Report of the CCOP-GSJ-VGD Groundwater Project Phase IV Meeting
12-14 March 2024, Nha Trang, Vietnam

COORDINATING COMMITTEE FOR GEOSCIENCE PROGRAMMES
IN EAST AND SOUTHEAST ASIA (CCOP)
in cooperation with
GEOLOGICAL SURVEY OF JAPAN (GSJ), AIST

Gaurav Shrestha (Chief Editor)

I. PREFACE

Groundwater is one of the important natural resources essential for various purposes in human life. However, its improper exploitations have resulted in various groundwater issues and problems, mainly in the late 20th century. In recent days, land subsidence, seawater intrusion and groundwater pollution by toxic substances are serious problems all around the world. East and Southeast Asia also have faced many of these problems which need international cooperation to be solved. The CCOP-GSJ Groundwater Project has been launched aiming to provide some solutions for groundwater management in the CCOP region.

The CCOP-GSJ-VGD Groundwater Project Phase IV Meeting was held on 12-14 March 2024 in Nha Trang, Vietnam. It was attended by 42 participants from Brunei Darussalam, Cambodia, China, Indonesia, Japan, Republic of Korea, Lao PDR, Malaysia, Mongolia, Myanmar, Papua New Guinea, Philippines, Thailand, Vietnam and the CCOP Technical Secretariat. In the meeting, participants confirmed the outcomes of the CCOP-GSJ Groundwater Project Phase IV and discussed the upcoming plans and objectives.

Each CCOP member country made a presentation on the topic of “Hydrogeological information of the representative area/city with active water usage (groundwater or surface water or both in one’ country and water utilization ways”. All the participants discussed the topic actively.

This publication compiles all the country reports presented in the CCOP-GSJ-VGD Groundwater Project Phase IV Meeting, 12-14 March 2024, Nha Trang, Vietnam.

I am very grateful to the authors for their invaluable contribution to the project and to their organization for giving the permission for this publication.

Gaurav SHRESTHA

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Groundwater Project Phase IV Meeting
12-14 March 2024, Nha Trang, Vietnam

The CCOP-GSJ-DGR Groundwater Project Phase1 IV Meeting was held on 12-14 March 2024 in Nha Trang, Vietnam. It was attended by 42 participants from Brunei Darussalam, Cambodia, China, Indonesia, Japan, Republic of Korea, Lao PDR, Malaysia, Mongolia, Myanmar, Papua New Guinea, Philippines, Thailand, Vietnam and the CCOP Technical Secretariat (CCOPTS).

Dr. Young Joo Lee, CCOPTS Director and **Dr. Youhei Uchida**, the GSJ International Cooperation Promotion Group Leader welcomed all the participants to the meeting. **Dr. Le Quoc Hung,** Permanent Representative of Vietnam to CCOP and Deputy Director General of Vietnam Geological Department (VGD) officially opened the meeting.

Dr. Gaurav Shrestha, the GSJ Groundwater Project Phase IV Leader, presented the Past Achievements of CCOP-GSJ Groundwater Project and reviewed the Plans, Objectives and Outcomes of Phase IV.

The Phase IV kicked-off in 2019 in Bali, Indonesia, and the annual meeting reports have been published as well as the electronic version which have been made available at the GSJ website, https://www.gsj.jp/en/publications/ccop-gsj/index.html and at the CCOP website, https://ccop.asia/e-library. During this phase, the project updated, expanded and improved the CCOP Groundwater Database made accessible via the GSi Web System, https://ccop-gsi.org/gsi/groudnwater/index.php.

Country reports on “Hydrogeological information of the representative area/city with active water usage (ground or surface water or both) in one’s country and water utilization ways” were presented and discussed actively among the participants.

Participants also had an open discussion on the theme and ideas on the next Groundwater Project Phase V. Some of the key words were CCOP standard, inclusion of surface water, sea water intrusion, water contamination, modeling based on the groundwater database, climate change, groundwater management policy, etc. GSJ will discuss it with the participants in the coming days and decide the new theme.

The submission deadline of the full paper of country report is on 31 July 2024. Participants are required to submit the full paper on time to be able to participate in the next CCOP-GSJ Groundwater Project Meeting.

Brunei Darussalam (Mr. Muhammad 'Asri Akmal Bin Haji Suhip)	Cambodia (Sambo Heng)
China (Dr. ZHU Ge)	Indonesia (Mr. Munib Ikhwatun Iman)
Japan (Dr. Gaurav Shrestha)	Republic of Korea (Dr. Hee Jun Suk)
Lao PDR (Mr. Ounakone Xayviliya)	Malaysia (Mrs. Mazatul Akmar binti Aros)
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Thailand (Ms. Ocpasorn Occarch)	Vietnam (Dr. Hoang Van Hoan)
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Hydrogeological information of active water usage (surface water) in Brunei Darussalam and water utilization ways

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Abstract

As Brunei Darussalam heavily relies on surface water resources for both domestic consumption and various industrial applications, several agencies and institutions have undertaken initiatives to continuously monitor and identify potential issues. This paper examines the current state of water resources in Brunei Darussalam, focusing on surface water sources, water treatment processes, and the ecological health of the Brunei River. It analyzes data from the Department of Water Services (DWS) on water abstraction and treatment from 7 treatment plants located throughout the country, emphasizing the reliance on 4 major dams and including the performance of key water treatment plants. Additionally, it highlights findings from Universiti Brunei Darussalam (UBD) led monitoring program of the Brunei River, which evaluated critical water quality parameters at 8 monitoring stations along the river, where the historical Kampong Ayer is situated, and identified pressing challenges such as wastewater pollution, seawater intrusion, and sedimentation based on pH, temperature, DO, ORP, BOD, ammonia-nitrogen, CFU, TDS, EC, salinity, and turbidity results. The research highlights the urgent need for enhanced water resource management strategies, including improved wastewater treatment systems, stricter industrial discharge regulations, and active community engagement, to ensure the sustainability of Brunei's water resources and the preservation of the Brunei River's ecological balance.

Keywords: Brunei Darussalam groundwater, hydrogeological map, Asia

1. Introduction

Surface water is one of the most vital and widely used natural resources in Brunei Darussalam, playing a fundamental role in the nation's water supply system. Located in the northwestern part of Borneo, Brunei is blessed with a tropical rainforest climate and substantial annual rainfall, which is a key factor in its abundant surface water resources. The country experiences an average annual precipitation of over 2,800 mm, with some inland regions receiving more than 4,000 mm. This plentiful rainfall, occurring in two distinct peak periods, October to January and May to July feeds into an extensive network of rivers, streams, and other surface water bodies. These watercourses not only provide essential freshwater but also support diverse sectors such as agriculture, industry, and domestic use.

Brunei's geology further complements this abundance. The country's landscape is largely shaped by sedimentary formations, including sandstones and shales, which promote efficient surface water runoff. These geological features facilitate the flow of rainwater into rivers and streams, creating an interconnected system of surface water resources. Major rivers, such as Brunei, Tutong, Belait, and Temburong Rivers, are critical to both local communities and ecosystems, offering water for drinking, agriculture, and transportation.

However, despite these favorable conditions, the management of surface water resources in Brunei is not without its challenges. The tropical climate, while a source of water abundance, also brings unpredictability in the form of intense monsoonal rains and occasional flooding. These weather events can impact water quality and disrupt the consistency of water supply. In addition, the growing pressures of urbanization and industrial development pose significant threats to the sustainability of surface water resources. Increased urban runoff, sedimentation, and pollution from human activities place considerable strain on the health of the nation's rivers and streams. To address these challenges, several organizations have initiated comprehensive monitoring programs to assess both the uptake and condition of water resources throughout the country, which will be discussed further in this paper.

2. Major water resources mangement

Water sources in Brunei Darussalam are predominantly derived from surface water, with an overwhelming 99.5% of the country's total water supply originating from improved surface water systems. This significant reliance emphasizes the critical importance of robust water resource management strategies to safeguard the nation's water security. The Department of Water Services (DWS) plays a pivotal role in ensuring the continuous supply and consistent quality of water throughout the country. This is achieved through an extensive network of pumping stations, reservoirs, and dams, which collectively form the backbone of the country's water distribution system, ensuring the diverse needs of the population are met efficiently and sustainably.

Currently, Brunei hosts a total of 56 reservoirs distributed across the nation. However, most of the water extraction is concentrated at several key dams (see figure 1), including the Ulu Tutong Dam, spanning an estimated area of 6.2 million m^2; the Benutan Dam, covering approximately 5 million m^2; the Kargu Dam, with an area of 2.4 million m^2; and the Mengkubau Dam, encompassing around 1.9 million m^2. These dams serve as primary sources of raw water for treatment and distribution, ensuring a reliable supply of various applications.

Data from the DWS report covering 2018 to 2023, as shown in Table 1, highlights the performance of seven major water treatment plants across the country, which collectively abstract an average of 197,281.46 m^3 of raw water. Among these, the Bukit Barun treatment plant stands out, recording the highest average abstraction volume of 111,375.90 m^3, followed by the Layong treatment plant with an average of 37,895.57 m^3. The strategic locations of these plants, particularly near the Ulu Tutong and Benutan Dams, ensure a steady and efficient raw water supply to meet the growing demand for clean, treated water.

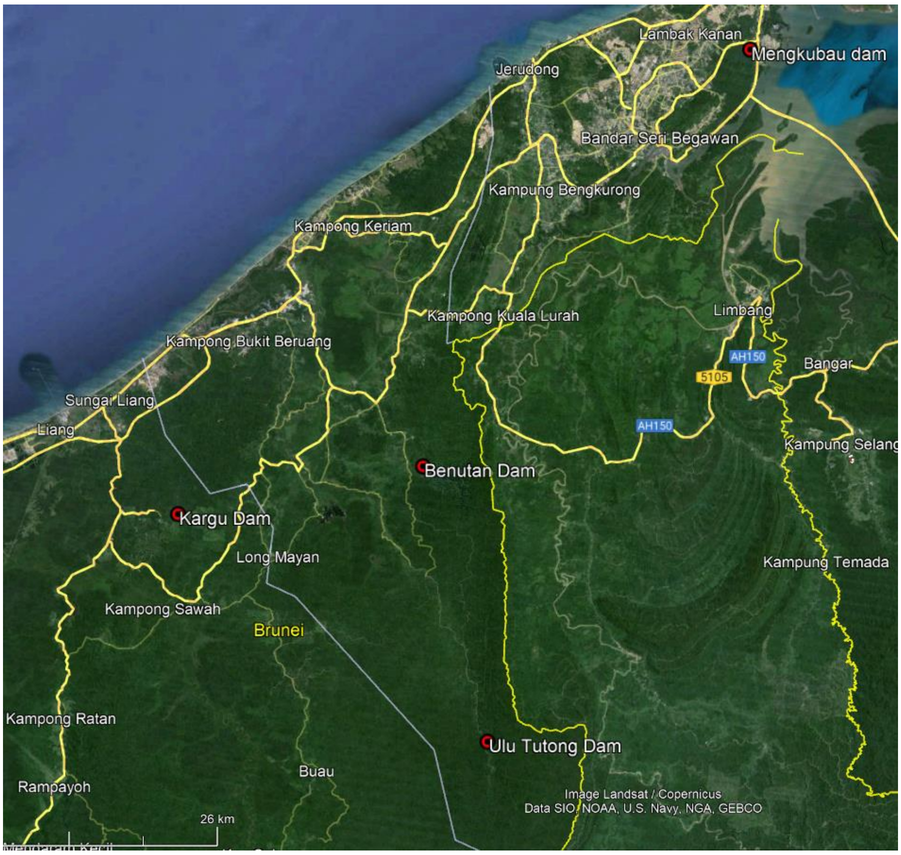

Fig. 1. Location of Brunei Darussalam's major dams

The treatment plants collectively achieve an average production of 160,118.20 m³ of treated water daily, reflecting an effective production rate of 81.2%. This efficiency shows the effectiveness of Brunei's water treatment infrastructure in converting raw water into safe, potable water for public consumption.

Table 1. Brunei Darussalam water abstraction and production

WATER TREATMENT PLANT	AVERAGE ABSTRACTION
BUKIT BARUN	111,375.90
LAYONG	37,895.57
SERIA	19,328.45
SG. LIANG	12,024.27
MANGKUBAU	13,229.76
SUMBILING	1,253.80
BATANG DURI	2,173.71
TOTAL AVERAGE ABSTRACTION	197,281.46

WATER TREATMENT PLANT	AVERAGE PRODUCTION
BUKIT BARUN	86,062.17
LAYONG	34,738.53
SERIA	11,974.33
SG. LIANG	10,749.44
MANGKUBAU	12,942.58
SUMBILING	1,629.70
BATANG DURI	2,021.45
TOTAL AVERAGE PRODUCTION	160,118.20

To maintain the safety and quality of the water supply, DWS operates eight water laboratories across the nation. These laboratories monitor critical water quality parameters, including temperature, colour, turbidity, conductivity, pH value, Hardness, calcium, Magnesium, Alkalinity ($CaCo_3$ and Phenolpthalein), acidity, residual chlorine Aluminum, Iron, Manganese, Fluoride, Chloride, Total suspended solids as well as dissolve solids according to World Health Organization (WHO) guidelines. This proactive water quality monitoring system forms a cornerstone of Brunei's water management strategy, enabling the early detection and mitigation of potential contaminants.

3. Monitoring of the Brunei River: A Hydrogeological Perspective

The Brunei River, located in the densely populated Brunei-Muara district, serves as a vital waterway and is home to Kampong Ayer, one of the world's largest and oldest water settlements. With a population of 10,250, Kampong Ayer is a cultural and historical icon, consisting of homes, schools, and infrastructure built on stilts above the river. This settlement, dating back over a thousand years, it is Brunei's heritage while playing a significant socio-economic role. However, increasing environmental pressures and human activities in the region call for comprehensive monitoring to safeguard the river's ecological balance and water quality. Universiti Brunei Darussalam (UBD) has taken the initiative to monitor the Brunei River, focusing on critical water quality parameters and their broader implications for local communities and aquatic ecosystems.

Eight monitoring stations (see figure 2) using have been established by UBD along the Brunei River to evaluate its water quality comprehensively. Eleven parameters are regularly assessed, including pH, temperature, DO (dissolved oxygen), ORP (oxidation-reduction potential), BOD (biological oxygen demand), ammonia-nitrogen, CFU (colony-forming units), TDS (total dissolved solids), EC (electrical conductivity), salinity, and turbidity as shown in table 2.

Fig. 2. Location of 8 monitoring stations for monitoring water quality of Brunei River

Table 2. Water quality of Brunei River

Year	Parameter	Mean values Q	P	N	J	G	E	D	B
1984	pH		7.18	7.16	7.10	7.03	7.05	7.04	
2019		6.75	7.10	7.15	7.04	7.29	7.19	7.37	7.57
2020		6.68	6.91	7.07	7.04	7.23	7.26	7.25	7.33
2021		6.82	6.76	6.88	6.95	6.96	7.12	7.22	7.24
1984	Temperature (°C)		29.87	30.05	27.93	29.83	29.51	29.65	
2019		29.85	30.01	29.97	30.00	30.16	30.01	30.04	30.14
2020		29.70	29.93	29.92	29.81	29.97	30.22	30.02	29.81
2021		28.73	28.97	29.15	29.12	29.09	29.16	29.26	29.29
1984	ORP (mV)		185.00	198.25	213.67	228.00	233.25	224.00	
2020		288.94	285.76	277.30	278.14	271.96	267.17	267.85	278.60
2021		188.51	159.33	135.91	142.21	143.60	145.98	133.16	140.34
1984	Salinity (ppt)		20.97	20.63	20.38	20.90	23.51	22.84	
2019		12.43	18.58	18.73	16.16	20.23	16.64	21.30	22.93
2020		11.44	14.51	13.56	12.98	16.64	20.55	17.87	21.19
2021		10.24	12.99	14.65	14.83	14.07	16.50	18.34	18.73
1984	Conductivity (μs/cm)		36,750.00	37,325.00	34,600.00	36,625.00	40,900.00	39,525.00	
2019		20,224.19	29,406.23	29,630.68	25,896.60	31,744.09	26,616.31	33,360.55	35,651.77
2020		21,652.31	26,136.43	25,739.44	25,322.71	29,879.40	32,666.41	31,601.59	35,921.55
2021		20,873.69	22,336.72	25,063.99	25,318.07	24,116.52	27,967.24	30,864.58	33,496.91
1984	TDS (ppt)		23.52	23.89	22.14	23.38	26.68	26.05	
2019		13.15	19.11	19.26	16.83	20.63	17.30	21.68	23.17
2020		12.89	15.52	15.27	15.05	17.72	19.34	18.74	21.35
2021		11.01	13.81	15.44	15.59	14.88	17.19	19.87	20.31
1984	NH_3-N (mg/l)		0.13	0.12	0.14	0.13	0.14	0.12	
2019		0.05	0.16	0.16	0.05	0.40	0.07	0.30	0.58
2020		0.02	0.03	0.02	0.02	0.05	0.06	0.04	0.06
2021		0.05	0.03	0.03	0.03	0.02	0.04	0.05	0.07
1984	DO (mg/l)		2.90	3.50	3.65	3.90	3.90	4.08	
2020		4.36	4.76	5.43	5.21	4.75	4.87	5.00	5.46
2021		5.43	5.13	4.88	5.34	5.08	4.53	4.43	4.05
2020	BOD (mg/l)	2.58	2.35	3.17	2.63	2.02	2.63	2.33	1.82
2021		2.49	2.06	2.11	2.02	2.27	1.88	2.64	2.41
2020	Turbidity (NTU)	26.26	21.99	17.61	23.24	17.75	15.83	13.99	9.48
2021		7.01	6.58	7.80	12.32	10.29	8.46	7.70	9.04
1984	Total coliform (CFU)		1,640.83	3,548.33	17,745.00	3,590.83	5,973.33	2,574.17	
2020		18,000.00	7,075.00	10,250.00	25,000.00	11,250.00	5,400.00	4,175.00	4,075.00
2021		26,000.00	7,325.00	12,750.00	10,250.00	5,250.00	7,325.00	9,500.00	6,150.00

These monitoring efforts have revealed key trends and challenges. For instance, slightly acidic pH levels were recorded in upstream areas in 2019, likely due to acidic runoff from nearby mangroves and quarrying activities. Downstream areas experienced significantly higher salinity levels, influenced by seawater intrusion, which is further exacerbated by rising sea levels and tidal changes. Such changes threaten freshwater ecosystems and impact the river's usability for agriculture and domestic purposes.

The monitoring program also revealed elevated conductivity levels, attributed to high tides and untreated wastewater discharge. Turbidity, a measure of water clarity, showed poor conditions, primarily driven by dredging activities and altered river flow patterns during the COVID-19 lockdown. Downstream stations recorded increased levels of TDS, reflecting seawater intrusion and anthropogenic activities near urban areas. Furthermore, high BOD concentrations and elevated ammonia-nitrogen levels in some stations pointed to untreated wastewater discharge, agricultural runoff, and contamination from sewage works, which can deplete oxygen levels and harm aquatic life.

The situation is particularly concerning near Kampong Ayer, where total coliform levels were significantly high due to direct effluent discharge and septic tank leakage. This bacterial contamination poses severe health risks to residents who depend on the river for daily activities. To address these challenges, improved waste management systems, stricter regulations on industrial discharges, and community engagement programs are critical. Public awareness programs could educate citizens about the importance of maintaining river cleanliness and the detrimental effects of pollution on ecosystems and human health.

To address these issues, efforts have intensified through collaborative research on water quality monitoring and assessment, alongside investments in innovative solutions. Technologies such as floating rubbish traps have been successfully deployed (see figure 3), effectively collecting significant amounts of waste and contributing to the river's cleanliness and ecological health. These efforts, combined with public education and stricter policy implementation, could ensure the Brunei River remains a sustainable resource. By fostering community participation and adopting innovative approaches, Brunei can protect the river's ecological health, safeguard Kampong Ayer’s heritage, and ensure the well-being of its residents. The Brunei River is not just a vital natural resource but also a cornerstone of Brunei’s cultural heritage, particularly through its connection to Kampong Ayer. However, ongoing environmental pressures and anthropogenic activities threaten the river’s health and sustainability. The monitoring program led by Universiti Brunei Darussalam provides crucial insights into these challenges, highlighting areas that require immediate attention, such as wastewater management, sediment control, and the mitigation of seawater intrusion. As Brunei continues to modernize and grow, ensuring the ecological balance and sustainability of the Brunei River will require coordinated efforts from government agencies, researchers, and local communities. These efforts are essential to protect both the river's ecological integrity and the livelihoods of those who depend on it.

Fig. 3. Deployment of rubbish traps along tributaries of Brunei River

4. Conclusions

In conclusion, the management and preservation of surface water resources in Brunei Darussalam are of paramount importance, given the nation's reliance on these resources for both domestic consumption and industrial use. The findings discussed in this paper highlights the significance of effective water resource management strategies that address the unique challenges posed by Brunei's tropical climate, rapid urbanization, and industrial growth. With surface water constituting almost the entire water supply of the country, it is essential to ensure its sustainability through the implementation of improved wastewater treatment systems, stricter industrial discharge regulations, and the enhancement of monitoring programs.

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Application of hydrogeological information in North China Plain

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Abstract

Hydrogeological information is very important for the development of society and economy, especially in areas where surface water resource is not adequate. Since the founding of the People's Republic of China (PRC) in 1949, the former Ministry of Geology, that is China Geological Survey (CGS), the Ministry of Natural Resources (MNR) has always been dedicated to the hydrogeological survey and groundwater exploration. The national hydrogeological mapping at scales of 1: 200 000, 1: 100 000 and 1: 50 000 have been carried out in last decades, figuring out the structures of main aquifers, occurrence conditions, and quantity of groundwater in China. From 2014 to 2022, a national groundwater monitoring network has been established and in operation. Through those hydrogeological survey projects as well as groundwater monitoring works, vast amount of hydrogeological information has been obtained and played an important role in the past decades, such as North Chian Plain (NCP).

Keywords: Hydrogeological Information; North China Plain (NCP); Geological survey

1. Introduction

Groundwater has the characteristics of wide distribution, large storage with generally good quality and seasonal adjustable. As a reliable water supply source and important ecological environment factor, groundwater ensures the base flow of rivers, ecosystem health, industrial production, agricultural irrigation, and human life.

Hydrogeological information is of great importance to better develop, utilize and protect groundwater. Since the 1950s, CGS has carried out hydrogeological surveys, water supply hydrogeological surveys, groundwater resources and environment surveys, National Groundwater Monitoring Project (NGMP) construction, and National Groundwater Resource Assessments (NGRA), which have obtained systemic national hydrogeological information.

Representative work includes: (1) 1:200 000 hydrogeological survey which covers 6.67 million square kilometers, focusing on basic hydrogeological conditions, such as hydrogeological units, aquifer structure quantity and quality, etc. (2) 1:50 000 hydrogeological survey which covers 1.20 million square kilometers, focusing on solving specific hydrogeological problems such as groundwater drinking water safety, environmental protection. (3) NGMP has been established and in operation since 2018 with 20,469 groundwater monitoring boreholes which can provide groundwater levels and temperature information with hourly frequency. In addition, another 56,000 wells were investigated in order to make a supplementary to the NGMP. (4) Three rounds of groundwater resource assessment have been carried out since the 1950s, and the quantity and quality of groundwater, spatial distribution and change rules have been obtained.

A large amount of hydrogeological information has been obtained, including the aquifer structure of different hydrogeological units, the drainage conditions of groundwater, the dynamic change characteristics of groundwater, the amount of groundwater resources, groundwater reserves and their changes, etc. This hydrogeological information has played an important role in water supply security, ecological environment protection and restoration, etc.

2. Introduction of Hydrogeological Information in the NCP

2.1 Introduction of NCP

The NCP bordered by the Taihang Mountains to the west, the Yan Mountains to the north, the Bohai Sea to the east, and the Yellow River to the south, encompasses all of Beijing, Tianjin, and Hebei, as well as the northern plains of Henan and Shandong covering an area of approximately 139,000 square kilometers. The climate of the NCP is characterized as a semi-arid, semi-humid continental monsoon climate. The rainfall occurs predominantly from July to September with an average annual precipitation of 500 to 700 millimeters. The average annual temperature gradient is noticeable from south to north, ranging from -1.4°C to 14°C. As one of China's three major plains, the NCP is not only the most populous but also a critical grain production base. Groundwater resources are of great significance for agricultural production, residential life, and industrial water use in the region. Therefore, obtaining long-term, real-time, and high-precision hydrogeological information is essential for supporting the coordinated development of the Beijing-Tianjin-Hebei region, ensuring water resource security and supply by local governments, and protecting and restoring the ecological environment.

2.2 Hydrogeological Information in the NCP

Hydrogeological mapping on various scales has been conducted since the 1950s. Recent years, hydrogeological survey for supporting poverty alleviation and rural revitalization, groundwater monitoring, the third-round periodic assessment of groundwater resource, researches on water balance, and etc., have been conducted in the NCP. Hydrogeological information, such as aquifer structure, hydrogeological parameters, data of groundwater levels, dynamics of groundwater, have been collected using diverse methods and techniques.

2.2.1 Hydrogeological mapping in the NCP

From 1959 to 1986, regional hydrogeological surveys on a scale of 1:200,000 were carried out, encompassing the entire NCP. These surveys firstly identified hydrogeological conditions, defined hydrogeological divisions, and estimated groundwater resources.

From the 1960s to the end of the 1980s, hydrogeological survey for water supply in agricultural and pastoral areas at the county level were undertaken. Hydrogeological surveys for water supply at a scale of 1:50,000 were conducted in urban industrial and mining areas. After 2000, hydrogeological survey on a scale of 1:100,000 were conducted in endemic disease area, covering 119,700 km^2. The groundwater resources in the deeper aquifers in the agricultural areas has been preliminarily evaluated, mainly buried depth from 200 to 400m. And groundwater exploitation planning and irrigation water quality standards were established.

From 1988 to 2006, regional hydrogeological surveys on a scale of 1:250,000 were conducted, covering the entire NCP. These surveys further identified regional hydrogeological conditions and preliminarily evaluated the environmental and ecological functions of groundwater. Since 2004, a new generation of hydrogeological survey on a scale of 1:50,000 has been initiated. 59 maps of hydrogeological surveys covering a total area of 23,600 km^2 have been completed, enhancing the accuracy of regional hydrogeological investigations. Studies on aquifer protection, rational exploitation, and utilization of groundwater have been conducted.

2.2.2 Groundwater monitoring in the NCP

The book "Agriculture in North China (IV) - North China Agriculture Centered on Water," published in 1948, documented data from 97 shallow groundwater wells in the North China, providing valuable historical data for studying the regional groundwater conditions. During this period, groundwater monitoring was primarily manual, with a limited number of monitoring wells and relatively rudimentary methods.

From the 1950s, groundwater monitoring work was organized by the former Ministry of Land and Resources and the Ministry of Water Resources, focusing on geological environmental protection and water resources development. Monitoring during this period concentrated on the water level, volume， and temperature. Data on shallow groundwater levels since 1959 and the layout of shallow and deep groundwater levels in the NCP by 2005 were collected and analyzed through the geological survey project "Investigation and Assessment of Sustainable Utilization of Groundwater Resources in the NCP" (Zhang et al., 2009), conducted by the Institute of Hydrogeology and Environmental Geology of the Chinese Academy of Geological Sciences in 2009. This marked the first systematic and large-scale comprehensive survey of groundwater in the 20th century.

