifer (Qyt), and Older Terrace aquifer (Qot). According to the survey on groundwater consumption and permission of production well data from the Bureau of Groundwater Resources Region 7 (BGR 7), groundwater consumption for zones 1, 2, and 3 of the TTD irrigation area in 2020 were estimated at 24.0, 25.3, and 41.8 MCM, respectively, or 91.1 MCM in total.

In general, groundwater flows from the northwest (Ping River) to the southeast (Phichit and Phitsalunok Provinces). The groundwater levels (GWLs) fluctuated from 50 to 70 m-MSL (5–15 m from the ground surface) except only at a hotspot (shown in **Figure 3**). The hotspot of the groundwater system distributed a high density of households as well as farms using groundwater. A lightly decreasing trend in GWLs of TTD is shown in the periods of 2010 and 2020 due to an increase in groundwater abstraction in that period.

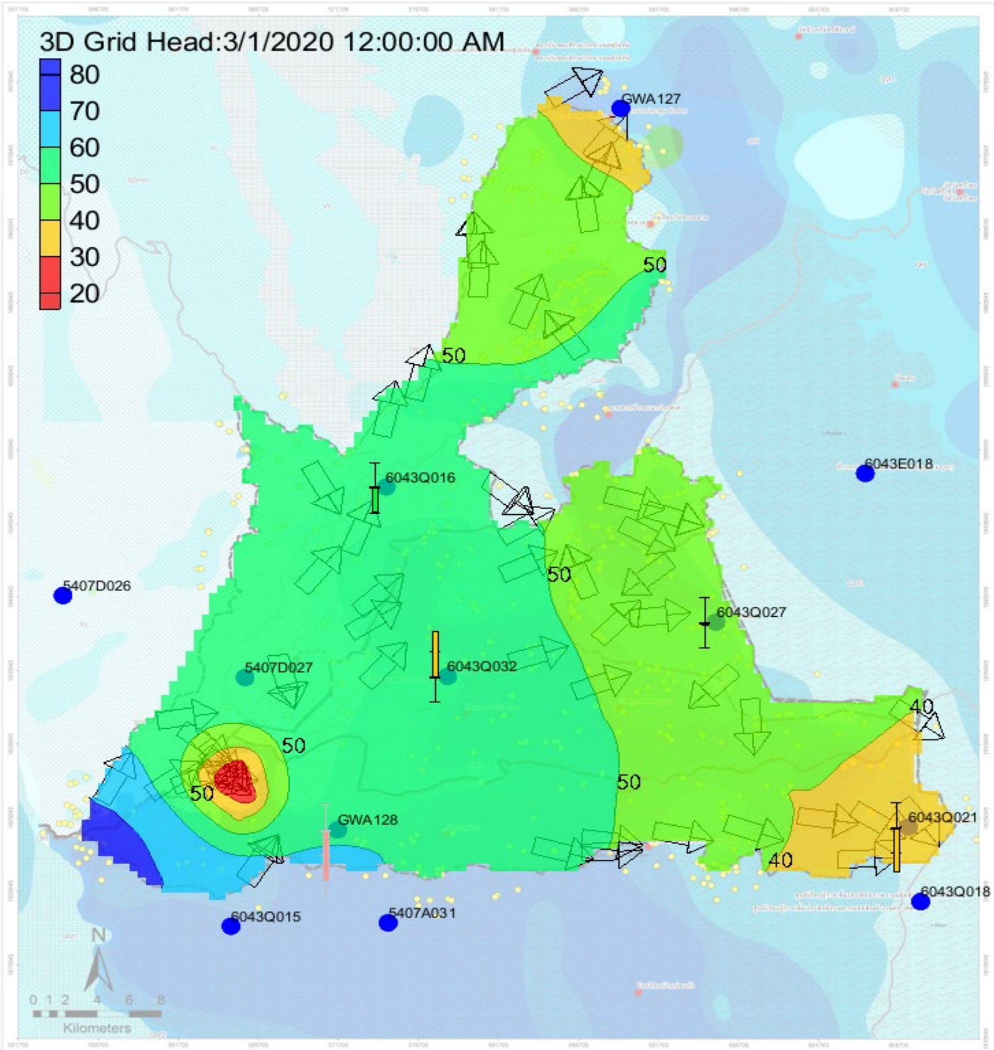

Figure 3 Groundwater level distribution of the shallowest aquifer in March 2020

3.2.3 Groundwater balance

On the basis of the groundwater model results, a water balance of three aquifers shows that rainfall is the main recharge component of the shallow aquifer and then contributes to groundwater abstraction in the Qyt aquifer. The shallowest aquifer (Qfd) also absorbed most of the river leakage of the study area. Total outflow including groundwater abstraction and filtration to the below aquifer (Qfd aquifer) is approximate total inflow of aquifer (lateral flow, river leakage, and land recharge), about 71.9 MCM. GWLs fluctuation shows a strong correlation with the distribution of GWA (shown in **Figure 4**). In very drought years such as 2016 and 2020 with a high rate of groundwater abstraction, GWLs dropped by about 2–3 m in general. By contrast, GWL increased by around 1 to 2 meters in wet years with a much lower rate of groundwater abstraction.

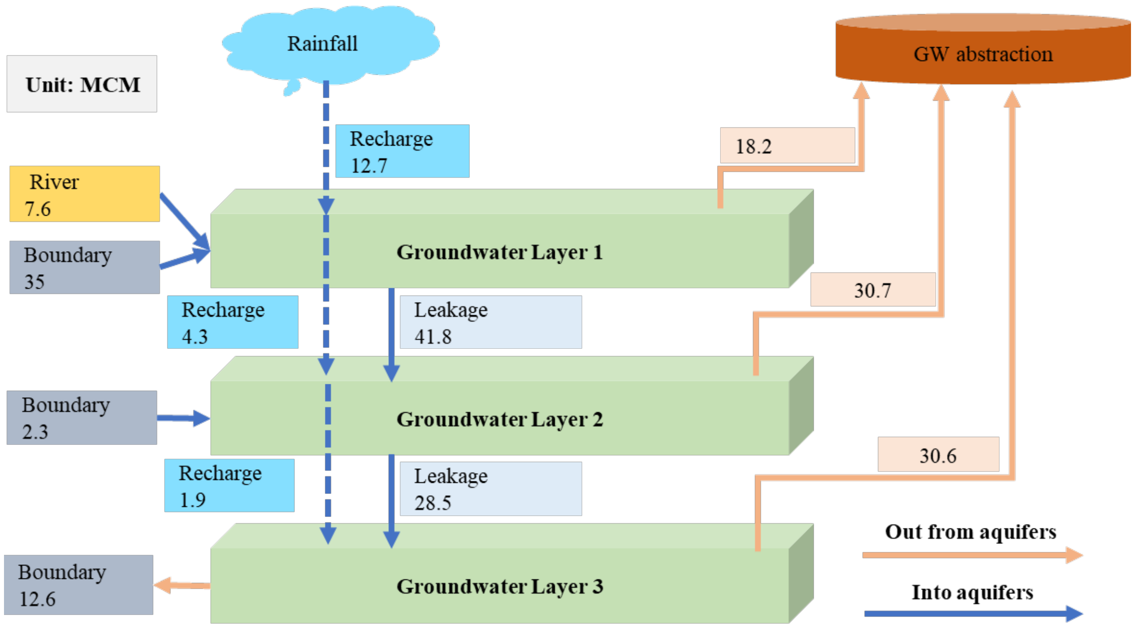

Figure 4 Annual Groundwater balance in 2020 of the aquifer system in TTD

3.2.4 Groundwater use and permissible yields

From the groundwater model, the actual groundwater pumping in each irrigation zone (1, 2, 3) and water year (dry, normal, and wet based on the annual rainfall amount) can be estimated from the past simulation results and are summarized in **Figures 5** and **6**. Based on the permissible groundwater level (for a 20 m drawdown) control, the available groundwater abstraction can sustain the rate up to 128% (~116 MCM), 92% (~83 MCM), and 50% (44 MCM) of the current abstraction rates in 2020 in wet, normal, and dry year scenarios, respectively. Research results can be used to make better decisions about water resource management in the TTD irrigation area conjunctively with surface irrigation water to control better groundwater management in the irrigation project. The methods used here can be applied to other irrigation areas to explore future suitable groundwater abstraction.

Current GW abstraction in Thorthongdaeng Irrigation Project

Water year	GW abstraction (MCM) in Thorthongdaeng Irrigation Project			
	zone 1	zone 2	zone 3	total
dry	26.5	30.9	30.3	87.7
normal	20.2	22.9	23.1	66.2
wet	13.4	14.3	15.2	43.0
average	20.3	23.0	23.2	66.5

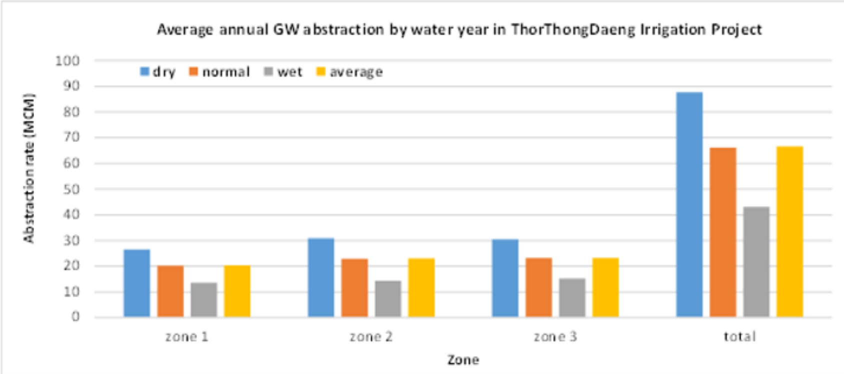

Figure 5 Current groundwater pumping in TTD Irrigation Project by zone and water year

Permissible available GWA in TTD

Time	Available GW abstraction (MCM) by zone in Thorthongdaeng Irrigation Project			
	zone 1	zone 2	zone 3	total
dry	34	51	49	134
normal	43	64	66	173
wet	49	77	80	206
average	42	64	65	171

Time	Available GW abstraction (MCM) by layer in Thorthongdaeng Irrigation Project			
	Layer 1	Layer 2	Layer 3	total
dry	35	59	39	134
normal	46	76	51	173
wet	54	90	60	206
average	45	75	50	171

Figure 6 Permissible groundwater pumping in TTD Irrigation Project by zone and water year

3.3 Central Plain Conjunctive Use and permissible pumping estimate in the North Central part of Thailand and ANN applications

3.3.1 Approach

The work approach includes two parts: (a) to improve the groundwater model in weekly time steps via coupling surface water to estimate the permissible groundwater pumping and (b) to develop an ANN tool to estimate existing groundwater pumping from groundwater level, rainfall, and dam storage in each province and to estimate the available pumping rate. First, the weekly river stage was estimated from runoff data of the surface water research team. The weekly groundwater pumping was estimated via satellite and a survey during 2008–2021. The integrated river stage, rainfall, and available groundwater use data were input into the regional groundwater model to verify the weekly groundwater drawdown. The permissible groundwater conditions were estimated under extreme climate scenarios: the drought year 2016 (rain<1200 mm), the normal year 2009 (1200<rain<1400 mm), and the flood year 2011 (rain>1400 mm) with the control groundwater level set to be the maximum well depth of the local users in the past (30 m below the surface). Second, the study analyzed the weekly relationship between rainfall, groundwater level, groundwater pumping, and dam storage during this stage. Then, the data set of precipitation, groundwater level of five provinces, and upstream reservoir storage from three climate scenarios were trained through a modular neural network (MNN). Three different MNN structures were applied to evaluate the suitable response data time and input data. The performance of the MNN model is assessed by the coefficient of determination (R2), root mean square error (RMSE), and standard deviation (SD) (**Figure 7**). Hence, the monthly groundwater (existing) pumping of five provinces could be estimated from given weather situations (table of inputs: groundwater level, rainfall, dam storage in **Figure 9**).

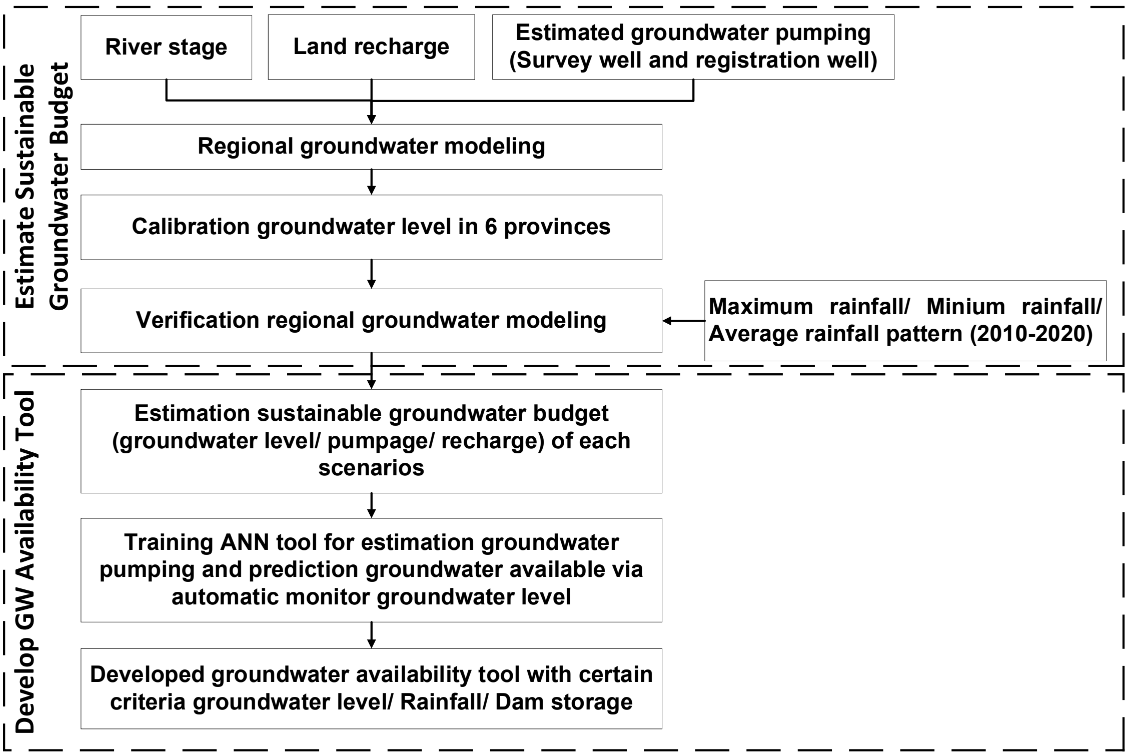

Figure 7 Framework of the study
Available groundwater pumping estimation

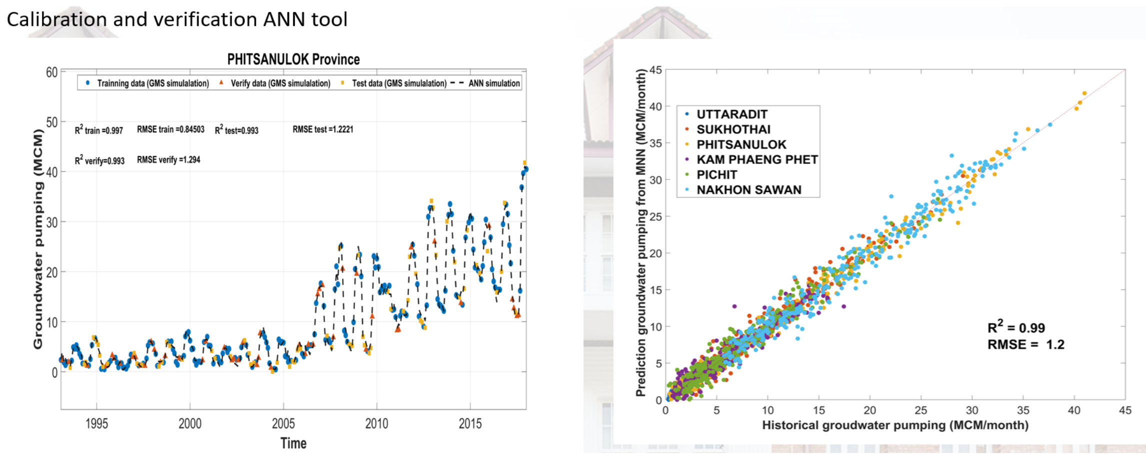

Figure 8 Training and verification test of ANN tool to estimate the groundwater pumping from groundwater level in the study area

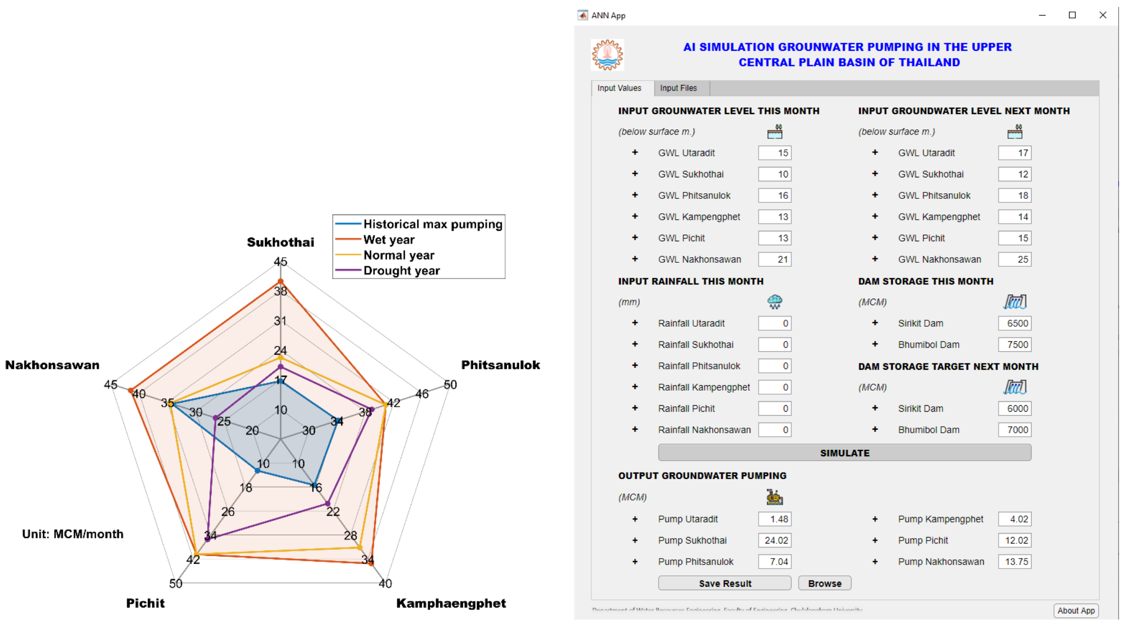

Figure 9 Permissible groundwater pumpage in five provinces (unit: MCM/year) and input table to estimate actual groundwater pumping

3.3.2 Available groundwater pumping estimation

Available groundwater pumping means permissible groundwater pumping minus actual groundwater pumping. The permissible groundwater pumping is estimated from the maximum drawdown (up to 30 m) setup while the actual groundwater pumping is estimated from the trained MNN model described above.

The historical maximum groundwater pumping caused the groundwater drawdown 20 m below the surface in Sukhothai, Phitsanulok, and Nakhonswan. The average thickness of aquifer 1 is 60 m. Hence, the groundwater water level criteria expanded to 30 m below the surface at the cone of depression in the region to ensure sustainable groundwater pumping. In the estimation of the groundwater potential process, the groundwater pumping in each province was increased by 10% each year until the groundwater drawdown meets the criteria. The permissible groundwater pumpage was estimated based on three climate scenarios: max historical rainfall, average historical rainfall, and min historical rainfall. The permissible groundwater pumpage in the dry season of Sukhothai, Phitsanulok, Kampeang, Pichit, and Nakhonsawan varies from 20–42, 38–40, 20–35, 35–40, and 26-41 MCM/month. Hence, the upper Central Plain can pump permissibly from 145–203 MCM/month (**Table 3**).

The available groundwater of all provinces, derived from permissible and actual pumping data from the past shown in **Table 3**, fluctuates with the water situation in each year. The table indicates that Phisanulok and Pitchit Provinces retain high permissible groundwater because the river recharge contributes a high proportion in the dry season. With limited river recharge, the permissible groundwater pumpage of other provinces relies on the rainfall recharge in the wet season. Nakhonsawan Province pumped considerable amounts in the dry year, impacting the available groundwater in other provinces. Hence, the available groundwater shows a large gap between dry and wet years. The research results induced the artificial recharge scheme in the flood-prone area, the Bang Rakam model, to help improve groundwater levels in the hot spot area, i.e., Phitsanulok Irrigation Project.

Table 3 Actual and available groundwater pumping in each province in the North Central Plain

ACTUAL GROUNDWATER PUMPING								
UNIT (MCM/SEASON)		UTTARADIT	SUKHOTHAI	PHITSANULOK	KAM PHAENG PHET	PHICHIT	NAKHON SAWAN	REGIONAL
DRY YEAR	DRY SEASON	13.7	119.5	148.1	62.4	174.6	93.1	611.4
	WET SEASON	13.4	113.6	162.9	77.6	142.5	98.8	608.8
NORMAL YEAR	DRY SEASON	5.2	85.7	114.1	27.7	82.2	69.9	384.8
	WET SEASON	6.4	112.1	150.6	34.6	114.2	90.9	508.8
WET YEAR	DRY SEASON	6.5	48.6	80.5	29.6	28.7	57.1	251
	WET SEASON	13	84.1	160	59.2	57.7	113.6	487.6
AVAILABLE GROUNDWATER PUMPING								
UNIT (MCM/SEASON)		UTTARADIT	SUKHOTHAI	PHITSANULOK	KAM PHAENG PHET	PHICHIT	NAKHON SAWAN	REGIONAL
DRY YEAR	DRY SEASON	8	121	126	62	144	74	535
	WET SEASON	26	253	242	205	252	162	1140
NORMAL YEAR	DRY SEASON	30	197	251	116	301	146	1041
	WET SEASON	30	157	243	166	253	137	986
WET YEAR	DRY SEASON	24	270	263	141	283	139	1120
	WET SEASON	23	246	231	174	237	156	1067

3.3.3 ANN Applications

To improve future groundwater management, the developed MNN tools (with artificial neural network (ANN) techniques) can be applied to estimate future available groundwater as well if the future weather data (rainfall, groundwater level, dam storage) are given and every option of water allocation in both surface and groundwater resources jointly can be tested before choosing suitable conjunctive allocation schemes in the study area considered from the regional aspect not from each local condition separately.

4. Lesson learned

To make groundwater visible, groundwater modeling is an important tool to elaborate flows, and budget, balance, and set the permissible yield under conditions set up. However good groundwater simulation needs good parameters and data to be calibrated and verified. Field monitoring and field investigations achieve good data for setting parameter values are needed.

Countermeasures and management policies based on the research results will be convincing for joint agreement and are basic requirements for good policies and agreeable implementations.

For invisible groundwater, modeling is evitable with fieldwork checking. Research works with parameters verification are needed to analyse flow budget and permissible yields. Then research results become a basic information to issue good policy and engage participatory implementation.

Case studies in the article represented cases from urban groundwater, irrigation groundwater, and basin-wide groundwater management. The permissible yield of the study area is a basis for groundwater zoning, permits, and control data. Good research, good results, and good guide are needed to convince stakeholders.

5. Conclusions

Groundwater management issues are complex and interactive, and tools are needed to solve the problems among stakeholders. The research samples raised in the article show the application of groundwater modeling and permissible yield setups to develop measures, policies, and solutions to counter the issues.

Groundwater modeling tools are essential to understand groundwater flows and budget, balance, and provide valuable data to set permissible yield for groundwater control in the area. Proper data are needed for calibration, verification, and parameter substitutions.

Groundwater management, especially in critical timing and critical areas, needs to consider different environments (e.g., urban, rural, agriculture, industry, services) and integrated from the supply side (e.g., finding new groundwater sources, recharge) demand side (reduce, reuse, recycle), and management side (e.g., zoning, regulation of permits, pricing, monitoring).

6. Acknowledgements

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Water Resources, Groundwater and Institutional Challenges in Timor-Leste

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Introduction

The government of Timor Leste continues putting effort by collaborating with National NGO, local NGO, and international development partners to develop priorities in sectors such education, agriculture, health including water and sanitation in responding and securing the people of Timor Leste right for better life although facing many challenges. The government of Timor Leste has a commitment and ratifying convention for Timorese disability of strengthening and more securing the principle of inclusivity.