In 2018, the National Groundwater Monitoring Project was fully implemented, signifying the establishment of a national three-dimensional automated groundwater monitoring network combining both shallow and deep layers with distinct monitoring strata. This network focuses on key areas such as densely populated areas, major national engineering zones, Groundwater centralized extraction areas. Real-time information is accessible on the national groundwater monitoring platform.

1275 monitoring wells including national, provincial, and municipal levels, constitute the groundwater network in the NCP. The data generated by this network supports special studies on the dynamic characteristics of groundwater in the NCP under recent extreme rainfall events, flood disaster prevention and control, groundwater regulation, the ecological effects of groundwater along the South-to-North Water Transfer Project, and the assessment of the management effects in groundwater over-exploitation areas in the Beijing-Tianjin-Hebei region, etc.

2.2.3 Groundwater resource assessment in the NCP

Three rounds of groundwater resource assessment have been carried out in the Haihe River Basin, respectively from 1956 to 1979, from 1980 to 2000, and from 2001 to 2020. These assessments systematically collected and deeply integrated existing hydrogeological and water resources investigation results, groundwater monitoring data, and updated hydrogeological parameters. The latest evaluation of groundwater resources in the Haihe River Basin is 295.90

$\times 10^8 m^3$.

3. Application of Hydrogeological Information in the NCP

Hydrogeological Information in the NCP plays an important role for various applications, including groundwater resource supply for production and domestic living, allocation and management of surface water and groundwater, ecological environment protection, etc.

3.1 Application of Hydrogeological Information for groundwater resource supply

Historically, groundwater has served as the primary source for agricultural irrigation, industrial production, and domestic living in the NCP.

As a major agricultural production hub and densely populated region in China, the availability of groundwater resources in the NCP is critical for the management of regional water resources, agricultural production, resident quality of life, and industrial development. Optimizing the allocation and scheduling strategy of water resources, based on hydrogeological information, ensures the rational fulfillment of water demands for various purposes, such as agriculture, industry, domestic living, ecological water supply, etc. Hydrogeological surveys facilitate the assessment of total amount, distribution, and extraction of groundwater resources in the NCP, as well as the renewal capacity. This provides a scientific foundation for long-term planning and the rational utilization of water resources (Liu et al., 2011). The establishment of a comprehensive groundwater monitoring network is essential for real-time monitoring of water level changes and water quality, preventing excessive exploitation and pollution of groundwater, and ensuring water supply security(Zhou et al., 2021). Furthermore, a groundwater extraction plan can be formulated based on hydrogeological data, identifying locations for water source construction as well as optimizing water resource utilization efficiency. In the case of the groundwater funnel area in the NCP, hydrogeological information is used to monitor its dynamic changes, to formulate corresponding management and remediation measures, to assess the impact of climate change and human activities on groundwater recharge capacity, and to provide a basis for the sustainable use of water resources(Yang et al., 2021). It is evident that hydrogeological information plays a pivotal role in managing groundwater resources in the NCP. It enables the rational development, effective protection and sustainable use of water resources, thus ensuring national water security and fostering sustainable economic and social development.

3.2 Application of Hydrogeological Information for allocation and management of surface water and groundwater

The NCP is characterized by lack of surface water resources and long-term dependence on groundwater, leading to the formation of 'funnel areas' (Su et al., 2018). Studying the recharge and discharge relationship between surface water and groundwater and evaluating the supply and discharge conditions of groundwater and its dynamic changes as well as the reserves and availability of surface water bodies like rivers and lakes are essential scientific measures. These measures help develop reasonable allocation plans for both surface and groundwater, balancing water demand for agricultural, industrial, and domestic, optimizing the joint scheduling of surface water and groundwater, and allocating water resources rationally(Dun et al., 2014). For example, by observing variables such as groundwater level, water quality, and flow rates, it is possible to assess the relationship between surface water and groundwater, anticipate future changes in groundwater levels, and provide guidance on the sustainable water resource utilization(Li et al., 2017). Utilizing data from hydrogeological surveys, it is possible to identify sources of contamination of both surface and groundwater. These may include industrial discharge, agricultural use and urban sewage. It is essential to establish a monitoring network for surface water and groundwater quality, with the objective of monitoring changes in water quality in real time and taking timely measures for treatment. Furthermore, a hydrological model is constructed based on hydrogeological information to simulate the flow process of surface water and groundwater in the NCP. This model can predict the changes of water resources and the interaction process of groundwater and surface water under different scenarios of climate change and human activities(Harken et al., 2019).

3.3 Application of Hydrogeological Information for ecological environment protection

As an ecologically sensitive area in China, protecting the ecological environment in the NCP is very important. Hydrogeological surveys can be employed to determine the recharge conditions and water level fluctuations of groundwater, which can be utilized for the ecological restoration of damaged rivers and lakes (Yang et al., 2006). This process can facilitate the restoration of their natural purification and ecological functions. Furthermore, it can monitor changes in groundwater levels and evaluate the impact of groundwater level decline on the ecological environment, including wetland degradation and vegetation withering. Hydrogeological information is vital for the rational allocation of ecological water use and ensuring the ecological security of rivers, lakes, and wetlands(Hao et al., 2018). Additionally, identifying and protecting sensitive groundwater areas, along with preventing geological environmental risks associated with groundwater pollution and excessive exploitation (e.g., ground subsidence and karst collapse), provides valuable reference points for urban planning(Harken et al., 2019). Hydrogeological information is equally important for identifying sources of groundwater pollution, assessing diffusion pathways, and developing measures for the prevention and remediation of pollution. Furthermore, it serves as a crucial foundation for formulating ecological restoration strategies and restoring the ecological functions of surface and groundwater systems.

In summary, hydrogeological information has been extensively employed in the NCP. For instance, in regions experiencing groundwater overdraft, measures have been implemented based on hydrogeological information to prevent excessive declines in groundwater levels and land subsidence. These measures include prohibiting or limiting groundwater extraction (Su et al., 2018), determining the scope of the water source, implementing protective measures to prevent pollutants from infiltrating groundwater, assessing the ecological status of rivers and lakes, and developing ecological restoration plans. Additionally, suitable wetland construction sites are selected to ensure that wetlands can effectively fulfill their ecological functions. Furthermore, precision fertilization is guided(Zhou et al., 2021).

4. Existing Problems

While hydrogeological information has been extensively utilized, there remains significant potential for its enhanced application.

On one hand, traditional methods, such as point measurements that provide point data, cannot satisfy the demand for more comprehensive hydrogeological data analysis. Before 2015, most monitoring stations mainly relied on production wells and civilian wells, with commissioned observers conducting manual observations. The frequency of observations, the efficiency of information reporting, the accuracy of observations, and the coverage of observed elements were all relatively low. Since the launch of the national groundwater monitoring project, the level of automation in the collection and transmission of groundwater information has significantly improved, and the frequency and timeliness of monitoring have also been markedly enhanced (Li et al.,2022). Despite this, the groundwater monitoring system still faces two major challenges: (1) The monitoring system is not yet perfect, More automated monitoring stations need to be established to obtain more accurate real-time hydrogeological dynamic information.; (2) The lack of intelligent operation and maintenance and service capabilities, the imperfection of information infrastructure leads to problems in data availability. In areas with weak public network signals or untimely maintenance, the problems of poor communication and low data reporting rate are particularly prominent. The stability and reliability of some equipment are poor in extreme environments such as high cold, high temperature, and high humidity, and the battery life is also affected. In addition, the integration of artificial intelligence, deep learning, and knowledge graphs with groundwater prediction and early warning is not sufficient, making it difficult to form mature products oriented towards practical applications.

One the other hand, new methods, such as remote sensing techniques, are not widely applied to obtain hydrogeological information. Since remote sensing reflects surface features and cannot penetrate subsurface layers, the obvious answer to hydrogeologists is that groundwater is shielded against remote measurements by complex and often poorly understood geological features. Therefore, the application of remote sensing technology in the study of groundwater level fluctuation and water volume change is limited. In addition, there are fewer studies that utilize environmental information to invert groundwater quality and monitor groundwater pollution. This indeed presents the main challenge and obstacle for applying remote-sensing techniques to solving hydrogeological problems. Consequently, it is necessary to increase the hydrogeological meaning in remote sensing observations with the help of multidisciplinary and multi-technology integration, such as models, assumptions and approximations.

5. Plan for Future

In the future, new methods and techniques will be applied in areal hydrogeological information acquisition and data processing.

5.1 Areal hydrogeological information acquisition

Remote sensing techniques will be used to map parameters such as evapotranspiration and soil moisture. Mu (2011) simplified the Cleugh Method for different vegetation types using the leaf area index, minimum air temperature limiting factor and water vapor pressure limiting factor, respectively, and the algorithm became the official algorithm for the MODIS evapotranspiration product MODIS16. Several studies based on surface temperature have developed a number of indices that can characterize the dry and wet conditions of the surface, such as the crop water stress index, the temperature vegetation drought index, and the water deficit index. Moreover, remote sensing can establish the relationship between NDVI and the groundwater depth. Jin et al., 2007 investigated the optimal groundwater depth of 3.5 m for vegetation growth in Yinchuan Plain by modeling the correspondence between NDVI and groundwater depth. In addition, combined with Grace gravity satellite, microwave remote sensing and other technologies, hydrogeological information such as soil quality and groundwater volume in the air pocket can be obtained through the fusion of multi-source information. By utilizing hyperspectral images to extract feature information, and combining with GIS and DEM data, the recharge and discharge areas of karst fissure water can be divided to provide the basis for detailed hydrogeological exploration, and at the same time, serve for water resources evaluation and management.

5.2 New data processing techniques

Machine learning methods and numeric modeling will be used to deeply mine the obtained data. The emergence of high-frequency, high-density water level monitoring data has given rise to the need for in-depth information mining. For instance, big data technologies such as machine learning and numerical modeling methods are employed to delve deeply into the data, assisting people in better understanding hydrogeological information. Big data technology has brought revolutionary changes to the field of groundwater monitoring; it can efficiently monitor, collect, analyze, and store groundwater data, and capture anomalies in real time. By deeply mining data of various types and complexities, big data technology can extract and uncover valuable information. Moreover, with the use of visualization tools, the timeliness of data analysis has been significantly enhanced, which not only improves the efficiency of groundwater monitoring but also increases the utilization rate of groundwater monitoring data (Najafabadipour, A., et al.). In this field, machine learning algorithms have demonstrated significant advantages in automation, scalability, and applicability. These algorithms can process and analyze vast amounts of data, thereby enhancing the accuracy and efficiency of groundwater monitoring. Currently, data-driven technologies based on machine learning are also gaining increasing attention in the application of groundwater models, becoming a hot topic in research and practice (Chen, et al.).

6. Conclusions

Hydrogeological information is very important for the development of society and economy in the NCP. The national hydrogeological mapping on different scales has been done since 1950s, from 2015 to 2018, a national groundwater monitoring network has been established and in operation. Through those works, vast amount of hydrogeological information has been obtained and played an important role. Although hydrogeological information has been used a lot in the past, there still exists a huge potential to make better use of it. For example, new methods such as remote sensing technology urgently need to be widely applied to obtain hydrogeological information, big data technologies such as machine learning and numerical modeling methods need to be employed to better understand and use hydrogeological information.

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Hydrogeological information of Brantas Groundwater Basin in East Java, Indonesia

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Abstract

The population of the Brantas Groundwater Basin (Brantas GwB) in 2023 reached 13 million people or 32% of the population of East Java Province with a positive population growth rate of 0.8%. This condition reflects the potential for additional water demand to support life and activities. Brantas GwB was previously under the authority of the local government, but since the Water Resources Law No. 17 of 2019 is based on River Basin, Brantas GwB has become the authority of the state along with its status as a national strategic river basin. The main aquifers in the Brantas Groundwater Basin are alluvium in the upper part and volcanic rocks of Quaternary age composed by lithologies such as sandstone, siltstone, sand, gravel, pebbles, pebbles, volcanic sand in intermontane basins that extend from the south in Blitar and Tulungagung to the north towards Kediri and Jombang then to the east towards Mojokerto and Sidoarjo. The thickness of the aquifer varies from 17-74 metres with the depth of the water table in the north < 3 m and in the south < 10 m, flowing from G. Liman in the west and G. Kawi. Brantas GwB has a total estimated groundwater potential of 11,238 million m^3 /year. Groundwater quality is generally good with TDS values < 400 mg/L, with only a few areas in the north having TDS values > 1,000 mg/L. Groundwater utilisation is mostly for domestic needs, reaching 66% and total utilization of 433,975,625 m^3 /year in 2023 and still safe to fulfil water needs.

Keywords: groundwater, groundwater basin, Brantas

1. Introduction

The hydrogeological information system of the Brantas Groundwater Basin (GwB) is the result of work that has been carried out by the team of the Department of Geological Engineering, Gadjah Mada University in 2023 based on the collaboration between the Center for Groundwater and Environmental Geology and the Faculty of Engineering, Gadjah Mada University, Yogyakarta. This work is prepared to produce groundwater conservation zones that are used as a basis for granting groundwater use permits. Previously, Brantas GwB was part of the regional authority, namely the province of East Java and since the Water Resources Law No. 17/2019 based on groundwater basins in the river basin, Brantas GwB became the authority of the central government according to its status as a national strategic river area.

The Brantas GwB is located in the province of East Java occupying the central part bordering the province of Central Java. The area is bordered by the blue line in Fig. 1 reaches 43.86% of Brantas River Basin Area about 618.600 square kilometers covering the area of four municipality and eleven regency, namely Mojokerto, Jombang, Kediri, Blitar, Tulungagung, Trenggalek, Nganjuk, Madiun, Magetan, Ponorogo, and Pacitan.

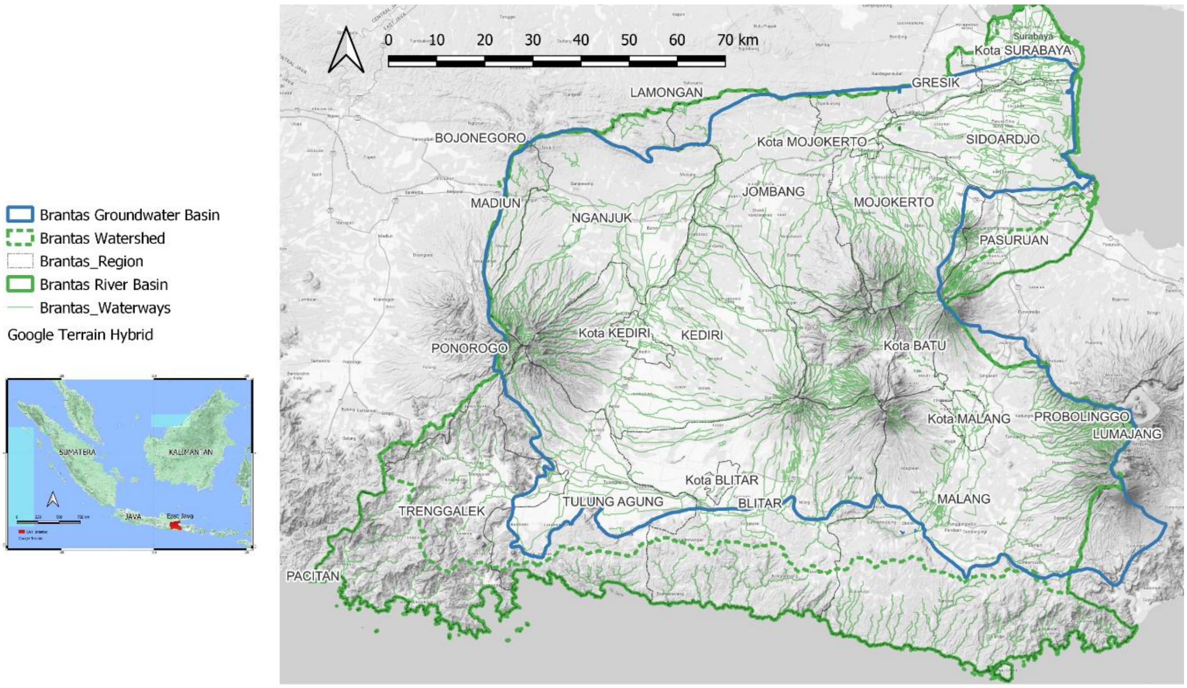

Fig. 1. Brantas River Basin and Groundwater Basin

2. Hydrogeological information of the area

The aquifer system is composed of lithologies of rocks that control the hydrogeological conditions of the research area. In addition, there are other factors such as topography and geological structure that also affect the aquifer system (Fig. 2). Each lithology that makes up geological formations has the ability to store and drain groundwater in a certain amount and storage capacity according to these controller parameters. Table 1 shows the relationship between the lithology of the constituent aquifers and the types of aquifers. Based on the physical properties of the aquifer-forming rocks in CAT Brantas, it can be determined that the aquifer system is developed, namely an unconfined aquifer system with wide distribution can be identified based on observations of rock outcrops and lithology of dug well walls. Generally, the rocks that make up the unconfined aquifer system are sandstone, sand, gravel, gravel, clay, tuft, and silt sand derived from alluvium, weathering, and deposits of volcanic rocks from Semeru, Buring, Bromo, Kelud, and so on, as well as several rock formations exposed in the research area. In addition, the presence of confined aquifers was found on the slopes of Mount Kawi and Anjasmoro with local distribution composed of volcanic material (Fig. 3).

Table 1. Correlation of lithology and aquifer type

Color	*Lithology*	*Hydrogeology Unit*
Blue	Sandstone, siltstone, sand, gravel, pebbles, pebbles, volcanic sand	Aquifer
Yellow	Tuffaceous tuff, volcanic breccia, tuff breccia, tuff, tuff breccia, agglomerate, breccia, inserted clastic limestone, lava deposits, lapillary tuff, claystone tuff, tuffaceous sandstone, conglomerate, pyroclastic	Aquitard
Green	Limestone	Aquiclude
Red	Lava, andesite lava, olivine-pyroxene basalt lava, olivine basalt lava, lahar	Aquifug

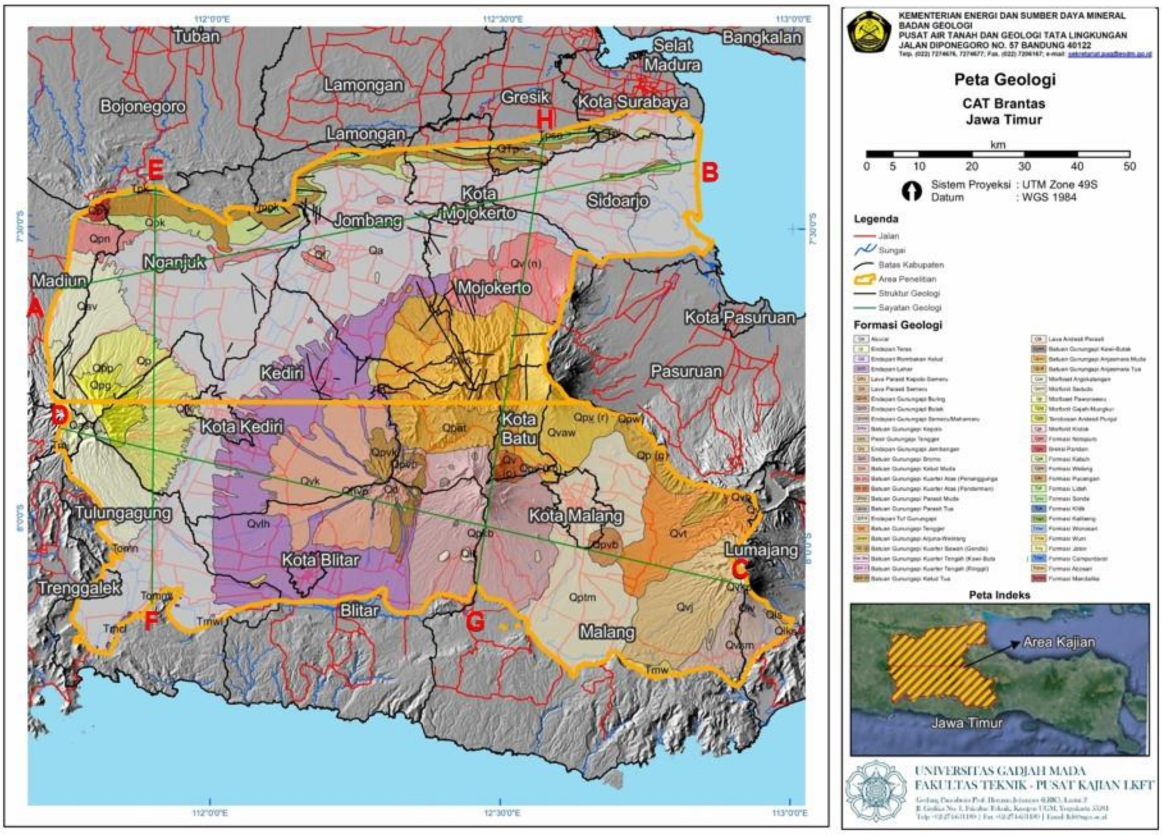

Fig. 2. Geological map of Brantas GwB

The appearance of the aquifer pressure can be found in the area around the slopes of Mount Kawi and Mount Anjasmoro, in where the volcanic material produced by the volcanic eruption process is then producing volcanic rocks that act as aquifers, aquitard, aquiclude, and aquifug. By knowing the position of the groundwater table, the depth and thickness of the aquifer along with the level of decline, as well as the quality of the groundwater itself, can be determined by the model conceptual hydrogeology of Brantas GwB presented in Fig. 4.

In general, the more south and west the thickness of the aquifer increases, while the further north and east the thickness of the aquifer decreases. Based on thickness data and calculations of hydrostratigraphic cross-sections of A-B, C-D, E-F, G-H, I-J, and K-L, the average thickness of the aquifer in the study area was 21 – 71 m. The geometry and availability of aquifers can be visualized in Fig. 5.

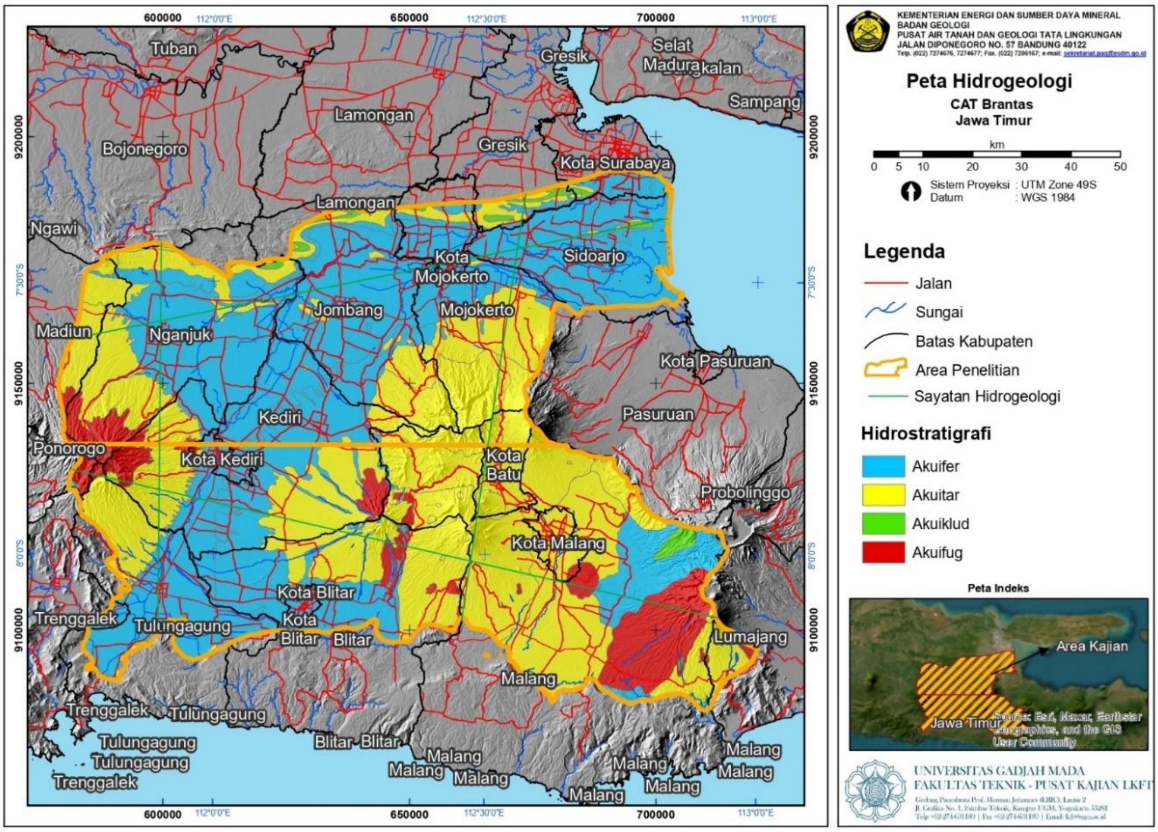

Fig. 3. Hydrogeological map of Brantas GwB

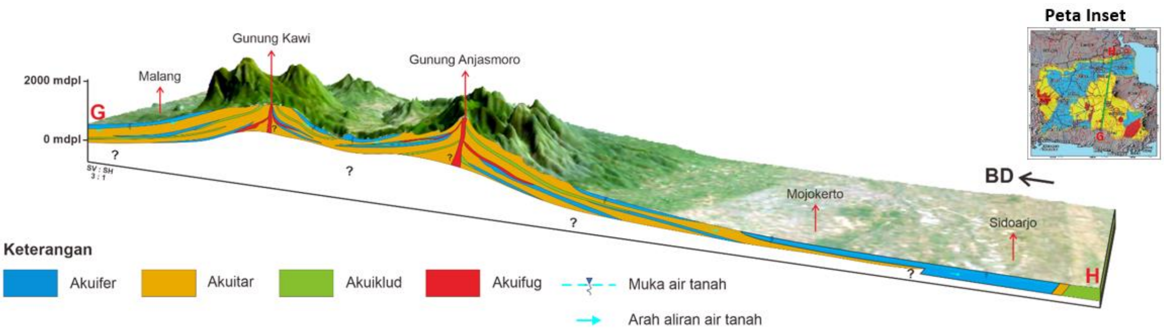

Fig. 4. Cross-section profile from west to southeast

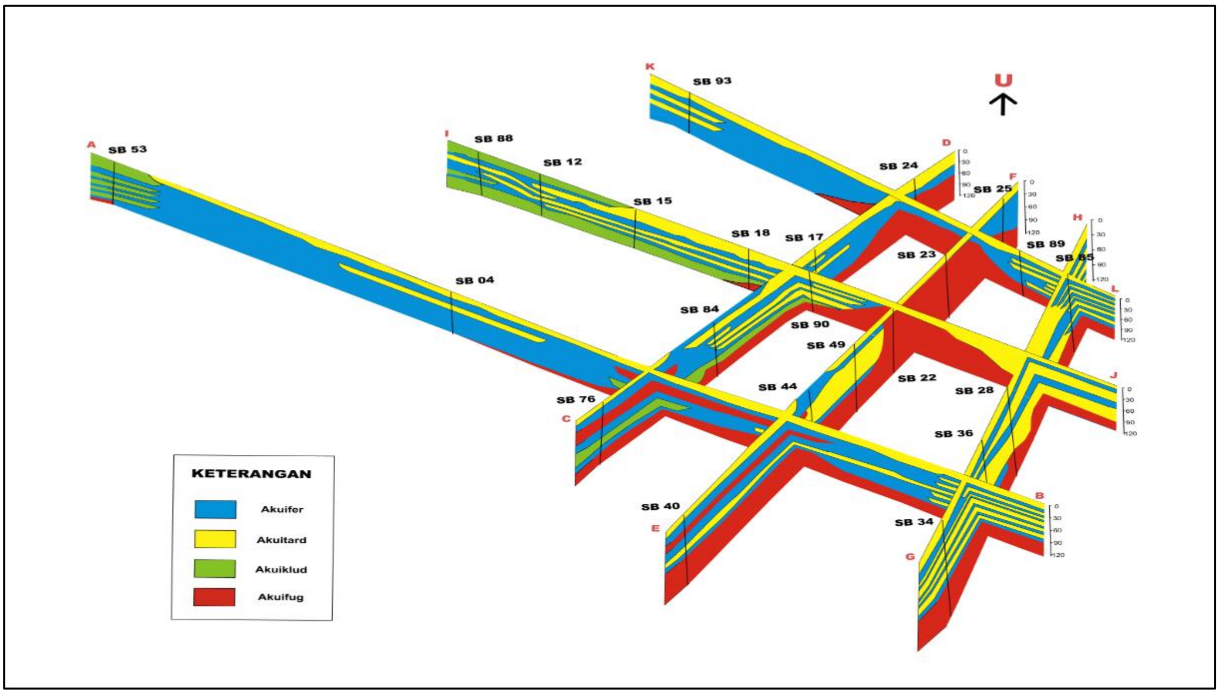

Fig. 5. Fence diagram of Jombang in the northern part

Aquifers in the Kediri Regency area are formed due to alluvial processes with variations in the porosity of the constituent rocks. The lithological characteristics of the aquifer constituents in the central part of Kediri Regency are dominated by relatively coarse material with a depth of up to 200 meters. Based on the configuration of the aquifer, there is a fairly wide distribution of material with high porosity in the central part of Kediri Regency, indicating that the central part of Kediri Regency is dominated by unconfined aquifers with bedrock in the form of aquifer units consisting of volcanic lava (Fig. 6).