In the agenda 2030 through sustainable development goal, SDG the whole world insisted on eliminating hunger and malnutrition. The principle of SDG has been incorporated within Timor Leste's national strategic development plan 2011-2030 while the water sector is still struggling even though considerable investment has been made by the government of Timor Leste and development partners. According to the water and sanitation investment plan done by ADB and the government of Timor Leste in 2019 that to boost the progress of water and sanitation sector establishment of the water and sanitation sector to a public institute as regulatory body to control the sectors and public enterprise as service provider for the public customer. Those plans were implemented by the previous government in 2021 but not continued by the current government might slow down the progress of WASH sector. One of the examples is water resources are not regulated well and no adequate plan on the water resource on a country level due to inadequate institutional bodies responsible for this vital sector. Groundwater drilling activities are not regulated due to no clear law and regulation.

Status and Challenges

The 2015 census indicated that about 85% and 68% of urban and rural populations have access to water sources respectively. However, only 34% of the urban population has access to public water supply systems at the household level. Despite the sector having been in the Government's annual priority for the last four successive years, the level of investment is noticeably low to meet the sector targets. The annual combined average budget to the sector for the period of 2015 – 2017 was 24 million.

Furthermore, the lack of consistency in the multi-year public investment has been related to the absence of the investment plan and limited coordination between stakeholders in financing the sector.

The institutional capacity is one of the challenges that need to be addressed immediately in order to improve sector service performance. Some of the challenges include limited administrative and financial autonomy, lack of human resources, limited accountability and incentives for sustaining services, and lack of planning and coordination, etc. In addition, the current institutional setting is also not appropriate for the sector to deliver services because there is no separation between autonomy regulatory authorities (ADB, WASH investment plan 2019).

Timor-Leste's water security is heavily dependent on groundwater resources that are sensitive to climate change. With Timor-Leste's groundwater supplies likely to become increasingly vulnerable to shortages and seawater intrusion with changes in rainfall patterns and sea-level rise, it is critical that safe and reliable water is maintained for communities and industries (Geosciences Australia, 2012).

Despite the lack of investment, inadequate arrangement of institutions to regulate and manage the sector, another huge challenge is lack of knowledge in managing the sector, especially serious challenges of water resources on this tiny island which is indeed not favorable for water resources. Few research done by scholars not considered due to lack of knowledge and improper setting institutional to manage the sector sustainably.

Conclusion and way forward

The development of WASH sector which is not consistent with the National Strategic Development Plan (NSDP) and the Sustainable Development Goal (SDG) including disintegrated management and plan will face great difficulties to obtain the objective described within the NSDP and SDG 6 in 2030.

To boost Timor Leste WASH sector, it is necessary to have integrated management and planning among relevant ministry, national NGO and development partner. Prioritize investment and reform the sector in the form public institute as regulatory body and public enterprise as public water supplier are highly recommended.

Key Study

Assessment of groundwater yield of Dili Aquifer, Timor Leste

Abstract

The capital city of Timor Leste depends heavily on groundwater resources. The Dili alluvial plain is located in the northern part of the Comoro watershed known as Dili groundwater basin which Dili city laying on. The groundwater flow modeling was carried out to determine in detail the groundwater flow in the deep unconfined aquifer of the Dili groundwater basin. The Dili basin was modeled with a grid of 67 rows x 120 columns with two layers viz., unconfined, and semi-confined aquifers extending up to 120 m depth. The Comoro River traverses in the Western part, while Kuluhun and Becora River are nearby in the Eastern part of the basin. Natural recharge due to rainfall formed the main input to the aquifer system and the output was made of abstraction from pumping wells and drain in the costal line. Upstream lateral inflows and downstream outflows were simulated with recharge and drain package. The Comoro, Kuluhun and Becora rivers were simulated using recharge package due to unusual river condition. A steady state groundwater flow simulation was carried out using MODFLOW software. The aims to quantify its sustainable yield from Dili aquifer located within the Comoro watershed of Timor Letse. It uses MODFLOW model to estimate aquifer safe yield and sustainable yield; Results revealed that the steady-state model was calibrated successfully using a trial-and-error approach and found to be sensitive to changes in hydraulic conductivity. The statistical parameter of calibrated model gave ME of -0.743 m, RMSE of 0.997 m and R^2 of 0.994 m. A six set of scenarios was developed to estimate the groundwater sustainable yield. By hypothetical scenario, it was found that (i.e., increasing or decreasing groundwater extraction rate and/or increasing or decreasing groundwater recharge), to maintain groundwater level at 7.8 mbgl, groundwater sustainable yield is defined as a ranges of 0.23-0.28 m3/s. This study has enhanced the understanding of Dili aquifer by quantifying facts such as sustainable yield. These findings have led to a conclusion that the Dili aquifer will likely to be under stress from over-extraction of groundwater in future. Therefore, appropriate groundwater management strategies such as conjunctive use of surface water and groundwater; and utilizing excessive runoff in wet season to increase groundwater storage by artificial recharge techniques; among others, should be seriously considered to avoid negative impacts of groundwater development and use in future.

***Keywords**:* Groundwater, MODFLOW, Sustainable yield, Timor Leste.

1. Introduction

Groundwater is a vital natural resource for domestic use in majority of the coastal areas of Timor Leste. Dili, the capital city of the country, depends heavily on groundwater resources and receives more than 60% of the total annual water supply from groundwater (Aurecon Australia, 2012). Groundwater in the area is abstracted from Dili aquifer system (or Dili Groundwater Basin, DGB) located in the Alluvial plain in the downstream of the Comoro watershed (**Fig. 1**). With a high rate of population growth and urbanization and subsequent increase in water demands over the last decade, Dili is facing water scarcity during dry season. The increased demand for water, combined with pressures from global environmental issues such as climate change and sea level rise, is creating niche for sustainable utilization of groundwater resources as a reliable source of water supply. It has shifted direction of groundwater research from understanding basic hydrogeology to sustainable development and management of aquifers. The term "safe yield (Sy)", proposed originally by Lee in 1915, has been extensively used in this regard to describe the ultimate water withdrawal rate from an aquifer without any risk in future. This concept has since been further developed from different perspectives and has been transformed to the concept of "sustainable groundwater yield (SGy)". However, Sy and SGy of the DGB is yet to estimate.

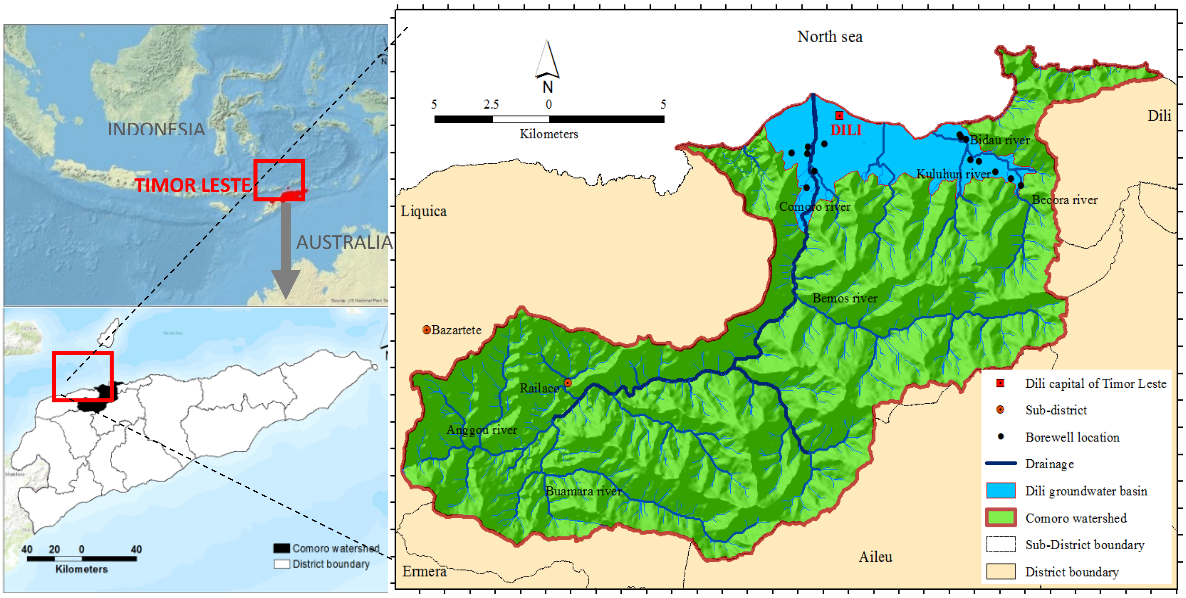


Fig. 1 Comoro watershed and Dili groundwater basin in Timor Leste (Pinto and Shrestha, 2016)

The concept of sustainability in study of groundwater yield was first introduced in the International Workshop on Groundwater Sustainable Development in Britain held in April 2000. The concept since then is still evolving and there is no universal definition and model to estimate SGy. In more generic form, the SGy can be defined as an available yield under a rational development strategy that can maintain the normal exploitation for a long-term without adverse effects while bringing the maximum integrated benefits to the economy, society and environment (ASCE, 1961; Fetter, 1972, 2001; Freeze, 1971; Kalf and Woolley, 2005; Lee, 1915; Sophocleous, 2000; Sophocleous et al., 1999; Sophocleous and Perkins, 2000; Thomas, 1951; Yang et al., 2008, 2011, 2012; Zhang, 2003). Studies focused on SGy have considered economic feasibility, protection of groundwater quality, water laws and rights, and potential environmental problems as its determinants. However, the determinants for a particular aquifer may depend on various factors including availability of data and information.

Current methodologies to determine SGy consist of water equilibrium method, numerical simulation, baseflow division, and isotopic tracer technique, among others (e.g., Alley and Leak, 2004; De Wrachien and Fasso, 2007; Henriksen et al., 2008; Hurditch, 2005; Jha et al., 2009; Maimore, 2004; Ponce, 2007; Sophocleous, 2000). Hurditch (2005) defined the sustainability in water management from a business perspective, whereas Ponce (2007) suggested to consider baseflow conservation as an indicator to measure groundwater sustainability and Jha et al. (2009) suggested cost-effective recharge approaches for sustainable groundwater management. Some studies have also recommended calculation of SGy based on percentage of total recharge, for example, a 10% of the total recharge as a rational and conservative yield, 40% as an average value, and more than 70% as unsustainable (Alley et al., 1999; Alley and Leake, 2004; Maimore, 2004; Sophocleous, 2000).

Various methods have their own comparative advantages and disadvantages. Among them, the numerical simulation has been proposed as the most reasonable way to estimate groundwater balance in an aquifer (Barthel et al., 2008; Bredehoeft, 1997, 2002; Henriksen et al. 2008; Kalf and Woolley, 2005; Sophocleous et al., 1999; Sophocleous and Perkins, 2000). The simulation models when coupled with optimization models can help evaluate SGy for a large stream-aquifer systems involving conflicting goals and complex hydrologic, environmental, population and economic constraints (Chen and Zeng, 2005; Chi et al., 2010). Geographical Information System (GIS) and Remote Sensing (RS) techniques can be used together with the models to pre- and post-process the data and explore the groundwater availability in an aquifer. This study therefore aims to adopt groundwater modeling approach to assess yield of DGB with following specific objectives: i) developing a well calibrated groundwater flow model of the area; ii) estimating safe yield (Sy); and iii) estimating sustainable yield (SGy).

2. Study Area

The Comoro watershed located in the Northern part of Timor Leste **(Fig. 1)** covers 250 km^2 area of four districts in the region (Aileu, Dili, Ermera and Liquica). Climate in general is tropical. Weather is influenced by the Northern Monomodal Rainfall Pattern and has four to six months of wet season through December to April (Wallace et al., 2012). Average annual precipitation in the Comoro watershed varies from 940 to 1,761 mm. Dili aquifer (or DGB) and its recharge zones are located in the Alluvial plain at the downstream of the Comoro watershed. The aquifer starts from the coastal area with elevation 0-60 meters above the mean sea level (masl) and covers about 26 km^2 of the Comoro watershed area (Pinto and Shrestha, 2016). The deposits in the DGB are of Quaternary sediments. The texture of these sediments varies but comprises typically of unconsolidated and moderately poorly sorted silts to cobbles (Wallace et al., 2012). It forms a single unconfined aquifer interbedded with thin clay layers in between and underlain by a saprolite layer and hard rock (**Fig. 2**). There are three rivers (i.e., Comoro, Kuluhun and Bidau) as source of recharge to the aquifer; however, Comoro River is the single largest one in terms of recharge contribution.

The Dili aquifer is highly heterogeneous and likely to have zones of preferential flow. Rather than containing large areas of homogeneous sand, the aquifers have many clay lenses which will require more detailed investigation to determine architecture for water prospectively (Wallace et. al., 2012). Overall, the maximum percentages of aquifer storage situated in the western and eastern part of the basin; and they are exploited largely by the National Directorate of Water and Sanitation Services (NDWSS) through designated well-fields and also private wells (e.g., such as open dug well) (Pinto and Shrestha, 2016). From the perspective of groundwater development, the DGB is hydrogeologically divided into three major well fields, namely, Comoro, Kuluhun and Bidau (JICA, 2001).

Groundwater abstraction from the Dili aquifer is increasing as indicated by increase in number of abstraction wells from only 14 in the early 2000 to more than 20 in a few years. The estimated volume of groundwater abstraction in the aquifer in 2010 was 27,821 m^3/d (Aureon Australia, 2012), which is equivalent to 10.15 million-cubic-meters (MCM)/year. The increasing number of abstraction wells indicate that even with maximized abstraction rate, groundwater alone may not be able to fulfil water demands of the ever-growing population of the entire city. Due to increased groundwater abstraction rates, deeper parts of the aquifer have started to show signatures of salt water intrusion (Pinto and Shrestha, 2016). Therefore, it is required to estimate safe and sustainable yields of the Dili aquifer to design the control measures for restoring and managing groundwater environment for sustainable utilization of the groundwater resources.

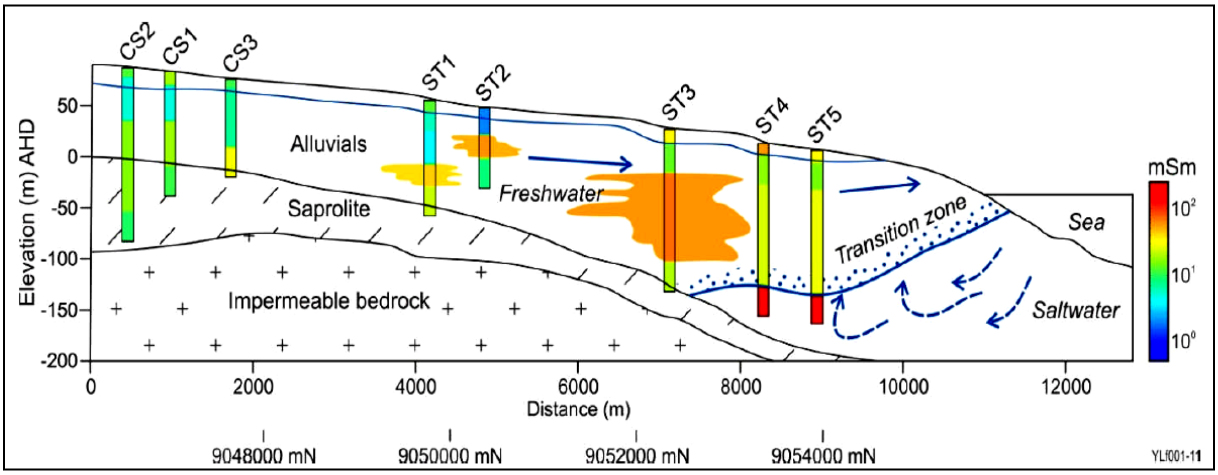


Fig. 2 South-North cross section of the Dili aquifer along Comoro River (Furness, 2012).

3. Methodology And Data

The methodology flowchart adopted in this study is depicted in **Fig. 3** and detailed in the following sub-sections.

3.1 Setting up of groundwater flow model

A three-dimensional (3D) groundwater flow model of the Dili aquifer was developed to simulate groundwater flow, calculate flow rates and flow directions, and estimate groundwater storage. MODFLOW (2005) code, the widely used model for groundwater flow simulation, in the ModelMuse Graphical User Interface (GUI) was selected to develop 3D groundwater flow model of the Dili aquifer. It can simulate two- and three-dimensional groundwater flow through a porous media. It can be designed to have a modular structure that facilitates ease of understanding and ease of enhancing. Technical details of the MODFLOW (2005) are available at http://pubs.usgs.gov/tm/tm6A29/tm6A29. The MODFLOW-2005 uses the general form of 3D groundwater flow equation as expressed in Equation-1 (McDonald and Harbaugh, 1988), which can be solved using a block-centered finite-difference approximation for a given set of boundary and initial conditions. The flow regimes can be represented by blocks made of grids (plan view) and layers (side view). The MODFLOW has been successfully used in many studies around the world to aquifers of varying scales (e.g., Ezzy et al., 2006; Gharbia, 2013; Hudon-Gagnon et al., 2015; Gao, 2011; Klinchuch, 2012; Kumar, 2016; Sathish and Elango, 2015; Takounjou et al., 2009; Tate et al., 2014; Yang et al., 2011; Zhou and Li, 2011).

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t} \qquad \text{… … … (Equation 1)}$$

where: Kx, Ky and Kz are hydraulic conductivities along the x, y and z coordinates $[LT^{-1}]$; Ss is the specific storage of the porous material $[L^{-1}]$; $W = W^{*}.b$ is the volume flux per unit area $[LT^{-1}]$; *and* W^{*} is the volumetric flux per unit volume which is positive for out flow and negative for inflow $[LT^{-1}]$.

The development of groundwater flow model starts with developing a conceptual model, collecting required data (e.g., aquifer layers, their hydrogeolocial characteristics, recharge, observed groundwater levels, and others); translating the conceptual model into MODFLOW using suitable GUI, and then calibrating and validating the groundwater flow model. They are discussed in the following sub-sections.

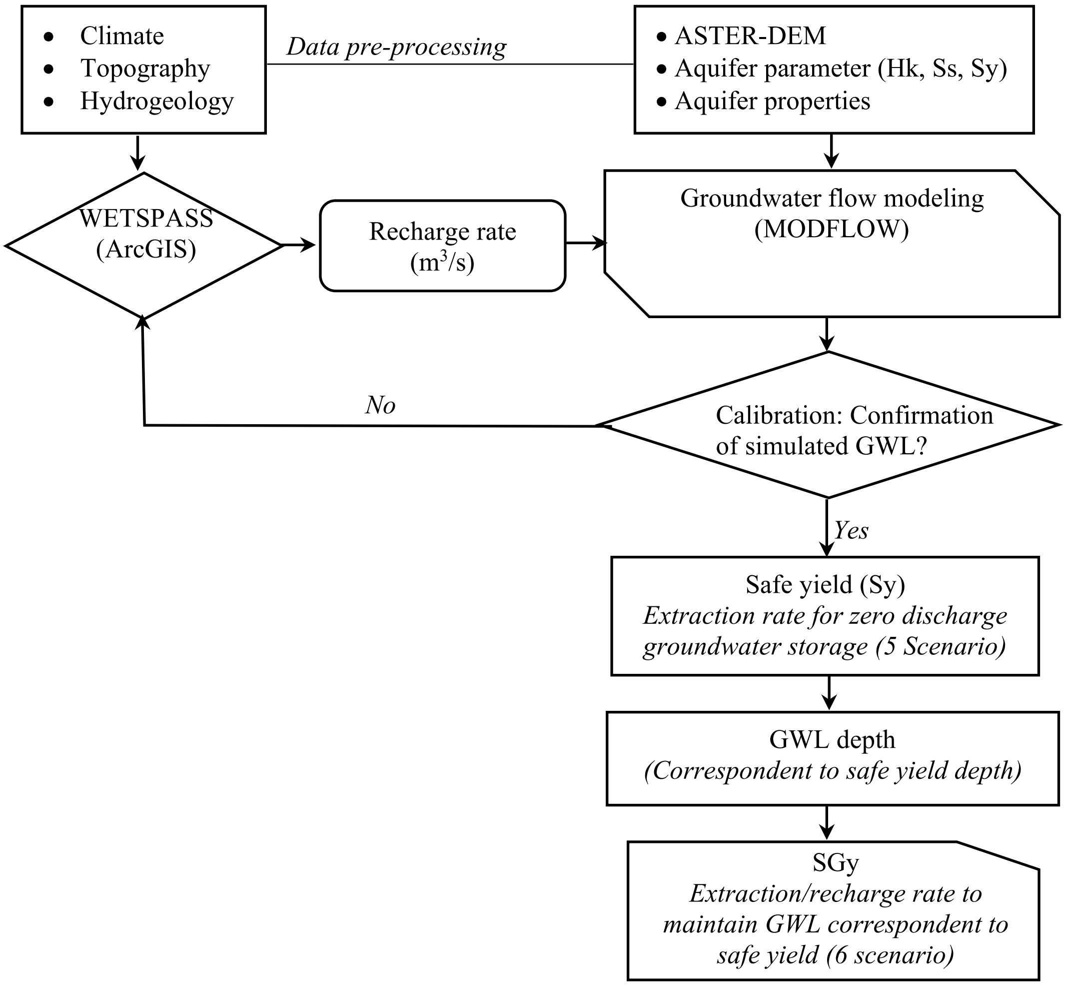


Fig. 3 Methodology flowchart adopted in this study. DEM is digital elevation model; GWL is groundwater level; Sy is safe yield; SGy is sustainable yield.

3.1.1 Development of conceptual model

The conceptual model of the Dili aquifer covers the groundwater basin (**Fig. 4**) with an area of 26 km^2 start from coast with elevation 0–60 masl (Pinto and Shrestha, 2016). The groundwater basin was delineated to best represent the physical condition of natural boundaries in the study area. The model domain in the upstream is bounded by foothills in the south that extends up to the western part and in the downstream (or north) is bounded by the coastal line. The model domain has the highest elevation in the southern boundary, which decreases gradually towards the coastal line in the north, which bounds the model domain as constant-head boundary. The eastern, southern and western boundaries of the model were considered as specified-flux boundaries with varying rate of flux in each direction. Similarly, the top boundary of the model domain was considered as the groundwater recharge and the bottom as no-flow. In the vertical direction, the lithology was considered as an unconfined aquifer and it was divided into two layers of varied hydraulic conductivities (Kx, Ky, and Kz). The first layer mainly comprises of sand, silty-clay, and gravel with a high degree of uncertainty in distribution in both horizontal and vertical directions. The second layer comprises mainly of saprolite, which is dominated by clay.

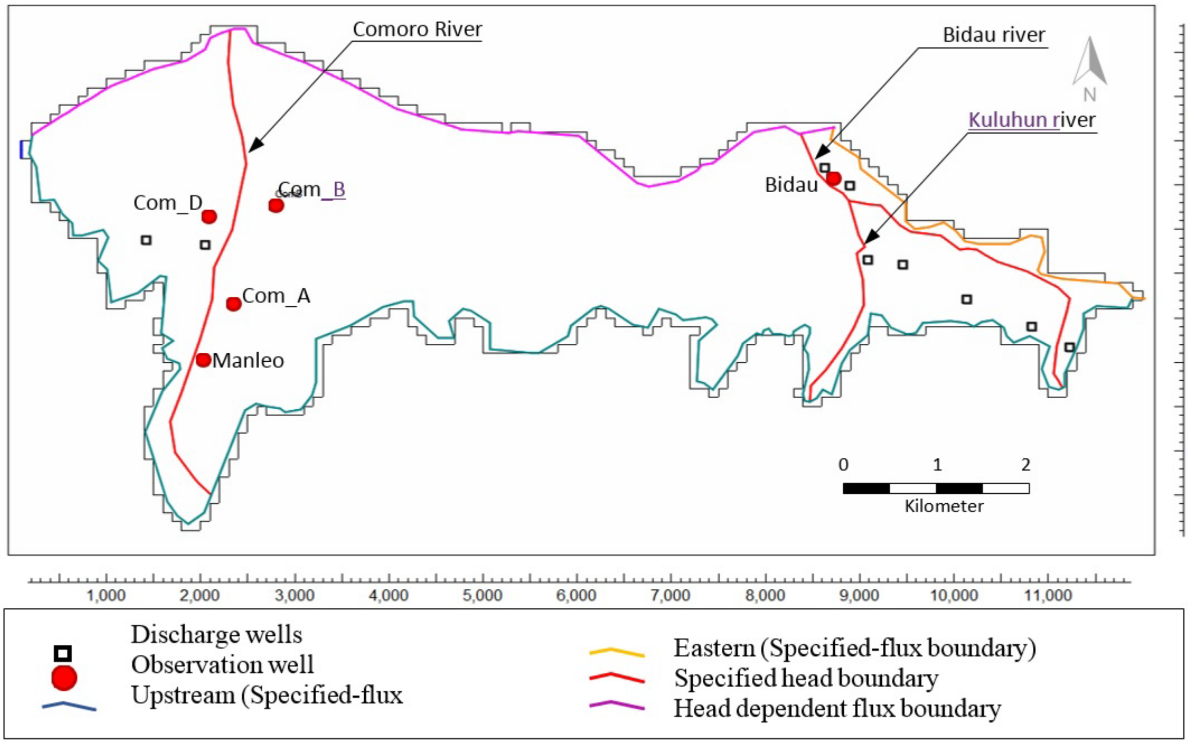


Fig. 4 Model domain and boundary conditions adopted in this study.