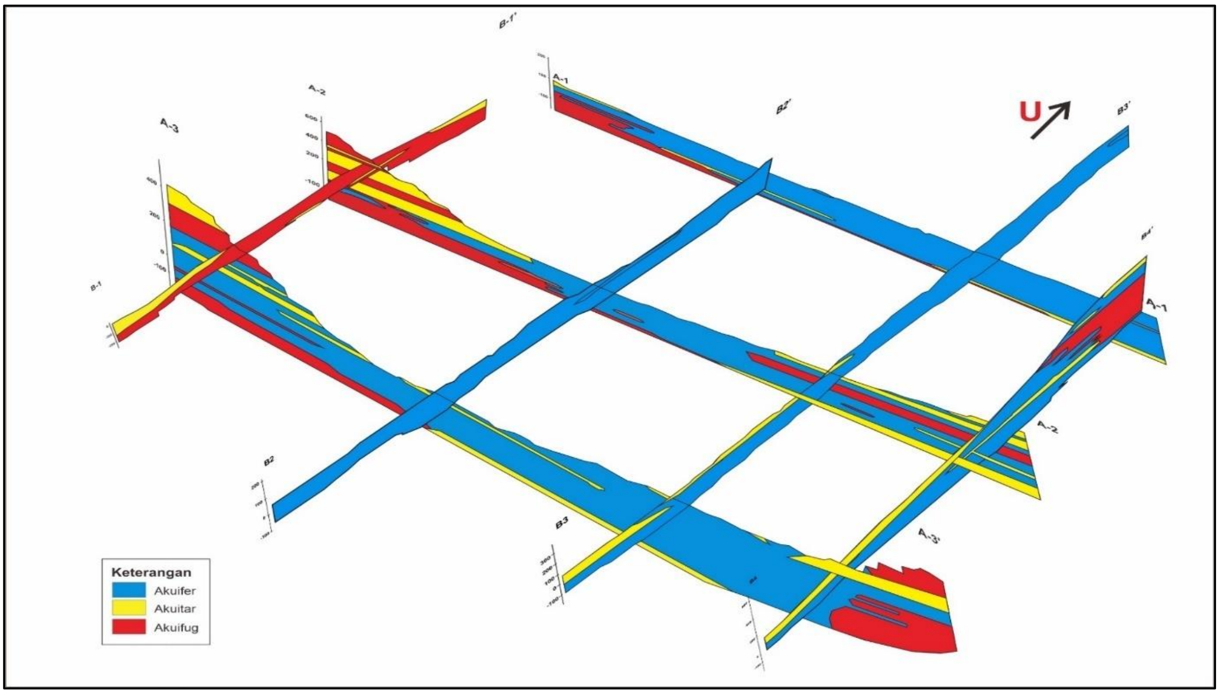

Fig. 6. Fence diagram of Kediri in the central part

3. Major water resources and water utilization ways

Total population in Blitar GwB reaches 32% of total population in East Java Province with evenly distributed (Fig. 7). In 2023, the population in the Brantas GwB will reach 13,278,730 with a positive population growth rate of 0.8 percent. Positive population growth means an increase in the amount of water demand for domestic needs and human activities such as agriculture or industry. 78.58% of the Brantas GwB area is classified as a village with a population between 3200 to 20000.

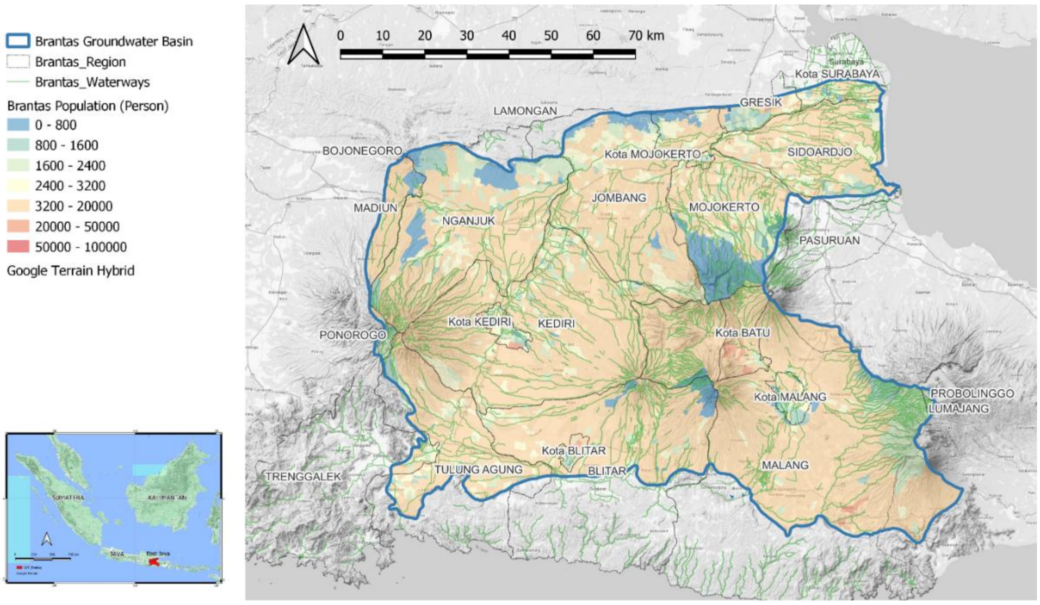

Fig. 7. Brantas Population on Groundwater Basin

Based on data from the Ministry of Public Works and Public Housing (PUPR), the need for groundwater for agricultural irrigation in Brantas GwB reaches 10.7 billion cubic meters per year. The groundwater needs are used to irrigate agricultural land covering an area of about 2.5 million hectares. In addition to agricultural irrigation purposes, groundwater needs in Brantas GwB are also used for domestic reaches 1.2 billon cubic meters per year, industrial about 0.7 billion cubic meters per year, and power plant about 0.1 billion cubic meters per year. This condition is illustrated from the land cover map which shows that most of the Brantas GwB area is an agricultural irrigation area in Fig. 8.

4. Hydrological database

Data collection through groundwater level measurement and groundwater quality was carried out on 92 Hydrogeological points of interest consisting of 51 drilled wells, 31 dug wells, and 10 springs at the end of 2023. Based on Fig. 9, it can be observed that the supplication area in CAT Brantas located in geomorphological units in the form of Volcanic Cone Unit and Foot Units Volcano which is an area with a higher elevation. The recharge area is located in mountainous and highland areas including Mount Liman, Mount Arjuna, Mount Kawi, and Mount Bromo. The groundwater flow will move to flow in a cross-section with the gravitational force of the slope of the elevation of the groundwater table. The groundwater flow system basically covers the recharge area and the discharge area. The thickness of the aquifer varies from 17-74 metres with the depth of the water table in the north < 3 m and in the south < 10 m. Groundwater flow patterns tend to move from west to east sea and from the southeast to the northeast (Fig. 10).

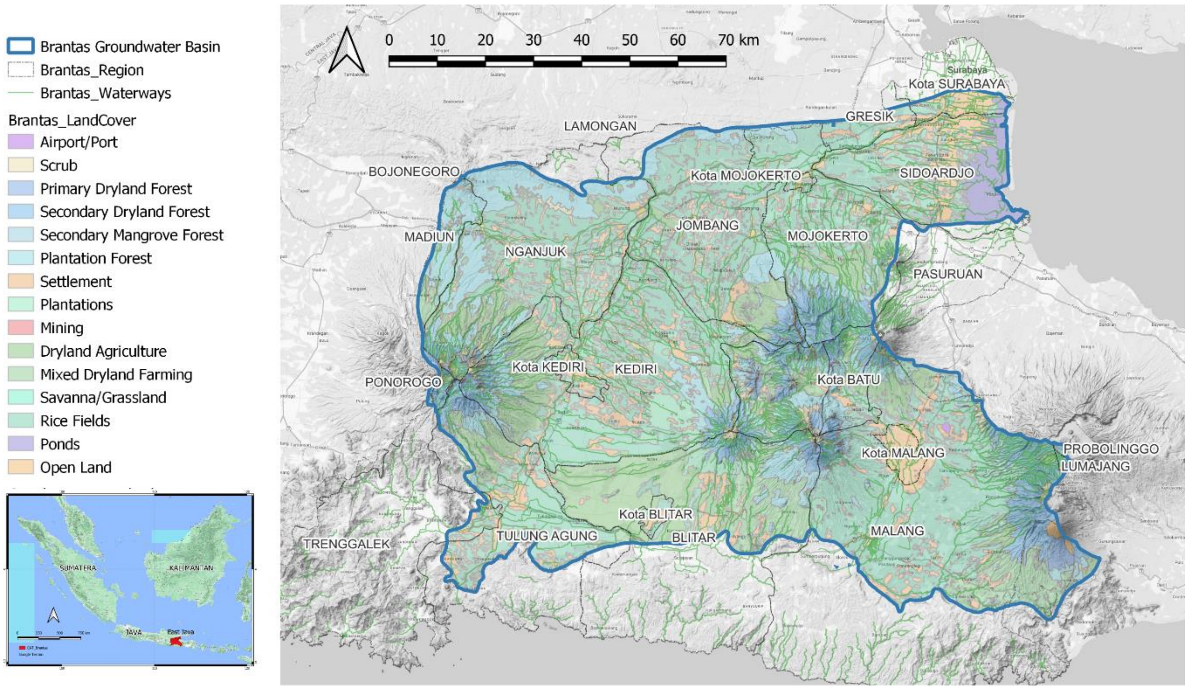

Fig. 9. Brantas Land Cover

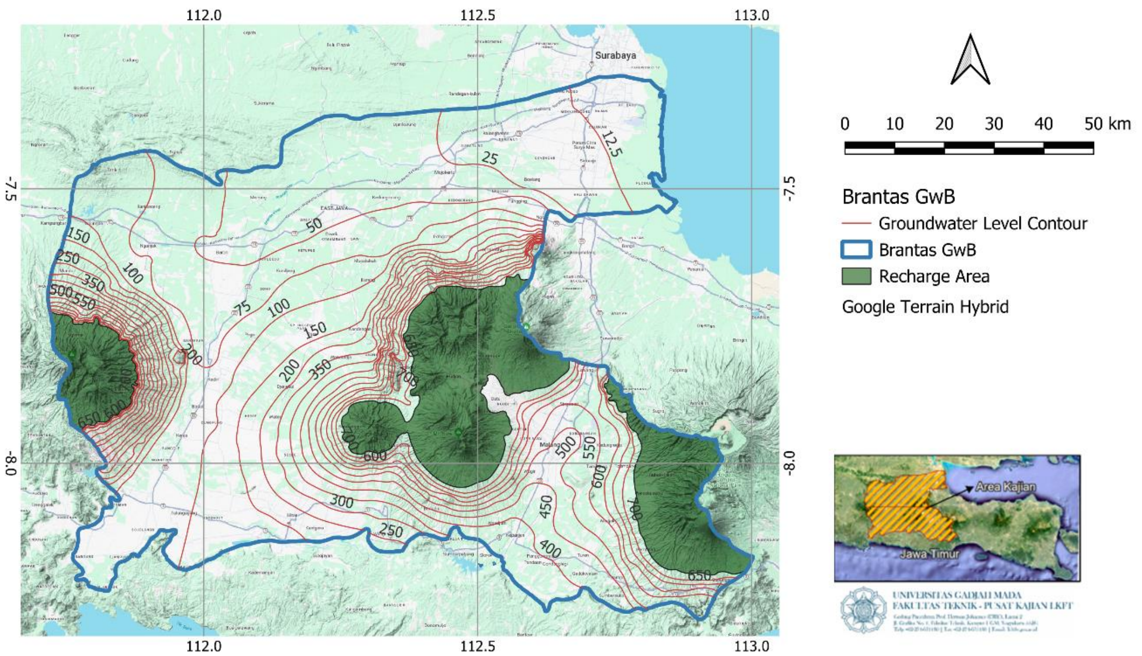

Fig. 10. Recharge area and groundwater flow of Brantas GwB.

5. Major problems and future challenges

The concentration of total dissolved solids (TDS) in groundwater is determined by weighing the solid residue obtained by evaporating a measured volume of filtered sample to dryness (Freeze and Cherry, 1979). TDS values exceeding 1,000 mg/l are an indication of non-freshwater that can be used directly by humans and are found in the northern part. The high TDS value in the unconfined aquifer and confined aquifer are caused by groundwater pollution as an industrial area and the composition of the constituent lithology of the subsurface (Fig. 10 and Fig. 11).

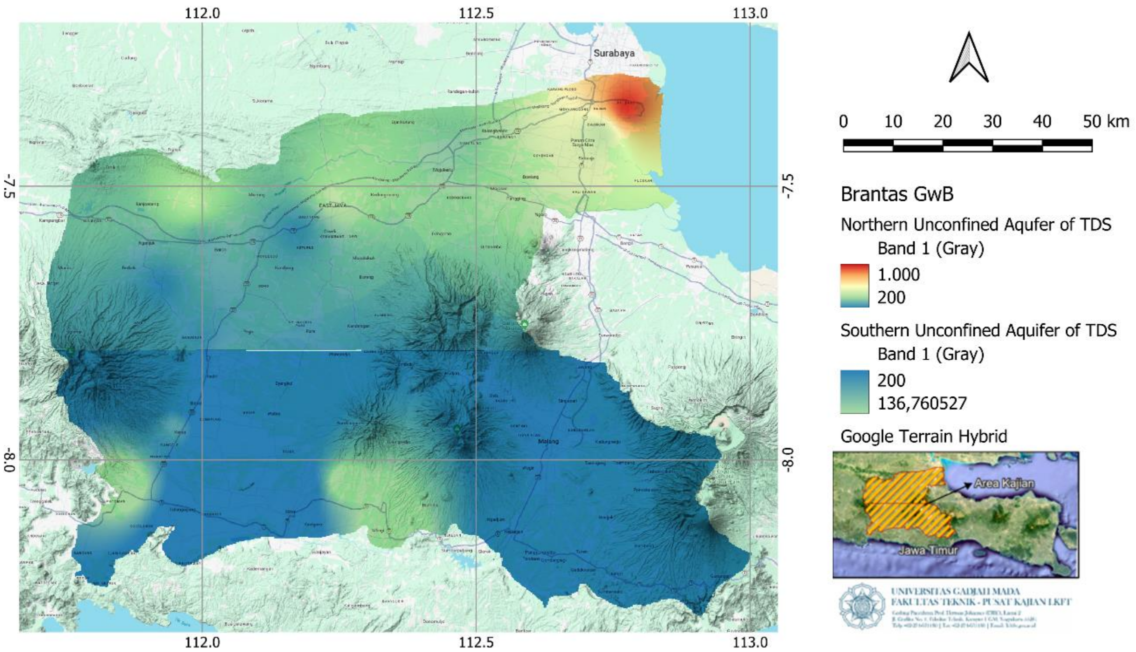

Fig. 10. Total Dissolved Solid of unconfined aquifer of Brantas GwB

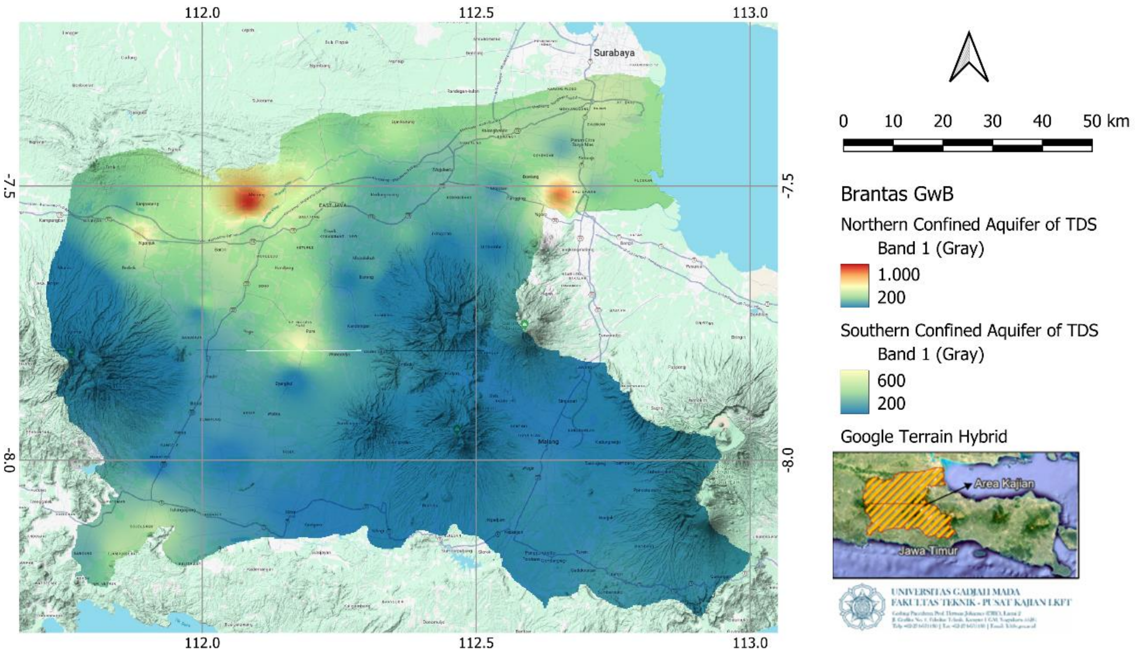

Fig. 11. Total Dissolved Solid of confined aquifer of Brantas GwB.

6. Conclusions

The main aquifers in the Brantas Groundwater Basin are alluvium in the upper part and volcanic rocks of Quaternary age composed by lithologies such as sandstone, siltstone, sand, gravel, pebbles, pebbles, volcanic sand in intermontane basins that extend from the south in Blitar and Tulungagung to the north towards Kediri and Jombang then to the east towards Mojokerto and Sidoarjo. The thickness of the aquifer varies from 17-74 metres with the depth of the water table in the north <3 m and in the south <10 m, flowing from G. Liman in the west and G. Kawi in the east to the north and then to the east. Groundwater utilization is mostly for domestic needs, reaching 66% and 433,975,625 m^3/year in 2023. Brantas GwB has a total estimated groundwater potential of 11,238 million m^3/year. Groundwater quality is generally good with TDS values <400 mg/L, with only a few areas in the north having TDS values >1,000 mg/L indicated groundwater pollution and lithology.

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Hydrogeological information, water utilization, and various challenges related to water resources of the Okinawa Island in Ryukyu Archipelago

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Abstract

The Okinawa Islands are located at the southwestern end of Japan and consist of numerous islands with subtropical climates. Okinawa, renowned for its beautiful seas, rich natural landscapes, and diverse flora and fauna, is a popular tourist destination. This report focuses on Okinawa Island, summarizing its hydrogeological information and highlighting associated water resource challenges.

Okinawa's main island has faced several water resource challenges in recent years. Drought is a significant challenge. Owing to the topography of Okinawa Island, the river basins are small with short, steep courses, leading to low flow rates during dry periods, thus resulting in droughts. Currently, the primary water source for the main island is dam water, which accounts for 70% of the island's supply. However, the current reliance on river water remains at 16.8%, rendering this region susceptible to droughts during periods of low rainfall. Various measures are being implemented to ensure sustainable water use. Therefore, the exploration of new, alternative water sources must also be considered. The second problem is water pollution. The widespread presence of Ryukyu limestone, which facilitates surface water infiltration, indicates that surface pollutants can easily penetrate the ground and contaminate groundwater. Additionally, owing to the geological and geomorphological conditions of the main island, surface pollutants can easily reach the coastal areas through river water and groundwater. This poses a threat to Okinawa's unique and beautiful beaches and rich coastal ecosystems. The impact of these pollutants is often not immediately visible because of their gradual accumulation over time and the considerable distance between terrestrial pollution sources and the affected coastal areas, making it difficult to perceive the severity of the pollution.

Effective water management requires understanding pollution sources, conducting comprehensive investigations that consider the connection between terrestrial and coastal areas from upstream and downstream perspectives, and sharing data with local communities for collaboration.

Keywords: water resources, groundwater, river water, island, limestone, pollution

1. Introduction

The Okinawa region is located at the southwestern end of Japan and consists of numerous islands with a subtropical climate distinct from the temperate climate prevalent in Japan. Okinawa, renowned for its beautiful seas, rich natural landscapes, and diverse flora and fauna, is a popular tourist destination.

This report focuses on the main Okinawa Islands, one of the Ryukyu Islands extending approximately 1,000 km from south to north, comprising over 160 islands, of which 49 are inhabited (1). Okinawa Island, located around 26°N, 127°E, is the largest island in Okinawa Prefecture. It spans approximately 100 km from the southernmost to northernmost points. Fig.

1 presents an overview of the island and its major cities. The capital city, Naha, is located in the southern region. For this study, the main island was divided into northern (around Nago City), central (around Kadena Town), and southern (around Naha City) regions. The topography varies, with relatively flat terrain in the south and mountainous regions in the north (2). Approximately 90% of the population of Okinawa Prefecture resides on Okinawa Island, with 80% concentrated in the central and southern regions (3). The average annual temperature in Naha city is around 23 °C (based on 2023 data) (4), significantly warmer than mainland Japan, where the average annual temperature in Tokyo is 18 °C. Notably, the average temperature in winter from January to February in 2023 was 18 °C in Okinawa and 7 °C in Tokyo - an 11 °C difference (4). The past weather data indicate that the annual average rainfall in Naha is around 2,000 mm, considerably higher than the national average of 1,700 mm in Japan (5). Okinawa's rainfall patterns are heavily influenced by the rainy season in May and June and the typhoon season in August, making it susceptible to climate change.

The island has numerous rivers of various sizes. Because of its elongated north-south orientation, the river basins are small with short, steep courses (1). Consequently, heavy rains can cause rapid increases in water levels, reaching dangerous heights much faster than the mainland rivers in Japan. However, these rivers have extremely low flow rates during dry periods, making it challenging to secure water resources and prevent flooding. The lack of large rivers and lakes, coupled with significant annual and seasonal variations in rainfall, complicate the stable supply of water, leading to frequent droughts (6, 7). Okinawa has historically relied on springs and groundwater and many villages have several springs and wells. These sources have been crucial in supporting the lives of Okinawa's residents.

Currently, the primary water sources for Okinawa Island are dams and rivers in the northern and central regions, with water consumed mainly in the densely populated central and southern areas (7). In recent years, Okinawa Island has faced challenges related to water resources, including the risk of water shortages due to climate change, natural disasters, and water pollution. These challenges have prompted administration in Okinawa to undertake various initiatives, including dam construction and environmentally friendly river management, aiming to secure the necessary water for residents, agriculture, and industries and to create safe, enriched waterfront environments, balancing water resources and environmental protection (1).

2. Hydrogeological information of the area

The topography of Okinawa Island can be divided into two main regions: the northern mountainous area and the central-southern plateaus and hills (9). The northern region consists of low mountains with an altitude of approximately 400 m. The central-southern regions feature hills with elevations below 100 m and various limestone plateaus.

Fig. 1 presents an overview of the geology of Okinawa Island. The northern part primarily comprises the Nago formation (Mesozoic), which consists of slate, phyllite, and schist, and the Kayo Formation (Paleogene), which includes sandstone, shale, and conglomerates (10, 11). The central-southern region is underlain by Shimajiri layers (Neogene), primarily composed of soft mudstone, overlaid by Ryukyu limestone, which fills the lower areas and forms groundwater basins. Ryukyu limestone, derived from coral reefs and marine sediments, is a prominent building material in Okinawa.

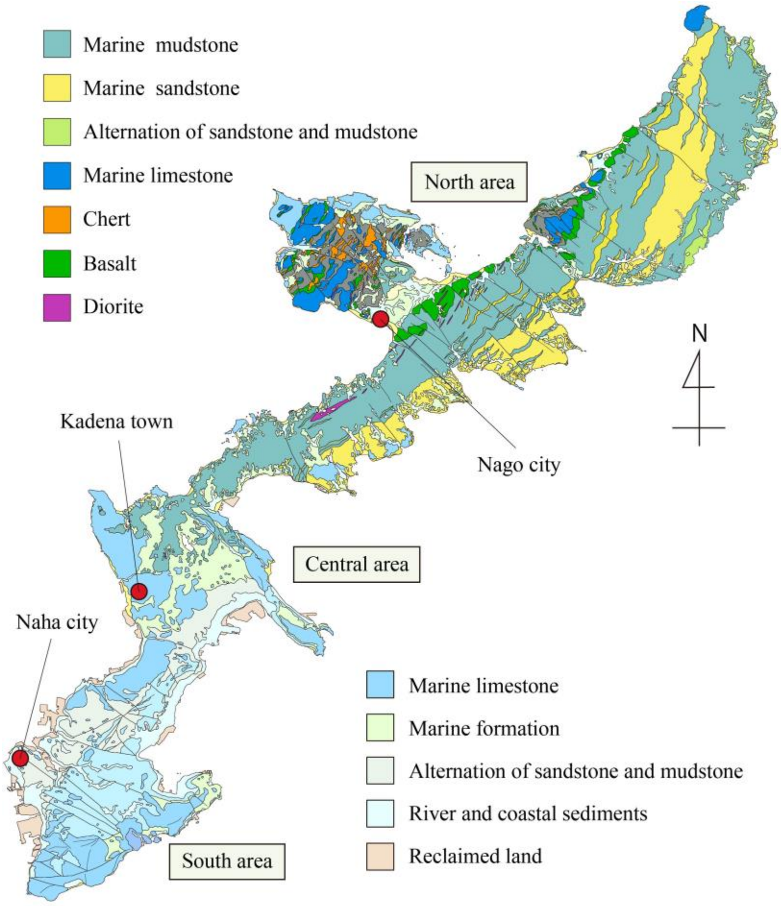

Fig. 1. Overview of surface geology and major cities on Okinawa Island (8)

Despite covering only 25% of Okinawa Prefecture, the Ryukyu limestone accounts for 75% of the groundwater reserves, making it the largest aquifer (9). The groundwater in the Ryukyu limestone layer flows according to the shape of the basement surface. When the basement is below sea level, the groundwater exists in a balance between the densities of freshwater and saltwater, forming freshwater lenses, especially in the deeper parts of the basement. This makes the groundwater susceptible to saltwater intrusion, particularly with overextraction or flooding. The limestone layer varies in thickness from 40 to 60 m, with a maximum of 130 m. It has a permeability coefficient on the order of 10^{-2} cm/sec and an effective porosity of approximately 10% (9).