The model domain in horizontal plane was discretized to 63 rows and 120 columns (i.e., 7,560 nodes with 2,600 active cells) with grid cell of 100m x 100m resolution. Hydraulic conductivity (K) was divided into two regions in the top layers and two in the bottom as well. Three rivers, as shown in **Fig. 4**, were also considered in the conceptual model. The rivers are expected to contribute significantly to the groundwater recharge. The rivers were considered as fixed-head boundary. The coastal line along the northern boundary was represented as a drain in the conceptual model. Drains define the elevation over which water should drain out of the aquifer and is a function of groundwater head, drain elevation and drain conductance (Elawan, 2011; Winston, 2009). The model was stressed to groundwater abstraction from 14 wells located as shown in **Fig. 4**.

3.1.2 Preparation of aquifer information

Aquifer information required for MODFLOW comprised of delineation of hydrogeologic layers and their hydrogeologic properties. As per the hydrogeological map of the entire Timor Leste, the Dili aquifer consists of sedimentary rock and/or intergranular deposits but with a high degree of uncertainty in its distribution in horizontal and vertical directions (Wallace et al., 2012). The cross-section of the Dili aquifer along the Comoro River (**Fig. 2**) reveals that the thickness of the unconfined aquifer layer varies from 30m to 150m and that of overall aquifer (including underlying Saprolite (i.e., clay) is up to 300m. The thickness of the two aquifer layers throughout the model domain was determined based on data and information collected from various secondary sources (Furness, 2012). Elevation of top layer of the model was taken from the ASTER-DEM of 30m x 30m resolution. The aquifer properties such as hydraulic conductivity (K), specific yield (Sy), specific storage (Ss), and porosity was not available from earlier studies. Their values were identified through model calibration process because there was no information on their estimated values. The model in the beginning was warmed-up by running it with default K value of 0.0001 m/day and then run with initial values of the aquifer properties, which were taken from the coastal aquifers of similar characteristics such as Gaza aquifer. Then the aquifer properties, especially K values, were altered (both increase and decrease) many times through trial-and-error procedure until the model simulated groundwater levels are reasonably close to the observed groundwater level.

3.1.3 Preparation of recharge input

MODFLOW requires spatially distributed recharge as top boundary condition. We developed WETSPASS, a physically based and distributed hydrological model, for the purpose (Pandian et al., 2014; Rwanga, 2013**;** Batelaan and De Smedt 2001). The model adopts water balance approach. The WETSPASS model was set up by dividing the 250 km^2 area of Comoro watershed into 100m x 100m grid cells. All the geospatial inputs were prepared as gridded data in 100m x 100m resolution using ArcGIS. The model sub-divides water balance components (i.e., rainfall, surface runoff, recharge and evapotranspiration) in each cell into vegetated area; bare-soil area; open-water area; and impervious area (Adnan et al., 2013). This allows one to account for the non-uniformity of the land-use in each cell. The water balance for each land use/cover areas (i.e. vegetated, bare-soil, open-water, and impervious) in a single cell are then calculated. The model takes precipitation as the primary input for the computation of the water balance in each of the abovementioned components of a raster cell, the rest of the processes (interception, runoff, evapotranspiration, and recharge) follow in an orderly manner. Total water balance components for a cell is the sum of water balance components in the aforementioned four areas (i.e., vegetated, bare-soil, open-water, and impervious). Finally, water balance components for the entire study area is computed as the sum of water balance components in all the grid cells. Groundwater recharge is estimated as the residual component of the water balance after deducting all the outflow components from the inflow components.

The model was calibrated for the period of 2008-2013 with seasonal time steps (i.e., two seasons per year) by changing land use parameter. The spatially distributed recharge rate (mm/year) in the Comoro watershed for the period were obtained as gridded output from the WETSPASS model. The gridded data of 100m x 100m resolution was resampled to 30m x 30m to match with resolution of other data used with ModelMuse. The recharge value in mm/year was converted to m^3/s using a conversion factor before feeding as input to MODFLOW. The recharge rate assigned for the entire period of model simulation are distributed in the six regions as; alluvial plain, upstream part, Bidau river area, Kuluhun river area, Comoro river area and Eastern part of the basin.

3.1.4 Preparation of observation and pumping wells

Information about piezometers and pumping wells in this study were obtained from Department of Water Resources and Management (NDWSS), Timor Leste (2009-2013) and Aurecon Australia (2012). Information of five groundwater level monitoring wells (**Fig. 4**) in the DGB were collected from earlier reports. They were imported into the model to use during the calibration process. Fourteen abstraction wells (**Fig. 4**) are identified in the DGB (please refer Annex-1 **Table 5** for the discharge from the abstraction wells).

3.1.5 Translating the conceptual model into MODFLOW

The conceptual model was translated into numerical model using MODFLOW-2005 in the ModelMuse environment. Several MODFLOW packages were assigned to the boundary conditions to set up the model. They include, Recharge package (RCH), Well package (WEL), Time Variant-Specified Head package (CHD), and Head Observation package (HOB). Specified-flux boundaries in the upstream (i.e., south) and east side of the model domain as well as along the three rivers were assigned using RCH package in the ModelMouse. The same Specified flux, WEL package was assigned for fourteen observation wells as well. In addition, head-dependent flux and drain (DRN) packages were used to assign groundwater discharge from the three rivers and coastal line in the form of drains. Drain package was assigned through a polyline object. Drain elevation was as elevation of existing outlet, average elevation of the coastal line was defined as zero and drain conductance as 100 m^2/day. The HOB package was used to represent observation wells in the model.

3.2 Model calibration

Then MODFLOW was calibrated as a steady-state model for the period of 2009-2013. Firstly, it was run with default parameters to warm up the model. Then initial parameters, which were selected from the groundwater flow model developed for the coastal aquifer of similar characteristics (i.e., Gaza aquifer) (Aish, 2004), were assigned to make the first run and model performance was evaluated to only one well. The parameters, especially, hydraulic conductivity, was fine-tuned until the model performance was relatively good at that well. With that set of parameters, the model was evaluated at five observation wells and attempts were made to improve the model performance by fine-tuning the parameters again. It could not improve the model performance to the satisfactory level. Then, the conceptual model was modified by assigning boundary condition of Comoro River from constant head to time-variant specified head (CHD) while for other rivers still kept as constant head, the same as before. With further fine tuning of the model parameters, it yielded a satisfactory performance.

Visual analysis using bar diagrams and scatter plots of simulated versus observed groundwater level as well as statistical indicators for model performance were assessed to evaluate model performance. The statistical indicators are described here under.

Mean Absolute Error (MAE): Mean absolute error (Eq.-2) is the mean of the absolute value of the difference between observed groundwater level (h_0) and simulated groundwater level (h_s).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}[h_0 - h_s] \ldots\ldots\ldots \text{(Equation 2)}$$

Percentage Bias (PBIAS): Percentage bias (PBIAS) measures the average tendency of the simulated values to be larger or smaller than their observed ones (Eq.-3). The optimal value of PBIAS is 0.0, with low-magnitude values indicating better calibration of the model.

$$PBIAS = 100 * \left[\frac{sum(sim-obs)}{sum(obs)}\right] \ldots\ldots\ldots \text{(Equation 3)}$$

Root Mean Square Error (RMSE): The RMSE (Eq.-4) is the average of the squared differences between observed and simulated groundwater level (Elawan, 2011).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_{0} - h_s)^2} \ldots\ldots\ldots \text{(Equation 4)}$$

Coefficient of Determination (R^2): It is a statistical measure indicating closeness of the simulated data to the observed ones. The R^2 of observed versus simulated groundwater level are plotted very close to the straight line. Its value ranges from 0 to 100% and the values above 75% are generally reflect reasonably good calibration of the mode.

3.3 Estimation of safe yield (Sy)

3.3.1 Concept of Sy

The language of aquifer-yield assessment is based in semantics that generally requires practitioners to clarify their use of particular terms. Discussions on the topic of aquifer yield assessments can be found in literatures (e. g., Alley and Leake, 2004; Custodio, 2002; Kalf and Woolley; 2005; Maimone, 2004; and Sophocleous, 2000). The Sy is a long-term balance between the annual recharge and groundwater abstraction (Lee, 1915). It aims at balancing groundwater discharge (e.g., pumping) at the level of groundwater recharge at a certain depth so that net output (or discharge) from the storage is zero. It can play an important role to avoid unsustainable groundwater depletion.

3.3.2 Estimation of Sy

Firstly, minimum groundwater abstraction required to fulfil the existing water demand of some 0.2 million populations (Pinto and Shrestha, 2016) in the Dili city was estimated based on NDWSS standard for water demand. Five possible future scenarios were developed with the assumption that the current abstraction rate of 0.23 m^3/s will be increased due to increasing development activities in the city. The scenarios were then used with the calibrated groundwater flow model to estimate total groundwater abstraction as well as change in groundwater storage under each scenario. The abstraction rate that balances groundwater recharge or results in zero output (or discharge) from storage was considered as the "safe yield (Sy)" from the aquifer (Arlai et al., 2012). For the abstraction equal to the Sy, the depth of groundwater level was also estimated for the purpose of evaluating other scenarios for estimating the SGy. The five scenarios considered were:

- *Scenario*-IA_{10}: Increase in current rate of groundwater abstraction by 10%
- *Scenario*-IA_{20}: Increase in current rate of groundwater abstraction by 20%
- *Scenario*-IA_{30}: Increase in current rate of groundwater abstraction by 30%
- *Scenario*-IA_{40}: Increase in current rate of groundwater abstraction by 40%
- *Scenario*-IA_{50}: Increase in current rate of groundwater abstraction by 50%.

3.4 Estimation of sustainable yield (SGy)

3.4.1 Concept of SGy

The two distinct concepts, Sy and SGy, in this study are defined in this way: (i) safe yield (Sy) – where groundwater level is constrained by the amount of groundwater abstraction from the basin; and (ii) sustainable groundwater yield (SGy) – where groundwater level is constrained by amount of groundwater recharge and discharge in the basin to maintain water level at the certain depth for avoiding hydrologic, environmental and socioeconomic consequences and maintain sustainable development as well. If the Sy should be less than recharge, then the SGy should not be more than Sy. Based on this concept, six scenarios were developed to estimate SGy of the Dili aquifer. The indicators were selected such that they are helpful in evaluating significant impacts from future groundwater development.

To define the SGy, the abstraction rate from the calibrated model was used as initial rate to a range of scenarios, both increasing and decreasing. The groundwater abstraction rate that results no change in the groundwater depth (m) compared to the level of Sy was defined as the SGy. Water balance principle is used as basic concept for this purpose. If the outflow is greater than inflow then some storage is depleted and groundwater level falls, whilst if the inflow is greater than outflow then there is storage accretion and groundwater level rises. If inflow equals outflow, then the water levels remain static because there is no gain or loss in storage (Arlai et al., 2011; Kalf and Woolley, 2005).

3.4.1 Estimation of SGy

The groundwater abstraction rate that can maintain groundwater level at 7.8 mbgl, the value at the stage of Sy (like in Koch et al., 2011), is defined as SGy in this study. It is expected to be less than the Sy. Six different scenarios were developed and evaluated with the help of the calibrated groundwater flow model. Those scenarios are classified into following two categories: 1) *Scenarios based on only one parameter*: There were two scenarios (i.e., DR and IR), which were developed based on either groundwater abstraction rate or recharge rate; 2) *Scenarios based on two parameters*: There were four such scenarios (i.e., IEDR, IEIR, DEIR and DEDR), which were developed by incorporating both abstraction and recharge rates. They were based on the assumption that there are possibilities for increasing or decreasing in average annual recharge due to climate variability/change, including uncontrolled pumping rate that is prevailing within the basin. The six scenarios are described here under.

- *Scenario*-DR: Groundwater recharge rate will decrease in future due to increase in impervious areas in the city. Scenarios DR_{10}, DR_{20}, DR_{30}, DR_{40}, and DR_{50} refer to the cases with decrease in current recharge rate by 10, 20, 30, 40 and 50%, respectively.
- *Scenario*-IR: Increasing groundwater recharge could be an option to avoid decrease in groundwater level and excess surface runoff in the Comoro watershed can be utilized for enhancing recharge by artificial means such as injection wells and spreading methods. Scenarios IR_{10}, IR_{20}, IR_{30}, IR_{40} and IR_{50} refer to the cases with increase in current recharge rate by 10, 20, 30, 40 and 50%, respectively.
- *Scenario*-IADR: Groundwater abstraction may increase, and recharge may decrease due to a complex dynamics of social, environmental, economic and political issues. Scenarios $IADR_{10}$, $IADR_{20}$, $IADR_{30}$, $IADR_{40}$ and $IADR_{50}$ refer to the cases with increase in current level of groundwater abstraction and decrease in recharge by 10, 20, 30, 40 and 50%, respectively.
- *Scenario*-IAIR: Groundwater abstraction as well as recharge may increase in future. Scenarios $IAIR_{10}$, $IAIR_{20}$, $IAIR_{30}$, $IAIR_{40}$ and $IAIR_{50}$ refer to the cases with increase in current level of groundwater abstraction and recharge by 10, 20, 30, 40 and 50%, respectively.
- *Scenario*-DAIR: Groundwater abstraction may decrease but recharge may increase. Scenarios $DAIR_{10}$, $DAIR_{20}$, $DAIR_{30}$, $DAIR_{40}$ and $DAIR_{50}$ refer to the cases with decrease in current level of groundwater abstraction and increase in recharge by 10, 20, 30, 40 and 50%, respectively.
- Scenario-DADR: Groundwater abstraction as well as recharge may decrease in future. Scenarios $DADR_{10}$, $DADR_{20}$, $DADR_{30}$, $DADR_{40}$ and $DADR_{50}$ refer to the cases with decrease in current level of groundwater abstraction and recharge by 10, 20, 30, 40 and 50%, respectively.

3.5 Data and sources

Table 1 depicts description of various data used in this study along with respective sources.

Table 1: Description of data and sources used in this study.

Description of the data	Source(s)	Remarks
Climatic data		
Precipitation (Resolution: Spatial – 7 stations; Temporal – Daily) Temperature (Resolution: Spatial – 7 stations; Temporal – Daily) Relative Humidity (Resolution: Spatial – 7 stations; Temporal – Daily) Wind speed (Resolution: Spatial – 7 stations; Temporal – Daily)	Meteorological Department of Timor Leste	2003-2014
Hydro-geologic data		
Geology map of Timor-Leste (Resolution: Spatial – 90m x 90 m; Temporal – one time (year 2012)	National Department of Water and Sanitation, Timor-Leste	GIS shape file
Total amount water withdrawal from borewells (Resolution: Spatial – 14 wells; Temporal – Monthly)	Department of Water and Sanitation, Timor-Leste	2009-2013
Water level and well screen depth (Resolution: Spatial – 14 wells; Temporal – Monthly)	Ministry of Public Work (NDWSS)	2009-2011
Monitoring well data (Resolution: Spatial – 5 wells; Temporal – Monthly)	Comoro B Bidau	2011-12
Geospatial & environmental data		
Digital Elevation Model (ASTER DEM) (Spatial resolution: 30m x 30 m; Year: 2011) Land use & Land cover (Spatial resolution: 90m	National GIS Agency (Department do Terestra) Ministry of Agriculture	GIS raster file

x 90 m; Year: 2012) Soil map (Spatial resolution: 90m x 90 m; Year: 2012)	(ALGIS)	GIS shape file

4. Results and Discussion

4.1 Performance of groundwater flow model

The very first model of the Dili aquifer was developed to simulate groundwater flow. As a calibration strategy, the model was first calibrated at Manleo well and the same set of parameters were used to calibrate at other four wells. Parameter values were fine-tuned to the best possible extent to get a satisfactory reproduction of groundwater level at all the wells. However, it was over-estimated. Then, the boundary condition of Comoro River, which was assigned as "constant head" in earlier simulations, was changed to "time variant specified head (CHD)" boundary condition and calibrated again. At this stage, all possible strategies to reduce simulated groundwater level were explored. They include:

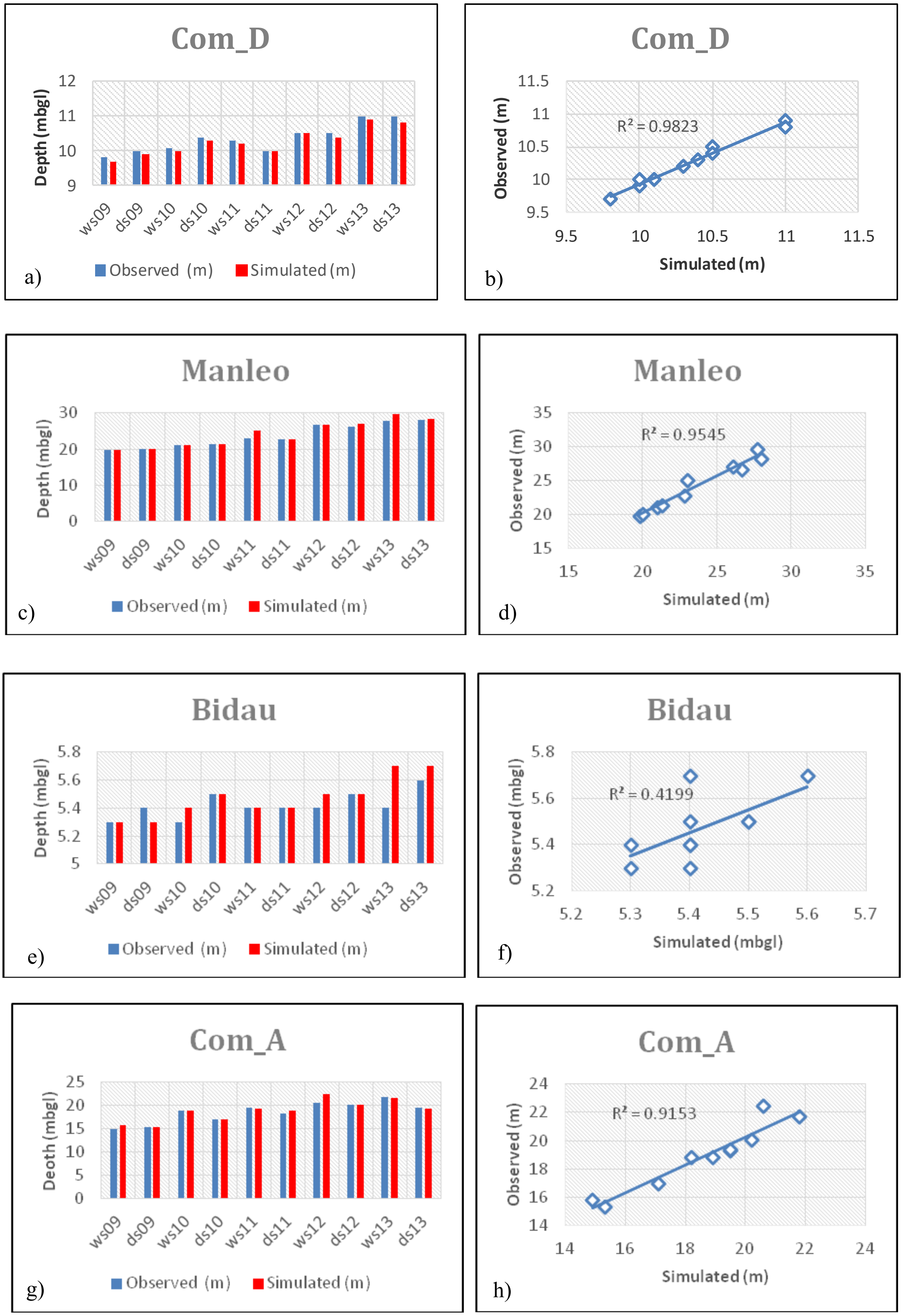
- *Increasing hydraulic conductivity*: it will lead to increase in Transmissivity in the groundwater flow equation, and it will ultimately speed up groundwater outflow from the aquifer and water level decreases.
- *Increasing thickness of the aquifer (i.e., modifying the conceptual model)*: it also will lead to increase in the transmissivity.

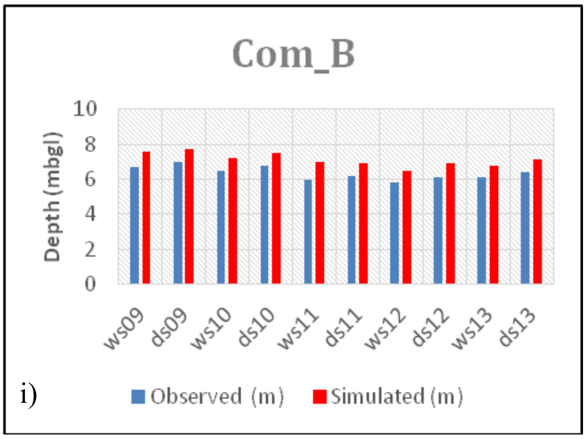
As the aquifer thickness map was fairly good with Comoro well field thicker than Bidau well-field, calibration strategy was to focus first on increasing hydraulic conductivity values at the two well fields (i.e., Bidau_2 and Comoro_B) and then adjusting thickness to a small extent to fine tune the simulation. The initial and calibrated values of the model parameters are shown in **Table 1**.

Table 2. Initial and calibrated values of the model parameters.

Parameter name		Parameter value (initial)		Parameter value (calibrated)	
		Top layer (sandy and gravel layer)	Bottom layer (clay layer)	Top layer (sandy and gravel layer)	Bottom layer (clay layer)
Hydraulic conductivity (m/day)	kx	33	1E-01	8.25	0.03
	ky	33	1E-01	8.25	0.03
	kz	3.3	1E-01	0.825	0.003
Specific yield (Sy)		0.18	5E-02	0.05	0.01
Specific storage (Ss) (1/m)		1E-04	1E-05	0.000025	0.0000025
Porosity (Tot. Por.)		3E-01	5E-01	0.08	0.11
Effective Porosity (Eff. Por)		3E-01	5E-01	0.08	0.11

The steady-state model simulation for the period of 2009-2013 were evaluated using visual analysis as well as a set of statistical indicators described in methodology section. The model was calibrated with a set of parameter values depicted in **Table 2**. The visual plots (i.e., simulated groundwater levels shown in **Fig. 5** and scatter plots shown in **Fig. 6**) and statistical indicators at all the five observation wells (**Table 2**) suggests that the model was satisfactorily calibrated. A scatter plot of observed versus simulated groundwater level of all the fifty simulations (i.e., five wells, five years, two seasons) are plotted very close to the straight line with R^2 value of 0.994 (**Fig. 6**), RMSE of 0.997, and NSE of 0.993 (**Table 3**).


Com_D
Depth (mbgl)
12
11
10
9
ws09 ds09 ws10 ds10 ws11 ds11 ws12 ds12 ws13 ds13
Observed (m)
Simulated (m)
a)
Com_D
Observed (m)
11.5
11
10.5
10
9.5
R² = 0.9823
9.5 10 10.5 11 11.5
Simulated (m)
b)
Manleo
Depth (mbgl)
30
20
10
0
ws09 ds09 ws10 ds10 ws11 ds11 ws12 ds12 ws13 ds13
Observed (m)
Simulated (m)
c)
Manleo
Observed (m)
35 30 25 20 15
R² = 0.9545
15 20 25 30 35
Simulated (m)
d)
Bidau
Depth (mbgl)
5.8 5.6 5.4 5.2 5
ws09 ds09 ws10 ds10 ws11 ds11 ws12 ds12 ws13 ds13
Observed (m)
Simulated (m)
e)
Bidau
Observed (mbgl)
5.8 5.6 5.4 5.2
R² = 0.4199
5.2 5.3 5.4 5.5 5.6 5.7
Simulated (mbgl)
f)
Com_A
Deoth (mbgl)
25 20 15 10 5 0
ws09 ds09 ws10 ds10 ws11 ds11 ws12 ds12 ws13 ds13
Observed (m)
Simulated (m)
g)
Com_A
Observed (m)
24 22 20 18 16 14
R² = 0.9153
14 16 18 20 22 24
Simulated (m)
h)



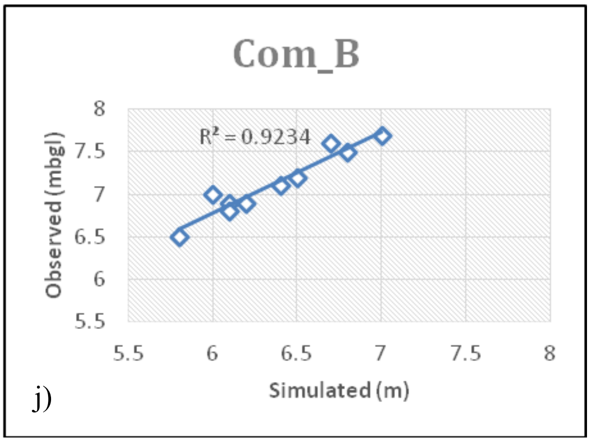


Fig. 5 Comparison of simulated and observed groundwater levels (meters below ground level, mbgl) at five observation wells in the aquifer. Left side figures show the comparison for 10 time steps (i.e., five years and two seasons for 2009-2013) and the right side figures show a scatter plot between observed and simulated groundwater levels.

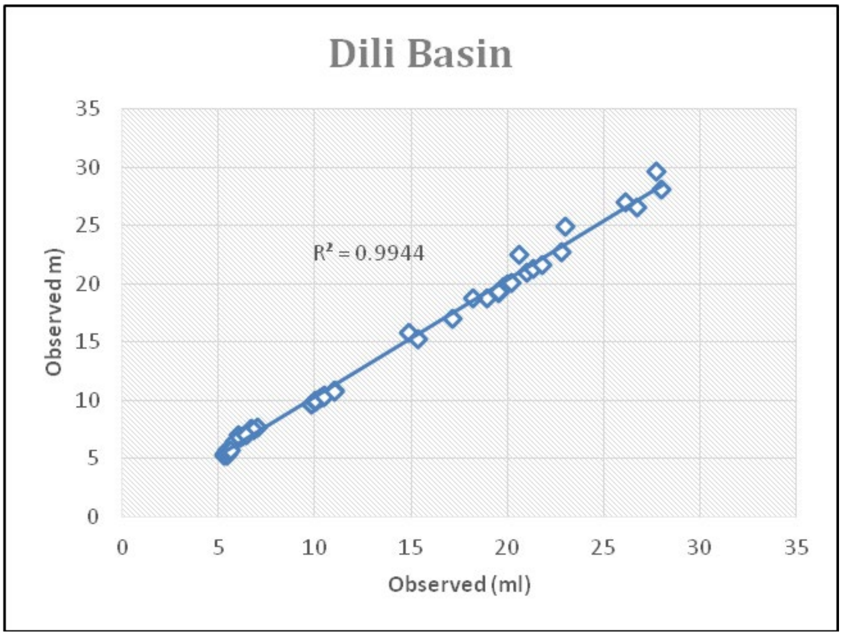


Fig. 6 Scatter plot of observed versus simulated groundwater level of the entire basin at the stage of model calibration.

Table 3. Performance of the calibrated model at five observed wells for the period of 2009-2013.

Well Name	Season	Observed water level (m)	Simulated water level (m)	Absolute Value	ERROR	MSE	(Xi-Yi)^2	(Xi-Xav)^2	(Xi-Xav)^2	(Yi-Yav)^2	(Xi-Xav)^2(Yi-Yav)^2
Manleo	wet09	19.8	19.8	0.04	0.04	0.00	0.002	43.41	2081.84	47.41	43.41
	dry09	20.0	20.0	0.05	-0.05	0.02	0.002	47.31	2402.10	51.48	47.31
	wet10	21.0	21.0	0.02	-0.02	0.000	0.000	61.59	4066.78	66.35	61.59
	dry10	21.3	21.3	0.03	0.03	0.00	0.001	65.58	4655.62	70.48	65.58
	wet11	23.0	25.0	2.00	-2.00	4.00	4.000	139.91	14344.17	147.02	139.91
	dry11	22.8	22.8	0.05	0.05	0.00	0.002	91.75	9038.17	97.52	91.74
	wet12	26.7	26.6	0.05	0.05	0.00	0.002	181.67	34724.12	189.76	181.67
	dry12	26.1	27.1	1.03	-1.03	1.06	1.060	194.84	34079.09	203.22	194.84
	wet13	27.7	29.7	2.00	-2.00	4.00	4.000	273.19	60044.58	283.09	273.19
	dry13	28.0	28.2	0.20	-0.20	0.04	0.040	225.85	51670.01	234.87	225.85
Com_A	wet09	14.9	15.8	0.94	-0.94	0.88	0.880	7.11	29.14	8.77	7.10
	dry09	15.3	15.3	0.04	0.04	0.00	0.001	4.37	25.73	5.70	4.37
	wet10	18.9	18.8	0.10	0.11	0.01	0.010	61.28	1148.14	66.02	61.28
	dry10	17.1	17.0	0.08	0.08	0.01	0.010	14.78	263.85	17.15	14.79
	wet11	19.5	19.3	0.16	0.16	0.02	0.020	38.04	1670.05	41.79	38.04
	dry11	18.2	18.8	0.59	-0.59	0.35	0.350	31.61	896.52	35.04	31.61
	wet12	20.6	22.5	1.86	-1.86	3.45	3.450	86.22	5145.52	91.82	86.22
	dry12	20.2	20.1	0.09	0.09	0.01	0.010	48.19	2585.23	52.39	48.18
	wet13	21.8	21.7	0.08	0.08	0.01	0.010	73.04	5817.76	78.19	73.03
	dry13	19.5	19.4	0.13	0.13	0.02	0.020	38.457	1687.96	42.22	38.45
Com_D	wet09	9.8	9.7	0.07	0.07	0.01	0.005	11.83	111.85	9.88	11.83
	dry09	10.0	9.9	0.12	0.12	0.02	0.020	10.87	89.83	9.00	10.87
	wet10	10.1	10.0	0.07	0.07	0.00	0.004	9.85	75.81	8.07	9.85
	dry10	10.4	10.3	0.14	0.14	0.02	0.021	8.51	52.09	6.86	8.51
	wet11	10.3	10.2	0.06	0.06	0.00	0.004	8.63	57.18	6.97	8.63
	dry11	10.0	10.0	0.04	0.04	0.00	0.002	10.32	85.26	8.50	10.32
	wet12	10.5	10.5	0.04	0.04	0.00	0.001	7.34	41.38	5.82	7.34
	dry12	10.5	10.4	0.10	0.108	0.01	0.010	7.69	43.34	6.13	7.69
	wet13	11.0	10.9	0.13	0.13	0.02	0.020	5.31	18.68	4.03	5.31
	dry13	11.0	10.8	0.18	0.18	0.03	0.030	5.55	19.50	4.24	5.55
Com_B	wet09	6.7	7.6	0.98	-0.98	0.96	0.960	29.72	1118.36	26.57	29.72
	dry09	7.0	7.7	0.71	-0.71	0.50	0.500	30.05	1044.10	26.88	30.04

Continue **Table 3**…..

	wet10	6.5	7.2	0.68	-0.68	0.47	0.470	9.43	1475.17	7.69	9.43
	dry10	6.8	7.5	0.70	-0.70	0.49	0.490	32.57	1217.95	29.27	32.57
	wet11	6.0	7.0	0.95	-0.95	0.91	0.910	38.66	1827.31	35.06	38.66
	dry11	6.2	6.9	0.67	-0.67	0.45	0.450	39.69	1768.45	36.04	39.69
	wet12	5.8	6.5	0.66	-0.66	0.43	0.430	44.43	2192.32	40.56	44.42
	dry12	6.1	6.9	0.78	-0.78	0.61	0.610	39.84	1839.29	36.18	39.84
	wet13	6.1	6.8	0.68	-0.68	0.46	0.460	40.84	1874.50	37.13	40.84
	dry13	6.4	7.1	0.69	-0.69	0.48	0.480	36.92	1547.84	33.40	36.92

Bidau	wet09	5.3	5.3	0.01	0.01	0.00	0.000	62.67	3624.09	58.05	62.67
	dry09	5.4	5.3	0.07	0.07	0.00	0.005	61.49	3435.54	56.92	61.49
	wet10	5.3	5.4	0.02	-0.02	0.00	0.000	61.01	3463.54	56.46	61.01
	dry10	5.5	5.5	0.02	0.02	0.00	0.001	59.23	3221.17	54.74	59.23
	wet11	5.4	5.4	0.08	-0.08	0.00	0.006	59.62	3358.02	55.13	59.62
	dry11	5.4	5.4	0.08	0.08	0.00	0.006	60.86	3354.79	56.31	60.86
	wet12	5.4	5.5	0.12	-0.12	0.02	0.020	58.95	3319.82	54.47	58.95
	dry12	5.5	5.5	0.02	-0.02	0.00	0.001	58.51	3182.19	54.07	58.51
	wet13	5.4	5.7	0.28	-0.28	0.08	0.080	56.53	3183.73	52.15	56.53
	dry13	5.6	5.7	0.13	-0.13	0.02	0.020	55.88	2981.47	51.52	55.88
Total average		12.9	13.2	18.87	-14.85	19.89	19.890	2750.98	286000.99	2758.45	2750.98
Total		643.7	658.6								
Nash Sutcliffe Efficiency			NSE	0.993							
Percent Bias			PBIAS	-2.255							
Mean Absolute Error			MAE	0.943							
Root Mean Square Error			RMSE	0.997							
Coefficient of Determination			R^2	0.994							

4.2 Simulated groundwater level

To characterize the regional groundwater flow system in terms of direction and rate of flow, the simulated groundwater level for the entire model domain was extracted from the calibrated model. The spatially distributed contour of groundwater (**Fig. 7**) shows a drop in the piezometric level from about 45 mbgl to 0.3 mbgl toward coastal line at the Comoro well field and from 16 mbgl to 0.3 mbgl in the Bidau well field. It reveals that groundwater flow follows the surface topography, i.e., it generally flows from the highlands in the southern part toward the flat areas along the coastal line of the Dili groundwater basin. The temporal trends in groundwater levels at all the monitoring wells are also very much similar.

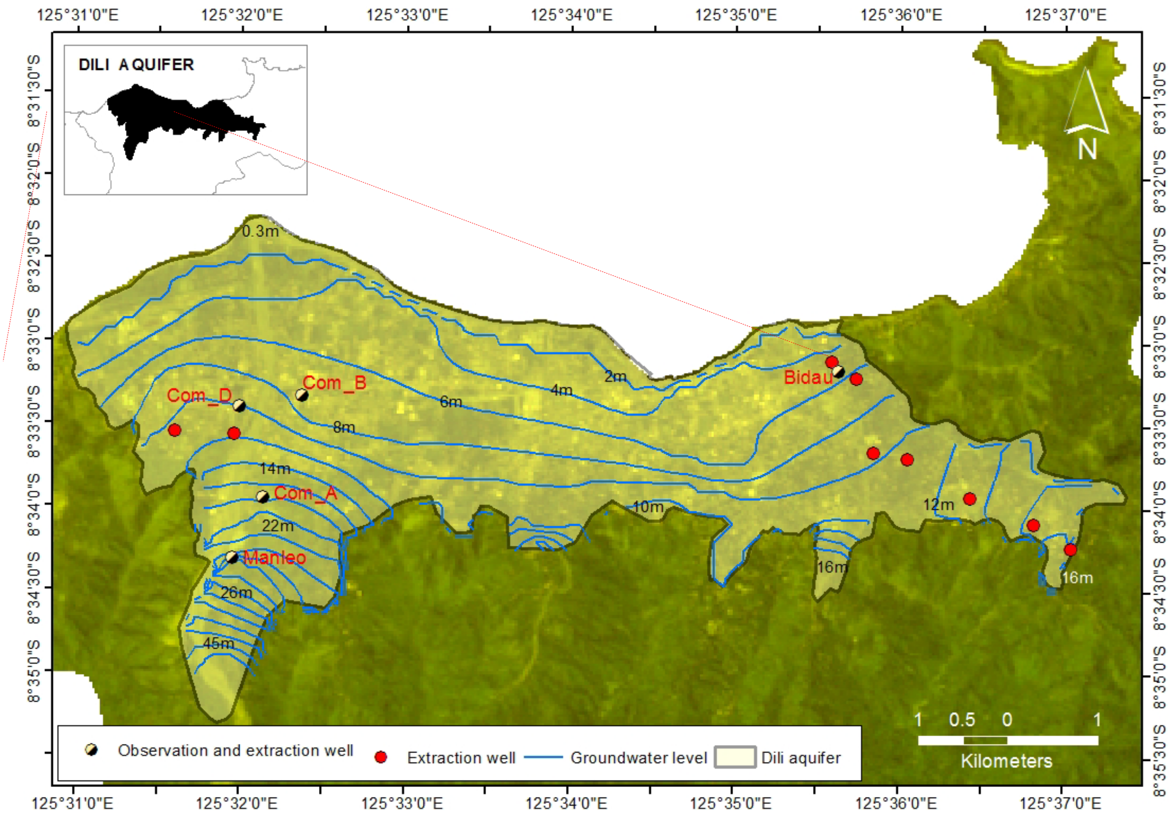


Fig. 7 Spatial distribution in simulated groundwater level from calibrated model (2009-2011 average).

4.3 Estimated safe yield (Sy) of Dili aquifer

The safe yield (Sy) in this study refers to the groundwater abstraction rate that balances groundwater recharge or results in zero output (or discharge) from storage in the aquifer. The amount of groundwater likely to be abstracted from an aquifer depends on Sy as well as water demand (or total number of people to be served), whichever is lower. Based on this concept, five scenarios IA_{10}-IA_{50} as discussed in the methodology were evaluated using the calibrated groundwater flow model. Results are shown in **Table 4** and plotted in **Fig. 8**.

It reveals that with increase in yield from 10 to 50% from the baseline case for the scenarios IA_{10}-IA_{50}, annual groundwater yield increases steadily (**Fig. 8b**). The trend is same for both the seasons; with more yield in the wet season (**Fig. 8a**). However, output volume from the groundwater storage decreases gradually from the baseline case. For the IA_{20} scenario (i.e., increase in current rate of groundwater abstraction by 20%), the change in groundwater storage is closer to zero (**Fig. 8c**; **Table 4**), and therefore, the groundwater yield of 0.28 m^3/s at this stage is estimated as Sy from the Dili aquifer. To estimate groundwater depth corresponding to the Sy, Com_B well was considered due to reasonable stability in groundwater level compared to other observation wells. The value was estimated as 7.8 mbgl (**Fig. 8d**).

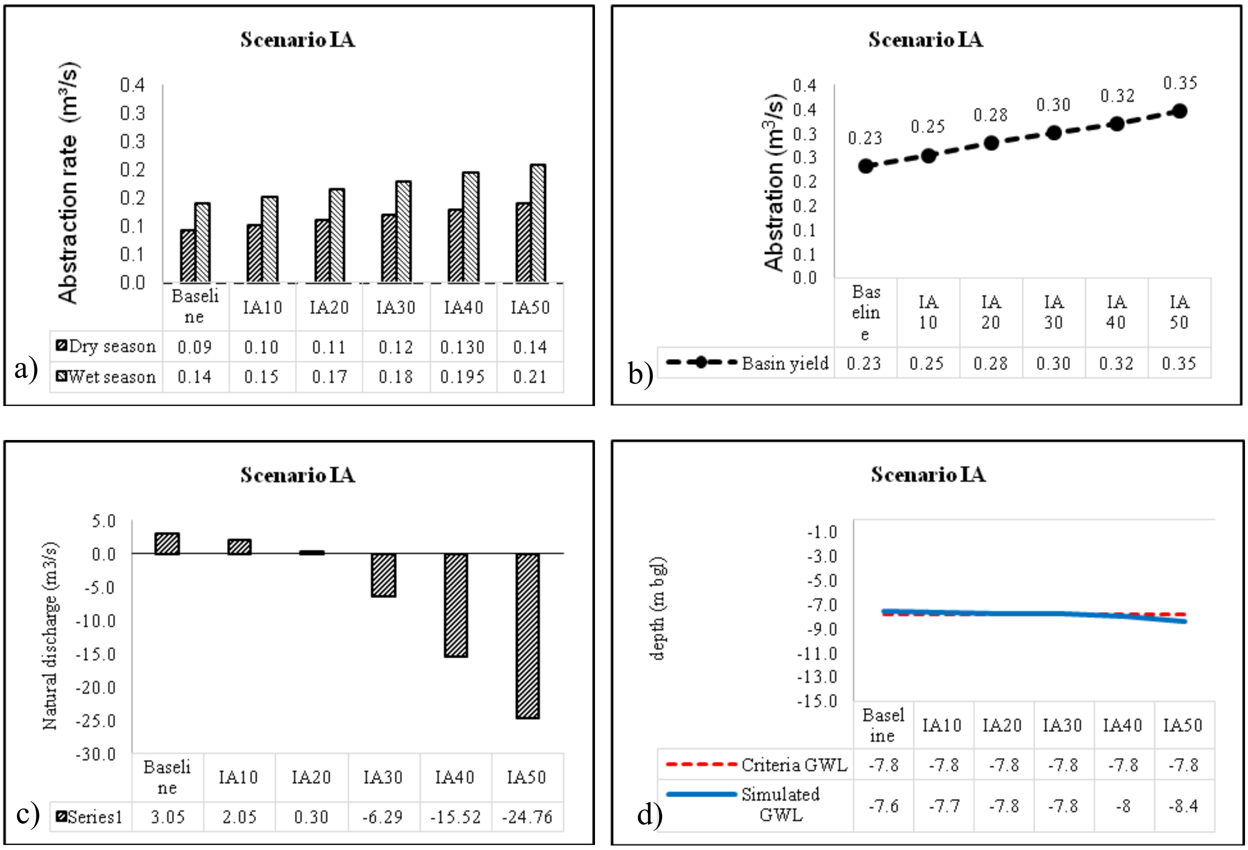


Fig. 8 Calibrated model outputs under the scenarios IA_{10}-IA_{50}: a) seasonal groundwater yield; b) annual groundwater yield; c) discharge volume from the groundwater storage; and d) simulated groundwater depth at Comoro_B well.

If the groundwater abstraction is maintained at the Sy of 0.28 m^3/s, the aquifer can produce 0.12 m^3/person/day of groundwater (based on current population of nearly 0.2 million), which is still in line with the NDWSS strategy to supply water in the range of 0.08-0.15 m^3/person/day. If we consider groundwater contribution as per the existing rate of 60% of total water supply and consider the lower bound of NDWSS strategy for supplying adequate water, rate of groundwater abstraction can be maintained within Sy.

Table 4 Volumetric outputs and piezometric heads under the scenarios IA_{10}-IA_{50}.

Scenario IA	Abstraction (m^3/s)	Percentage change (%)	Groundwater level (mbgl)	Total aquifer discharge (m^3/s)
Baseline	0.23	0	7.6	3.05
IA_{10}	0.25	10	7.7	2.05
IA_{20}	0.28	20	7.8	0.30
IA_{30}	0.30	30	7.8	-6.29
IA_{40}	0.32	40	8.0	-15.52
IA_{50}	0.35	50	8.4	-24.76

Note: Minus (-) The total aquifer discharge value indicated abstraction greater than storage

4.3 Sustainable groundwater yield (SGy)

The groundwater abstraction rate that can maintain groundwater level at 7.8 mbgl, corresponding to the Sy, is defined as the "sustainable yield (SGy)". Six different scenarios were developed and evaluated using the calibrated groundwater flow model to estimate SGy of the Dili aquifer.

Scenario-DR: Evaluation of the Scenario-DR (i.e., decrease in groundwater recharge) indicates that any decrease in recharge from the baseline case will result decline in groundwater level from 7.8 mbgl corresponding to the Sy (**Fig. 9a**). Scenario DR reveals that decreasing recharge from current recharge rate (118 mm/year) by 3%, the simulation groundwater level reaches to 7.8 mbgl and if it is increased beyond, groundwater level starts dropping below 7.8 mbgl. Therefore, groundwater recharge should not be reduced more than that to maintain the groundwater level at 7.8 mbgl.

Scenario-IR: Evaluation of the Scenario-IR (i.e., increase in groundwater recharge) reveals that groundwater level can rise to 7.6 - 4.8 mbgl under the scenarios IR_1-IR_5 (**Fig. 9b**), which are higher than the 7.8 mbgl corresponding to the Sy. The scenario-IR can therefore be one of the possible alternatives to sustain groundwater development in the area. However, there could be various technical difficulties and financial implications, which should be evaluated separately for any project aimed at augmenting groundwater storage by means of artificial recharge.

Scenario-IEDR: Evaluation of the Scenario-IEDR (i.e., increase in groundwater abstraction and decrease in recharge) indicates that groundwater level declines to 12.3 – 12.9 mbgl under the scenarios $IEDR_{10}$-$IEDR_{50}$ (**Fig. 9c**), which are significantly lower than the 7.8 mbgl corresponding to the Sy.

Scenario-IEIR: Evaluation of the Scenario-IEIR (i.e., increase in groundwater abstraction as well as recharge) reveals that groundwater level can rise at a slow rate to reach to 7.6–7.1 mbgl under the scenarios $IEIR_{10}$-$IEIR_{50}$ (**Fig. 9d**), which are slightly higher than the 7.8 mbgl corresponding to the Sy.

Scenario-DEIR: Evaluation of the Scenario-DEIR (i.e., decrease in groundwater abstraction but increase in recharge) reveals that it results in rise in groundwater level to 7.6-4.2 mbgl under the scenarios $DEIR_{10}$-$DEIR_{50}$ (**Fig. 9e**), which are higher than the 7.8 mbgl corresponding to the Sy.

Scenario-DEDR: Evaluation of the Scenario-DEDR (i.e., decrease in groundwater abstraction as well as recharge) reveals that it causes decline in groundwater level to 7.6 to 9.9 mbgl under the scenarios $DEDR_{10}$-$DEDR_{50}$ (**Fig. 9f**), which are lower than the 7.8 mbgl corresponding to the Sy.

4.3.1 Comparison of scenario outputs

All the six scenarios (i.e., DR, IR, IEDR, IEIR, DEIR and DEDR) have shown different responses with various levels of alterations in recharge and/or abstraction. The scenarios – DR, IEDR and DEDR have similar decreasing trends in groundwater level below the 7.8 mbgl (i.e., corresponding to the Sy), whereas all the remaining three scenarios (i.e., IR, IEIR, and DEIR) have increasing trends in the groundwater levels above the 7.8 mbgl (**Fig. 9b, 9dd, 9e**). Average groundwater levels (mbgl) for the scenarios DR, IEDR and DEDR are 10.32, 11.85, and 9.10, respectively; and those for IR, IEIR and DEIR are 5.90, 7.30, and 5.39, respectively (**Fig. 10**). Therefore, estimated SGy of the Dili aquifer that ensures groundwater levels are not lower than 7.8 mbgl at Comoro_B well is expected to be in a range of 0.23 (i.e., current) - 0.28 (i.e., Sy) m^3/s, which means, SGy of the Dili aquifer is estimated to be in a range of 0.23 to 0.28 m^3/s.