The main aquifers on Okinawa Island include: (1) Ryukyu limestone, (2) older limestone and other Paleozoic rocks, (3) volcanic rocks, (4) sandstone of the Shimajiri layers, (5) terrace deposits, and (6) alluvial deposits (9). Precipitation storage can be classified into three types: surface storage in dams, primarily in the northern rivers, springs, and groundwater in limestone areas in the northern and central-southern regions, and subsurface water in sandstone aquifers of the Shimajiri layers in the central-southern region.

Groundwater aquifers on Okinawa Island are mainly distributed in the central-southern region. These are primarily composed of sandstone from the Shimajiri layers, and limestone and older limestone from the Ryukyu layers. Groundwater discharge occurs at the contact points between aquifers and impermeable layers (mudstone of the Shimajiri layers in the central-southern region) [12]. Various hydrological studies have been conducted on Okinawa Island, providing valuable data on these groundwater systems [13-15].

3. Major water resources and water utilization ways

Fig. 2 illustrates changes in water withdrawal in Okinawa Prefecture. When Okinawa rejoined Japan in 1972, water supply restrictions were imposed every year. Okinawa experienced its longest period of restricted water supply in Japan from 1981 to 1982, lasting a total of 326 days. Although there have been subsequent crises, the development of water resources has gradually improved. Since 1994, there have been no water supply restrictions on Okinawa Island. Ensuring a stable water supply to prevent future droughts remains a crucial challenge. To address the increasing water demand driven by unique weather, topographical conditions, and population growth, both national and prefectural governments have advanced water resource development through the construction of dams and seawater desalination facilities, striving for a stable water supply [7]. In 2022, the water supply infrastructure in Okinawa Prefecture reached a 100% penetration rate, which was higher than the national average in Japan [16].

In 1972, river water constituted 54.6% of Okinawa's total water supply. By 2010, this decreased to 16.8%, with approximately 70% of the water being sourced from dams (Fig. 2). The current primary water sources include nine dams managed by the national government, one managed by the prefectural government, and one managed by the Okinawa Prefectural Enterprise Bureau, which is responsible for water supply. Additional sources included river water from 19 locations, groundwater from 23 wells in the town of Kadena, and a seawater desalination facility completed in the fiscal year 1996. Owing to the prevalence of Ryukyu limestone on most of Okinawa Island, water suppliers that rely on groundwater often require water quality improvements, such as hardness reduction. Consequently, hardness reduction facilities have been established at several locations [16]. Although dam water currently accounts for approximately 70% of the water supply, a portion still originates from rivers. This dependence on river water makes the region susceptible to droughts during periods of low rainfall [1]. In addition to surface dams, underground dams have been constructed to ensure a stable water supply for agriculture [15]. These underground dams store water in permeable Ryukyu limestone which contains numerous cavities. The immediate challenge for Okinawa is to secure a stable supply of domestic water, given the natural constraints of the region.

4. Hydrological database

Continuous monitoring of the water quality in public water bodies and groundwater was conducted under the provisions of Article 15 of the Water Pollution Prevention Act (Act No. 138 of 1970), and the results were published in accordance with Article 17 of the same Act in Okinawa [1]. In 2022, water quality measurement results for 25 rivers and 11 sea areas classified according to water use will be made public. Water quality testing for tap water includes both, regular and temporary inspections based on Article 20 of the Water Supply Act (legal

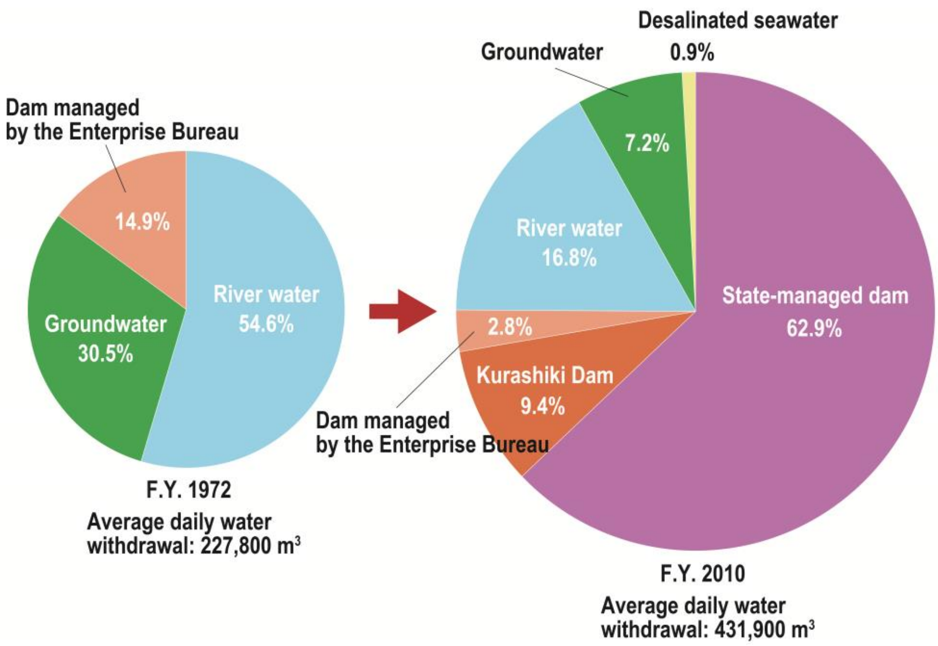

Fig. 2. Change in water withdrawal in Okinawa [17]

compliance inspections) and inspections conducted independently by the Okinawa Prefectural Enterprise Bureau to verify the overall water quality management from raw water through purification and distribution. The inspection items include those mandated by the Water Supply Act (51 items related to water quality standards, color, turbidity, and residual disinfection efficacy), supplementary items for water quality management objectives, and other necessary items to ensure the safety and quality of drinking water. The results of these inspections are also published, with some data available on the prefectural website [1].

Additionally, the National Institute of Advanced Industrial Science and Technology (AIST) publishes "hydro-environmental maps" which contain scientific data, such as groundwater levels, water quality, and isotope ratios. These maps were edited based on the hydrogeological conditions of each region and are expected to assist in the sustainable use and management of surface water and groundwater resources. Currently, hydro-environmental maps for 11 regions are freely available, and a hydrological database for Okinawa Island is under development [18]. As basic research approach, metagenomic analysis is also underway to assess the composition of microbes and their functions in surface water and groundwater, and to evaluate the potential of microbes for water purification and the visualization of terrestrial-coastal connections in the future.

5. Major problems and future challenges

As discussed in previous sections, various initiatives and studies on water resource utilization and conservation have been implemented on Okinawa Island. Based on accumulated data, the main challenges regarding water resources in recent years include drought and groundwater contamination from anthropogenic substances such as nitrate, phosphates, and perfluorinated alkylated substances.

Okinawa has historically faced drought-related issues because of its limited water resources and the significant influence of climatic conditions. As shown in Fig. 2, the current reliance on river water remains at 16.8%, making the region susceptible to drought during periods of low rainfall. Okinawa has utilized a combination of river water, groundwater, surface and underground dams, and seawater desalination to address these challenges. However, alternative water sources must be explored.

To be able to sustainably use river and groundwater, active efforts to address water pollution are required. Several studies have investigated water resource contamination in Okinawa. For instance, Hermawan et al. examined nitrate contamination in a limestone aquifer in the southern region of Okinawa Island [(19)]. Additionally, signals of anthropogenic nitrate contamination have been detected in groundwater in the northern region of Okinawa [(20)]. The widespread presence of Ryukyu limestone, which facilitates surface-water infiltration, indicates that surface pollutants can easily penetrate the ground and contaminate groundwater. In 2005, a 2.3 km-long underground dam was constructed in the southern region of Okinawa to secure water for agricultural activities and irrigation. However, surface-derived pollutants have also been linked to the groundwater contamination of underground dams [(19)]. Okinawa's geological and geomorphological conditions, such as the easy infiltration of surface water in the Ryukyu limestone areas, small watershed areas, and short river flow paths, contribute to the rapid transport of terrestrial pollutants to coastal areas via rivers and groundwater (Fig. 3). The long-term accumulation of these pollutants and their exposure to biota can potentially affect coastal ecosystems such as coral reefs [(21)]. This poses a threat to Okinawa’s unique and beautiful beaches and rich ecosystems.

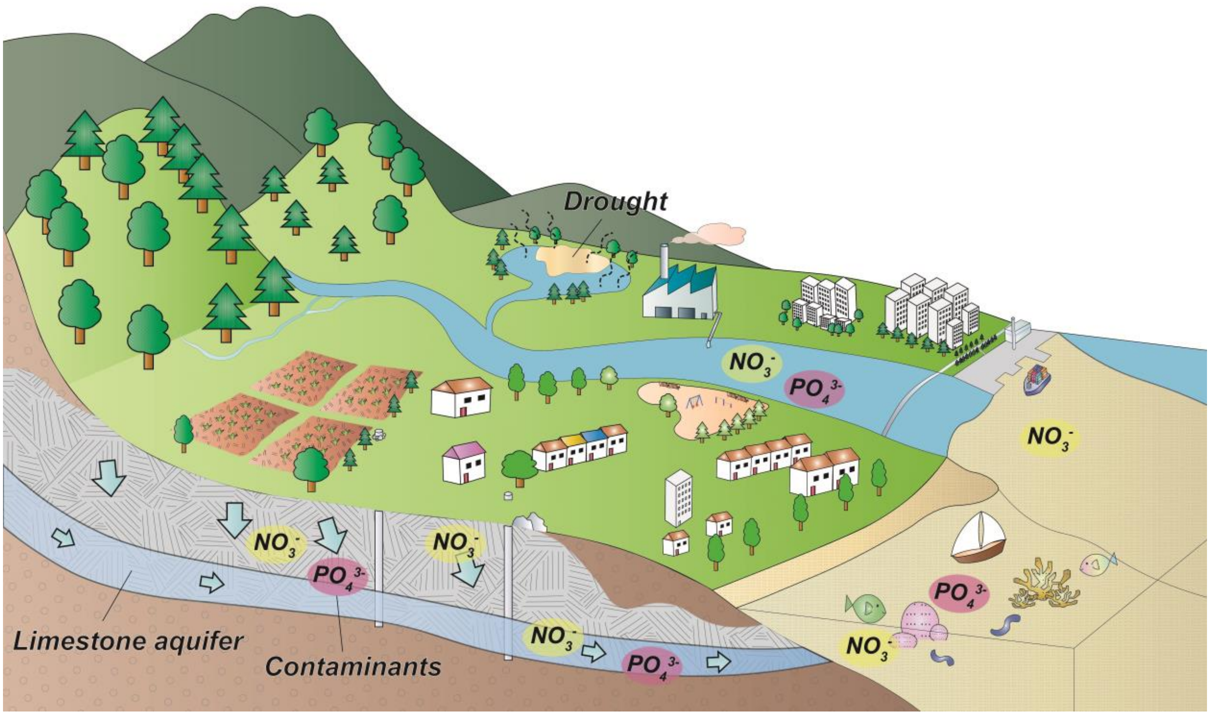

Fig. 3. Transport of terrestrial pollutants to coastal areas via rivers and groundwater on Okinawa Island

Given these circumstances, it is crucial to identify anthropogenic pollution sources and implement regional measures before water pollution becomes a serious issue. The effects of pollution from human activities are often not immediately apparent and are challenging to evaluate because of their long-term accumulation and temporal changes. In addition, the physical distance between pollution sources and coastal areas (where environmental and ecological impacts occur), makes it even more difficult to understand these effects. Effective water pollution control in island environments requires the following measures: visualizing the pollution status and its origins through scientific data, conducting comprehensive investigations and employing countermeasures that consider the connection between terrestrial and coastal areas from an upstream-downstream perspective, and sharing data and situations with local residents to foster collaborative efforts.

6. Conclusions

Okinawa, characterized by a subtropical climate, is renowned for its natural beauty and diverse ecosystems. However, it faces several water resource issues, including drought risk, water pollution, and the impacts of climate change and natural disasters. Due to its geographical conditions, the river basins on Okinawa Island are small, leading to rapid increases in water levels during heavy rainfall and extreme reductions during droughts. Additionally, the geological features of Ryukyu limestone, which facilitates surface water infiltration, increases the risk of groundwater contamination. The sustainable management of water resources requires understanding and visualizing pollution conditions through scientific data, conducting comprehensive investigations along the upstream-downstream continuum, and sharing information with local communities. It is crucial for regional stakeholders to collaborate in order to address these challenges effectively.

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Discovery of promising groundwater sources and development of large-capacity groundwater wells for groundwater-dam connection to cope with extreme emergency drought in Gwangju City, South Korea

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Abstract

In the fall of 2022 and spring of 2023, Gwangju Metropolitan City in South Korea experienced an unprecedented severe drought, leading to an emergency situation where the water level of Dongbok Dam, the major water source responsible for supplying drinking and domestic water to one million citizens of Gwangju, dropped below 20%. This report aims to introduce exemplary cases of drought response through groundwater utilization, considering the situation where citizens of Gwangju had to face water conservation or water supply interruptions due to low reservoir levels caused by severe drought at that time. At that time, the Korea Institute of Geoscience and Mineral Resources (KIGAM) devised promising groundwater sources exploration and novel high-capacity combined alluvial and bedrock well development techniques. KIGAM collaborated with the Gwangju City government to develop and implement demonstration wells. Promising groundwater sources were identified through the utilization of existing groundwater well data, alluvial layer information, and geological data analysis through Hot spot analysis, resulting in the selection of five potential sites. One of these sites was chosen for the implementation of the newly proposed high-capacity composite alluvial and bedrock well development technique, successfully establishing a high-capacity groundwater well for overcoming drought. These developed high-capacity groundwater wells complemented the water supply during such severe drought conditions in conjunction with the dam. Furthermore, KIGAM provided technical support to Gwangju City by offering manuals and design guidelines for drought response high-capacity groundwater development. Gwangju City developed ten additional high-capacity wells using such innovative drilling techniques.

Keywords: Groundwater, Drought, Gwangju city, Dongbok dam, novel high-capacity combined alluvial and bedrock well development techniques, Promising groundwater sources

1. Introduction

Recently, Gwangju Metropolitan City in South Korea experienced an unprecedented severe drought, leading to an emergency situation where the water level and water storage of Dongbok Dam, the major water source responsible for supplying drinking and domestic water to one million citizens of Gwangju, dropped below 20% (Fig. 1). The dam floor is exposed due to the worst drought (Fig. 2). This report aims to introduce exemplary cases of drought response through groundwater utilization, considering the situation where citizens of Gwangju had to face water conservation or water supply interruptions due to low reservoir levels caused by severe drought at that time.

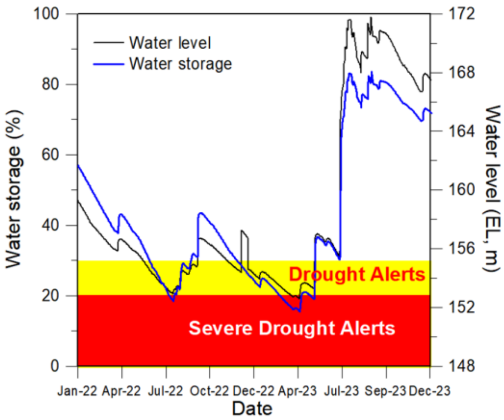


Fig. 1. The water level and water storage of Dongbok Dam

Fig. 2. Exposed dam bottom due to the worst drought in Dongbok dam

2. Hydrogeological information, Alluvial thickness, and Geological map of the Gwangju City

At that time, the Korea Institute of Geoscience and Mineral Resources (KIGAM) devised promising groundwater sources exploration and novel high-capacity combined alluvial and bedrock well development techniques. KIGAM collaborated with the Gwangju City government to develop and implement demonstration wells. Promising groundwater sources were identified through the utilization of existing groundwater well data, alluvial layer information, and geological data analysis through Hot spot analysis, resulting in the selection of five potential sites. In order to find out promising groundwater sources, we collected groundwater well data consisting of 13,740 wells(Fig. 3) in Gwangju City and alluvial thickness data, and geological map(Fig. 4).

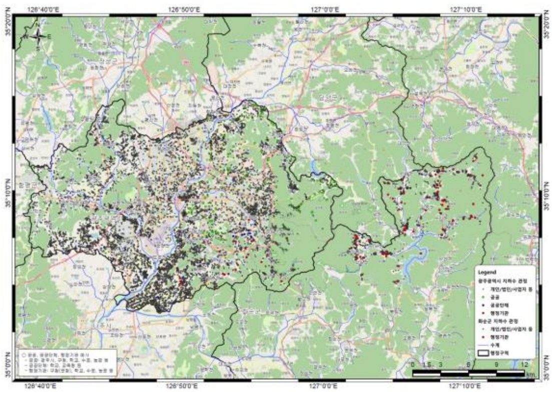


Fig. 3. Groundwater well data of 13,740 Wells in Gwangju City (Source:KIGAM(2023)

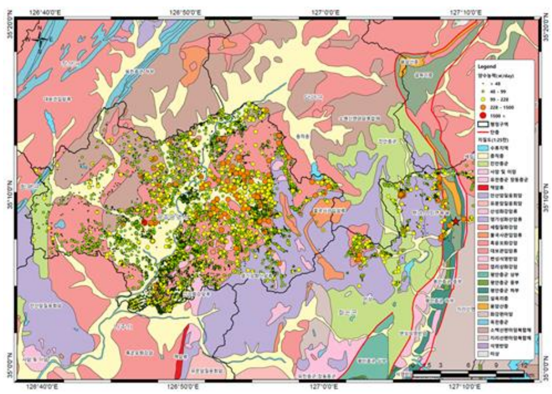


Fig. 4. Overlay of hydrogeological information of 13,740 wells and geological map (Source: KIGAM(2023)).

3. Major water resources and water utilization ways of Gwangju City.

99% of drinking water and domestic water in Gwangju Metropolitan City is supplied from the Dongbok Dam. With a population of approximately 1.4 million, Gwangju City relies heavily on Dongbok Dam, its primary water source, which was constructed in 1967. The watershed area covers 189 km2, and the dam has a water storage capacity of 99,530 thousand tons.

Table 1. Specification of the Dongbok dam in Gwangju City

Construction Year	Water Storage (thousand ㎥)	Water level of full reservoir (m)	Intake facility (thousand ㎥)	Watershed area (㎢)	Bank	
					Length(m)	Height(m)
1967	99,530	168.2	363	189	188.1	44.7

4. Hydrological database

The borehole survey data in Gwangju City was collected from the National Ground Information Portal System in Korea, revealing that alluvial layer thicknesses of 0-5, 5-10, and 10-15 meters respectively accounted for 22%, 33%, and 25% of the total. The 5-10 meter thickness interval constituted the highest proportion (Fig. 5).

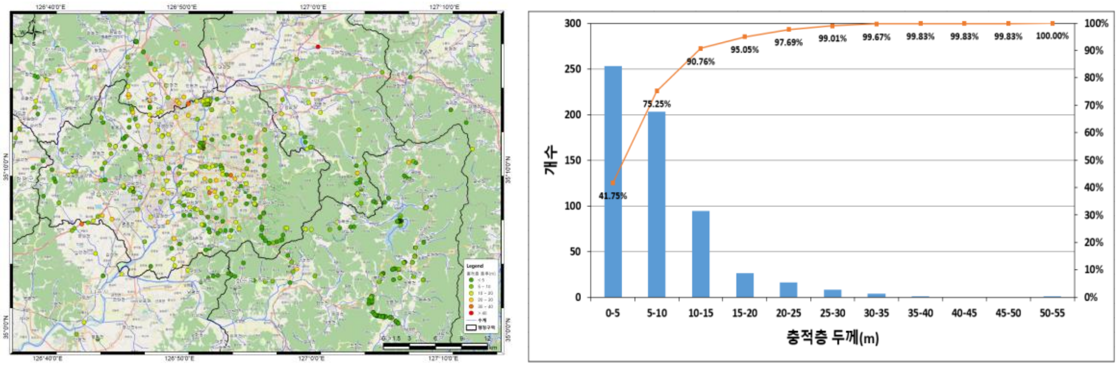


Fig. 5. Alluvial thickness distribution in Gwangju City collected from the National Ground Information Portal System in Korea (Source: KIGAM(2023).

5. Discovery of promising water sources for drought mitigation and novel high-capacity combined alluvial and bedrock well development techniques

To facilitate the discovery of promising water sources for drought mitigation, a HOT SPOT analysis (Aldtstadt, J., Getis, A. (2006)) was conducted utilizing reported and permitted pumping capacities of groundwater wells, along with data on pumping capacity/excavation depth. As a result of the analysis, 7 locations were identified, as shown in Fig. 6.

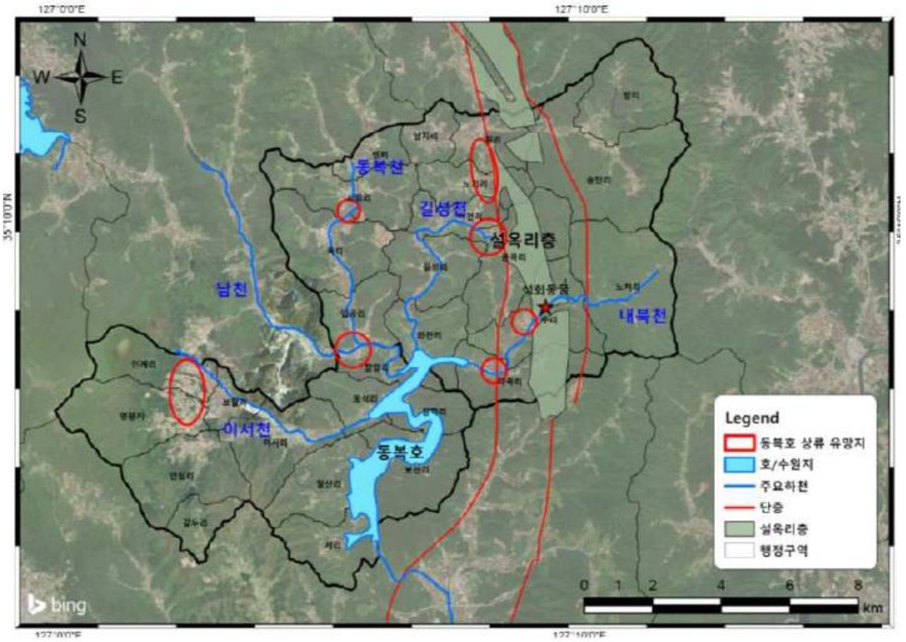


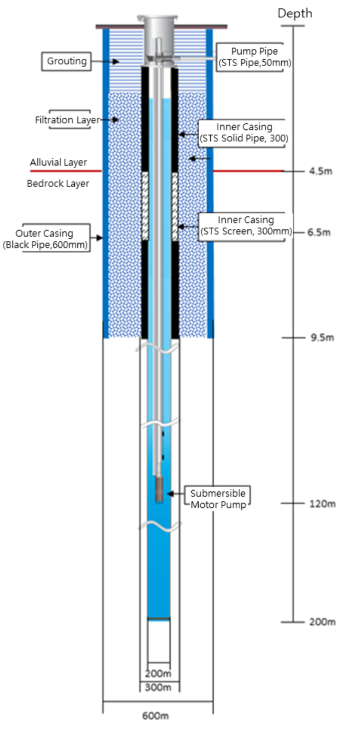
Fig. 6. 7 promising groundwater sources found out through HOT spot analysis(Source: KIGAM(2023))

In proximity to promising groundwater sources with anticipated high yield, two demonstration wells were developed using a newly proposed high-capacity composite borehole construction method. This innovative construction technique is designed to maximize groundwater extraction within a short construction period, aiming to mitigate drought effects. It is engineered to extract groundwater from both the alluvial aquifer concealed within the unconsolidated layer and the bedrock aquifer simultaneously. The excavation radius of the two wells is 600 mm, with an external casing diameter of 600 mm and an internal casing and screen diameter of 300 mm. The construction period is about 8 hours, and they exhibit yields of 900 m^3 /day and 600 m^3/day respectively.

6. Conclusions

To overcome drought, we explored promising groundwater sources using available literature data on groundwater wells, alluvial layer thickness, and geological maps. Additionally, we proposed novel high-capacity combined alluvial and bedrock well development techniques to facilitate the integrated utilization of groundwater and dam resources. Two demonstration composite well with a diameter of 300 mm and a depth of 200 m in the neighborhood of Dongbokho dam was developed. The development capacities of DB-1 and DB-2 are 900 m^3/day and 600 m^3/day, respectively, with fully enclosed upper protective caps installed for flood prevention. The total development capacity of 1,500 m^3/day, along with the additional development of 10 wells, ensures an ample water supply, reaching a capacity of 5,000 m^3/day. This high-capacity well development prepares for severe drought emergencies.

Schematic Diagram and Installation Specifications of Alluvial and Bedrock Wells



○ Targeting Alluvial Layers
– Excavation Depth: 9.5m
– Excavation Diamete∅ 600mm
– Casing Installation
· Inner Casin∅ 300mm (STS 304)
· Outer Casir∅ 600mm (Black Pipe)
※ The Outer Casing is to be Removed after the Completion of Excavation Work
– Screen Installation
· Stainless Steel Screen (Wire Screen)
· Diameter∅ 300mm
· Installation Length: 2m
· SLOT: 1mm
– Filtration Media Installation
· Particle Size: 25mm
· Installation Diameter: 300mm
· Installation Depth: Approximately 8m

○ Targeting Bedrock Layers
– Excavation Depth: From the End Point of the Alluvial Layer (9.5m) to 200m
– Excavation Diamete∅: 200mm

○ Upper Protective Well
– Installation of a Sealed Upper Protective Well (STS 304)

Fig. 7 Conceptual diagram of novel high-capacity combined alluvial and bedrock well development techniques (Source: KIGAM(2023)

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Groundwater and surface water utilization and management in Vientiane Province, Lao PDR

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Abstract

The state of groundwater and surface water management in utilization ways for Vientiane Province, Lao PDR. Since groundwater was used in small amounts, therefore in the current situation due to climate change impact to the changing potential of surface water that resulted to increase the use of groundwater, especially for household use and vegetable cultivation, which is mostly found in the plains area, but the use of groundwater for agricultural and industrial production is not much. However, in order to ensure the use of groundwater in the future may increase, it is necessary to have a groundwater management plan to be a tool to manage the usage of groundwater for efficiency and sustainability ways.