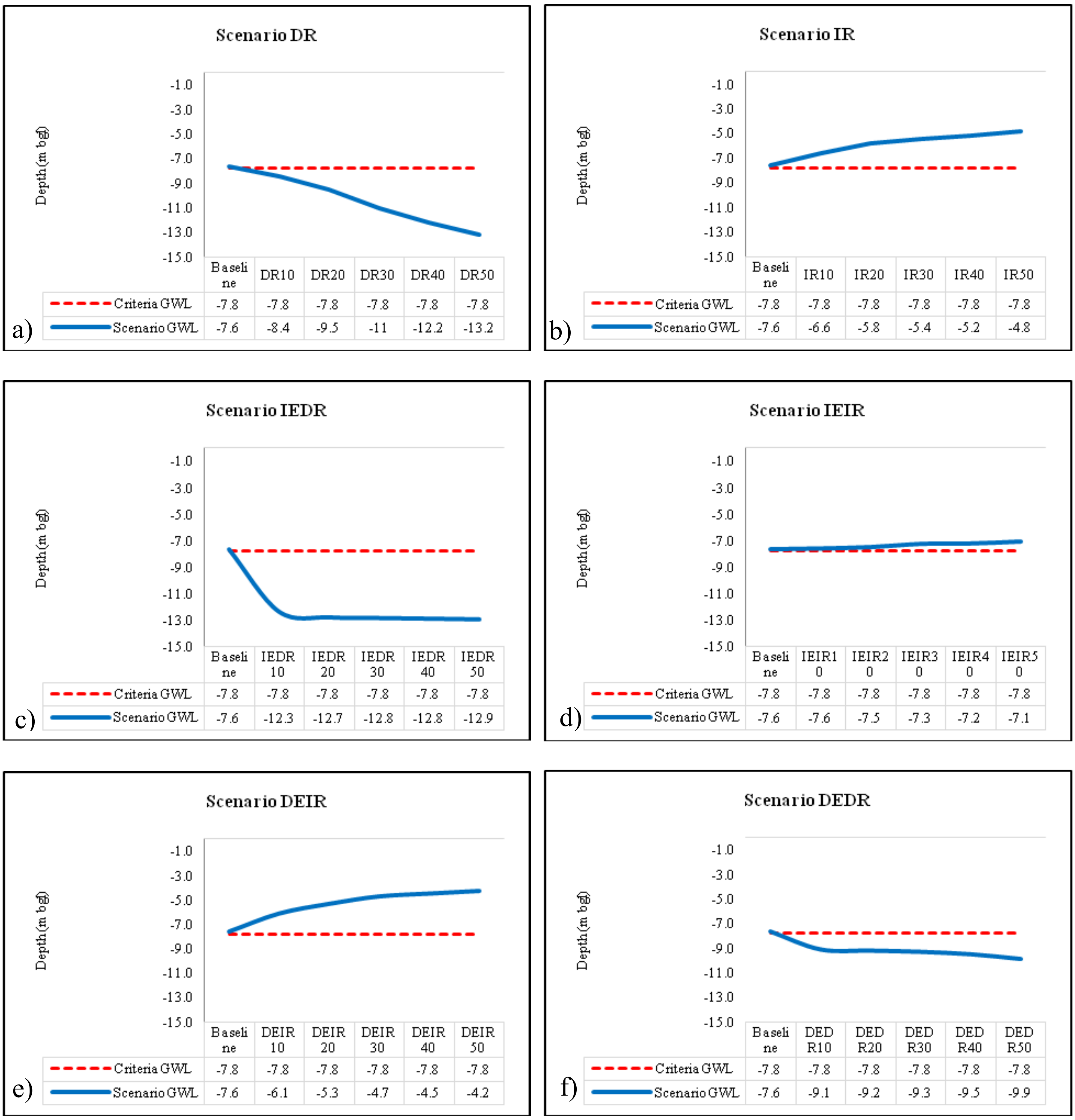


Fig. 9 Simulation groundwater depth under different scenarios (DR, IR, IEDR, IEIR, DEIR and DEDR) and the baseline (or criteria depth) corresponding to the safe yield (Sy).

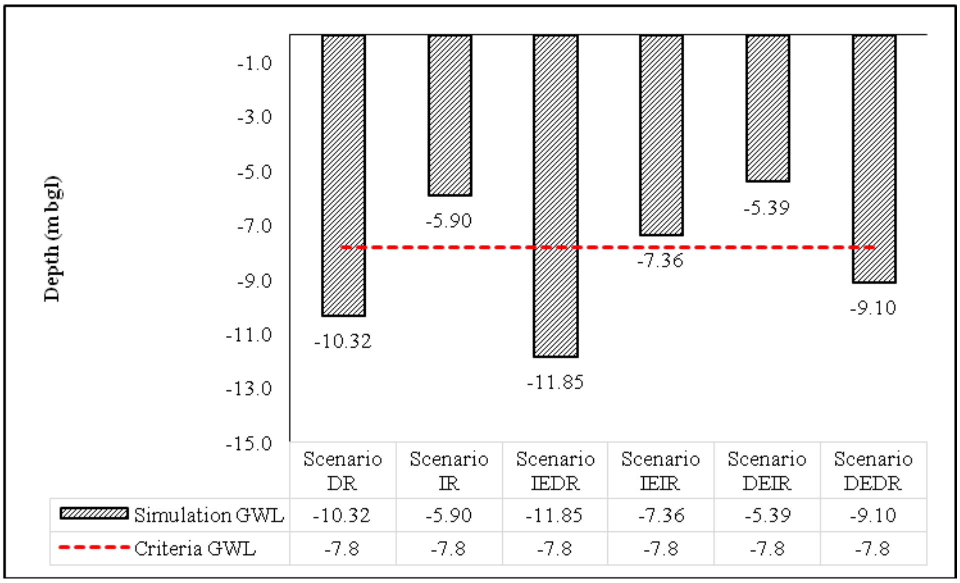


Fig. 10 Average simulated groundwater depth under different scenarios and the baseline (or criteria depth) corresponding to the safe yield (Sy).

5. Conclusions

This study applied modeling approach to estimate groundwater yield of Dili aquifer in Timor Leste. A groundwater flow model developed using MODFLOW in ModelMuse environment showed a reasonably good performance with higher values of NSE, RMSE and R^2. The model simulated results revealed that surface topography has a control on groundwater flow; it generally flows from the highlands in the southern part of the aquifer towards the flat areas along the coastal line. The rate of decrease in piezometric level, however, varies at different well fields.

Analysis of various scenarios reflecting rate of increase in current (or baseline) groundwater abstraction by various percentages revealed that safe yield (Sy), which results in change in groundwater storage close to zero, of the Dili aquifer is 0.28 m^3/s. Considering current level of population, with abstraction equal to Sy, the aquifer can produce 0.12 m^3/person/day of groundwater, which is adequate to supply the amount of water that NDWSS strategy envisions to supply. Further analysis shows that estimated groundwater depth corresponding to Sy at Comoro_B well field will be 7.8 mbgl.

Finally, groundwater abstraction required to main the groundwater depth of 7.8 mbgl (corresponding to Sy), which is defined as sustainable groundwater yield (SGy) in this study, was estimated by analyzing six different scenarios. It suggested that estimated SGy to sustain groundwater development in the Dili aquifer is likely to be within a range of 0.23 to 0.28 m^3/s.

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Groundwater management at Dong Thap province in Vietnam

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Abstract

The paper analyses the role of groundwater resources, which accounts up to 30% of the water used for domestic purposes in Vietnam, in the national water resources management plan. The administrative and legal framework for groundwater management in Vietnam is also analyzed pointing out no separate management system for groundwater resources but integrated in the general water resource management system. In the case study, an estimate of the exploitable reserves of freshwater in Dong Thap province is provided, with a detailed description of the location and distribution area for 07 aquifers in the study area. Existing and potential issues during groundwater extraction are discussed. The results of this analysis and assessment are the necessary basis for planners and policy makers in managing the exploitation and use of groundwater for local socio-economic development.

Key Words Groundwater management, groundwater exploitation, global issues

1. Introduction

Over the world, groundwater represents the largest stock of accessible freshwater and accounts for about one-third of freshwater withdrawals (Sieber, et al., 2010 and Famiglietti, 2014). However, groundwater exploitation and contamination have increasingly become global problems (Cheng, et al., 2014, Foster, et al., 2013; and Zheng and Liu, 2013). The cumulative impacts of increasing population, urbanization, increased water use with prosperity, land-use change, inexpensive drilling and pumping technology, industrialization, expansion of irrigated agriculture, institutional changes, stricter water quality standards, and perhaps the influence of climate change, have led to widespread, often unmanaged, use of groundwater throughout the world (Gorelick, 2015). The issue of groundwater management remains a practical concern in many regions worldwide, while water managers continue to grapple with the question of how to manage this resource (Koundouri, 2004).

As a coastal country, Vietnam is predicted to be one of the countries seriously affected by climate change, affecting population, agricultural land and gross domestic product due to saltwater intrusion. In addition, economic growth leads to high water demand (Doungmanee, 2016) in all sectors - agricultural, industrial, and domestic. With the increasing demand, groundwater exploitation is also intensifying, whereas the geological, hydrogeological conditions, and dynamics are very complex and the understanding of groundwater reserves and quality is limited, leading to difficulties for national management of groundwater resources. Therefore, research on groundwater resources will create the basis for future policy and strategy planning to adapt and mitigate the impacts of climate change and sea level rise, and ensure water resources for sustainable development.

Thus, this paper aims to discuss the difficult and complex challenge of groundwater management in Vietnam, review the role of groundwater resources in the national water resources management plan and the administrative and legal framework for groundwater management. A case study of groundwater status in Dong Thap province, which is one the key agricultural economic zone in Vietnam, is also discussed to clarify the existing and potential problems in groundwater management in Vietnam and suggest future pathways to preserve this precious resource to ensure food security.

2. Groundwater in the national water resources management (Vietnam)

2.1 The Role of groundwater resources in the national water resources management plan

Groundwater resources play a very important role in serving water supply for people's daily life and serving production for socio-economic development. In Vietnam, currently up to 30% of the water used for domestic purposes is groundwater. However, there are about 17.2 million people (equivalent to 21.5% of the population) using water from drilled wells without treatment (Vietnam Institute of Occupational Health and the Environment. 2013). In addition, due to unreasonable exploitation and lack of strict control and planning, groundwater resources in some areas have lowered excessively, especially in urban areas, causing saline intrusion and land surface subsidence.

Vietnam's territory is divided into 28 groundwater storage units. The total groundwater reserves across the entire territory of Vietnam (excluding islands) are estimated at about 189.3 million m^3/day (freshwater); about 61.4 million m^3/day (saltwater) and is large compared to the other countries (Vietnam Ministry of Natural Resources and Environment, 2018). However, exploitation ability depends on the characteristics and hydrogeological conditions of each area. Currently, only the plains, coastal plains and the Central Highlands have favorable conditions for large-scale exploitation of groundwater. According to preliminary statistics, the total amount of groundwater exploitation nationwide is estimated at 10.5 million m^3/day.night (accounting for about 17.2% of exploitable groundwater reserves) (Vietnam Ministry of Natural Resources and Environment, 2018). Groundwater resources are exploited mainly to supply water for domestic use (urban and rural). Besides, Groundwater is also exploited for other purposes such as: watering coffee and industrial crops in the Central Highlands; aquaculture, shrimp farming in the central coast and Ca Mau.

Concentrated groundwater exploitation on a large scale in some large urban areas has led to lowering of water levels in deep aquifers. Data from the national monitoring network shows that, in Hanoi, from 1992 to present, the decreasing rate of the water level of the main exploited aquifer (Pleistocene aquifer) ranges from 0.08 to 0.91 m/year, but from 2018 to present, it has tended to be stable. In the Mekong Delta region, monitoring data since 1998 shows that the average rate of water level lowering is about 0.06 to 0.4 m/year depending on the aquifer, in which the aquifer is Main exploitation (layer qp2-3 at the depth from 80 to 140 m and layer n22 at the depth from 250 to 280 m) has a larger lowering rate in the range of 0.3 to 0.4 m/year. From 2018 until now, the water level at monitoring points in this area has tended to stabilize, with almost no further lowering, especially at previous hotspots such as: Ba Tri district (Ben Tre province), Bac Lieu city (Bac Lieu province), Duyen Hai town (Tra Vinh province), Ca Mau city (Ca Mau province).

The exploitation of groundwater in Vietnam is often excessive, and the unreasonable arrangement of water exploitation works in large urban areas has caused the decline of groundwater levels rapidly, continuously and partially in aquifers. Although the total amount of groundwater exploitation compared to the potential is not significant. Specifically, exploited volume of groundwater resources in Hanoi and Ho Chi Minh City only accounts for about 21.3% and about 34% of the potential. Meanwhile, in the Mekong Delta region, groundwater exploitation is too concentrated on the qp2-3 aquifer, with the depth of about 80 to 140 m (accounting for about 50% of the total exploitation amount) and concentrated mainly in urban areas, causing a decrease in water levels and an increase in saltwater intrusion in the deep aquifer...

Currently, the investigation and assessment of groundwater resources is only focused on shallow aquifers and is only at a preliminary level. There is no inventory data on groundwater resources, and there is a lack of documents on the current status of groundwater exploitation and use. Currently, only a few provinces and cities have been investigated and assessed the current status of groundwater exploitation at a scale of 1:100,000 such as: Hanoi, Hau Giang, Bac Lieu, Ca Mau, Soc Trang, Can Tho city... On the other hand, the monitoring database management system is still outdated; synthesizing and processing information and monitoring data are still difficult due to lack of equipment and human resources, leading to forecast and warning information used for management being slow, untimely, and unresponsive to requirements.

2.2 Administrative and legal framework for groundwater management

The effective management, exploitation and use of groundwater resources are very important for human existence and development, so it has become an important issue not only for Vietnam. However, in Vietnam, there is no separate management system for groundwater resources but integrated in the general water resource management system (**Figure 1**). In which, two major ministries are responsible for water resources, the Ministry of Natural Resources and Environment (MONRE) and the Ministry of Agriculture and Rural Development (MARD).

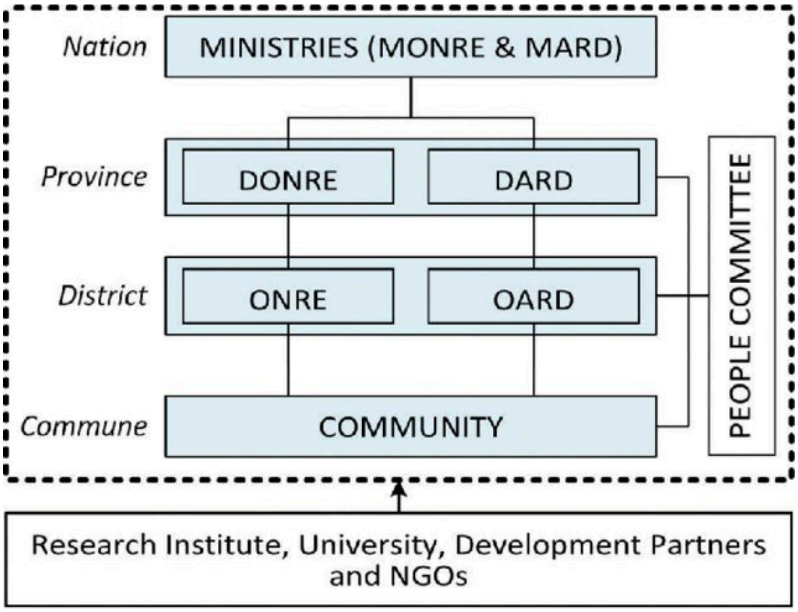

Figure 1: The principal institutional arrangements for water governance. Note: MONRE = Ministry of Natural Resources and Environment; MARD = Ministry of Agriculture and Rural Development; DONRE = Department of Natural Resources and Environment; DARD = Department of Agriculture and Rural Development; ONRE = Office of Natural Resources and Environment; OARD = Office of Agriculture and Rural Development (Nguyen, et al., 2020).

Groundwater resources are managed through legal documents. Specifically, since the Law on Water Resources in 1998, the protection of groundwater has been focused, the Ministry of Natural Resources and Environment has issued Decision No.15/2008/QD-BTNMT regulating the protection of groundwater resources; Decision No.14/2007/QD-BTNMT regulating the treatment and filling of unused drilled wells. When the Law on Water Resources in 2012 is promulgated and takes effect, based on the Law's assigned contents, the Ministry of Natural Resources and Environment issues relevant Circulars in protecting groundwater, including: Circular No.24/2016/TT-BTNMT regulating the determination and announcement of sanitary protection zones for domestic water intake areas; Circular No. 72/2017/TT-BTNMT regulating the treatment and filling of unused drilled wells; Circular No. 75/2017/TT-BTNMT regulating groundwater protection in drilling, digging, exploration and groundwater exploitation activities; Circular No. 27/2014/TT-BTNMT stipulating that the Department of Natural Resources and Environment evaluates, determines, and compiles a list of areas that must register for groundwater exploitation in the area.

Currently, the Ministry of Natural Resources and Environment proposes many solutions to strengthen management, inspection and supervision of exploitation activities to protect groundwater resources, specifically the Ministry has issued Circular No.17/2021 /TT-BTNMT regulating the supervision of exploitation and use of water resources (replacing Circular No.47/2017/TT-BTNMT), which regulates organizations and individuals exploiting and using water resources (including groundwater exploitation) must connect and provide monitoring data into the water exploitation and use monitoring system so that management agencies can monitor compliance with license regulations and the laws on water exploitation and use.

To control and minimize the groundwater exploitation in the areas that are degraded, polluted, or at risk of degradation, pollution and land subsidence, the Ministry has submitted to the Government to promulgate Decree No.167/2018/ND-CP dated December 26, 2018 regulating the restriction of groundwater exploitation, which stipulates that the Provincial People's Committee must delineate areas where groundwater exploitation is restricted and implement measures to prohibit the exploitation to protect groundwater resources. The Ministry has also sent documents urging local agencies to restrict groundwater exploitation, strengthen groundwater protection while ensuring the legal rights and interests of organizations and individuals.

In addition, the Ministry has also submitted to the Government to promulgate Decree No.82/2017/ND-CP stipulating the method of calculation of fees for granting the right to exploit water resources, as amended and supplemented in Decree No. 41 2021/ND-CP, which stipulates that organizations and individuals must pay fees for granting the right to exploit natural resources based on the amount of water used. The Decree has had an impact on organizations and individuals in increasing the awareness of economical and efficient exploitation and use of water, contributing to the protection of groundwater resources. Many organizations and individuals have changed the process, improved the efficiency of the model of economical water use and have proposed to adjust the license to reduce the exploiting volume.

The Ministry of Natural Resources and Environment is currently focusing on amending the Law on Water Resources, which will amend and supplement articles and clauses for strictly controlling and supervising the exploitation of groundwater to ensure the dual goal of strengthen the protection of groundwater, while fully ensuring the legal rights and interests of organizations and individuals in exploiting and using groundwater.

3. Case Study: Groundwater status in Dong Thap province, Vietnam

3.1 Water supply and demand of Dong Thap province, Vietnam

Dong Thap province is located in two sub-regions of the Mekong Delta: the Dong Thap Muoi sub-region and the sub-region between the Tien and Hau rivers, with the Tien River flowing through the province about 120 km and the Hau river about 30 km (**Figure 2**). Dong Thap province has a very important position in the Dong Thap Muoi region, which is known as a key agricultural production area of the country, playing a key role in ensuring national food security. Dong Thap is at the headwaters of the Mekong River in Vietnam, has abundant surface water and many groundwater heads at different depths which has only been exploited and used to serve urban and rural activities, not yet used for industry.

In Dong Thap province, there are 10,909 wells exploiting groundwater with the exploited volume of 161,065 m^3/day.night, of which 1,592 wells are damaged or degraded. In which, Hong Ngu is the district with a large number of aquaculture wells, so the exploited volume is the largest with 52,536 m3/day.night (mainly concentrated in the water-poor Holocene layer) accounting for about 33% of the total exploited volume of the province.

The exploitation works for domestic use in Dong Thap province are divided into 2 types: shallow wells (<150m) and deep wells (≥150m). Shallow wells are small exploitation wells with an exploited volume of a few m^3/day.night. These are mainly individual and household wells. The province has 10,290 shallow drilled wells. Thap Muoi is the district with the largest number of shallow wells with 2,255 wells. Deep wells are mainly water supply stations with large exploited volume from several tens to several hundred m^3/day.

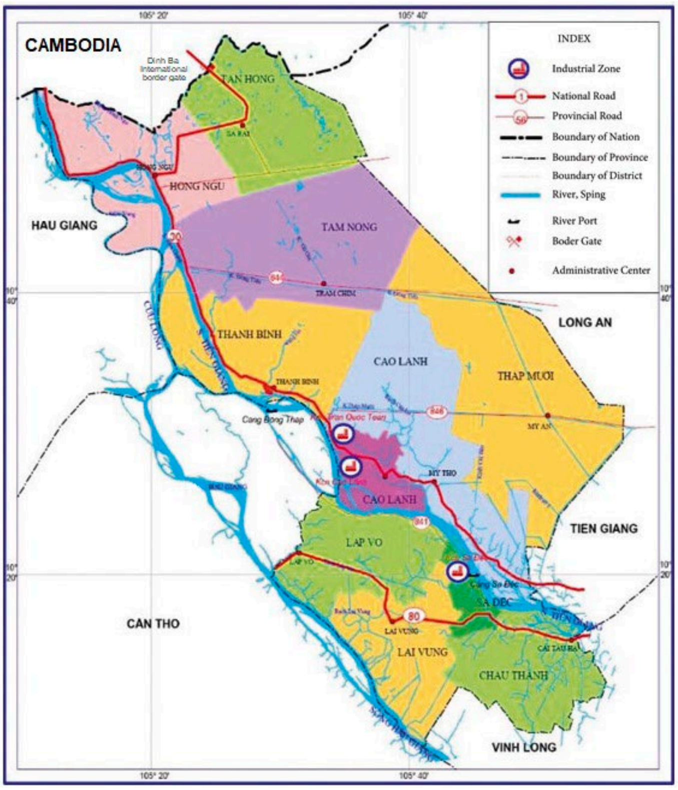

Figure 2: Map of Dong Thap province, Vietnam (Zhu and Liu, 2023)

Dong Thap province has 497 wells with an average exploited volume of more than 100 m^3/day with a total exploited volume of 129,627 m^3/day.night (**Table 1**). Hong Ngu is the district with the largest number of works and exploited volume with 264 works exploiting about 50,800 m^3/day.night. Meanwhile, Thanh Binh is the district with the least number of works with 12 works exploiting 6,411m3/day. Hong Ngu town does not have any works with exploited volume greater than 100 m3/day. For works with exploited volume < 100 m3/day.night, Dong Thap province has 8,753 works with a total volume of 31,438 m3/day.night, mainly concentrated in 4 districts of Thanh Binh, Thap Muoi, Tan Hong and Hong Ngu (**Figure 3**).

In general, Dong Thap is a province with a exploited volume of groundwater. Besides Hong Ngu, other districts such as Thanh Binh district, Cao Lanh city, Cao Lanh district and Sa Dec town, all of these localities have exploited volumes greater than 10,000 m3/day.night.

Table 1: Number of groundwater exploitation works with exploited volume ≥ 100m3/day.night (Dong Thap province Department of Natural Resources and Environment, 2020)

No	District/City	Number of wells	Exploited volume (m3 /day.night)
1	Tan Hong	17	7.615
2	Hong Ngu	264	50.800
3	Hong Ngu Town	-	-
4	Tam Nong	19	7.401
5	Thanh Binh	12	6.411
6	Thap Muoi	20	5.230
7	Cao Lanh City	22	11.149
8	Cao Lanh	36	10.202
9	Lap Vo	22	6.570
10	Lai Vung	44	7.730
11	Sa Dec	22	11.010
12	Chau Thanh	19	5.510
Total		497	129.627

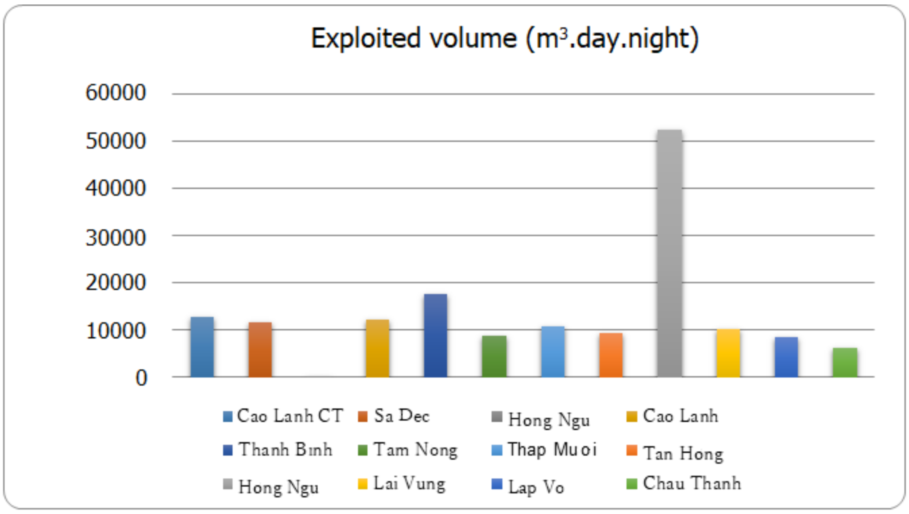

Figure 3: Groundwater exploited volume (m^3/day.night) in Dong Thap province (Dong Thap province Department of Natural Resources and Environment. 2020)

Based on water use standards for each sector, water demand in Dong Thap province is calculated and shown in **Table 2**, of which water demand for domestic use is 46.4 million m3/year, for industry is 56.6 million m3/year, for livestock is 12.85 million m3/year, for aquaculture is 210 million m3/year, mainly exploited at depths from 60 meters to 80 meters, for cultivation is 2,305 million m3/year, mainly exploited at depths from 12 meters to 20 meters. Water resources supplied for farming and aquaculture are not as high quality as those used for daily life and industry. Total water demand for daily life, industry and livestock is 115.85 million m3/year.