Keywords: groundwater, surface water, utilization, climate change, increase, efficiency and sustainability

1. Introduction

Vientiane Province is located in the central part of Lao PDR with a total area of 15,927.48 square kilometers. It has a border with 5 provinces: the north is with Luang Prabang province, the south is with Vientiane capital, the west is with Xayabuli and Khat Lai provinces (Thailand has a border length of 97 km) and the east is with Xiengkhouang province, Xayomphon province and Borikhamxay province. It consists of 7 districts namely: Hin Hep District, Phonhong District, Viengkham District, Keooudom District, Vang Vieng District, Kasi District and Mad District. The transportation route is along the mountain line also can access the main road, highway and high-speed train. It is rich in nature showing tourist attractions, agriculture-animal and minerals which are a source for social economic development and it is the potential income generation for the people in each locality.

2. Hydrogeological information of Vientiane Province

2.1 Geology

Vientiane Province is predominantly composed of sedimentary rocks, including limestone, sandstone, and shale, with some volcanic and metamorphic rocks in certain areas. Geological formations vary across the province, influencing groundwater systems. In the lowland areas, alluvial deposits of gravel, sand, and clay are common, while the upland areas feature more resistant limestone and sandstone.

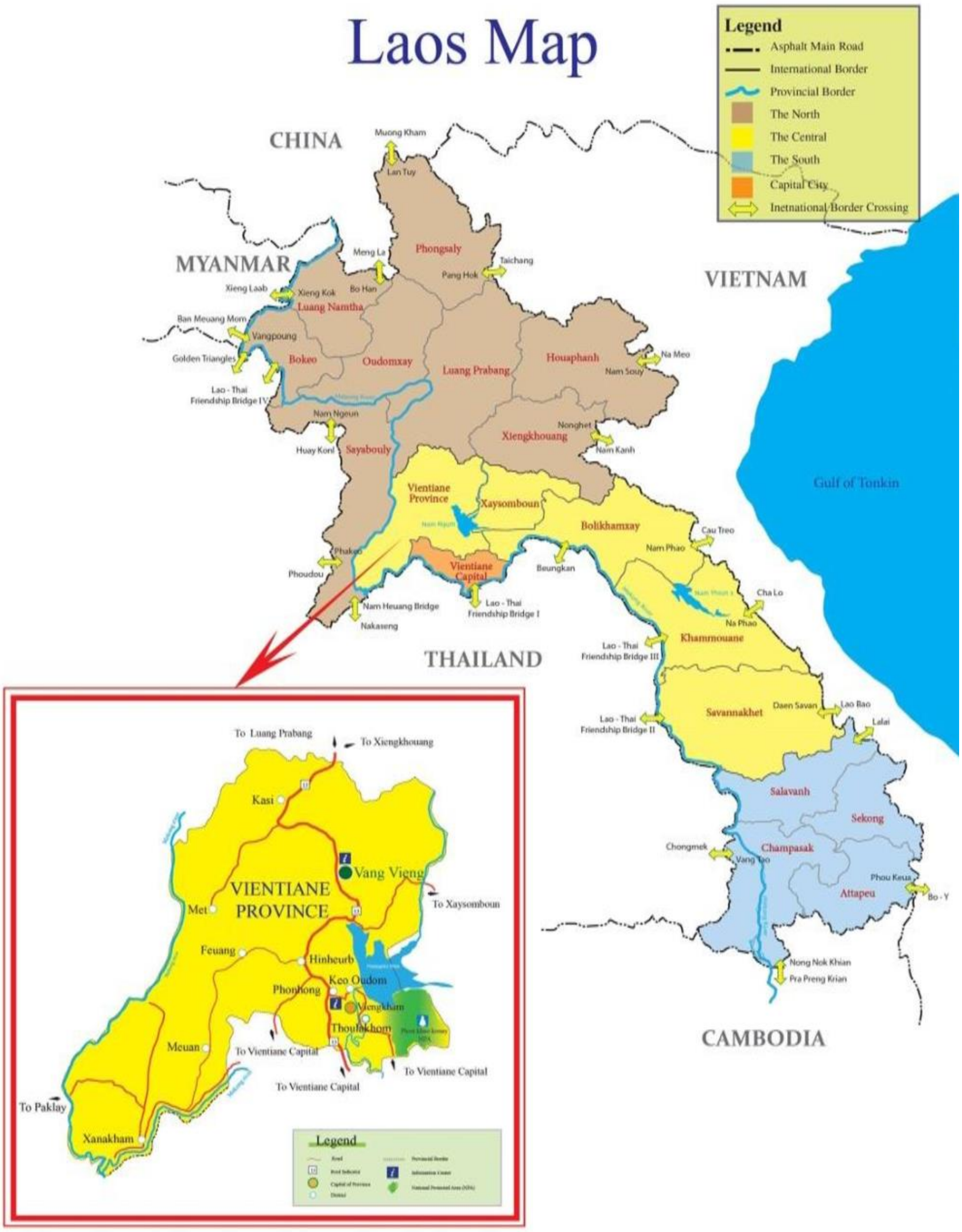

Fig. 1. Photography Map of Lao PDR

2.2 Aquifer Types

- **Fractured Limestone Aquifers**: Predominant in the mountainous regions, these aquifers are less productive but provide reliable groundwater resources. Groundwater is stored in fractures and joints within the limestone rock.
- **Alluvial Aquifers**: Found in river valleys and floodplains, especially along the Mekong River and its tributaries. These aquifers are highly productive due to the permeable nature of the sedimentary deposits, providing abundant groundwater for irrigation and domestic use.

2.3 Groundwater Flow System

The groundwater flow system in Vientiane Province is largely influenced by the topography and geological formations:

- Groundwater generally flows from higher elevations in the north and northeast towards the lowland areas in the south and southwest, following the natural gradient of the land.
- Recharge occurs primarily through precipitation, with significant contributions from surface water bodies, including rivers and the Mekong River. The flow in alluvial aquifers is more dynamic and seasonal, with higher recharge during the rainy season.
- In the fractured limestone aquifers, the flow is slower, constrained by the rock structure, and typically directed toward surface water bodies where there is hydraulic connectivity.

This hydrogeological framework supports both local water supplies and agricultural activities in Vientiane Province.

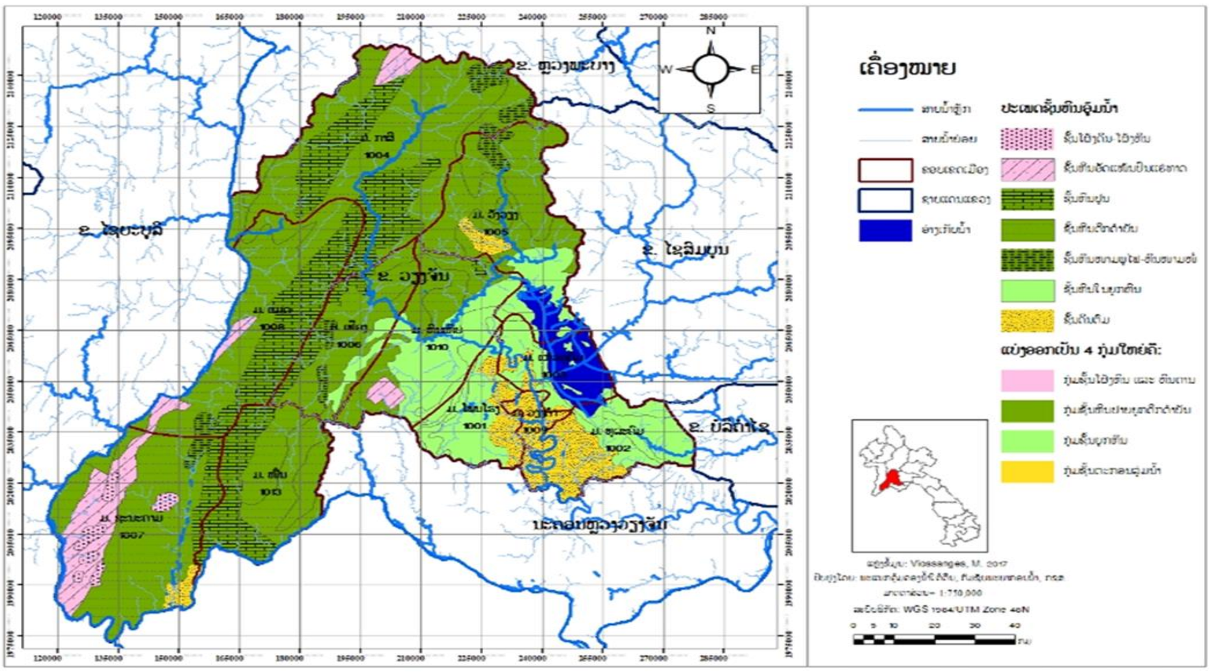

Fig. 2. Groundwater flow system in Vientiane Province

(Sources: Groundwater Management Plan of Vientiane Province 2023)

3. Major water resources and water utilization ways

3.1 Major Water Resources

Groundwater: Groundwater is a key water resource in Vientiane Province, providing water for both domestic and agricultural use. The alluvial aquifers in the lowland areas, particularly near the Mekong River, are highly productive. Fractured limestone aquifers in the mountainous regions also provide a more limited, but reliable, water source.

Surface Water: The Mekong River is the most significant surface water resource in the province, providing water for irrigation, domestic use, and industrial activities. Other rivers and tributaries, such as the Nam Ngum and Nam Lik rivers, also serve as important water sources for local communities.

Rainwater: The annual rainfall, which averages around 1,500 mm, plays a critical role in recharging both groundwater and surface water bodies. The wet season (May to October) is particularly important for replenishing water resources.

3.2 Water Utilization

Agricultural Use: The primary use of water in Vientiane Province is for **irrigation**. Agriculture, especially rice cultivation, is the dominant sector in the province. Water from groundwater and surface sources is used extensively for irrigation, particularly during the dry season when surface water availability decreases. Groundwater from the alluvial aquifers is commonly extracted for irrigation in the lowland areas.

Domestic Use: Groundwater is an essential source of **drinking water** and **household needs** in both urban and rural areas. In many rural areas, people rely on wells for drinking and cooking water. In urban areas, the municipal water supply system primarily sources water from groundwater and surface water sources.

Industrial Use: Water is used in industrial processes, including manufacturing and construction. Industrial zones, particularly in the capital city of Vientiane, rely on both groundwater and surface water from the Mekong River for their operations.

Hydropower: The **Nam Ngum Hydropower Plant**, located to the northeast of Vientiane, uses water from the Nam Ngum River to generate electricity. While this is not direct water usage for consumption, it plays a key role in the regional economy.

Recreation and Fisheries: The Mekong River and its tributaries also support **fisheries** and **recreational activities**, including boating and fishing, which are important to the local economy and culture.

In summary, Water Utilization Agriculture (irrigation) is the largest consumer of water in the province. Groundwater is heavily used for both agricultural and domestic purposes, especially in rural areas. Surface water, primarily from the Mekong River, supports agriculture, industry, and hydropower generation. Domestic water supply relies on groundwater and surface water, especially in urban areas. And efficient management and sustainable use of these water resources are crucial to supporting the growing population and economy of Vientiane Province.

4. Hydrological database situation

4.1 Hydrological Monitoring Overview

Vientiane Province's hydrological data collection and monitoring systems are still developing, with most efforts focusing on basic groundwater and surface water monitoring. Key institutions and organizations, including the Ministry of Natural Resources and Environment (MoNRE) of

Laos, and various local agencies, are responsible for gathering data related to water resources, water quality, and hydrological systems.

Monitoring Focus Areas:

- **Groundwater levels** and **quality**: Monitored through observation wells spread across the province.
- **Surface water levels**: Measured primarily in rivers and streams, especially the Mekong River and its tributaries like the Nam Ngum.
- **Rainfall**: Data on precipitation is collected through rainfall stations, primarily for agricultural planning and water resource management.

4.2 Hydrological Data Collection and Key Parameters

Hydrological data is collected in Vientiane Province through a combination of manual and automated systems. Some of the key data collected include:

- **Rainfall**: Recorded daily and monthly, with stations located in various districts of the province. This data is essential for tracking precipitation patterns and calculating potential groundwater recharge and runoff.
- **Groundwater Levels**: Monitoring is done via observation wells at key locations, particularly in areas with significant groundwater extraction. These wells help track seasonal variations and long-term trends in water table levels.
- **Surface Water Levels**: River gauges are installed at critical points, particularly on the Mekong and Nam Ngum rivers, to monitor water flow and the impacts of seasonal changes in rainfall.
- **Water Quality**: Monitoring of parameters such as pH, turbidity, salinity, and concentrations of pollutants (e.g., nitrates, heavy metals, and iron) is undertaken to ensure safe water for human consumption and agriculture.

4.3 Examples of Hydrological Data

Here are some examples of the types of data collected in the hydrological monitoring system:

Rainfall Data (Example):

- Station: Vientiane Capital
- Average Annual Rainfall: 1,500 mm
- Peak Rainfall Period: May to October (monsoon season)
- Monthly rainfall variation (Example):
  - May: 250 mm
  - June: 300 mm
  - July: 350 mm
  - August: 320 mm

Groundwater Level Data (Example):

- Well Location: Vientiane City (Urban area)

- Depth to Water Table (as of December 2023): 12 meters
- Seasonal Variation: Groundwater levels drop by approximately 2 meters during the dry season (November to April) and rise during the wet season (May to October) by up to 3 meters.

Surface Water Flow Data (Example):

- River: Mekong River, Vientiane Province
- Average Flow Rate: 3,000 cubic meters per second (during high-flow season)
- Peak Flow: 4,500 cubic meters per second (during the wet season)
- Low Flow: 1,500 cubic meters per second (during the dry season)

Water Quality Data (Example):

- Parameter: Nitrate Concentration
- Location: Well near agricultural area
- Average Concentration: 15 mg/L (threshold for drinking water is 10 mg/L)
- Note: High levels of nitrates in some areas due to agricultural runoff.

4.4 Challenges in Hydrological Monitoring

Despite efforts to monitor water resources, there are several challenges:

- **Limited Coverage**: The number of monitoring stations, particularly for groundwater, is limited and may not cover all critical areas in the province.
- **Data Gaps**: There may be inconsistencies or gaps in data collection due to infrastructure challenges, insufficient funding, or technical limitations.
- **Data Accuracy**: In some cases, manual data collection may lead to errors, especially in remote areas with limited access.

4.5 Future Developments and Recommendations

To improve the hydrological monitoring system in Vientiane Province, the following actions are recommended:

- **Expansion of Monitoring Networks**: Increase the number of rainfall, groundwater, and surface water monitoring stations across the province, especially in rural and agricultural zones.
- **Data Integration**: Use modern technologies such as Geographic Information Systems (GIS) to integrate and visualize hydrological data for better decision-making.
- **Capacity Building**: Train local staff and hydrologists in advanced data collection and analysis techniques to improve data accuracy and reliability.
- **Public Access to Data**: Make hydrological data more accessible to the public, policymakers, and local communities to promote sustainable water management practices.

In conclusion, while the hydrological database and monitoring system in Vientiane Province have made progress, further improvements in coverage, data quality, and accessibility are needed to support effective water resource management.

5. Major problems and future challenges in Vientiane Province

- **Groundwater Over-extraction**

    1. **Problem**: Over-extraction of groundwater, particularly in urban and agricultural areas, has led to significant drops in the water table, causing **land subsidence**. This can damage infrastructure and increase flood risks.
    2. **Future Challenge**: Continued unsustainable groundwater use could exacerbate land subsidence, affecting both infrastructure and agricultural productivity.

- **Groundwater Salinization**

    1. **Problem**: **Salinization** of groundwater, particularly near the Mekong River, has been reported due to saltwater, especially in areas with heavy groundwater extraction.
    2. **Future Challenge**: Increased salinity could degrade water quality, making it unsuitable for agriculture and domestic use, especially in coastal and river-adjacent areas.

- **Groundwater Contamination**

    1. **Problem**: Agricultural runoff (pesticides, fertilizers) and industrial pollution are contaminating both surface water and groundwater sources.
    2. **Future Challenge**: Contaminated groundwater may pose health risks and reduce the availability of safe drinking water, especially in rural areas.

- **Climate Change and Water Scarcity**

    1. **Problem**: Changing precipitation patterns and more frequent droughts could reduce groundwater recharge and surface water availability.
    2. **Future Challenge**: Climate change may make water availability more unpredictable, increasing the risk of water scarcity during the dry season.

- **Urbanization and Increased Water Demand**

    1. **Problem**: Rapid urban growth is increasing water demand for domestic, industrial, and agricultural uses, straining existing water resources.
    2. **Future Challenge**: Unmanaged urbanization could lead to water shortages and competition between various sectors, exacerbating water scarcity issues.

These challenges require sustainable water management, improved monitoring, and regulatory frameworks to ensure the long-term availability and quality of water resources in Vientiane Province.

6. Conclusions

Vientiane Province, located in the central part of Laos, is rich in natural resources, including water, which supports agricultural, industrial, and domestic activities. However, the province faces significant water-related challenges that could hinder its development and threaten the sustainability of its water resources.

- **Groundwater Salinization**: Particularly along the Mekong River, excessive groundwater extraction has led to saltwater intrusion into freshwater aquifers. As a result, groundwater quality is deteriorating, affecting both agriculture and domestic water supplies. If this trend continues, salinization could spread, further diminishing the region's water resources.
- **Groundwater Contamination**: Agricultural runoff, especially from pesticides and fertilizers, as well as industrial pollution, is contaminating both surface and groundwater sources. This poses health risks to local communities and reduces the availability of safe drinking water. Addressing this contamination will require improved agricultural practices and better waste management.
- **Climate Change and Water Scarcity**: Changing rainfall patterns, with increased droughts and unpredictable wet seasons, threaten the reliability of both groundwater recharge and surface water supplies. As climate change intensifies, Vientiane Province may experience greater water scarcity, particularly during dry seasons, affecting agricultural productivity and water availability for urban areas.
- **Urbanization and Increased Water Demand**: Rapid urban growth in Vientiane City and surrounding areas is escalating the demand for water. This increased demand, combined with limited resources, could lead to competition for water between domestic, industrial, and agricultural users. Without careful planning and resource management, this could result in water shortages and more frequent conflicts over water allocation.
- **Future Directions to address these challenges,** Vientiane Province must adopt more sustainable water management practices, improve hydrological monitoring, and enhance the regulatory frameworks governing water resources. Key steps include expanding the monitoring network, integrating advanced technologies like GIS for data management, promoting water-saving practices, and ensuring equitable distribution of water resources. Sustainable development in Vientiane Province depends on balancing economic growth with the protection and efficient use of its water resources.

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Hydrogeological information with active water usage in Selangor State, Malaysia and water utilization ways

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Abstract

The Department of Mineral and Geoscience Malaysia (JMG) is the primary agency responsible for groundwater-related affairs within the country. Demonstrating active engagement, JMG is dedicated to fulfilling international cooperation and obligations outlined in global frameworks such as the CCOP Geoinformation Sharing Infrastructure for East and Southeast Asia, particularly the CCOP-GSJ GSi Groundwater Project Phase IV. These efforts aim to enhance regional collaboration by sharing knowledge, technical advice, and adopting advanced technologies for better groundwater management.

In Malaysia, surface water remains the dominant source of water for public, agricultural, and industrial needs. The country's climate, characterized by high rainfall and extensive river systems, has made surface water the primary resource for water supply. However, groundwater holds significant potential as an alternative or supplementary source, and its use, although growing, is still relatively low compared to surface water.

Only a few states in Malaysia actively use groundwater but mainly for non-potable purpose. Selangor State for example, the groundwater resources are mainly used industrial and agriculture sectors. Despite these challenges, there is increasing interest in tapping groundwater resources, especially during dry periods or in areas where surface water resources are limited or polluted.

However, ongoing efforts by agencies like JMG aim to explore and develop groundwater resources more sustainably, ensuring that they are considered as a viable alternative or supplement to surface water in the future.

Keywords: groundwater, hydrogeological map, Asia

1. Introduction

Two main sources of water in Malaysia are surface water (rivers, lakes, reservoirs) and groundwater (aquifers). These resources are used across various sectors, including domestic, industrial, agricultural, and environmental needs. The conjunctive use of groundwater and surface water is an essential strategy for meeting the growing demands for water. Conjunctive use refers to the integrated management and use of both groundwater and surface water resources to maximize the efficiency, reliability, and sustainability of water supplies. This approach becomes increasingly important in regions where surface water alone may not be sufficient to meet demand, or during periods of water scarcity due to drought or seasonal variation.

As the primary agency responsible for groundwater-related affairs, Department of Mineral and

Geoscience Malaysia (JMG) is dedicated in conduct detailed groundwater mapping to assess the distribution, depth, and characteristics of aquifers across Malaysia. These maps include important data such as hydrogeological properties, aquifer types, and groundwater recharge zones. The mapping is determining the sustainable yield of groundwater in various regions. JMG operates a network of observation wells across Malaysia to monitor groundwater levels continuously. This monitoring works helps track changes in the water table and identifies areas that may face over-extraction or declining groundwater levels.

Hence, the groundwater mapping and monitoring data, is to support conjunctive use of groundwater and surface water. This approach aims to enhance the contribution of groundwater to the national water supply system, especially beneficial in regions facing high water demand. The integration of both water sources can optimize water availability across sectors.

In Malaysia, only a few states actively utilize groundwater, primarily for non-potable purposes. For instance, in Selangor, groundwater is mainly used by the industrial and agricultural sectors. Despite these challenges, there is growing interest in tapping into groundwater resources, particularly during dry spells or in regions where surface water is scarce or polluted.

2. Hydrogeological information of Selangor State

2.1 Geology of Selangor

The geological structure of Selangor plays a crucial role in determining its groundwater resources. The dominant rock formations include sedimentary rocks as well as igneous rocks, mainly granites. Additionally, Quaternary layers are deposited in the flat lowlands, extending across the downstream areas. The geology of the state can be divided into three main regions based on the rock types:

- Central and Eastern Regions: The central and eastern parts of Selangor are predominantly characterized by granite and igneous rocks. The granitic rocks cover a major portion of the surface area. These rocks are typically less permeable and have lower groundwater potential compared to sedimentary rocks. However, fractured zones in these rocks can store groundwater, and groundwater flow tends to follow the fractures and joints in the rock formations.
- Western and Northern Region: The western and northern parts of Selangor are dominated by sedimentary rocks, particularly sandstone, shale, schist and limestone. These areas are more conducive to groundwater occurrence due to the higher permeability and porosity of the sedimentary rocks. The groundwater in these regions is usually found in aquifers formed by sandstone and limestone beds.
- Coastal Regions: The coastal areas of Selangor, especially near Klang, Kuala Langat and Kuala Selangor, feature alluvial deposits, such as clays, silts, sands, and gravels, which are the result of sedimentation by rivers and tidal actions. Groundwater in these areas occurs in unconsolidated sediments, with varying levels of permeability. The most promising groundwater aquifers in the coastal areas of Selangor are often found within the Quaternary alluvium, particularly in areas with significant sand and gravel layers. These aquifers can store significant amounts of water and are relatively accessible for extraction.

2.2 Aquifer Types and Properties

The groundwater resources in Selangor are derived from a variety of aquifers in both alluvial and hard rock, each with different characteristics and potential for water extraction. The most significant aquifers in the state include the Quaternary alluvium, Kuala Lumpur Limestone, Kenny Hill Formation and Kajang Formation. These aquifers can be classified into various types, including hard rock aquifers, weathered sedimentary aquifers, shallow sedimentary aquifers, and combinations of alluvium and hard rock aquifers. The nature of these aquifers influences their yield, water quality, and overall sustainability for water supply.

The groundwater potential in Selangor can be broadly grouped into three main categories.

i. Unconsolidated Alluvium Aquifers (**Quaternary alluvium)**. Two types of alluvium aquifers. Those are the alluvial sediments in the lowlands of the river basin and the riverside alluvium sediments in the hilly and mountainous areas. These aquifers distributed in the regions like Klang, Kuala Langat, and Kuala Selangor. Riverside Alluvium: typically consisting of loose sediments like sand, gravel, and silt deposited by river systems. Alluvial sediments aquifers are formed by sediments deposited in tidal areas and along river mouths. The groundwater in these areas is often brackish or saline due to saltwater intrusion, although small pockets of freshwater can still be found in some areas.
   Riverside alluvium aquifers typically offer moderate to high yields, with certain areas like Banting (Kuala Langat) showing even higher yields due to the deposition of thick, coarse- grained materials such as sand and gravel. The yield from wells in these regions generally ranges from 25 m^3/hr to 100 m^3/hr. These aquifers vary in thickness, ranging from just a few meters to several tens of meters. The water quality from these aquifers is generally good, with slightly better quality than that found in alluvial sediments. In most cases, the water from these aquifers contains medium to high levels of dissolved solids.

ii. **Carbonate rocks** like limestone are important hosts for significant aquifers, particularly The Kuala Lumpur Limestone aquifer. This aquifer is a karstic aquifer, which means it is formed in limestone bedrock and characterized by significant fracturing and dissolution processes. These processes create a complex network of cavities, channels, and voids that allow groundwater to move and accumulate, making limestone aquifers some of the most productive groundwater sources in the region. Wells tapping into carbonate rock aquifers often produce substantial yields, typically exceeding 30 m^3/hr. Groundwater from the Kuala Lumpur Limestone aquifer is typically of good quality, especially in terms of clarity and taste, but it may have some dissolved solids.

iii. **Sedimentary rocks** like The Kenny Hill Formation are primarily composed of sedimentary rocks, such as sandstones, shales, and phyllite. These rocks can have good porosity and permeability, especially in areas with fractures and weathered zones (depends heavily on the geological conditions, including fractures and faults). Wells tapping into sedimentary rock aquifers, typically ranging from 10 m^3/hr to 20 m^3/hr (moderate yield). The water quality in sedimentary rock aquifers is generally medium to good, with low total dissolved solids. However, in some cases, the groundwater may have elevated levels of iron (Fe), which can lead to staining, taste issues, and require treatment for potable use.

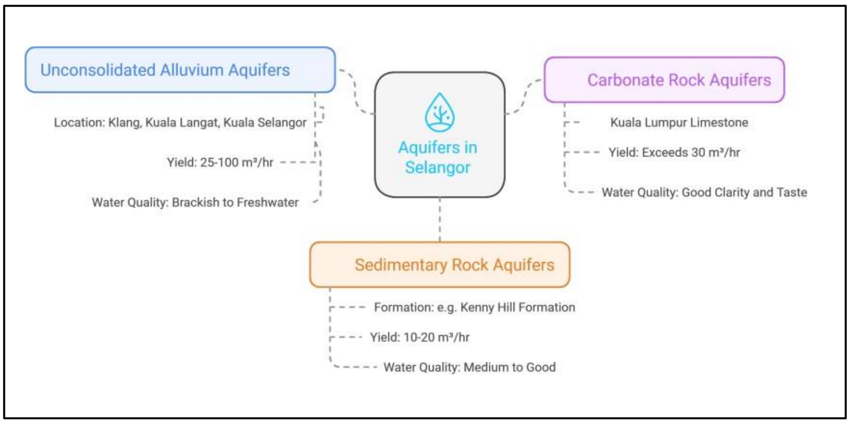


Fig. 1. Summary of aquifers type in Selangor

2.3 Groundwater flow system

The flow of groundwater in Selangor is determined by various factors such as the type of aquifer, the permeability of the underlying materials, and the presence of recharge and discharge zones. Groundwater typically moves from areas of high pressure or high recharge to areas of low pressure or discharge. Below is an explanation of the key components of the groundwater flow system in the region:

a. Recharge Areas

- In Selangor, recharge primarily occurs in the highland regions and hillsides, where the permeability of the underlying materials is relatively higher. The Titiwangsa mountain range, which runs along the eastern edge of the state, is an important recharge zone for groundwater.

b. Groundwater Flow

- Groundwater in Selangor generally flows from the highland recharge areas toward the lower- lying discharge areas. In coastal areas, groundwater may flow towards the sea, where it can eventually discharge into the ocean. In areas where confined aquifers are present, groundwater flow tends to be more localized, with movement directed along faults or fractures.

c. Discharge Areas

- In Selangor, groundwater is extracted for industrial use, especially in areas like Shah Alam, Petaling Jaya, and parts of the Klang Valley. Groundwater discharge is also linked to baseflow into rivers, providing a steady supply of water during dry periods. Coastal discharge zones are particularly sensitive to saltwater intrusion, where over-extraction of groundwater can lead to the intrusion of saltwater into fresh groundwater supplies.

d. Interactions Between Groundwater and Surface Water

- Surface water and groundwater interact as a single hydrological system. Streams that flow year-round are often connected to groundwater sources. For instance, research by the JMG highlights how groundwater feeds into bodies of water like ‘off river storage (ORS) and ex- mining lakes, indicating a strong connection between these two water sources. This interplay is crucial for maintaining water levels and quality in both surface and groundwater systems.

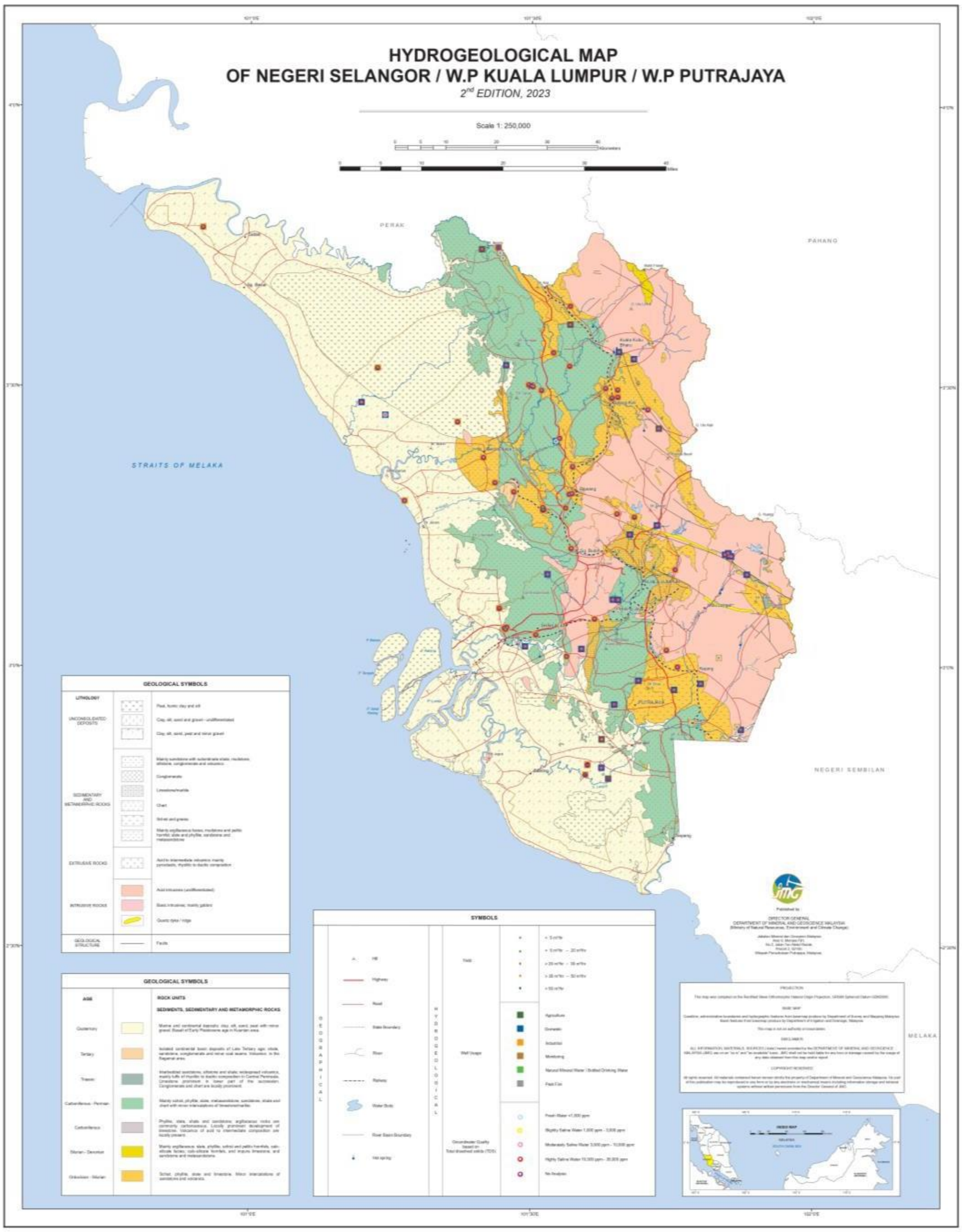


Fig. 2. Hydrogeological Map of Selangor State

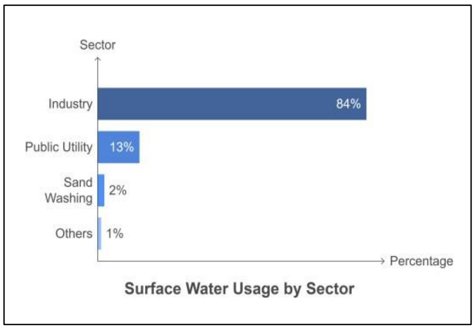
3. Major water resources and water utilization ways

Selangor primarily relies on surface water from rivers and reservoirs to meet its water demands. Major rivers like the Selangor River, Langat River, and Klang River serve as primary sources for public water supply. These rivers feed into large reservoirs and treatment plants that provide potable water to the state's population and industries. The state's industries, which include manufacturing, agriculture, and services, use groundwater for various purposes, including cooling, production processes, and other operational needs.

In Selangor, the extraction of groundwater, is tightly regulated to ensure sustainability and prevent over- exploitation. The process is managed through a permit system, primarily overseen by the Selangor Water Management Authority (LUAS), with the JMG playing a key role in providing technical advice related to the safe yield of groundwater resources for every well submission. The purpose of these permits is to prevent over-extraction and the subsequent negative environmental impacts, such as lowering the water table or reducing aquifer recharge rates.

The specifics of using water abstraction are as follows:

NO.	SECTOR	TOTAL ABSTRACT (M^3/year) - SURFACE WATER	PERCENTAGE BY SECTOR (%)
1	INDUSTRY	139,631,284.00	84%
2	HOTEL/ACCOMODATION	15,840.00	0%
3	QUARRY/CEMENT MIXING	781,077.00	0%
4	GOLF	165,060.40	0%
5	CEMETERY	5,764.00	0%
6	PUBLIC UTILITY	21,373,620.58	13%
7	AQUACULTURE	24,468.00	0%
8	AGRICULTURE	24,516.40	0%
9	PLANTATION	701,154.40	0%
10	LIVESTOCK	10,418.00	0%
11	SAND WASHING	2,926,355.60	2%
	TOTAL	165,659,558	



NO.	SECTOR	TOTAL ABSTRACT (M^3/year) - GROUNDWATER	PERCENTAGE BY SECTOR (%)
1	INDUSTRY	7942986.00	89%
2	HOTEL/ACCOMODATION	10434.00	0%
3	QUARRY/CEMENT MIXING	316661.00	4%
4	GOLF	44660.80	1%
5	AQUACULTURE	41660.00	0%
6	PLANTATION	349560.20	4%
7	LIVESTOCK	202864.00	2%
	TOTAL	8908826.00	

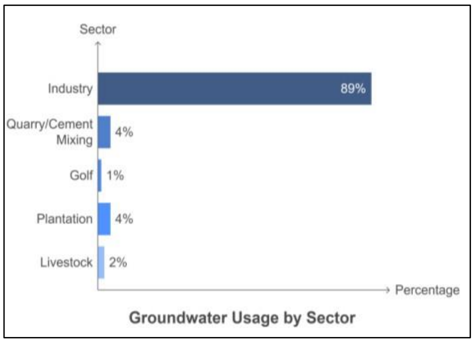


Fig. 3. Details of water abstraction in Selangor. (LUAS Annual Report, 2022)

4. Hydrogeological database

In Malaysia, hydrological stations and databases are crucial for monitoring and managing water resources across the country. These systems collect data related to surface water and groundwater, including quality, quantity, and environmental factors.

The monitoring and management of water resources in Malaysia involve a complex network of agencies, each with specific roles and responsibilities. The Department of Irrigation and Drainage (DID), The National Water Services Commission (SPAN), JMG, Department of Environment (DOE) and other agencies such as LUAS work together to ensure that both surface water and groundwater resources are managed sustainably, with attention to water quality, quantity, and environmental protection. They may share data through government portals, research collaborations, and joint monitoring programs to ensure an integrated approach to hydrological management in Selangor.

JMG in establishing the **Malaysia Geospatial Mineral and Geoscience Information System (MyGEMS)**. MyGEMS serves as the national spatial data bank, centralizing and managing crucial geoscience and mineral resource information for Malaysia. This system plays a pivotal role in the efficient collection, storage, and dissemination of geological and mineral data, supporting decision-making, resource management, and environmental monitoring.
JMG is progressively channeling this groundwater data into MyGEMS, which will help in better managing the nation's water resources, monitoring groundwater levels, and ensuring sustainability.

Fig. 4. Groundwater Monitoring Programme (JMG Annual Report, 2022)

5. Major problems and future challenges

Water resources, particularly groundwater, face several major problems and challenges due to factors like risk of land subsidence, groundwater salinization, disturbance of recharge areas, and changing land use. These challenges are driven by a combination of natural processes and human activities.

1. Major Problems

i. **Risk of Land Subsidence**. Illegal groundwater pumping, especially in urban and agricultural areas, may lead to land subsidence risks in Selangor.

ii. **Recharge areas** are critical regions where water naturally replenishes aquifers through the infiltration of rainwater or surface water. Activities that disturb or block these areas, such as urban development, deforestation, and agriculture, reduce the ability of groundwater to be naturally replenished. Without proper recharge, aquifers cannot be sustained, leading to depletion over time.

iii. **Land use changes** such as urbanization, deforestation, and industrial development can negatively impact water resources by altering the natural hydrological cycle. Urbanization, in particular, often involves the paving of large areas, reducing the natural infiltration of rainwater into the soil and reducing recharge. Agricultural practices, such as excessive irrigation and poor land management, can lead to the contamination of water sources with chemicals and waste. This can make groundwater unsafe for consumption.

2. **Future Challenges**

i. **Climate Change Impact.** Climate change is expected to alter precipitation patterns, leading to more frequent droughts and irregular rainfall. This can affect both surface water and groundwater recharge, making water resources more unpredictable.

ii. **Need for Sustainable Management**: Ensuring that groundwater extraction rates are aligned with the natural recharge capacity of aquifers will be essential for long-term water.

iii. **Integrated Water Management**: There is a need for better coordination between government agencies, industries, and local communities to manage both surface water and groundwater resources in an integrated manner. This includes better regulation, monitoring, and planning to prevent over-extraction and ensure equitable access to water.

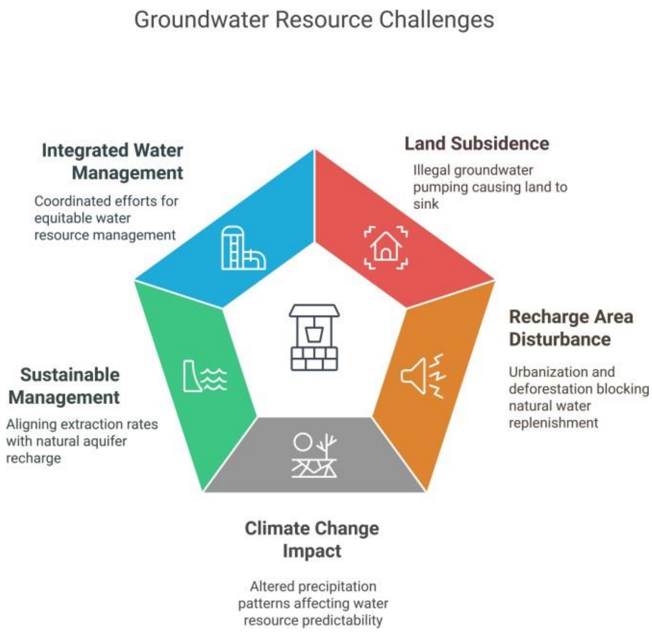


Fig. 5. Groundwater major problems and future Challenges

6. Conclusions

Through the groundwater mapping and monitoring efforts of agencies like JMG, the conjunctive use of surface and groundwater is optimized to meet the demands of a growing population and economy, while addressing environmental challenges such as droughts and water scarcity. As water-related challenges continue to evolve, coordinated efforts between governmental bodies, local communities, and industries will be essential to securing water for future generations. By focusing on sustainable practices, regulation, and the use of technology, Malaysia can safeguard its water resources for the long term. By continuing to engage with stakeholders, enhance monitoring efforts, and develop sustainable policies, JMG and other water agencies can work together to increase the contribution of groundwater to the national water supply, ultimately ensuring water security for Malysia and beyond in the future.

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Hydrogeological information of Ulaanbaatar city with active water usage in Mongolia and water utilization ways

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Abstract

One of the most basic needs of citizens is safe and sufficient drinking water. Mongolia's capital, Ulaanbaatar, is located along the Tuul River and has more than half of the country's population. Because river flows vary and rivers freeze in the winter, groundwater serves as city's primary water source (90%) for drinking and industrial purposes. The Quaternary granular alluvial aquifer of the Tuul River contains the most groundwater resources. Broad alluvium has been filled by more than 5-65m of gravel and sand with clay and it is commonly irregular in thickness and composition. Hydraulic conductivities ranging from 50 to 290 m/day; however, values of 300 m/day are more typical. The total surface water resources of the Tuul River basin are 1.49 km^3/year. Potential exploitable groundwater resources are formed of which 641 million m^3/year or 92.9 percent of the total resources are formed in 20 percent of the total area. 160 production wells, connected to centralized water system are extracting 163,000-198,000 m^3/day. We face issues like developing a dependable source of enough water to meet all needs, guaranteeing adequate water quality, safeguarding the source from pollution, and minimizing the unfavorable effects of water extraction at a time when the population is expanding and the demand for water is rising. To address these issues, groundwater monitoring data must be processed, and the resulting analyses used in urban planning.

Keywords: groundwater, water resources, hydrogeological condition, monitoring

1. Introduction

Urbanization is a huge global phenomenon. Currently, more than half of the world's population lives in metropolitan regions or cities. One of the most basic needs of citizens is safe and sufficient drinking water (Munkhsuld & Koop S van Leeuwen, 2020). Over the last few decades, Mongolia's urban development has resulted in a major increase in water demand for drinking, residential, and industrial use. The city's water supply is derived from shallow groundwater in alluvial aquifers in the Tuul River basin (Batsaikhan B. Y., 2020). Ninety percent of the groundwater of the Tuul River supplies drinking and industrial water in Mongolia as rivers freeze throughout the winter. 160 production wells, connected to centralized water system are extracting 163,000-198,000 m^3/day.

The Tuul River collects water from rivers originating from the southwestern slopes of the Khentii mountain range and drains into the Orkhon River, the main tributary of the Selenge River. The width of the river in the city area is about 35 m wide, but it narrows to 5-18 m during the dry season. From May to November, the river's average depth is roughly 1.3 m, with the shallowest during March to April (0.6 m) and the deepest in July 1993 (2.1 m). Depending on flow condition, 62-64 percent of annual runoff forms within June-August. Runoff of the Tuul

River recedes, freezing up to bed in winter season limiting water use. The flow begins initially in spring (March), and discharge steadily increases until it reaches a peak during the rainy season (July-August) (Batsaikhan N. J., 2018).

The study area is characterized by a semi-arid climate, with a hot, dry summer and cold winter. Summer, from June to August, receives approximately 74% of the total annual precipitation. Annual precipitation in the area varies from 242.7 mm to 396.7 mm, depending on the altitude of the station sites. During the winter (November to March), the ground freezes and precipitation accumulates as snow. Snow normally falls from mid-October to mid-April. The average annual air temperature is -1.2ºC, with lows of -39.6ºC in January and highs of 34.5ºC in summer (Buyankhishig, Aley, & Enkhbayar, 2009).

The water consumption-use in Ulaanbaatar city and its districts is increasing on a regular basis due to population growth, migration, urban expansion and construction activities in recent years. The assessment of future water resource availability involves interpretation based on well-measured groundwater monitoring data. There is an urgent need to collect information from a variety of organizations and individuals to determine the future state of groundwater in the Tuul River Basin.

2. Hydrogeological information of the area

The geological features of the study area consist mainly of Devonian and Carboniferous sedimentary rocks of very low permeability intruded by granite, characterized as the basement rock (Fig. 1). This basement rock is overlain by Cretaceous sandstone and mudstone, clay and sand of Neogene deposits, and Quaternary sand and gravel deposits. Quaternary deposits are also distributed widely throughout the Tuul River Basin (Unudelger G Banzragch B, 1993).

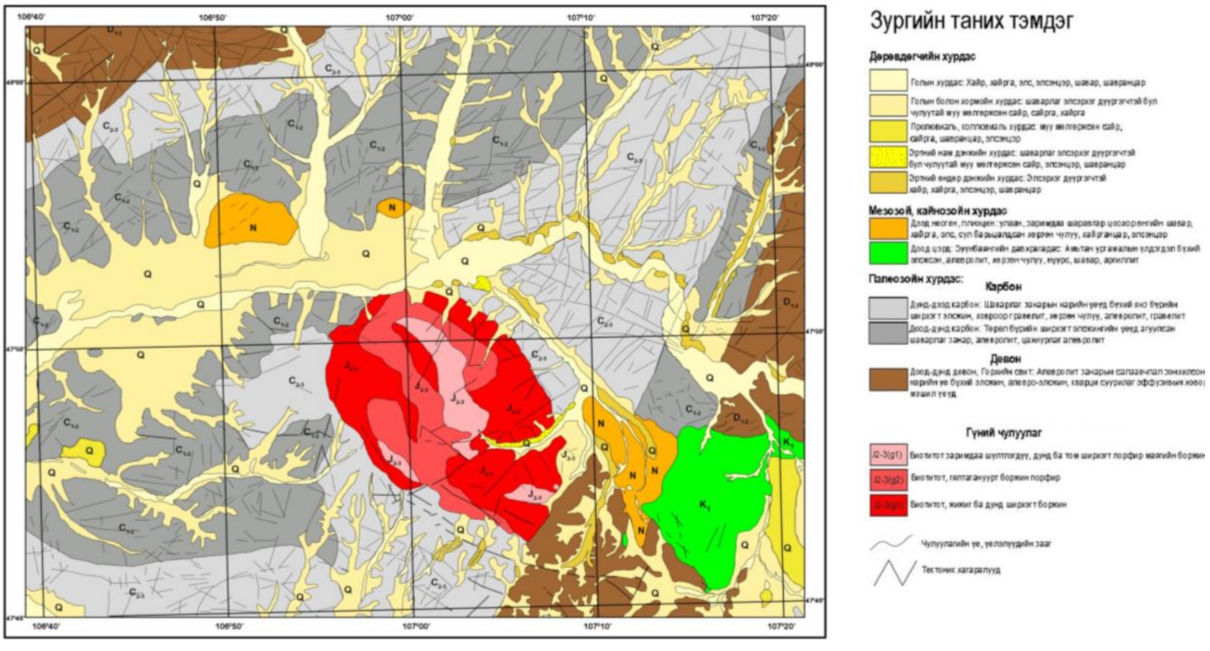

Fig.1. Geological setting of the area

The sedimentary rock formations are primarily siliceous shale, fine-grained silt, and sandstones with chert and coal intercalations; granitoids are primarily coarse-grained porphyritic granite. Quaternary alluvial deposits along the Tuul River and its tributaries cover these basement rocks.

Alluvial deposits (thickness: 3 to 54 m, average 20-30 m) are mostly composed of permeable sand and gravel with thin interlayers of clay and silt and form the primary aquifer for Ulaanbaatar's water supply system (Batsaikhan B. Y., 2020).

The Tuul river basin has granular or fissured aquifers. Granular formations in lower Cretaceous, Neogene, and Quaternary deposits, as well as fissured aquifers, can be found in sedimentary and metamorphic rocks from the Jurassic and Triassic periods (Table 1).

Table 1. Aquifers in the area

Aquifer type	Groundwater depth, m (low-high)	Drawdown, m (low-high)	Yield, l/s	TDS, g/l
Holocene alluvial aquifer	0.2-6	0.0-23.0	1-105	0.1-0.6
Pleistocene alluvial, proluvial, proluvial-alluvial aquifer along Tuul river	2.0-11.5	1.9-20.5	0.5-24.1	0.5-1.5
Holocene-Pleistocene alluvium, proluvial aquifers distributed along affluent river	0.2-12	2-40	0.5-8	0.3-1.2
Neogene aquifer	19.37-119	2-40	0.5-3.8	0.5-1.6
Cretaceous aquifer	1.5-80	-	0.3-10	-
Triassic-Jurasic aquifer	3-33	1-15	1.0-1.3	0.2-0.3
Aquifers of sedimentary, metamorphic, effusive rocks of Paleozoic	3.7-60	4.5-17	0.07-25	0.1-1.2
Fissured aquifers	8.6-26.5	2.7-5.1	0.1-4.3	0.1-0.7

Source: *Hydrogeology Volume VIII, 2010*

Granular aquifer formation in Holocene aged alluvial sediment

Between 1981 and 1985, the Russian Federation's Scientific Institute drilled boreholes in the quaternary alluvial water layer of the Tuul River basin's valley. The aquifer yields were 50.0 l/sec, 70.3 l/sec, and 105.0 l/sec, respectively, and boreholes with the highest yields were discovered during drilling for exploitation. Most boreholes dug during exploration in the upper layer of the aquifer formation of alluvial sediment origin of Holocene age in the Central Source area had a yield of 23.7-48.8 l/sec, with a drawdown of 0.24-3.3 meters. Most boreholes drilled in the industrial region yield 14.4-36.9 l/sec, with water level drawdowns ranging from 0.65 to 18.84 meters. The water quality of the upper layer of the aquifer formation in Holocene alluvial sediments meets the standard requirements for bicarbonate sodium and bicarbonate-calcium content, with a TDS of 1.1 mg/l (Jadambaa, 2010).

Granular aquifer formation in Pleistocene aged alluvial, proluvial, alluvial-proluvial sediment

The formation is found on the west side of the Tuul river valley, generating terraces. The aquifer sediment is predominantly composed of gravel, gravel, sand, sandy loam, and mild clay. This aquifer sediment has a thickness ranging from 19.5 to 33.5 meters. The tiny clay layers and lenses range in thickness from 2.6-20.0 meters. The capacity of this formation is distributed unevenly: a yield of 24.6 l/sec in a borehole lowered the water level by 1.9 meters, which is considered the highest yield in Pleistocene alluvial sediment, whereas a lower yield of 0.9 l/sec in a borehole drilled near the end of the Uliastai river lowered it by 10.0 meters. In the

Pleistocene alluvial deposits, bicarbonate, calcium-sodium, and calcium-magnesium water have TDS values of 0.704 g/l and hardness values of 8.87 mg-equ/l, respectively.

Granular aquifer formation in alluvial, proluvial, proluvial-alluvial sediment of Holocene-Pleistocene age in side valleys

Debris from side rivers like the Uliastai, Selbe, and Tolgoit Rivers forms this formation in deltas close to their mouths. Silt, clayey sand, sandy loam, and occasionally sharply fragmented rock-like boulders are the ingredients that combine to make aquifer sediment. This formation contains water at depths ranging from 0.2-11.3 meters, with most water found between 4-6 meters. This deposit has a total thickness of 16–36 meters. A well drilled in the Uliastai River delta's smooth fractured debris had the highest production in this formation, 8.0 l/sec, which decreased the water level by 8.1 meters. However, a borehole drilled in the river's mouth produced a much lower yield, 0.5 l/sec. With a TDS of 1.5 g/l and a hardness of 8.3 mg-equ/l, the water content of sulphate-chloride-magnesium-sodium and chloride-sulphate-sodium typically falls short of the standards for drinking and household tap water by all measures, and certain boreholes show nitrate and nitrite contamination.

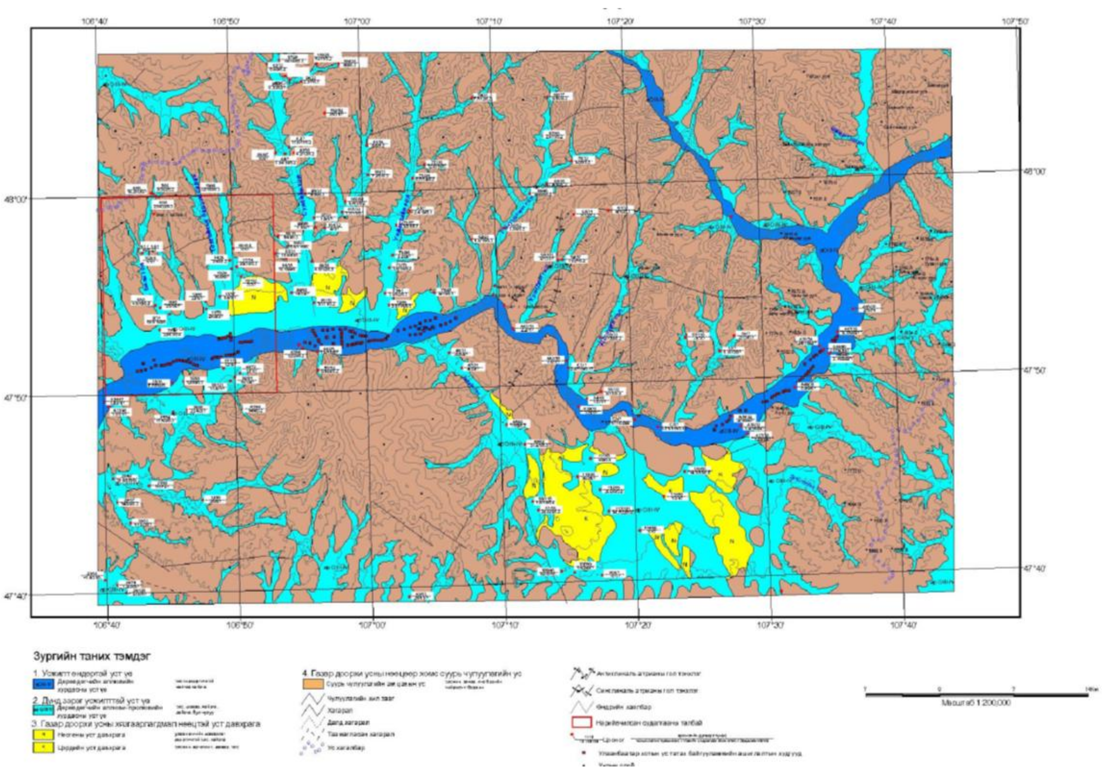

Fig.2. Hydrogeological map of the area

Granular aquifer formation of continental origin of Neogene age

Sediment of Neogene age continental origin, mostly red in color, covers the whole Tuul river basin and is sparsely scattered. Sand, conglomerate clay, sandy loam, clay bonded with coarse gravel and grit inside of mild clay make up the aquifer formation. The first layer of two strata containing water was found in a borehole drilled on the Gandan embankment at a depth of 19.37 meters, and the second layer was found at a depth of 156 meters. The borehole was also found in massive breccias at a depth of 119 meters. Thin confined layers, ranging in thickness from

1.0 to 1.75 meters, were discovered in a borehole dug close to Amgalan. The static water level was 15.5 meters, while the tops of the layers were 17.4 and 36.75 meters deep, respectively. The results of the three boreholes that were drilled were as follows: the one in Amgalan produced 3.5 l/sec, the one on the Gandan embankment produced 0.5 l/sec, and the one in Yarmag produced 2.0–3.8 l/sec. Because of its chemical content, the water does not meet criteria for drinking water.