Table 2. Water demands of different sectors (Dong Thap province Department of Natural Resources and Environment, 2020)

Unit: million m^3/year

No	District/City	Domestic use	Industry	Cultivation	Livestock	Aquaculture	Total
	Total	46,4	56,6	1.599,55	12,85	210,0	1.925,4
I	Zone I	16,3	21,4	363,12	4,76	55,3	460,88
1	Chau Thanh	3,8	2,7	114,65	1,49	29,5	152,14
2	Lai Vung	3,9	5,9	109,97	1,51	6,7	127,98
3	Lap Vo	4,6	6,8	121,62	1,31	13,4	147,73
4	Sa Dec	4,0	6,1	16,88	0,45	5,7	33,13
II	Zone II	30,1	35,1	1.236,43	8,08	154,7	1.464,41
II.1	Sub-zone IIa	14,8	22,1	571,75	3,10	66,0	677,75
1	Thap Muoi	3,7	5,6	299,90	1,37	10,0	320,57
2	Cao Lanh	5,1	7,6	243,29	1,31	52,9	310,2
3	Cao Lanh City	6,0	9,0	28,57	0,42	3,0	46,99
II.2	Sub-zone IIb	15,3	13,0	664,69	4,99	88,7	786,68
1	Thanh Binh	3,9	2,7	157,85	1,25	18,5	184,2
2	Tam Nong	2,7	1,9	206,13	1,13	36,5	248,36
3	Tan Hong	2,5	1,7	141,51	0,93	13,3	159,94
4	Hong Ngu Town	2,8	4,2	94,79	0,50	13,9	116,19
5	Hong Ngu	3,4	2,4	64,41	1,17	6,5	77,88

3.2 Overview of the aquifer, including hydrological and hydrochemical characteristics

In Dong Thap province, there are 07 aquifers distributed from the surface ground to a depth of 450m, including: 1) Porous aquifer in Holocene sediments (qh); 2) Porous aquifer in upper Pleistocene sediments (qp3); 3) Porous aquifer in middle - upper Pleistocene sediments (qp2-3); 4) Porous aquifer in lower Pleistocene sediments (qp1); 5) Porous aquifer in upper Pliocene sediments (n22); 6) Porous aquifer in lower Pliocene sediments (n21); and 7) Porous aquifer in upper Miocene sediments (n13).

a) Porous aquifer in Holocene sediments (qh)

Formation of the porous aquifer in Holocene sediments (qh) are coarse grained sets of mixed river-sea sediments of the Lower-Middle Holocene (amQ21-2). The petrographic composition of the aquifer is mainly gray, dark gray, light brown fine-grained sand, interspersed with powder, in many places containing plant humus, mica scales, powdery deposits and small pebbles. The Holocene aquifer has some outcrops on the surface, the rest is covered by very poor Holocene geological formations and has a thickness of 0 to 46m, averaging 26.8m, tends to be thick in the south along the length. along the banks of the Tien River.

The freshwater area is widely distributed throughout the province except for Hong Ngu district, Hong Ngu Town, Tam Nong district, total mineralization M = 0.18g/l-0.96g/l, pH = 6.5-7.0. Saltwater distribution area is about 602 km2. Common chemical form of water is Chloride - Sodium Calcium Magnesium. In general, the Holocene aquifer (qh) has a small freshwater distribution area, limited thickness, poor water storage, and large saltwater distribution area. The aquifer is shallow, showing signs of being salinized, favorable exploitation conditions but low quality and low groundwater reserve. Therefore, this is not a promising aquifer for the study area.

b) Porous aquifer in upper Pleistocene sediments (qp3)

Formation of the porous aquifer in upper Pleistocene sediments (qp3) are coarse-grained sets of sediments originating from the upper Pleistocene river (aQ13). The lithological composition of the aquifer is mainly fine- to coarse-grained sand of gray, blue-gray, dark gray, light brown colors, in many places containing gravel and small pebbles interspersed with lenses of clay powder and sand powder. The average aquifer thickness is 29.16m. This aquifer is widely distributed throughout the region and is not exposed on the surface but is covered by geological formations that are very water-poor in the Upper Pleistocene (amQ13).

Freshwater is distributed along the Hau River, in the West, Southwest and a small area in the North of the region, where resistivity values range from >11ohm.m to 15ohm.m and from

>11ohm.m to 25ohm.m, the area is about 182km2. Common chemical forms of water are Bicarbonate - Sodium Magnesium, Bicarbonate Chloride - Sodium Magnesium and Bicarbonate Chloride - Sodium Magne. Saltwater distributes in the remaining area of the province, where resistivity values range from 1ohm.m to 5ohm.m and from 5ohm.m to <11ohm.m. Common water chemistry types are Chloride - Sodium, Chloride - Sodium Magnesium and Chloride - Sodium Calcium Magnesium.

c) Porous aquifer in middle - upper Pleistocene sediments (qp2-3)

Formation of the porous aquifer in the middle - upper Pleistocene sediments (qp2-3) are coarse grained collections of sediments originating from the middle - upper Pleistocene river (aQ12-3). In terms of petrographic composition, the aquifer consists of two parts: The upper part is a layer of poorly permeable fine grains with continuous distribution, consisting of clay, silt, sometimes gray, yellowish brown to brown sand powder, which is strongly weathered, containing a lot of laterite conglomerate, thickness varies from 5.0m to 27.6m; The lower part is water-bearing soil and rock, including layers of fine, medium, and coarse-grained sand of blue-gray and light-gray color containing loose gravel and gravel, with rich water capacity. In the sand layers, there are alternating layers of yellow, brown-gray, ash-gray or blue-gray silt and clay. Coarse sand and gravel layers usually have a thickness of 26.0m to 81.3m, with an average of 58.7m. This aquifer is widely distributed throughout the region, only exposed on the surface in the North of Sa Rai area and a few small strips in Tan Hong district, covered by geological formations with very poor water in the middle - upper Pleistocene (amQ12-3).

Freshwater is distributed into patches scattered across the districts, where resistivity values range from >11ohm.m to 25ohm.m. Common water chemistry types are Bicarbonate - Sodium, Bicarbonate Chloride - Sodium Magnesium and Bicarbonate Sulfate - Sodium Calcium Magnesium. Saltwater distributes in the remaining area, where resistivity values range from 1ohm.m to 5ohm.m and from 5ohm.m to <11ohm.m. Common chemical forms of water are Chloride - Sodium Magnesium and Bicarbonate Chloride - Sodium Magnesium. The middle - upper Pleistocene aquifer (qp2-3) is only exploited in suitable areas for the domestic water needs of small clusters and households.

d) Porous aquifer in lower Pleistocene sediments (qp1)

Formation of the porous aquifer in lower Pleistocene sediments (qp1) are coarse-grained sets of lower Pleistocene river sediments (aQ11). This aquifer is widely distributed throughout the region and is not exposed on the surface but is covered by geological formations that are very water-poor in the lower Pleistocene (amQ11). The lithological composition of the aquifer according to the cross-section of the stratigraphic columns, the aquifer consists of 02 parts: The upper part is a weak permeable layer consisting of clay, clay-silt with a thickness varying from 6.0m to 12.0m. ,0m. This layer grows continuously, with the average depth of 9.0m; The lower part is soil and rock capable of holding water, including medium to coarse, unconsolidated sand of green-gray, ash-gray color, sometimes containing gravel. This water layer is quite homogeneous. In general, the roof and floor are concave in the center of Dong Thap Muoi. The thickness of the unstable aquifer is thin in the North, thick in the South, thickness varies from 7.0m to 44.0m, average 22.32m.

Freshwater is distributed into patches (Tan Hong district), where resistivity values range from >11ohm.m to 25ohm.m. This aquifer's freshwater is only promising for exploiting to provide for individual households. Saltwater distributes in the remaining area of the province, where resistivity values range from 1ohm.m to 5ohm.m and from 5ohm.m to <11ohm.m.

e) Porous aquifer in upper Pliocene sediments (n22)

In Dong Thap, the upper Pliocene aquifer (n22) has a wide distribution across the province, but is mostly covered by younger sediments. The thickness of the aquifer is very unstable, decreasing from the center and south and west of the province, averaging 36.43m. The petrographic composition of the aquifer is mainly fine- to medium-grained, coarse sand, in some places the petrographic composition of the aquifer is silty sand, gray-blue, gray-white, yellow-grey patchy, in some places interspersed with rocks. clay layer, powder, clay powder.

Freshwater is distributed in parts at Tan Hong, Thanh Binh, Cao Lanh districts, where the resistivity value is from >11ohm.m to 25ohm.m, the area is about 3162.2km2. Common water chemistry types are Bicaconate - Sodium, Bicarbonate Chloride - Sodium. Saltwater distributes in the remaining area about 212.1km2, where resistivity values from 1ohm.m to 5ohm.m and from 5ohm.m to <11ohm.m. The chemical form of water is Chloride - Sodium.

f) Porous aquifer in lower Pliocene sediments (n21)

Formation of the porous aquifer in lower Pliocene sediments (n21) are coarse-grained sets of mixed river-marine sediments of the lower Pliocene. The lithological composition of the aquifer is mainly fine- to coarse-grained sand mixed with gravel, in some places, the lithological composition of the aquifer is silty sand, green gray, white gray, patchy yellow gray, alternating layers of clay, silt, and clay powder. The thickness of the aquifer is unstable, on average 33.10m. This aquifer is widely distributed throughout the region, not exposed on the surface but covered by geological formations that are very water-poor in the lower Pliocene.

Freshwater is widely distributed, from the center (area of Sa Dec Town - Lai Vung Town) to the west of the region, where resistivity values range from >11ohm.m to 25ohm.m. Common chemical forms of water are Chloride Bicarbonate - Sodium, Bicarbonate - Sodium. Saltwater distributes in the remaining area in the east of the region, where resistivity values range from 1ohm.m to 5ohm.m and from 5ohm.m to <11ohm.m. The chemical form of water is Chloride Bicarbonate - Sodium.

g) Porous aquifer in upper Miocene sediments (n13)

Formation off the porous aquifer in the upper Miocene sediments (n13) are coarse-grained sets of mixed fluvial-marine origin of the upper Miocene sediments (amN13). The thickness of the aquifer is large and quite stable, averaging 87.50m. The lithological composition of the aquifer is mainly fine- to medium-coarse-grained sand mixed with gravel in some places, green-gray, ash-gray, yellow-gray, interspersed with quite thick layers of clay, silt, and sand powder. The distribution area is mainly in the central part to the south, the north is thinly beveled. This aquifer is widely distributed throughout the region, not exposed on the surface but covered by geological formations that are very water-poor in the Upper Miocene (amN13).

/Freshwater distributes in almost the entire area of the province, where resistivity values range from > 11ohm.m to 25ohm.m (some places > 25ohm.m), with an area of about 3,123.00 km2. Common chemical forms of water are Bicarbonate - Sodium, Bicarbonate Chloride - Sodium and Chloride Bicarbonate - Sodium. Saltwater has a narrow distribution, where resistivity values are from 5ohm.m to <11ohm.m. The chemical form of water is Chloride Bicarbonate - Sodium, Chloride - Sodium.

3.3 Existing and potential problems associated to groundwater extraction

Problem 1. Investigate and evaluate factors affecting groundwater resources

The factors affecting groundwater resources are diverse. Based on the level of impact, the following issues need the most attention:

Related to natural factors, the issues include: Research, evaluate impacts and predict the effects of climate on groundwater resources such as saline intrusion, floods, sea level rise; Research on the impact of exploitation activities on groundwater resources (salt water exploitation for aquaculture, irrigation...). Related to artificial factors, the issues include: There has been no periodic inventory and assessment of the current status of groundwater exploitation; The specific exploitable reserves of each aquifer have not been determined based on standard procedures and regulations; Reasonable exploitation density in each aquifer, exploitation zones, and restricted exploitation areas has not been determined.

Problem 2. Creating a database of groundwater resources and sharing information between relevant sectors and localities as well as bordering provinces

In Dong Thap province, the application of information technology and computerization has been done. However, this database is implemented according to old protocols that are not compatible with current GIS system, so access is very difficult. Thus, the implementation of water resources database needs to pay attention to the following issues:

Prepare an information system and database of groundwater resources, associated with databases on environment, land and other fields under the management of the Department of Natural Resources and Environment, ensuring integration with government's information system and database on water resources.

Problem 3. Licensing and registration

It is necessary to regularly review and inspect and detect organizations and individuals drilling and exploiting groundwater without a license or registration.

It is necessary to promote the role of people, communities and local authorities at the grassroots level, especially commune cadastral officials in regularly reviewing and inspecting and detecting organizations and individuals drilling, exploring, exploiting groundwater without license or registration.

Problem 4. Not promoting and investing properly in communication activities

The development and implementation of the program on dissemination of the Law on Water Resources has not been emphasized in provincial agencies. The building of a network of propagandists has not been emphasized, along with training professional knowledge and basic knowledge on water resources and water resource protection.

Specific mechanisms and policies have not yet been developed to mobilize organizations and residential communities in participating in supervising activities of well drilling, exploration and exploitation of groundwater and implementing solutions to protect local groundwater resources.

Problem 5. Capital sources for water management and protection of groundwater resources

The localities in Dong Thap province need a fairly large capital source while the budget is limited, so it is necessary to have an appropriate mechanism to diversify investment forms and attract investment capital from all economic sectors in the society. Therefore, it is necessary to have a specific and long-term implementation program to publicize the list of works and invite investors. In particular, it is necessary to take full advantage of ODA capital (with low interest rate and long repayment period) and non-refundable support capital from foreign organizations.

It is necessary to have programs, projects, long-term plans and annual plans to be invested from the governmental budget for water resource management, strengthen equipment for management, as well as to encourage domestic and foreign organizations and individuals to participate in the exploitation and protection of groundwater resources.

Problem 6. Taxes on natural resources and environment

The issue of environmental resource taxes has long been of concern in localities, but it has not been systematically implemented. It is necessary to develop a system of methodology and legal framework. Organizations and individuals carrying out exploratory drilling and underground water exploitation are obliged to pay taxes according to law. Organizations and individuals exploiting and using water need to fulfill their environmental resource tax obligations according to law.

Problem 7. Prevent and deal with the risks of groundwater pollution

The risk of pollution due to urban development, population growth, and economic development leads to increased demand for water exploitation and use, and concentration of exploitation leads to excessive exploitation. The risk of pollution from wastewater discharged into groundwater resources increases from industrial production, craft villages and from urban domestic wastewater.

4. Good practice, Lesson learned

To strengthen the management and protection of groundwater sources and respond to the decline in groundwater quality, Vietnam has been implementing a number of solutions as follows:

1) Focus on amending the Law on Water Resources, focusing on amending and supplementing policies to improve effectiveness and efficiency in management to protect, exploit, and use groundwater resources rationally and sustainably;
2) Continue to promote the implementation of legal documents related to the protection of groundwater resources in localities, especially the promulgation of the List of areas where groundwater exploitation is restricted; Implement appropriate measures to restrict groundwater exploitation; Treat and fill unused wells to minimize groundwater pollution;
3) Organize the implementation of the master plan for basic investigation of national water

resources, including reasonable exploitation planning, adjusting current groundwater exploitation plans accordingly, ensuring that the total amount of exploitation does not exceed the groundwater reserve and the safe exploitation limits;

4) Organize the implementation of the national water resources inventory project approved by the Government;
5) Invest in upgrading and completing the construction and operation of the groundwater exploitation monitoring system to monitor and detect works with excessive water level decline and propose solutions; Upgrade and complete the groundwater database system;
6) In addition, conduct research and apply solutions to increase freshwater storage capacity and gradually reduce groundwater exploitation; Apply rainwater storage solutions in urban and residential areas to reduce flooding and artificially replenish groundwater.

5. Conclusions

The lack of planning and the lack of measures and tools to manage the exploitation and use of groundwater makes water resources at risk of being degraded in both quality and quantity. As a result, there will be water stress problems for daily life and production, while the regulation of water sources to ensure the overall efficiency of the exploitation and use of water resources has not been proactive.

With the goal of development of an integrated, multi-sectoral and multi-sectoral economy, the increasing pressure on groundwater resources is inevitable. Changes in economic structure, development of industries - services, innovations in land management policies, the formation of economic centers, industrial zones and clusters and the rapid urbanization process will drastically change the demand for water exploitation and use, both in terms of quality and quantity. If there are no solutions to regulate, distribute and protect groundwater sources to ensure harmony between the interests of different sectors, the exploitation and use of groundwater will not be sustainable.

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Groundwater Pumping Management in Saigon River Basin

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Abstract

The rapid socio-economic expansion in Ho Chi Minh City and nearby regions since the 1990s has led to a notable increase in groundwater extraction to meet the growing demands for domestic and industrial water. Despite the crucial role of groundwater and Saigon River interaction in maintaining groundwater reserves, a comprehensive understanding of river recharge has received less research attention thus far. This study aimed to delve into the impact of groundwater-river interaction on the aquifer system and optimize pumping strategies, with field seepage measurements and isotopic analysis (O_{18}, H_2) within the Saigon River Basin in Southeast Vietnam. Analysis of δO_{18} compositions in groundwater, river water, and precipitation revealed that river recharge is concentrated in the lower basin regions, whereas downstream observations indicated that the river primarily receives water from upstream groundwater sources. As a response to increasing economic demands, groundwater extraction in the Saigon River basin surged from 175,000 m^3/day in 1995 to 880,000 m^3/day in 2017. This rise in pumping rate led to a reduction in groundwater discharge to the river upstream, declining from 1.6 to 0.7 times the groundwater pumping rate. However, Saigon River recharge increased by 33% to 50% of the total downstream groundwater pumping. Under excessive pumping conditions, the aquifers within the basin released less water to the river and more actively involved in the river–groundwater interaction process. These findings provided recommendations for optimal pumping intensities, including 2000 m^3/day/km^2 for aquifer 1, 3500 m^3/day/km^2 for aquifer 2, and 4000 m^3/day/km^2 for aquifer 4. Consequently, sustainable pumping yields were estimated at 0.88 MCM/day for the existing urban area and 1.02 MCM/day for the new area, resulting in a combined sustainable yield of 1.9 MCM/day. Downstream aquifer management requires more comprehensive coordination with surface water development initiatives, particularly the expansion of surface water supply systems that currently struggle to meet the demands of socio-economic development.

Keywords: Groundwater management, groundwater modeling, surface–groundwater interaction parameters, Saigon River Basin

1. Introduction

1.1 Background

Groundwater holds a critical role in fostering sustainable development in Asian cities, serving domestic, industrial, and agricultural needs. Around one-third of Asia's drinking water is sourced from groundwater, with over half of the potable water supply in many cities coming from this resource. Notably, 60% of rural Cambodia and a significant portion of people without piped systems in Bangladesh, as well as cities like Lahore and Vientiane, rely solely on groundwater for drinking. Cities including Bandung, Ho Chi Minh City, Hyderabad, Kathmandu, Tokyo, and Yangon have piped water systems but heavily depend on groundwater for their drinking water (Koncagül, 2015).

Despite its prevalence and significance, the overexploitation of groundwater poses a considerable challenge to its sustainability in various regions, including Central Asia, China, South Asia, and specific urban areas in Southeast Asia. Although management practices and regulatory frameworks are in place, their effectiveness is hindered by the prevalent unrestricted access regime in many countries. To counteract these concerns, it is imperative to bolster groundwater governance, combining widespread public support and robust enforcement mechanisms to ensure the responsible and sustainable use of this vital resource (UNESCO, 2022).

According to Vietnam's Ministry of Natural Resources & Environment, the nation possesses around 840 billion m^3 of surface water, with only 37% (310 billion m^3) coming from domestic rainfall, while the remaining 63% depends on external water runoff. The potential groundwater exploitation, excluding islands, is estimated at 60 billion m^3, with current investigations targeting approximately 8 billion m^3 annually. Despite Vietnam's average water consumption of about 10,600 m^3 per capita in 2008, comparable to the United States, it falls below the 4,000 m^3 per capita threshold set by the International Water Resource Association (IWRA) for water sufficiency. This consumption is notably lower than that in neighboring countries like Lao PDR, Cambodia, Malaysia, Myanmar, and Indonesia. Amid these challenges, Vietnam confronts a growing demand for water driven by population growth, deforestation, severe water contamination, and rapid urbanization. In terms of inland water sources, Vietnam aligns with nations facing water scarcity on a global scale. Adding to the complexity, the country's water supply lacks seasonal consistency due to unpredictable climate changes and uneven geographical water distribution (Huong, 2016).

1.2 Groundwater problems in the study area

Ho Chi Minh City (HCMC), situated on the banks of the Saigon River in the southern part of Vietnam (refer to **Figure 1**), serves as a significant economic center, contributing approximately 20% to the country's gross domestic product. The city's water supply comes from surface water and groundwater sources (Vuong & Long, 2016). However, the rapid urban and economic growth experienced in HCMC and its surrounding provinces since the 1990s has resulted in excessive groundwater extraction, leading to the depletion of aquifers and subsequent shortages downstream (Phu, 2008; Chan, 2015). Unregulated groundwater exploitation, previously free of charge, has also further exacerbated the extraction rate (Vuong & Long, 2016).

At present, 55% of groundwater is used for household purposes, while industries utilize the remaining 45% for their operations (DWPRIS, 2019). The city's economy is currently dominated by the industrial sector, constituting 63% of the economy, followed by services at 23.5% and agriculture at 4.3%. Notably, the industrial and construction sectors have exhibited significant growth at a rate of 9.1%, the highest among all sectors. The service sector and agro–forestry–fisheries sector have also shown steady progress, with growth rates of 6.9% and 2.2% respectively. In terms of GDP growth, the projected annual increase rates for water demand in the irrigation sector, industry sector, and households are 1%, 7%, and 4%, respectively (World Bank, 2017).

Efforts to safeguard groundwater resources in the Saigon River region have prompted numerous research publications focused on the area's groundwater reservoirs. Researchers have consistently alerted local authorities to pressing concerns such as saltwater intrusion, declining groundwater levels, and inadequate recharge rates. Since 2007, HCMC has implemented a decree that designates areas where groundwater exploitation is prohibited (primarily in inner districts) and areas with limited exploitation (where the pipe pressure of the drinking water network is < 0.2 kg/cm^2). The mapping of these areas is updated annually (Tran Ngoc et al., 2016). Then, local groundwater governance (GWG) is a more effective approach than national strategies (Bruns, 2021), emphasizing stakeholder participation and sustainability (Calliera et al., 2022). Nations reliant on groundwater like Brazil and Iran acknowledge the need for local management to reduce extraction and address specific challenges (Zwickle et al., 2021; Muenratch & Nguyen, 2022). To enhance sustainable socio-economic development through robust groundwater resource planning, a deeper exploration of groundwater recharge mechanisms on a local scale is imperative, particularly under transient conditions.

2. Groundwater in Vietnam's national water resources management

2.1 Role of groundwater

Groundwater exploration has been limited to just 15% of Vietnam's land area, primarily focusing on economically important regions. The evaluated reserves of underground water are classified into A-class (735 million m^3/day), B-class (813 million m^3/day), and C_1/C_2 classes (18,452 million m^3/day). The country's potential water availability from all aquifers, excluding sea islands, amounts to about 2,000 m^3/s or 63 billion m^3 annually. Major groundwater reserves are concentrated in areas like the Red River Delta, Cuu Long River Delta, and Southern East regions. Smaller reserves are found in the Central Highlands, while the mountainous regions of Northern West, Northern East, and Southern Central Coastal areas have the least abundant resources. Monitoring of groundwater movement, a crucial aspect for identifying water sources and assessing dynamic reserves, is primarily carried out in the northern and southern deltas and the Central Highlands, relying on a relatively limited network of monitoring stations (MORE, 2006).

2.2 Groundwater administration

The establishment of a formal water resources inventory in Vietnam is currently lacking. Decision No. 81/2006 QD-TTg (MORE, 2006) highlights the importance of periodic assessments and waste discharge evaluations in water resource utilization. Decision No. 305/2005/QD-TTg (MORE, 2005) introduces indicators related to water resources and the environment, and Decision No. 18/2007/QD-BTNMT (MORE, 2007) specifies statistical indicators for the natural resources and environment sector. This system encompasses criteria for water resources, including reserves of underground water, assessment of underground water reserves, hydrogeological mapping, rainwater and surface water volumes, reservoir counts, wastewater volume, surface water extraction ratio, and exploitable groundwater proportion.

Extraction rights for groundwater were delineated by the initial establishment through the "Temporary Decision on Permits for Extraction of Groundwater and Licensing of Drilling Companies" in 1996 and the later incorporation into the 1999 Law on Water Resources. This entailed permitting holders to utilize groundwater resources for various purposes such as residential use, agriculture, forestry, industrial production, mining, electricity generation, and aquatic farming. Criteria for permit issuance were outlined, including a mandate for permits for groundwater exploration or extraction, except for specific cases. Even the dewatering of groundwater during construction or material excavation necessitated a permit. Expanding or altering water use purposes for existing groundwater facilities also required permit applications. Some exemptions from permits encompassed small-scale household groundwater extraction for non-business uses and certain rehabilitation efforts that did not alter the original permit's scope. However, recent calls have urged for the regulation of household groundwater extraction. This entails private tube-wells established by private drilling teams, those provided by the UNICEF program, and groundwater supply unit (GSU) plants primarily set up by WEMCs. Although regulations were implemented for community tube-wells and GSU plants, the unregulated private tube-wells—constituting a substantial number—remained a concern. Without proper oversight of private tube-wells, effective control over groundwater pollution and subsidence became challenging. Local authorities, particularly at the grassroots level, continue to grapple with groundwater resource management. Despite the establishment of management units for groundwater resources in specific districts, such as Cai Rang, Saigon River Basin's limitations in expertise hindered comprehensive resource management, highlighting the need for more effective control measures (Danh, 2019).