Granular aquifer formation in Triassic - Jurassic aged sediments

This formation is found on the lower slopes on the west side of the Kharvakh (Khar bukh) river and in the Tuul River Valley around the Khustai mountain range. In the Jurassic sedimentary deposit close to the Khustai mountain range, there is spring from the aquifer formation. There is a hydraulic relationship between the Triassic-age aquifer formation found in borehole sediment and a proluvial aquifer. The hydrogeological map indicates that the confined water level in these boreholes varies between 1 and 1.5 meters, with a yield that varies between 1.3 and 1.4 liters per second and a drawdown of 1 to 15 meters.

Granular aquifer formation in Cretaceous aged sediments

Within the Tuul river basin, this aquifer is only sparsely distributed. The boreholes that were previously drilled in Nalaikh contained artesian water. The level of groundwater is dropping because of both natural and human activity. Artesian borehole density declined. By 2007's end, artesian water was found in only one borehole.

Fissured aquifers in sedimentary, sedimentary-metamorphic, effusive, effusive-metamorphic, metamorphic rocks of Paleozoic age

These aquifers are spread over the hilly terrain that encircles the Tuul River Basin. The water content is mostly composed of biocarbonate-sodium and biocarbonate-sodium-calcium, with a TDS of 0.1-1.06 g/l. The yield of the boreholes drilled in the fissured aquifers varies between 0.07-25.0 l/sec. Water was found in sandstone and shale at depths of 14.9, 13.0, and 40.0 meters in boreholes dug in fissured aquifers in effusive rocks of Paleozoic age northeast of Ulaanbaatar City. Groundwater was found to a depth of 4.7–15.85 meters within metamorphosed sandstone in boreholes drilled in Tolgoit, on the west side of the city. Groundwater is found between 3.7 and 40.0 meters below in boreholes drilled in Ulaanbaatar City's valley. Although it varies from 0.07 to 5.6 l/sec, the yield is often relatively low. Numerous springs with a maximum production of 14 l/sec are found along the tectonic fracture zones.

Fissured aquifers in intrusive sediments

Fissured aquifers in intrusive sediment of Jurassic era are located in the whole Tuul river basin in the large granite massive and other small areas. A groundwater layer is found at a depth of 11–26 meters close to the National University of Agriculture. Where groundwater is found in a fissured granite aquifer between 8.6 and 51.4 meters in depth, the borehole has a drawdown of 2.66 meters and a yield of 3.48 liters per second, while the other well has a drawdown of 5.12 meters and a yield of 4.3 liters per second. Granite bodies have more water reserves than Paleozoic sedimentary rock. Water in granite has TDS of 0.1 g/l or less, although in the spring, it varies from 0.162 to 0.679 g/l.

3. Major water resources and water utilization ways

One of the specific peculiarities of the runoff source of the Tuul River is the relatively low portion of groundwater contribution. It was estimated that about 69% of the annual runoff forms from rainfall, 6% from snow melting and 25% from groundwater source. This indicates that according to the flow regime classification the Tuul River belongs to the rivers with spring snow melting and rainfall floods. The total surface water resources of the Tuul River basin are 1.49 km^3/year calculated from the specific runoff map of the Tuul River basin.

Around 20 percent of the Tuul River basin's 49,774 km^2 region contains 596 million m^3/year, or 92.9 percent, of the possible exploitable groundwater resources (Table 2). These resources comprise 641 million m^3/year (0.641 km^3/year) in total (Ministry of Environment and Green Development, Tuul River Basin. Integrated Water Resources Management Plan, 2012).

Table 2. Potential expoitable groundwater resources

Classification	Area, km^2	l/s/km^2	m^3/year/km^2	Resource, Mm^3/year
Granular aquifers, large resources (>10 l/s)	165.6	10	31,5360	52
Granular aquifers, large than medium resources (3-10 l/s)	3,705	3	94,608	351
Granular aquifers, medium resources (1-3 l/s)	6,123	1	31,500	193
Granular aquifers, lower than medium (0.3-1.0 l/s)	246	0.65	20,500	5
Granular aquifers, lower than medium (0.3-1.0 l/s)	633	0.65	20,500	13
Granular or fissured aquifers, low resources (0.03-0.3 l/s)	1,278	0.165	5,203	6
Granular or fissured aquifers, low resources (0.03-0.3 l/s)	2.239	0.165	5,203	12
Granular or fissured aquifers, very low resources (0.003-0.03 l/s)	49	0.0165	520	0
Fissured aquifer, very low resources (0.003-0.03 l/s)	12,879	0.0165	520	7
Granular or fissured aquifer, basically no water resources (<0.003 l/s)	22,456	0.003	94.6	2
Total	49,774			641

Source: (Ministry of Environment and Green Development, Integrated Water Resources Management National Assessment Report, Volume I, 2012)

At the joint meeting of the Mineral Resource Reserve Commission of the USSR (the former Russian Federation) and the People's Republic of Mongolia on June 20, 1980, the exploitable groundwater resource (Table 2) in the alluvial aquifer in the wide section of the Tuul River near Ulaanbaatar City was formally approved (Ministry of Environment and Green Development, Integrated Water Resources Management National Assessment Report, Volume I, 2012).

The water supply service for Ulaanbaatar city is the responsibility of Ulaanbaatar Water Supply and Sewerage Authority (USUG) and the Housing and Public Utilities Authority of Ulaanbaatar City (OSNAAUG) and comprises of both piped network and trucked services. USUG is a public company owned by the Ulaanbaatar city, which was established based on the “Law on State and Local Property” with a mission to manage the operation and maintenance of water supply and wastewater, including the wastewater treatment plants in the city. The water is distributed to industries, organizations, apartments which have a connection to the central network and water is also distributed through 300 kiosks that have a connection to the ger district central network. USUG also supplies the urban ger district population by water truck through 260 not connected kiosks.

Table 3. Expoitable groundwater resources in alluvial aquifer

Source name	Classification category		Types of use
	A+B	C1	
Central	90.3	34.8	Domestic, industrial
Upper source	89.7	-	Domestic, industrial
Undustrial	30.3	-	Domestic, industrial
Meat complex	8.6	-	Domestic, industrial
CHP-1	3.5	-	Technical use
CHP-2	4.9	-	Technical use
CHP-3	2.5	-	Technical use
CHP-4	41.4	-	Technical use
Other	7.2	35.8	Technical use
Total	278.4	70.6	

Source: (Ministry of Environment and Green Development, Integrated Water Resources Management National Assessment Report, Volume I, 2012)

4. Hydrological database

Until 1991, groundwater monitoring stations in Mongolia were located at mine sites and aimags. The observation books provided for document processing and reports contain all the monitoring data and information gathered from the observation wells in the soums, cities, province centers, and rural regions. The report shows that groundwater levels in the Tuul aquifer at Ulaanbaatar indicates an increase of the groundwater drawdown from 2-3 m observed in 1979-1980 to 3-4 m at present days. Groundwater is abstracted in an expanding area, therefore the groundwater drawdown increases every year.

According to the findings of the data interpretation conducted by G. Tserenjav and D. Unurjargal from the Geo-Ecology Institute, pumping production wells along the Tuul River have comparatively less groundwater drawdown. In production wells 12, 14, and 17, the groundwater drawdown was 4.1–10.07 m at the start of the recharge period in March and April, and it decreased to 1.3-2.05 m during the peak recharge period.

There is an increase in groundwater level drawdown in production wells located perpendicular to the Tuul River. For production well 5, the drawdown grew to 8.16-10.6 m at the start of the recharge season in March and April and decreased to 4.15-3.01 m during the peak recharge period.

The groundwater drawdown in production wells No. 30, 32, which are situated far from the river, increased to 13.14–13.28 m at the start of the recharge season in March and April. During the peak recharge period, the groundwater drawdown decreased to 5.56-7.24 m.

The water supply sources of Ulaanbaatar City should be under regular control and its water level monitoring points should be subjected for measurement work regularly. Water Supply and Sewerage Authority monitors water quality and level. In addition, research institutes such as the Institute of Geography and Geoecology and the University of Science and Technology use their own borehole equipment to collect data. The Water Supply and Sewerage Authority collects groundwater data but does not interpret it.

5. Major problems and future challenges

As populations grow and demands on water resources rise, policymakers and water managers face several critical questions, including developing reliable sources with enough water to meet all the diverse needs, ensuring adequate water quality, protecting sources from pollution, and mitigating the negative effects of water abstraction and water pollution. Addressing these problems requires the implementation of processes that lead to long-term solutions:

- Create a groundwater monitoring plan for the national monitoring network.
- To establish a new database on groundwater quality and chemical compositions, expanding each year systematically.
- Create a systematic information platform, collect information from all sources, and analyze it using the advancement of information technology.
- Any organizations have groundwater data that is not publicly available. Due to the level of confidentiality, researchers are unable to access Ulaanbaatar's groundwater data. It can be difficult to share information.
- Previously, the Geological Information Center got copies of hydrogeological survey reports. The Department of Water, part of the Ministry of Environment and Tourism, is now in charge of hydrogeological research that is not open to the public. Hydrogeology has been split from the geological branch and is now a part of the environmental branch.

6. Conclusions

Ulaanbaatar, a capital of Mongolia is one of the coldest city in the world. The Tuul River freezes due to the severe winter environment, and groundwater is the primary water source. The city's water supply is derived from shallow groundwater in alluvial aquifers in the Tuul River basin. The aquifer with the relatively largest groundwater resources is the Quaternary granular alluvial aquifer of the Tuul River. The total surface water resources of the Tuul River basin are 1.49 km^3/year. Surface water is vulnerable to climatic conditions. Rivers are frozen for up to 7 months of the year. The Tuul River basin has 641 million m^3/year of potential groundwater resources. 160 production wells, connected to centralized system are extracting 163,000-198,000 m^3/day. The water level declines less in wells that are closer to the river and more in wells that are farther away from it. City planning must be based on the interpretation of monitoring data from Ulaanbaatar's water supply source.

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Groundwater assessment in Irrigation Project in Tatkon Township, Union Territory Area, Naypyitaw, Myanmar

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Abstract

The present study deals with groundwater assessment in the northern part of Naypyitaw Territory, including Tatkon Township and aerial extent is about (57) square kilometers. The specific objectives are : (1) to understand the hydrogeologic framework of the area (2) to characterize the aquifer parameter (3) to evaluate the groundwater quality (4) to estimate the rainfall recharge and (5) to create hypothetical water balance model for the project area. The study is lying flat lying recent alluvial plain drained by major stream of Sinthay. The evaluated project area is about (57) square kilometers, and it is also lying southern margin of Central Dry Zone of Myanmar. The total of (3) village tracts of Shaukkon, Nweyit and Kyathayaing of Tatkon Township are included. The government planned to sink the (35) numbers of 10 inches diameter irrigation tubewells in the project area for the supplementary irrigation water supply and for conjunctive usage of surface water and groundwater. Recently, the total of (35) irrigation tubewells have already sunk and the remaining tasks are ongoing stage. The judicious estimation of groundwater balancing in the project area is an essential need for the large-scale groundwater use project. The main objective of this study is to know the groundwater balance including inflow and withdrawal in the project area. According to the study, the overall groundwater quality in the project area reliable for irrigation and the annual rainfall recharge in the aquifer is found as 34920 acre-feet and recent total groundwater withdrawal including both irrigation and domestic is estimated about 22% of total renewable groundwater resource in the project. In groundwater irrigation project, the public awareness and knowledge sharing of the efficient water use for water saving irrigation technology including drip irrigation, sprinkler irrigation …etc. And the appropriate cropping pattern and appropriate irrigation method (e.g. Alternating Wet and Dry irrigation Method) is the important for achieving target yield of the crops.

Keywords: groundwater, hydrogeological map, Asia

1. Introduction

Myanmar is trying to formulation of Naypyitaw, capital of the country as a Green, Clean and Smart City and ideal for remaining cities of the country. Agricultural development is the important contribution in the promotion of socio-economic of the local people. In this connection, the sufficient water supply plays a vital role. The project area which is in the northern part of the Union Territory in which the surface water sources are not sufficient in the whole season for growing crops and according to the previous hydrogeological investigations, the groundwater potential is favorable for usage of irrigation water.

Location

The project area is located the northernmost part of Naypyitaw Union Territory and includes Tatkon Township. The 3 village tracts of Shaukkon, Nweyit and Kyathayaing are included. The total area extent is about (57) square kilometers.

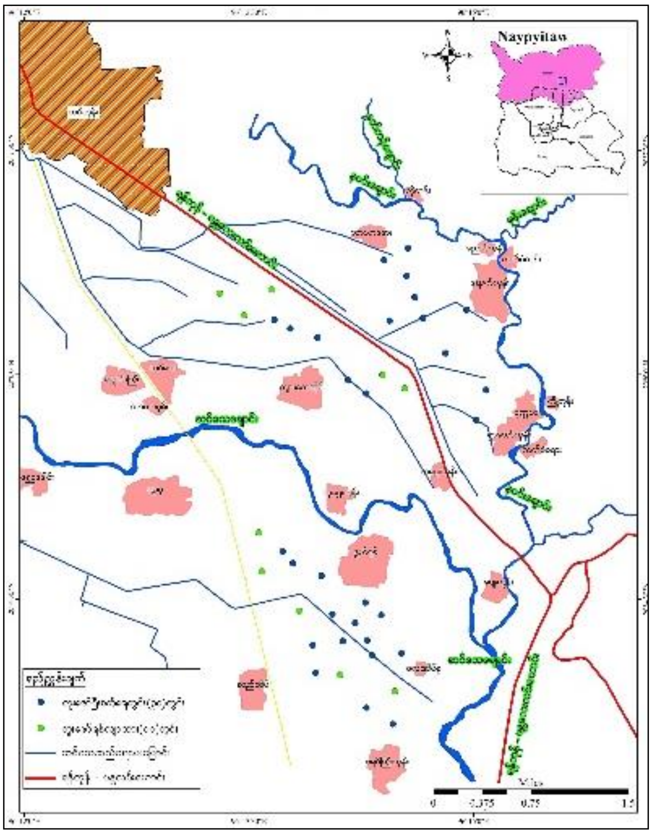


Fig. 1. Location Map

2. Topography and drainage

The Shan Plateau is situated as the eastern boundary and the Central Folded Mountain (foothills of Bago Yoma) is situated as the western boundary of the project area. The project area lies in the central flat and lowland basin. The topographic features are trending in the north-south direction. The lowest and highest elevation above the mean sea level of the project area is 350 feet and 750feet respectively. The Sinthe and Nawin Streams are flowing as the major drainage in the project area.

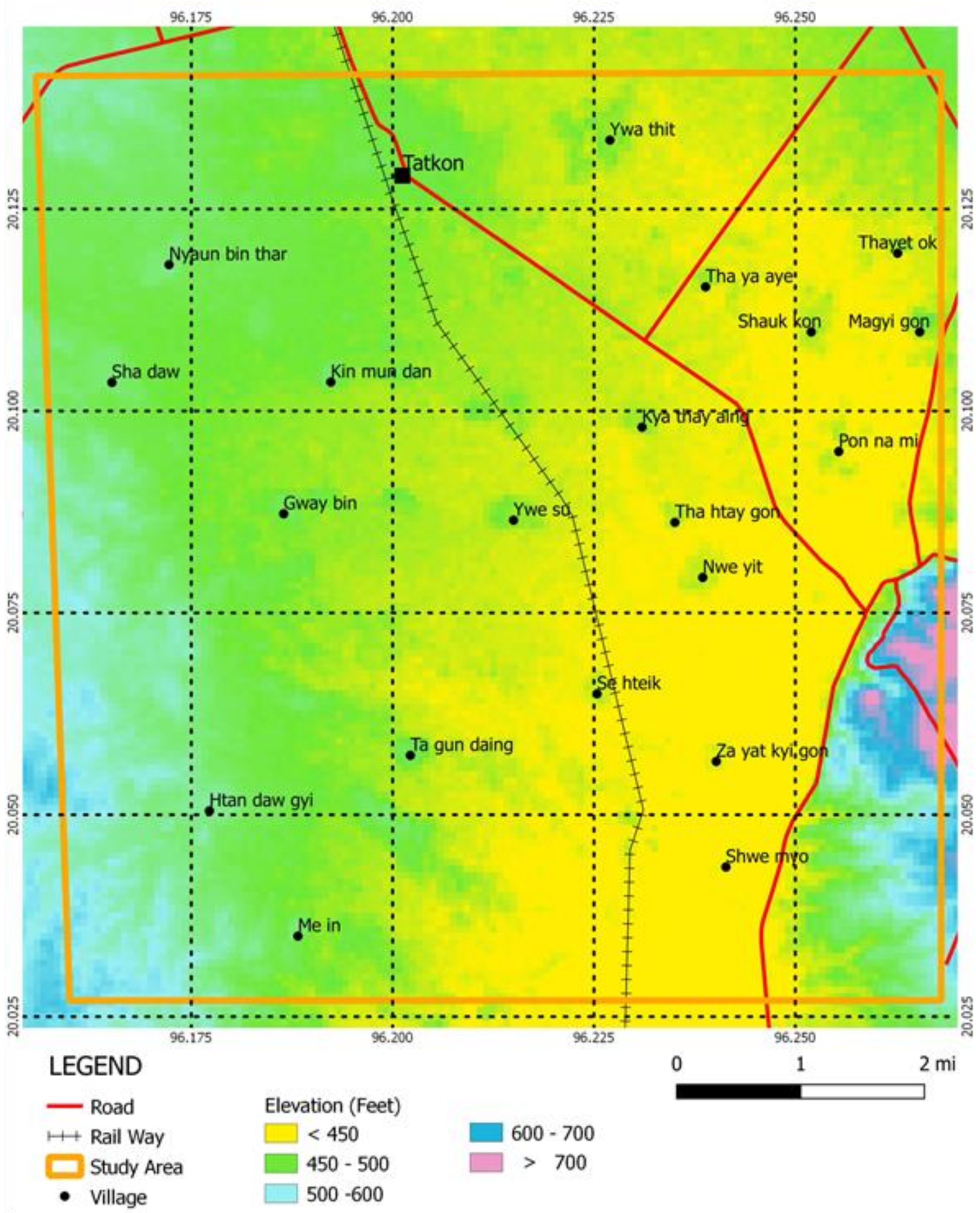


Fig. 2. Digital elevation model

3. Distribution of groundwater aquifers

There are two types of major aquifers are observed in the project area those are Recent Alluvial Aquifer and Pliocene aged Irrawaddian Aquifer. The Recent Alluvial Aquifer consists of sand, silt, clay, gravel and pebbles and those are deposited from the recently flowing stream, rivers and slope wash deposits. The Pliocene aged Irrawaddian Aquifer includes the layers of loosely cemented sandstones, gravel and channel filled deposits and silt and clay layers. Generally, the major groundwater extraction if form Recent Alluvial Aquifer.

4. Depth of aquifer and water table

According to the records of drilled tubewells, the minimum depth to aquifer is about 160 feet below ground level (bgl) and the maximum depth is about 250 feet (bgl). The static water level (groundwater table) is ranging from 5 feett to 16 feet (bgl).

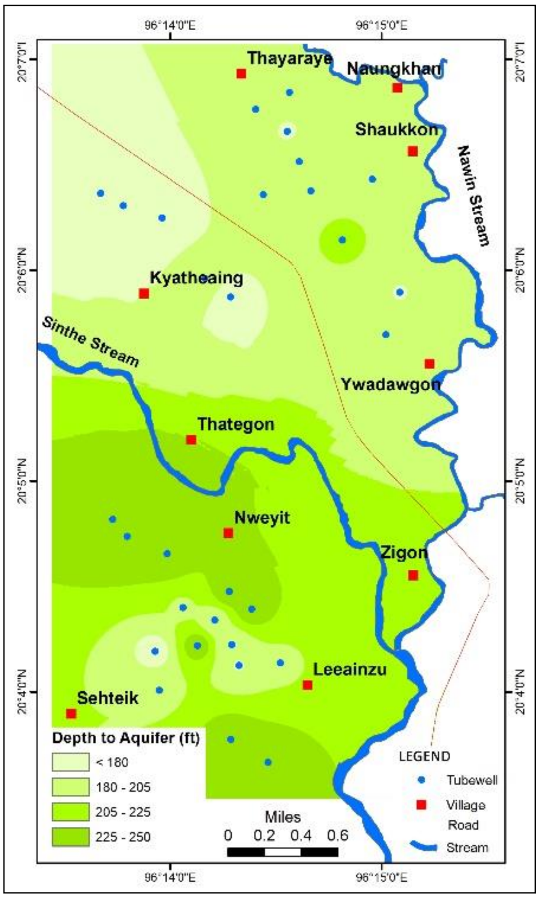


Fig. 3. Depth to Aquifer

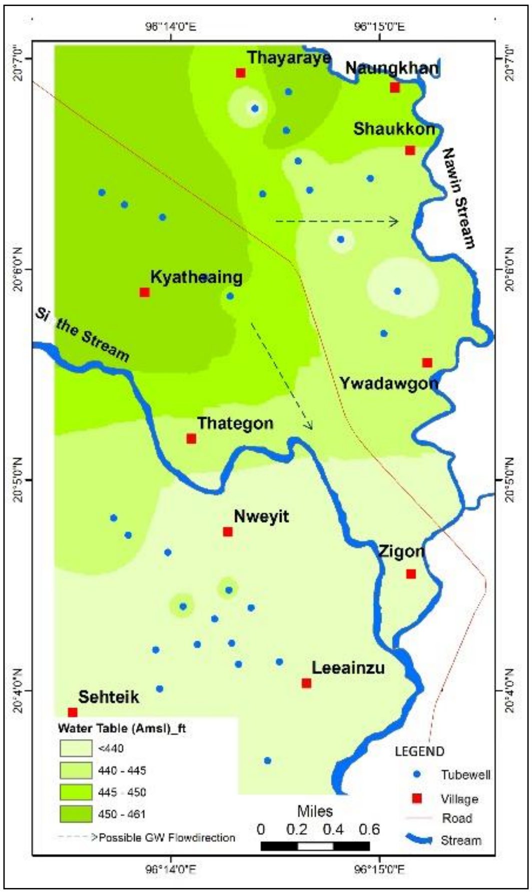


Fig. 4. Water Table (AMSL)

5. Groundwater quality

(pH / Electrical Conductivity (EC)/ Total Dissolved Solid (TDS)/ Sodium Absorption Ratio - SAR)

Based on the groundwater quality analysis results from the laboratory, the value of pH, EC, TDS and SAR values are shown in the following table,

Table 1. Groundwater quality of selected parameters

Parameter	Minimum Value	Maximum Value
pH	7	7.80
EC (µmho/cm)	480	1010
TDS (mg/l)	310	660
SAR	0.21	5.10

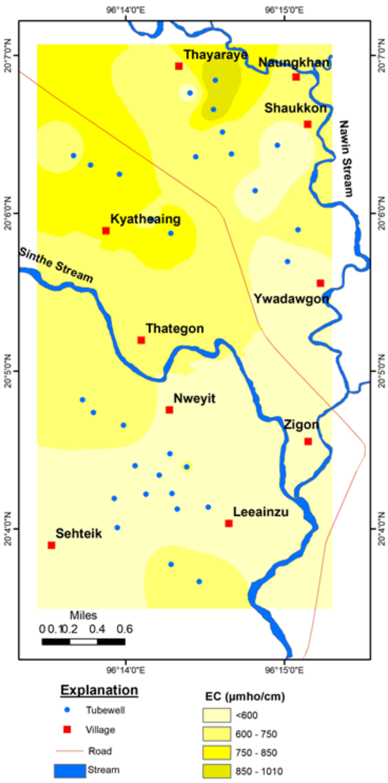


Fig. 5. EC

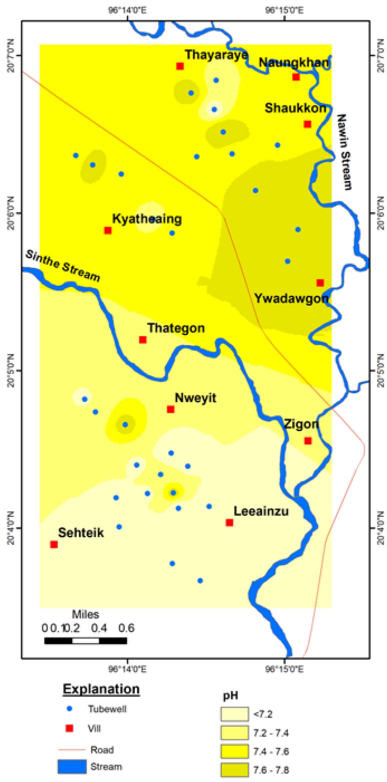


Fig. 6. pH

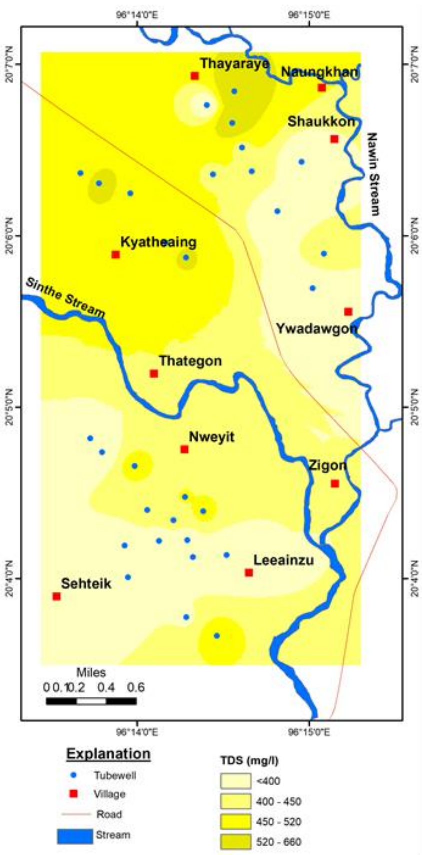


Fig. 7.TDS

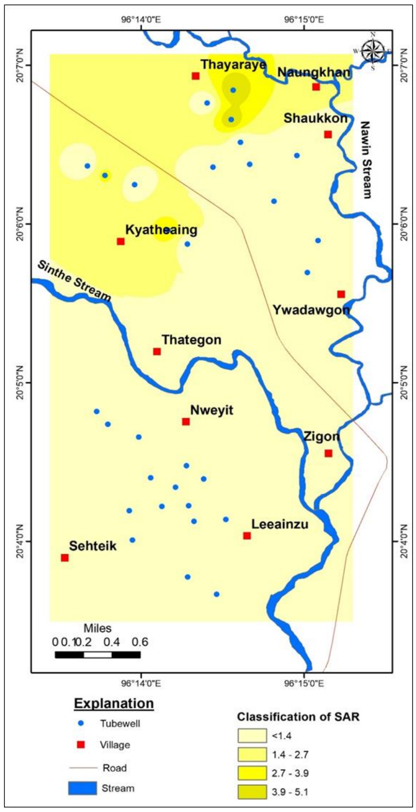
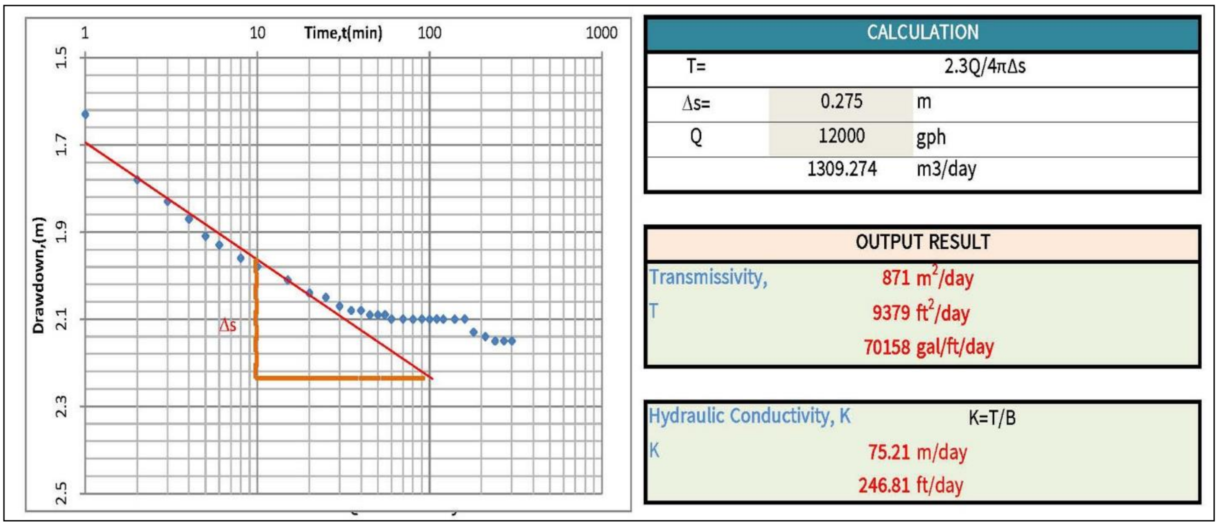