3. Study objectives and approach

3.1 Study area

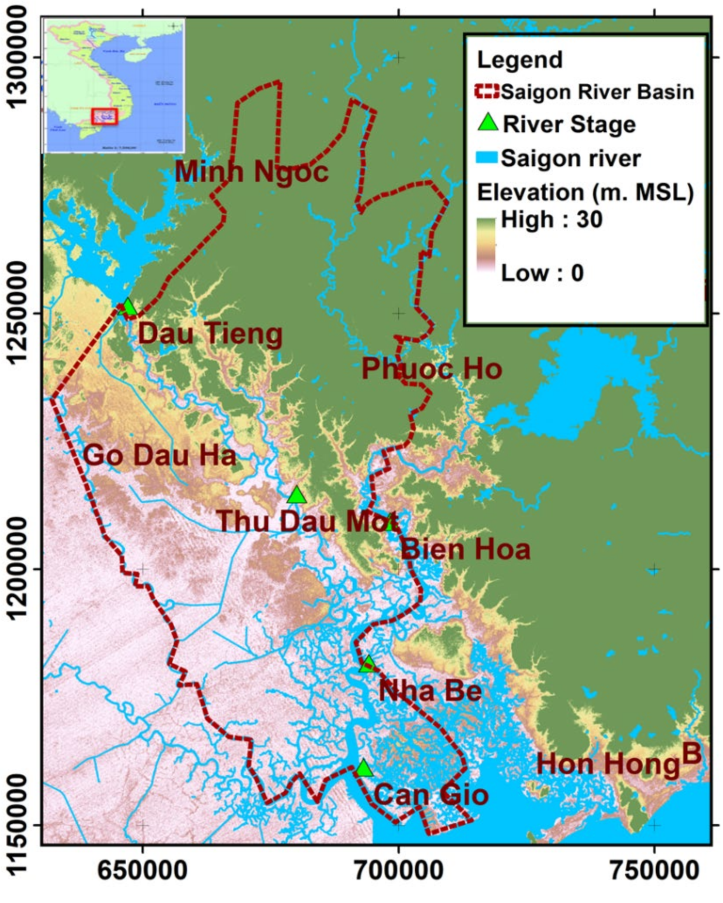

Figure 1: Saigon River basin

The Saigon River Basin encompasses a total area of 6,640 km^2 situated between latitudes 10.320 E to 11.201 E and longitudes 106.215 N to 107.024 N (**Figure 1**). This study domain experiences a tropical climate, characterized as a tropical wet and dry climate, with an average humidity of 75%. The region witnesses two distinct seasons: the rainy season from May to

October and the dry season from November to April. The annual average rainfall reaches 1,612 mm, while the mean annual temperature hovers around 27 °C. The topography varies from sea level to 70 meters above sea level (MSL). Originating in Cambodia, the Saigon River flows through Vietnam, passing the Dau Tieng Dam in Tay Ninh Province, Binh Phuoc Province, Binh Duong Province, and Ho Chi Minh City before reaching the sea. Its course spans 280 km from the Dau Tieng Dam to the estuary. Around 60 km downstream from the dam, the Saigon River bifurcates into two sections: the upper reach with a width of 100 m and a water depth of 12 m, and the lower reach spanning 225 to 370 m in width with depths of up to 24 m (**Figure 2a**). The Dau Tieng reservoir has a storage capacity ranging from 470 million m^3 (at a dead storage water level of 17 m) to 1.68 billion m^3 (at a normal operating water level of 24.4 m). Its functions include flood control and irrigation for agricultural activities in the HCMC region. The reservoir also plays a pivotal role in maintaining a salinity level of 4‰ at the Phu An station (downstream of the Saigon River) during dry periods (Dan et al., 2007).

This study specifically investigates the effects of groundwater and river interaction on fresh aquifers within the Saigon River Basin in Vietnam, excluding the potential impacts of salt intrusion movement and seawater rise. The groundwater model's scope extends from the dam release location to the Phu An station, as depicted by the dashed line in **Figure 2a**.

3.2 Hydrogeological conditions of the study area

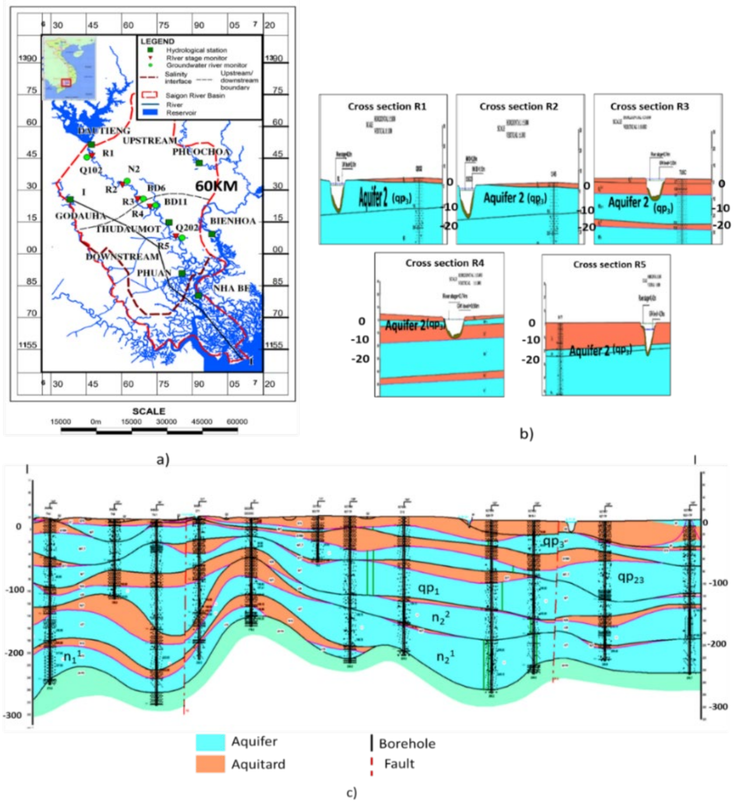

Figure 2: Location map (a), seepage measurement cross-section and (b) Surface water and Groundwater field test cross-section in the study area (c) hydrogeology cross-section in the study area (Vuong, 2010; Vuong & Long, 2016)

The Saigon River Basin encompasses six confined aquifers comprised of alluvial sediments, each separated by clay layers (**Figure 2b**). These aquifers are labeled based on their formation order, ranging from highest to lowest: the Upper Pleistocene aquifer (qp_3), with an average thickness of 23 m; the Upper-Middle Pleistocene aquifer (qp_{2-3}), with an average thickness of 27 m; the

Lower Pleistocene aquifer (qp_1), with an average thickness of 27 m; the Upper Pliocene aquifer (n_2^2), with an average thickness of 38 m; and the Lower Pliocene aquifer (n_2^1), with an average thickness of 34 m. By implementing a total dissolved solids (TDS) threshold of 1,000 mg/L (Freeze, 1979), groundwater in the region can be categorized into two groups: the central and northern areas exhibit TDS concentrations below 1,000 mg/L, signifying freshwater, while the southern and certain parts of the western areas exhibit higher TDS concentrations characteristic of saline water (**Figure 2a**). Following 23 years of rapid groundwater extraction, water levels across all aquifers have undergone a decline of 12 m in the Upper Pleistocene aquifer and 40 m in the Lower Pleistocene aquifer. At present, the volume of groundwater withdrawal in the Saigon River Basin is approximated at 880,000 m^3 per day (Department of Natural Resources and Environment of Binh Duong Province (DNRE-Binh Duong), 2017; Vuong & Long, 2016). Of this total, 484,000 m^3 per day is allocated for domestic usage (including residential, public amenities, and services), while the remaining 396,000 m^3 per day is allocated for industrial applications (Nga, 2006; Vuong & Long, 2016).

3.3 Literature review

In 2000, Win Boehmer (2000) established conductance values for hydraulic stations across the river system using hydraulic conductivity data from pumping tests in the Nambo Plain, encompassing the Saigon River Basin. Calculated conductance levels for the Saigon River ranged from 2.2 m/day to 4.4 m/day. In 2010, Chân & Kỳ (2010) and along with Khai (2014), evaluated potential groundwater replenishment through inverse numerical groundwater modeling, using the conductance values set by Win Boehmer (2000) for groundwater–river interaction parameters. Outcomes indicated that river recharge contributes 20% to 40% of the groundwater budget in the Saigon River Basin, with the river recharge volume demonstrating a linear connection to groundwater extraction. Tuan and Koontanakulvong (2018) established interaction parameter equations for the Saigon River's central section using piezometric head data. However, most studies centered on aquifer hydraulic conductivity, neglecting sediment riverbed properties and the balance between land and river recharge ratios.

3.4 Study objectives and approach

To enhance the effectiveness of groundwater resource planning for sustainable socio-economic development, a comprehensive investigation of groundwater recharge mechanisms becomes crucial, particularly within dynamic contexts. This study is dedicated to unraveling interaction parameters and understanding the repercussions of groundwater and river interaction on the aquifer system within Vietnam's Saigon River basin. The confirmation of interaction parameters along the Saigon River basin was achieved through piezometric head measurements and on-site seepage evaluations. Subsequently, isotopic analysis (O_{18}, H_2) was employed to evaluate the seasonal water balance between the river and groundwater across five distinct segments. By comparing these indicators, a deeper comprehension of the impact of groundwater–surface water interaction on the aquifer system can be attained. To support more robust groundwater resource planning for sustainable socio-economic development, the study introduced a method to assess optimal pumping intensity and sustainable aquifer yield while adhering to criteria of sustainable drawdown under historical climate conditions (1995–2017).

This approach encompassed an analysis of optimal pumping intensity derived from the maximum existing pumping per square kilometer across four aquifers in the Saigon River Basin while ensuring the absence of adverse effects on the groundwater system. Additionally, the study estimated the sustainable aquifer yield by progressively increasing pumpage until the minimum drawdown aligns with the prescribed criteria. These criteria were informed by Vietnam's regulations on groundwater pumping and the hydraulic gradient at the salinity interface.

3.5 Study procedures

The aims of the study involve assessing the interaction between surface water and groundwater processes to propose an optimized groundwater pumping strategy within development scenarios in the Saigon River basin, as depicted in **Figure 3**. The study is divided into two main steps:

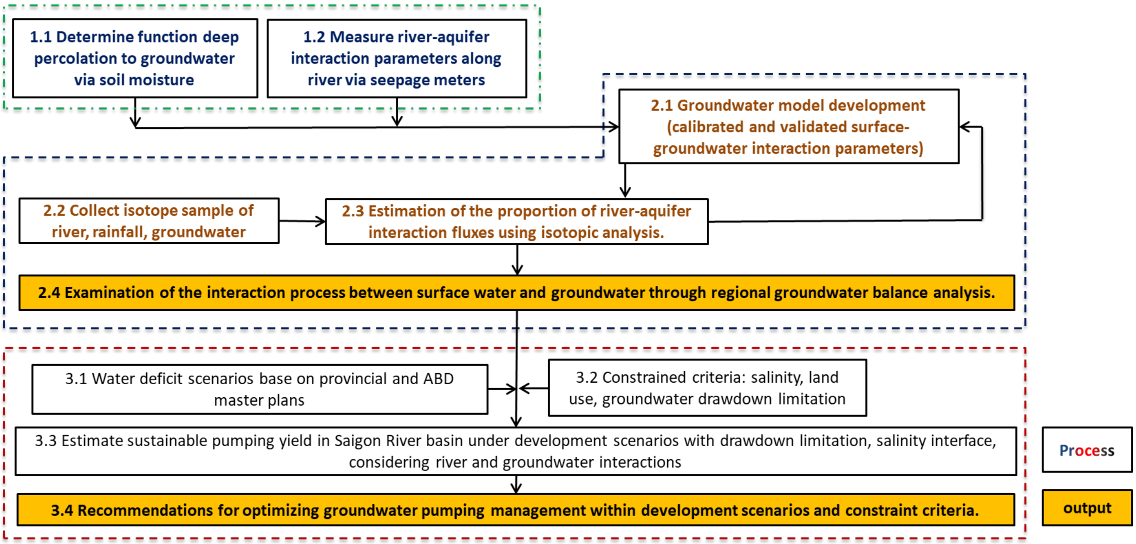

Figure 3: Schematic representation of the study framework

In the first step, the proportion of fluxes exchanged between rivers and aquifers was determined using isotope analysis and groundwater modeling. Isotope samples of H3 and O18 were collected from five river stations on a quarterly basis to analyze the proportions of rainfall, river water, and groundwater. The interaction parameters for the regional groundwater model were calibrated at these stations along the Saigon River using inverse modeling and piezometric data. The calibration was carried out for the period 1995–2006, while verification was done for 2007–2017. The evaluation of the model's performance was based on statistical measures like the coefficient of determination (R^2) and root-mean-square error (RMSE). The interaction parameters were also validated against field seepage rates along the Saigon River. Additionally, the proportions of recent groundwater recharge sources were assessed through the isotopic composition of rainfall, river water, and groundwater. The regional groundwater model's development provides insights into the impacts of groundwater and river interactions on aquifer systems within the Saigon River basin.

The second step involves recommending an optimal groundwater pumping scheme by integrating regional groundwater modeling with surface water-groundwater interactions. Scenarios for groundwater use were projected based on trends (DWPRIS, 2019) and the Master Plan (Ho Chi Minh City People's Committee, 2012), with pumping intensity analyzed to ensure sustainable yield. The optimal pumping intensity was determined by analyzing the maximum existing pumping per square kilometer in four aquifers, ensuring no negative impact on the groundwater system in the Saigon River Basin. The sustainable yield of aquifers was estimated by increasing pumpage until the lowest drawdown of aquifers met the drawdown criteria (**Figure 5**), considering Vietnamese groundwater pumping regulations and the hydraulic gradient at the salinity interface. The "trial and error" approach was employed to simulate sustainable groundwater pumping, factoring in drawdown criteria, saline interface gradient, and land use for the Saigon River Basin. Ultimately, optimal groundwater pumping management was recommended to meet water demand under socio-economic growth, ensuring sustainability, with simulations based on historical climate data spanning the last 20 years (from 1997 to 2017).

4. Theories and materials used

4.1 Groundwater modeling

The simulation of aquifer storage change in response to natural and human-induced stresses is conducted using a groundwater flow model. This model incorporates piezometric head (groundwater level) and fluxes into and out of an aquifer as its parameters. The governing equation for the three-dimensional movement of groundwater is represented as follows (McDonald & Harbaugh, 1988):

$$\frac{\delta}{\delta x}\left[K_{xx}\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta y}\left[K_{yy}\frac{\delta h}{\delta y}\right]+\frac{\delta}{\delta z}\left[K_{zz}\frac{\delta h}{\delta z}\right]+W=S_s\frac{\delta h}{\delta t} \quad (1)$$

where:

K_{xx}, K_{yy}, and K_{zz} represent hydraulic conductivity along the x, y, and z coordinate axes (m/day) respectively;

h signifies the potentiometric head (groundwater level) (m/day);

W denotes the volumetric flux per unit volume of sources and/or sinks of water. Negative values correspond to water exploitation while positive values indicate injections or recharge. W is a function of space and time (i.e. W = W(x, y, z, t));

S_s represents the porous material's specific storage as a function of space;

t signifies time (day).

4.2 Riverbed conductance

The Darcy approach is a prevalent technique for quantifying the flow exchange between groundwater and surface water on a larger scale, such as in ponds or basins. The gradient and exchange of water flow between wells and the surface water body are calculated based on water level measurements in wells near the river and river water stage measurements. The relevant formulas are as follows(McDonald & Harbaugh, 1988; Rushton, 2007):

$$Q=C(h_1-h_2) \quad (2)$$

$$C=\frac{K*A}{L}=K\frac{w}{t} \quad (3)$$

where:

Q represents the volumetric flow rate (m^3/day),

C denotes riverbed conductance (m^2/day/m),

K is the hydraulic conductivity of the material in the riverbed (m/day),

A is the cross-sectional area perpendicular to the flow (m^2),

h_1 signifies the head of the river (m),

h_2 represents the head of the aquifer to flow (m),

L is the length of the prism parallel to the flow path (m),

t signifies the thickness of the sediment in the bottom of the river (m),

w is the width of the material along the length of the arc (m).

Additionally, riverbed conductance can also be determined through seepage measurement, a commonly used method to directly quantify water flux across the sediment–water interface (Murdoch & Kelly, 2003):

$$C = \frac{Q*\Delta z*w}{A_{b*}\Delta h} \quad (4)$$

where:

Q represents the flow rate, measurable via seepage meters (m^3/day),

Δz is the thickness of sediments (m),

Δh signifies the difference in piezometers (m),

A_b is the cross-sectional area of seepage meters (m^2),

w represents the width of the cross-section of the river (m).

4.3 Mass balance of isotopic compositions of groundwater

The Saigon River basin's groundwater resources are influenced by land recharge and the Saigon River itself. To gain a better understanding of the river–groundwater interaction process, the proportion of river charge and land recharge was analyzed using the concentration of stable isotopes. A simple two-component mixing model was employed for this analysis (Rosenberry & LaBaugh, 2008):

$$Q_{GW}\delta_{GW} = Q_S\delta_S + Q_P\delta_P \quad (5)$$

where:

Q represents volume discharge,

δ indicates the stable isotopic composition in parts per thousand enrichment or depletion ("per mil") relative to a standard,

S signifies stream water,

GW denotes groundwater,

P represents precipitation.

4.4 Conceptual groundwater model development

To comprehensively comprehend the dynamics of the river–groundwater budget within the Saigon River Basin, a conceptual model was formulated, visually representing the hydrogeological domain and the intricate physical processes of the aquifer systems, as demonstrated in **Figure 3**. The modeling grid maintained a resolution of 1 km x 1 km. Given the basin's predominant configuration of confined aquifers, the system was segmented into eight layers, encompassing four confined aquifers and four aquitards, illustrated in **Figure 4**. The elevation profiles of these layers were established through interpolation, utilizing inverse distance weighting with data from 403 boreholes. The elevation pattern indicated a gradual decrease from the northwest to the southeast, while the thickness of aquifers exhibited a progressive increase from the upper to lower regions of the Saigon River.

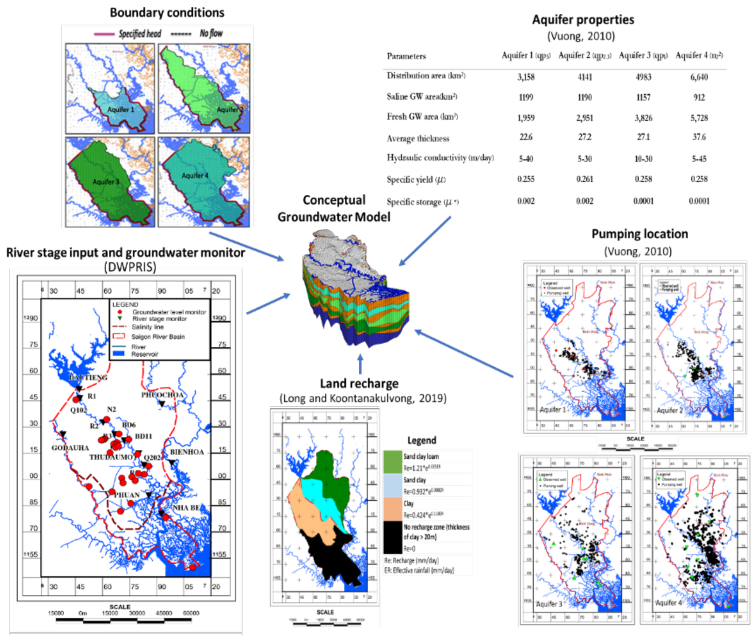

Figure 4: Conceptual groundwater model and inputs in the study (Long & Koontanakulvong, 2020)

Hydraulic conductivity data for the four aquifers were derived from a dataset of 200 well logs, utilizing the Kriging method. A summary of the hydrogeological properties of these aquifers is outlined in **Figure 3**, referencing the works of Vuong (2010) and DNRE-Binh Duong (2017). The aquifer hydraulic conductivity in the upper part Saigon River basin varies from 10 to 20 m/ day, while 20– 30 m/ day hydraulic conductivity is common downstream. The specific storage coefficients of aquifers are 0.0001–0.00001 m^{-1}.

Boundary conditions for the study area were established based on a combination of no-flow, specified head, and general head conditions. Areas interfacing with mountainous terrain and locations perpendicular to groundwater flow were designated as "no-flow" boundaries due to their impermeable nature (Qiu et al., 2015). Along the study area's constraint line, the boundary took on a "specific head" definition, with specified head values determined from average monthly observed piezometric heads encircling the Saigon River Basin. These aquifer properties were extracted from the hydrology map by Vuong (2010). Incorporating groundwater pumping for domestic and industrial usage, the pumping rate remained uniform across both dry and wet seasons. Observed well and pumping well locations were sourced from the Division for Water Resources Planning and Investigation for the South of Vietnam (Vuong, 2010). To mitigate the intrusion of saline water into freshwater areas, pumping wells within the Saigon River Basin were strategically positioned at a distance from the saline boundary. The hydraulic gradient line of the saline boundary remained stable over a 23-year pumping period.

To propose appropriate groundwater pumping strategies aligned with development scenarios, the determination of potential groundwater yield was undertaken by integrating surface water and groundwater interactions, while also considering drawdown, saline interface, and land use criteria. The pumping scheme was particularly focused on urban and surrounding areas, which experience increasing water demand due to socio-economic growth. The criteria for estimating suitable groundwater pumping were established as follows:

Drawdown criteria: Groundwater level was used from the regulation provided by Ho Chi Minh City People's Committee (2007) regarding the reduction of groundwater exploitation; specific drawdown thresholds were defined based on aquifer depths within the Saigon River basin. For aquifers 1 and 2, situated between −50 and −100 m MSL, pumping activities are prohibited if the drawdown exceeds −20 m MSL. Conversely, aquifers 3 and 4, distributed from −100 MSL, permit pumping with a drawdown exceeding 40 MSL. However, considering an elevated pumping rate, drawdown in certain parts of aquifer 2 could reach as low as −25 m MSL. Consequently, the drawdown criterion for aquifer 2 has been revised to not fall below −25 m MSL. Meanwhile, the drawdown criteria for aquifers 1, 3, and 4 adhere to Vietnam's groundwater pumping regulations (**Figure 5**).

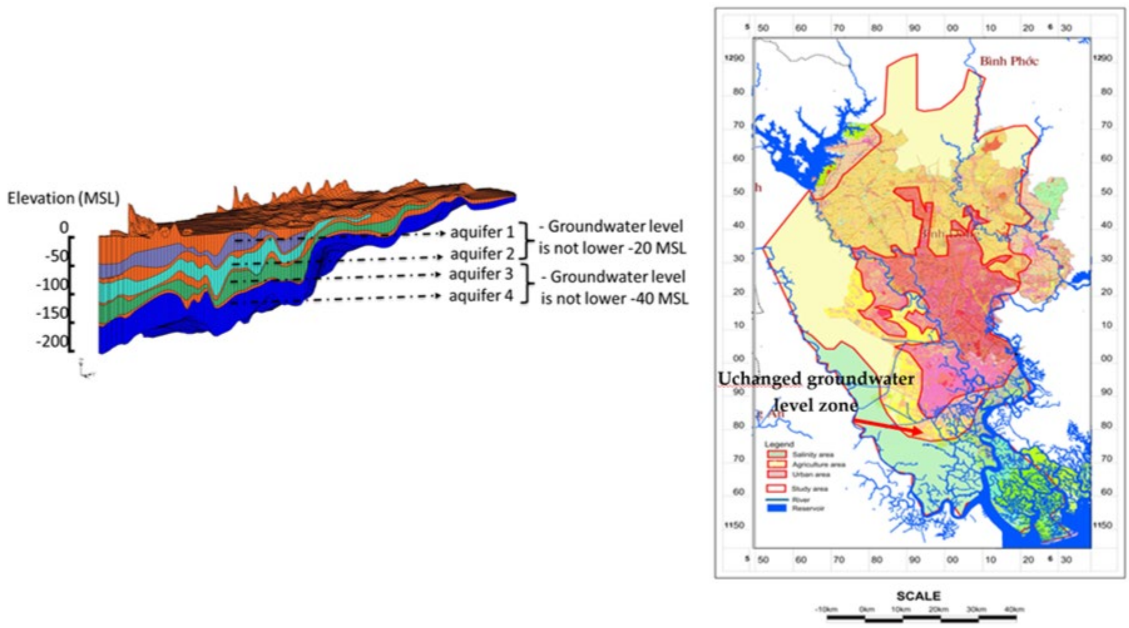

Figure 5: Drawdown criteria and salinity boundary

Saline interface criteria: Considering the presence of salinity in downstream regions in certain areas, preserving the existing hydraulic gradient becomes essential to prevent any escalation in salt intrusion (Guo, Huang, Zhou, & Wang, 2019). Consequently, to curtail any elevation in saltwater intrusion, the groundwater levels downstream must be constrained to their existing levels.

5. Research outputs and discussions

5.1 Groundwater model development and parameter setup

Initially, the estimation of conductance coefficients was derived through inverse modeling in groundwater simulations across five sections denoted as R1-Q102, R2-N2, R3-BD06, R4-BD11, and R5-Q202 (as illustrated in **Figure 2a**). The efficacy of the model calibration and verification hinged upon achieving favorable statistical alignment between computed piezometric heads and the observed data from five wells, specifically designated as Q102, N2, BD06, BD11, and Q202 as indicated in Table 1). The calibration and validation conductance samples are graphically represented in **Figure 5**, revealing mean errors ranging from 0.07 m to 0.61 m, with maximum errors spanning from 0.37 m to 2.5 m. The coefficients of determination (R-squared) fall within the intervals of 0.6–0.86. Notably, the simulation values align within the confidence interval range of the observation data (an example of which is depicted in **Figure 6**). This collective evidence underscores the model's overall commendable performance, thereby validating the suitability of the conductance parameters for subsequent analyses pertaining to river–groundwater interaction.

Table 1. Statistical performance metrics for the calibration and verification phases (Long & Koontanakulvong, 2020)

Section name	R1 - Q102	R2 - N2	R3 - BD06	R4 - BD11	R5 - Q202	R1 - Q102	R2 -N2	R3 - BD06	R4 - BD11	R5 - Q202
	Calibration (1995 - 2006)					**Verification (2007-2017)**				
Max Error (m)	1.73	0.15	2.5	0.37	1.99	1.78	0.28	0.68	0.58	1.22
Min Error (m)	0	0.04	0.04	0	0	0.01	0.03	0	0.02	0
Mean Error (m)	0.61	0.12	0.1	0.12	0.02	0.16	0.11	0.06	0.05	0.07
R^2	0.86	0.94	0.68	0.72	0.65	0.83	0.79	0.6	0.7	0.57
Conductance (m^2/day/m)	4.5	4.2	2.5	1.7	0.25	4.5	4.2	2.5	1.7	0.25

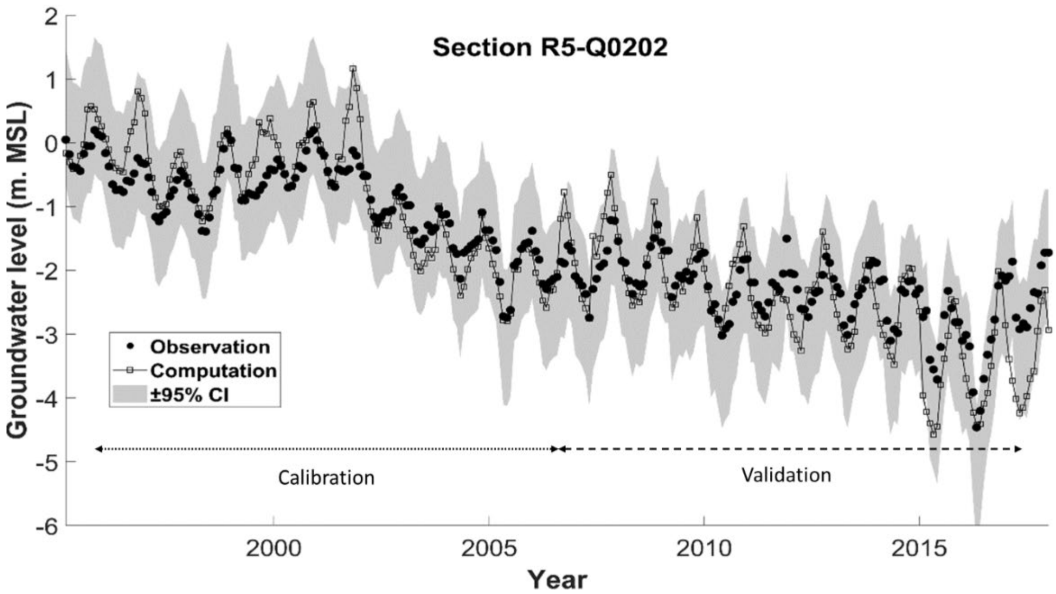

Figure 6: Calibration and verification result at section R5-Q0202 (Long & Koontanakulvong, 2020)

Subsequently, the accuracy of the computed riverbed conductance was verified through comparisons with seepage field measurements conducted along the river in August and October 2018. The outcomes of these field seepage measurements are graphically represented in **Figure 7**. The values proximate to the dam range from 4 m^2/d/m to 6 m^2/d/m. At a distance of 35 km, the range spans 3.2 m^2/d/m to 4.7 m^2/d/m progressing to the 60 km mark, and the riverbed conductance exhibits variations within 2.1 m^2/d/m to 2.9 m2/d/m. At 80 km, the measured values encompass a range of 1.2 m^2/d/m to 1.7 m^2/d/m. Further downstream, specifically at 120 km, the riverbed conductance registers at 0.25 m^2/d/m. Consequently, the estimated riverbed conductance derived from modeling concurs with the outcomes of the seepage field measurements. Moreover, insights garnered from soil test analysis reveal a discernible trend in the reduction of sand-sized sediment proportion along the course of the river. This changing composition of sediment properties along the river signifies that the lithological makeup of Saigon River's sediments directly corresponds to the decreasing conductance from the upper reaches to the downstream region.

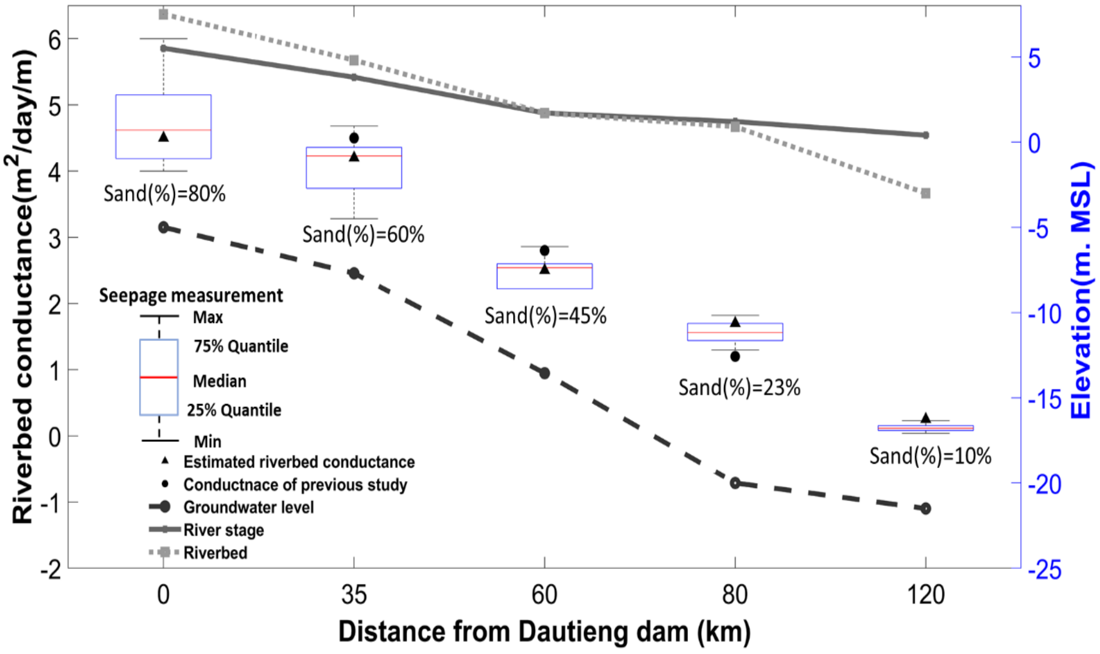

Figure 7:Groundwater–river interaction parameters and riverbed soil type along the Saigon River (Long & Koontanakulvong, 2020)

5.2 Surface-groundwater fluxes and water balance

To evaluate river–groundwater exchange fluxes, quarterly isotope analyses were performed on rainwater, well water, and river water samples in 2018. **Figure 8** illustrates a strong correspondence between hydrogen and oxygen isotope compositions in groundwater from observation wells and those along the Saigon River. Groundwater samples from five stations exhibited δO_{18} values ranging between −7.4‰ and −5.5‰, while δH_2 values ranged from −46.3‰ to −38.2‰. The river's δO_{18} values fell between −7‰ and −5.5‰, and δH2 values ranged from −47‰ to −39‰. A meteoric water line was established using HCMC precipitation isotopes, with δO_{18} from −8.89‰ to −6.57‰ and δH_2 from −53.79‰ to −32.16‰. Clear isotopic differentiation existed among groundwater, river, and precipitation. Groundwater isotopic composition aligned with upstream and downstream river values, indicating shared origins. Matching isotopic profiles of groundwater and Saigon River water upstream suggested common sources. Additionally, higher groundwater levels above upstream river stages induced seepage along the riverbank (**Figure 8**), primarily discharging into the upstream Saigon River. Conversely, downstream, groundwater δO_{18} values were lower than river values but higher than rainfall's, with fluctuating groundwater levels corresponding to river stages and precipitation events. Downstream, groundwater levels were below the river stage (**Figure 9**), indicating that downstream groundwater is a mixture of land recharge and Saigon River sources.

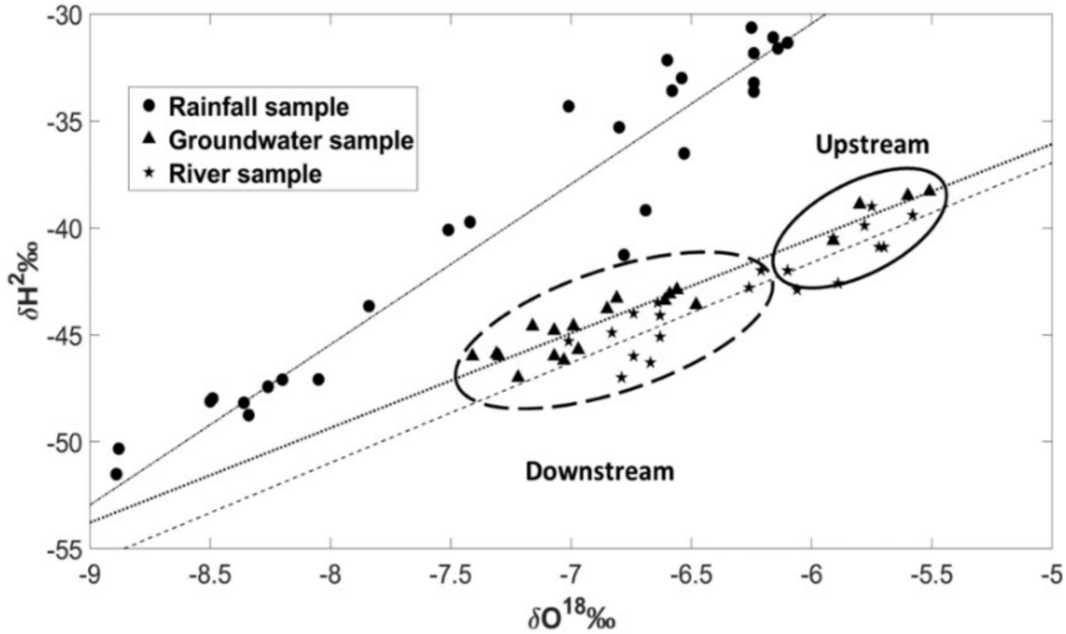

Figure 8: Connection among the δH_2 and δO_{18} measurements within groundwater, river, and rainfall samples across the Saigon River Basin (Long & Koontanakulvong, 2020).

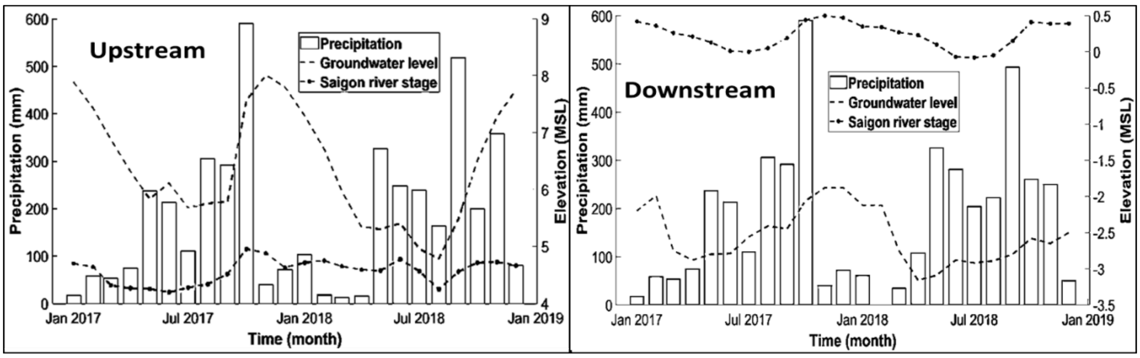

Figure 9: Fluctuation of groundwater levels, Saigon River stage, and precipitation within the Saigon River Basin (Long & Koontanakulvong, 2020).

In the context of understanding groundwater recharge processes, a comprehensive evaluation of actual recharge mechanisms through rainfall and river water was indispensable. The alignment between the isotope analysis-derived ratio of land and river recharge and the Saigon regional groundwater model's exchange fluxes was crucial (Table 2). In the vicinity of 0 km, groundwater with an enriched isotopic signature predominantly contributed to the discharge into the Saigon River. Advancing from the 36 km point, the δO_{18} composition in surface water and groundwater revealed that river water constituted 14% to 73% of the overall groundwater recharge, while land recharge encompassed 27% to 86%. Significantly, the share of river recharge progressively escalated from the 60 km to 120 km segments. With heightened downstream pumping rates causing groundwater levels to dip beneath river levels, a compelling movement of river recharge into aquifers occurred, complementing groundwater storage. The Saigon regional groundwater model underscored land recharge variations of 148 m^3/day to 336 m^3/day across five field stations, alongside river recharge spanning from −1005 m^3/day to 874 m^3/day. Building upon the preceding evidence of river–groundwater interaction, the Saigon River Basin exhibited a bifurcation at the 60 km juncture from the Dautieng Dam: an upstream area characterized by groundwater absorption of land recharge and subsequent release into the Saigon River, and a downstream sector where the river emerged as the principal driver of groundwater recharge.

Table 2. Comparison of isotope composition and fluxes recharge from modeling.

Name section	Distance from Dautieng dam	Isotope			Groundwater modeling	
		GW (%)	Land recharge (%)	River recharge (%)	Land recharge (m^3/day)	River recharge (m^3/day)
R1-Q202A	**0km**	**100**	**0**	**100**	**336 (100%)**	**0 (0%)**
R2-N2	**35km**	**100**	**86**	**14**	**336 (100%)**	**0 (0%)**
R3-BD6	**60km**	**100**	**69**	**31**	**148 (70%)**	**64 (30%)**
R4-BD11	**80km**	**100**	**61**	**39**	**148 (64%)**	**83 (36%)**
R5-Q102A	**120km**	**100**	**27**	**73**	**268 (23%)**	**874 (77%)**

5.3 Groundwater pumping management

Figure 10 visually demonstrates the influence of river interaction on the aquifer system resulting from increased pumping leading to drawdown in the Saigon River Basin during the period 1995–2017. Over this span, distinct pumping patterns in the downstream of the basin divided the water budget into three phases: low pumping (1995–2000), escalating pumping (2001–2010), and sustained high pumping (2011–present). During the initial phase, elevated groundwater storage prevailed in the upstream, with groundwater discharge to the river exceeding pumping by a factor of 1.6. Downstream, positive groundwater storage persisted, with river recharge contributing 33% to groundwater pumping volume. However, intensive economic growth led to pumping surpassing recharge in the downstream, causing a decline in hydraulic head and enlarging the gap between river and groundwater levels. This trend extended to the upstream but to a lesser degree. The recent years have witnessed sustained high pumping rates, where the Saigon River furnishes 40%–50% of the total downstream groundwater pumping. Groundwater storage downstream stabilized, while in the upstream, marginal decreases occurred in storage and discharge. This intricate interaction between river and groundwater emerged as a vital supply source for sustaining groundwater reserves within the Saigon River Basin.

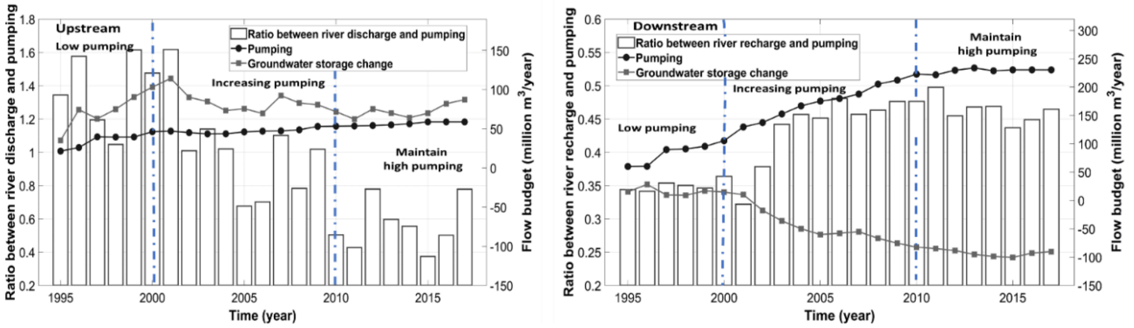

Figure 10: Influence of river interaction on the aquifer system resulting from pumping leading to drawdown in the Saigon River Basin.

The proposed optimal pumping intensity for the Saigon River Basin primarily focuses on aquifers 2–4 due to the relatively low abstraction of aquifer 1. The study involved analyzing groundwater pumping intensity across kilometer blocks for aquifers 2–4, based on data from numerous pumping wells within the basin. The groundwater pumping intensity across the three aquifers in the Saigon River Basin varies within the range of 0 to 5000 m^3/day/km^2 (**Figure 11**). In rural areas, the pumping intensity for these aquifers remains below 500 m^3/day/km^2, which can be attributed to the lower population density in these regions. Conversely, urban areas with higher population densities witness significantly elevated pumping intensities, with aquifers 2 and 4 experiencing levels exceeding 4000 m^3/day/km^2. This heightened pumping exerts downward pressure on the piezometric heads of these aquifers, causing them to decline below the elevation of 30 MSL. Exceptionally, aquifer 3 exhibits lower abstraction due to its low thickness.

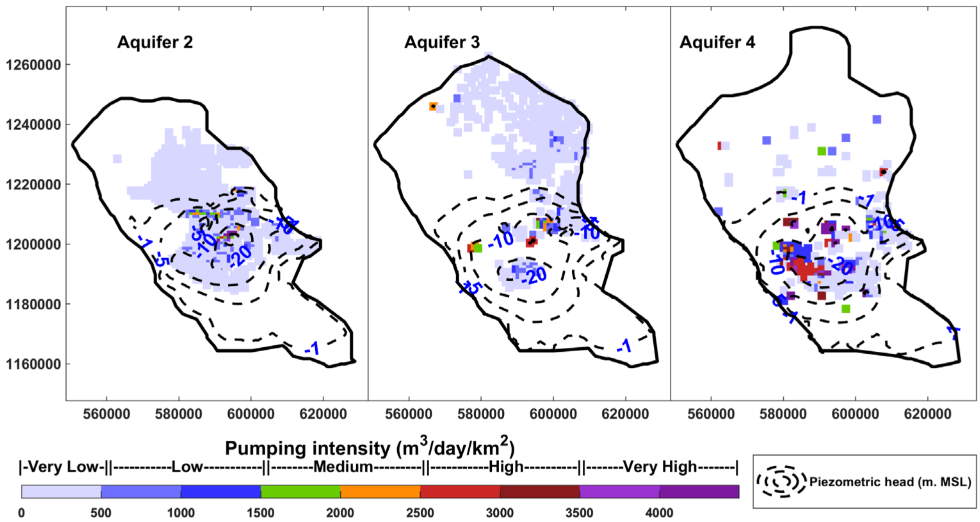

Figure 11: Pumping intensity and piezometric heads in Saigon River in May 2016 (Long et al., 2022)

To determine an appropriate pumping intensity, a comparison was made between the pumping intensity of the three aquifers and the resultant groundwater drawdown in the Saigon River Basin. To prevent the exacerbation of salt intrusion resulting from increased groundwater pumping, the suitable intensity levels for the three aquifers were selected based on established drawdown criteria. Specifically, the piezometric heads of aquifers 1 and 2 were not permitted to drop below −20 m MSL, while for aquifers 3 and 4, the allowable threshold was −30 m MSL (Ho Chi Minh City People's Committee, 2007). Consequently, the proposed sustainable pumping intensity for aquifers 2, 3, and 4 were set at 2500, 3500, and 4000 m^3/day/km^2, respectively (as illustrated in **Figure 12**).

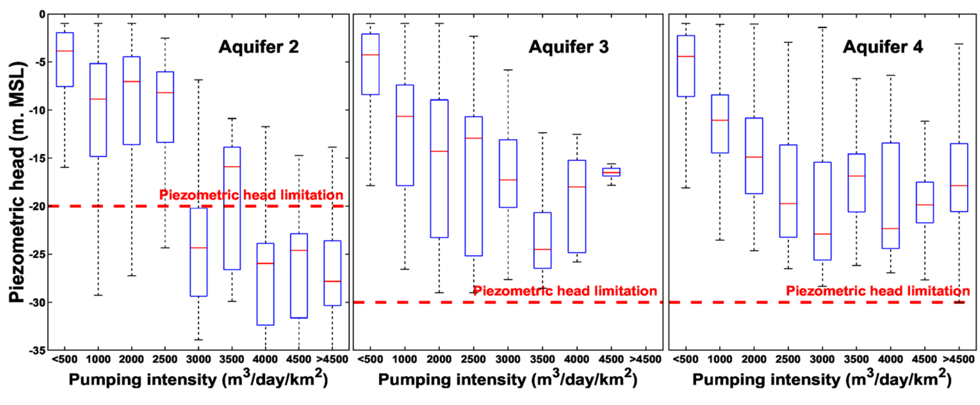

Figure 12: Piezometric head of three aquifers under different pumping intensities

6. Conclusions and recommendations

Groundwater and river interaction dynamics were comprehensively assessed using a hybrid approach involving field measurements and inverse groundwater modeling. This investigation yielded valuable insights, revealing a gradual decrease in conductance values from upstream to downstream: 4.5 m^2/day/m to 0.25 m^2/day/m. This decline correlated with shifts in riverbed composition from sand to silt. Stable isotope analysis of groundwater, river, and rainfall samples offered an accurate depiction of exchange fluxes between groundwater and the river. The outcomes indicated that upstream groundwater discharged into the river while downstream areas experienced groundwater recharge from the river.

However, the escalation of groundwater pumping due to economic expansion in the Saigon River basin from 1995 to 2017, increasing from 175,000 m^3/day to 850,000 m^3/day, prompted shifts in river–groundwater interactions. This transformation impacted upstream and downstream zones, resulting in a reduction in groundwater discharge to the river from 1.6 to 0.7 times the pumping rate in the upstream. By contrast, Saigon River recharge surged, contributing 33% to 50% of the total groundwater pumping in the downstream area. Effective management of aquifers in the downstream region necessitated alignment with river water management strategies, particularly the expansion of HCMC surface water supply infrastructure to meet burgeoning water demands.

Drawing from these insights, recommendations for optimal pumping intensities were developed under transient conditions. These were 2000 m^3/day/km^2 for aquifer 2, 3500 m^3/day/km^2 for aquifer 3, and 4000 m^3/day/km^2 for aquifer 4, considering drawdown criteria and a 20-year historical climate dataset. Consequently, sustainable pumping yields were estimated at 0.88 MCM/day for the existing urban area and 1.02 MCM/day for the new area. This cumulative sustainable yield of 1.9 MCM/day underscored the significance of a balanced approach to effective water resource management. Importantly, this comprehensive methodology for sustainable pumping yield estimation in groundwater-rich regions like the Saigon River can serve as a blueprint for optimizing water resources of surface and groundwater planning in other urban contexts.

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