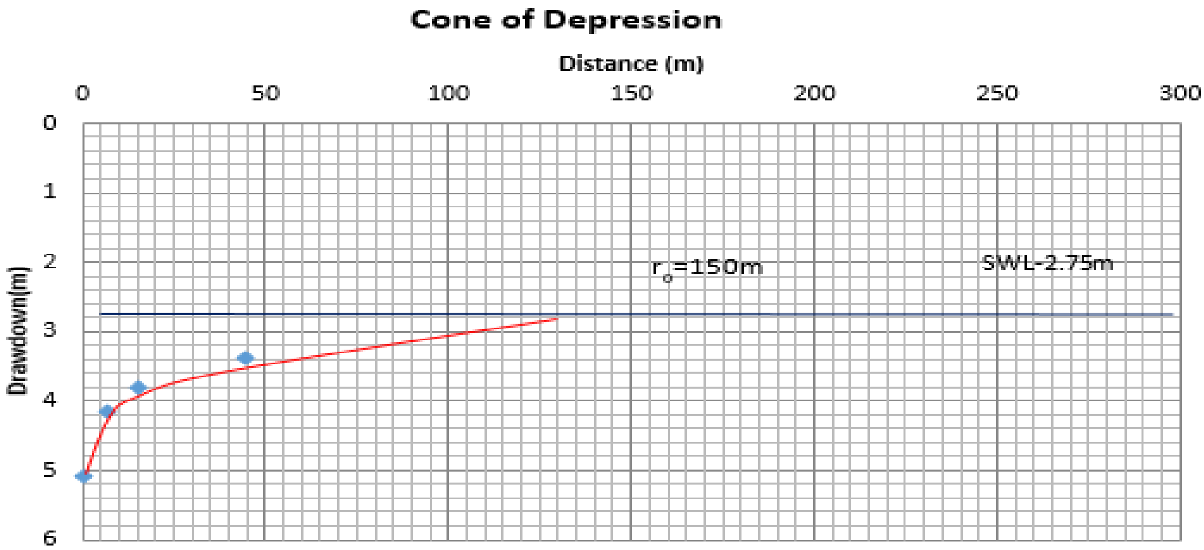
Fig. 8. SAR

6. Aquifer characteristics

Hydraulic Conductivity

According to the interpreted data of pumping test and grain size distributions of aquifer in the project area, the calculated value of Hydraulic Conductivity is showing about 246 ft/day. The calculation result of the Transmissivity of the aquifer is about 70000 gal/ft/day. One of the important control factors for the selection of well point is based on the value of cone of depression of the aquifer. After observation of the pumping test (pumping out test and recovery test) the value of cone of depression is about 1000 feet.





7. Annual groundwater recharge from rainfall

The estimation of groundwater recharge in the project is referenced on the Detailed Guidelines for implementing the groundwater estimation Methodology, Central Groundwater Board (CGWB), Ministry of Water Resources, government of India (2009).

According to the calculation, the annual groundwater recharge from rainfall is showing about 24420 acre-ft. Hypothetical model for the water balance for the project are considered the monthly rainfall data, rainfall recharge, Potential Evapotranspiration, groundwater usage for both agriculture and domestic, surface runoff, base flow in the streams and irrigation returned flow.

According to the recent study, it is found that the total annual available groundwater resources in the project area is estimated to be about 34920 acre-ft and the total annual groundwater usage estimated about 7750 acre-ft. In conclusion, the groundwater usage for recent is calculated about 22% of annual renewable resource.

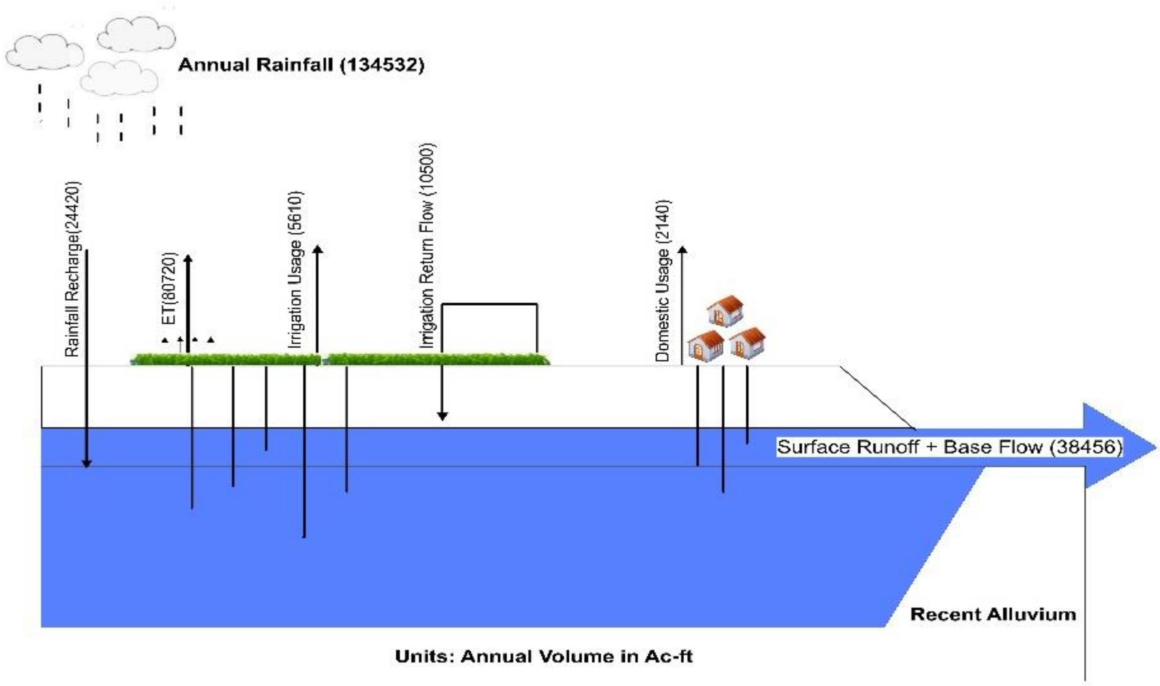


Fig. 9. Water balance model for Project Area

8. Recommendations

The following monitoring and evaluations need to be considered in the future for sustainable development of groundwater in project area,

1. The judicious estimation of groundwater resources is vital role for the before implementation of large groundwater exploration projects.
2. Installation of groundwater monitoring wells for monitoring of water table and water quality.
3. Artificial groundwater recharge systems should be carried out for long term usage and climate change adaptation.
4. Usage of renewable energy (solar power-driven pumping system) for water extraction will benefit for reducing investment cost for local farmers and saving environment.
5. Should practice water saving technologies for increasing water use efficiency.
6. Should use appropriate cropping patterns based on the soil properties and water quality for the sustainable growing of the crops in the whole year.

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Hydrogeological information of the Kiunga Town, Western Province, Papua New Guinea with active groundwater usage and water utilization ways

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Abstract

The Mineral Resources Authority (MRA) of Papua New Guinea (PNG), through its hydrogeology section have given priority to carry out groundwater investigations within mine-impacted areas and the mining provinces of the country. At this juncture, a team of hydrogeologists and geophysicists from the Geological Survey Division of the MRA carried out groundwater investigations within Kiunga Town. The results proved that a local deep aquifer consisting of saturated sands with some silt and clay exists at around 22 – 38 m depth from ground level. This proves that additional bores can be constructed in target areas surveyed to increase supply to meet the water demand of the growing population. Any information from further drilling can go into the Kiunga hydrogeological database which is an ongoing project for the country.

Keywords: groundwater, borehole, seepage, Kiunga

1. Introduction

The Mineral Resources Authority (MRA) of Papua New Guinea (PNG), through its hydrogeology section have given priority to carry out groundwater investigations within mine-impacted areas and the mining provinces of the country. At this juncture, a team of hydrogeologists and geophysicists from the Geological Survey Division of the MRA carried out groundwater investigations within Kiunga Town. This field survey was done in late February – mid March, and a second survey done at the end of July, 2023. This work was carried out to assess the groundwater potential of the town and locate any potential aquifer(s) within the area. A groundwater site investigation through hydrogeological mapping of current or existing groundwater sources was conducted, as well as a geophysical investigation using the resistivity survey method, also known as the vertical electrical sounding (VES) method to delineate potential subsurface water-bearing layers and/ or aquifers.

The Kiunga town is located along the Fly River within the North Fly District of Western Province, Papua New Guinea (Fig. 1). A current operating gold and copper-producing mine within this district, known as the Ok Tedi Mine operated by the Ok Tedi Mining Limited (OTML) is located approximately 100 km north of Kiunga town. The town was established for the main purpose of serving as the main port for the Ok Tedi Mine. Two other local level government (LLG) stations were surveyed, the Rumginae Station and Ningerum Station, however, for this report, only Kiunga will be discussed. Approximately 30 km west of Kiunga Town is the international PNG-Indonesia boundary.

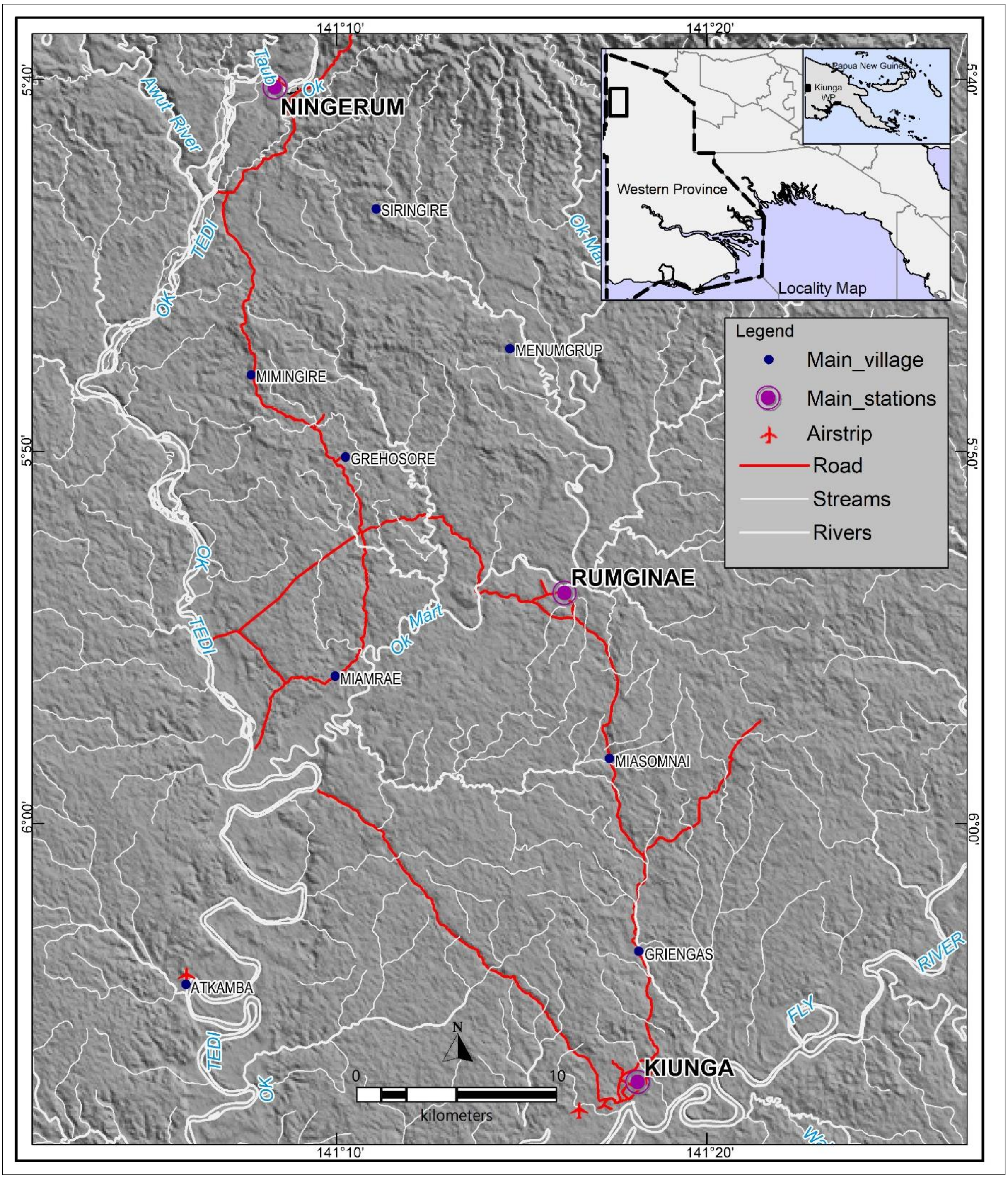

Fig. 1. Locality map of the Kiunga Town, Western Province, PNG.

2. Hydrogeological information of the area

Currently, Kiunga town and most parts of the Western Province do not have an existing geological map. Under the Ok Tedi Kiunga town site project, a report done by the company

Dames & Moore (1983) stated that the Kiunga geology is similar to that of Rumginae and Ningerum, comprising of alluvial floodplain deposits of the Awin Formation of Late Pliocene to Pleistocene age, which form low hills. The bedrock consists of clean quartz sandstone, bluish volcaniclastic arenite, siltstone, mudstone, thin lignite and coal seams, and white sandy claystone as seen in boreholes drilled within the area. Reddish brown clayey silt occurs near the surface which are poorly consolidated sedimentary rocks of the Awin Formation. As reported by *Dames & Moore* (1983), this was evident in test pits.

According to Lytham (2005), drilling and pump testing done in Kiunga by Leonhardt Drilling of Darwin Australia showed that the local aquifer comprises of dark grey, fine-grained, poorly sorted, lithic sands which are moderately consolidated. This was identified as a confined aquifer since argillaceous formations of mostly clays and silty clays (with minor lignite) overlie the local aquifer. According to pump test data, the transmissivity values showed a low-medium range (69 – 175 m2/ day), giving an average of 106 m2/ day, which is comparable to the local aquifer type.

The hydrogeology of Kiunga, further confirmed from the results of this site investigation hosts potential aquifer(s) within the sedimentary floodplain deposits. This consists of saturated sands, with some silt and clay interpreted to be at an approximate depth range of 22 – 38 m. The Kiunga area generally has a flat terrain and swampy topography, hence, the main aquifer is expected to consist of clay loams. This means that the aquifer intercepted in these geophysical surveys comprises of sand, silt, and clay loams, i.e. a mixture of these sediments. The efficiency of this aquifer will highly depend on the percentage of clastic sediments compared to the clay component. The presence of more clastic sediments (silt and sand) within the aquifer layer will increase the water-storing properties of these layers, while increased levels of clay will decrease the water-storing properties of the aquifer. The main aquifer may be semi-confined (leaky) to confined as indicated by overlying clay layers (aquitard). Refer to Figure 2 for survey locations.

A few boreholes and shallow wells and/ or springs inspected were tapping into the top layers above the main aquifer, i.e. shallow aquifer. This was identified as the wet silty sand duricrust layer (Fig. 3A). The duricrust sand was laminated and semi-consolidated, hence, giving it the potential to store water, however, this may not be sufficient for a continuous supply. Immediately northeast of Kiunga within the Grengas Corner, the shallow aquifer consists of clayey gravel or gravelly clay bands (Fig. 3B).

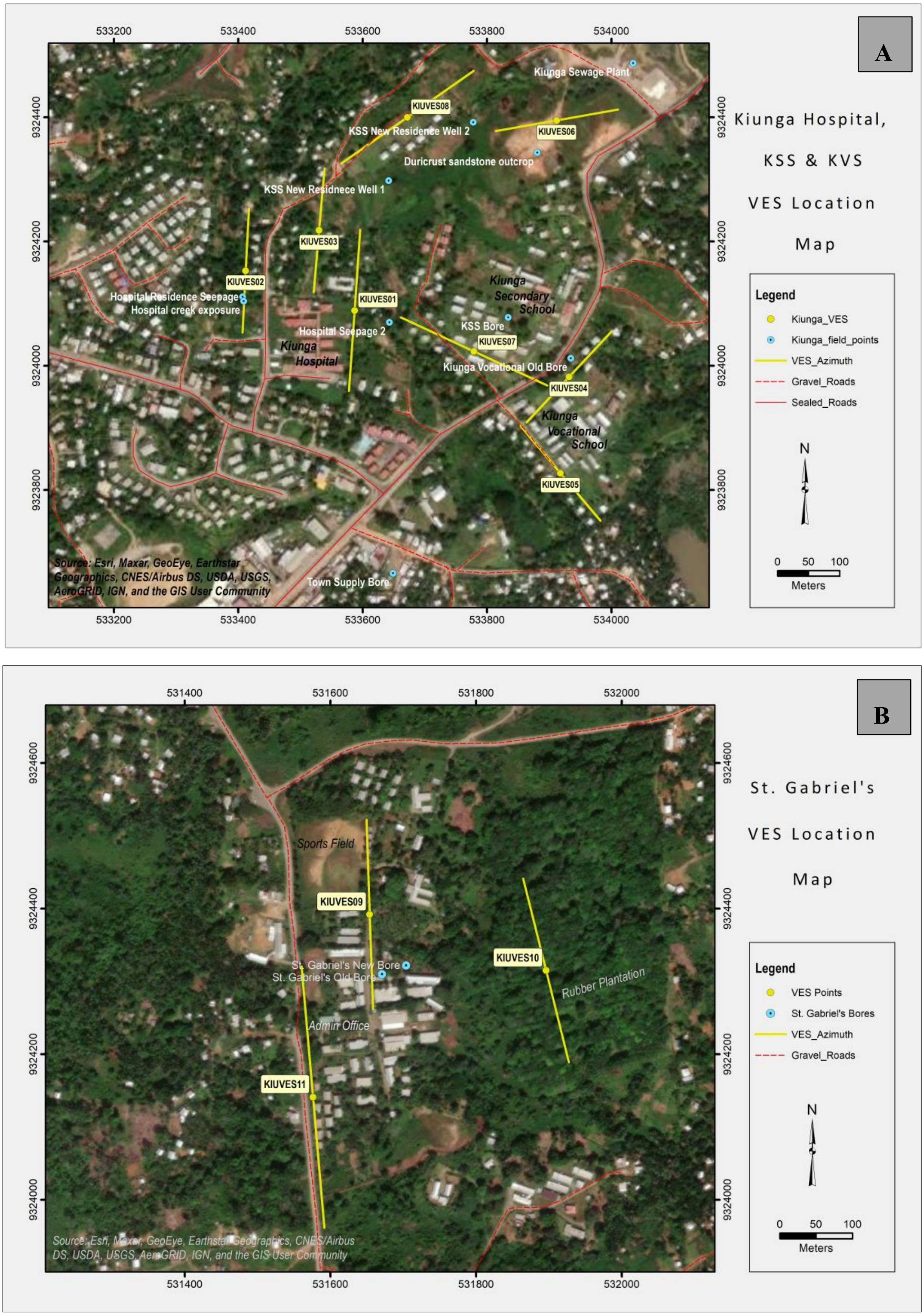

Fig. 2. Locations of VES survey lines conducted in A) Kiunga town and B) St. Gabriel's Technical Secondary School

Fig. 3. Shallow aquifers encountered within Kiunga town, A) from duricrust sand layer and B) clayey gravel/ gravelly clay bands

3. Major water resources and water utilization ways

The current water supply system of Kiunga town was established by the Ok Tedi Development Foundation (OTDF) in the early 1980's (Lytham, 2005) in response to the development of the Ok Tedi Mine. This supply system is sourced from a combination of five (5) water bores located in different well fields within the town. At the time of its establishment, the supply proved to be sufficient. However, population increase has caused higher water demand, and hence, the supply is insufficient at present. Certain parts of the town experience very low pressure to no flow at all. As advised by the District Administration Office, another reservoir tank was set up to help rectify this water supply problem, however, due to landowner issues, this reservoir is not in use. Owing to this, much of the town population depends on rainwater catchment tanks for supplementary water supply, including groundwater wells and seepages.

Few schools currently have boreholes within the school premises; however, the supply is only seasonal. Most of the population within the settlement blocks just outside the town highly rely on rainwater catchments, shallow wells, piped seepages, and creek water (Fig. 4).

4. Hydrogeological database

Currently, there is no database for the Kiunga area, however, some data was sourced from a couple of old reports. These data will be entered into the hydrogeology database, which is a current ongoing project within the Hydrogeology section of the MRA. As reported by Lytham (2005), a total of four (4) water bores within the well fields supplying the Kiunga town were pump tested using the Step Drawdown test, the Constant Discharge test, and the Recovery test. There were variations in the transmissivity values of each bore, which indicated changes in the aquifer properties across the well field (Lytham, 2005). The transmissivity values showed a low-medium range of 69 – 172 m^2/ day, with an average of 106 m^2/ day (Table 1). These transmissivity values are comparable to the local aquifer type.

Fig. 4. Some of the water sources used within and aroud the Kiunga town area.

Table 1. Aquifer performance test results of the four bores in Kiunga, as report by Lytham (2005)

Pump Tested Boreholes (Date).	Discharge Rate & Duration (mins)	Transmissivity T (m^2/d)	Q (l/s)	s (m)	S.C.* (l/s/m)	Method of Analysis
CC1 (26.03.82)	10 l/s 2,880 - 48 hrs	93 91	10	12.30	0.81	Jacob-Cooper Theis Recovery
CC2 (5.04.82)	10 l/s 2,880 - 48 hrs	69 75	10	20.11	0.50	Jacob-Cooper Theis Recovery
WF1 (18.04.82)	10 l/s 2,880 - 48 hrs	158 175	10	8.55	1.17	Jacob-Cooper Theis Recovery
PH1 (24.04.82)	13 l/s 2,880 - 48 hrs	82 -	13	14.88	0.87	Jacob-Cooper Theis Recovery

Analysis by Australian Groundwater Consultants 1982; * SC = Specific Capacity

Lithology logs for these bores were not reported, however, a bore drilled in 2011 within the current town water supply treatment yard was reported by Kuman (2011). From this log, the first 30 m from the ground surface consisted of mostly argillaceous material comprising of silty clays and some sandy silt with a thin band of semi-consolidated silty sand. The water table depth was not recorded, however, the main aquifer may be around 30 m depth, as seen in the lithology log where sand and sandy loams are more dominant from 30 m down (Table 2).

Table 2. Lithology log of the Kiunga bore drilled in 2011, extracted from Kuman (2011).

Depth (m)	Description
9 – 10	Reddish brown, silty sticky Clay. Highly weathered. Crumbles easily.
10 – 15	Orange brown, fine sandy Silt with minor clay. Weathered & semi-consolidated. Crumbles easily.
16	Pale reddish brown silty Sand. Semi-consolidated. Well sorted sand grains that are sub angular-round. Harder than layers above and below.
17 – 18	Same as above but with colour change to brown.
19 – 22	Orange-brown sandy Clay. Crumbles easily.
23 – 30	Reddish brown, semi consolidated silty Clay.
30 – 32	Greyish brown clayey Sand. Sand grains are well sorted, angular-sub rounded. Semi consolidated & crumbles easily.
32 – 36	Brown, moderately sorted, angular – sub angular sand.
36 – 40	Brownish grey clayey Sand. Sand are poorly sorted, angular grains that crumble easily.
40 – 49	Dark grey, sandy, clayey Silt. Semi-consolidated & crumbles easily.
49 – 60	Dark grey, clayey Silt, semi-consolidated & crumbles easily.
60 – 73	Dark grey, silty Clay semi-consolidated & crumbles easily.

5. Major problems and future challenges

At present, the supply from the five bores is insufficient to meet the demand of the growing population within the Kiunga town. Therefore, the main problems and future challenges of the water supply within Kiunga is a socio-economic factor. To match the growing population and demand, more boreholes need to be constructed to add to the combined supply of all bores. From this groundwater investigation, it is evident that more potential areas can be targeted for drilling to increase the supply. Kiunga experiences an average annual rainfall of 5,113 mm, with 3,564 mm and 3,058 mm total rainfall for the years 2014 and 2015 respectively (Ok Tedi Mining Limited, 2016), therefore, this will help recharge the local alluvial aquifers. This in turn should prove sufficient to supply the town if more bores are installed.

6. Conclusions

From this groundwater investigation, it may be concluded that the Kiunga town has good groundwater potential to supply the growing population of the town. To address the water supply issues, more boreholes need to be constructed to add to the combined supply of the existing five bores. Additional bores must target the deep aquifer at 30 m or more to get a more sufficient supply. Any additional information of bores that may be drilled will go into the Kiunga hydrogeological database.

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Hydrogeological insights and water utilization strategies in an area with active water usage: A case study in Bohol, Philippines

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Abstract

This study addresses the critical need for comprehensive hydrogeological insights and adaptive water utilization strategies in an area characterized by active water usage. Employing a multidisciplinary approach, the research integrated electrical resistivity and hydrochemical data to characterize the current hydrogeological conditions in western Bohol, Philippines, and anticipate the future implications of sea-level rise on freshwater resources. The geophysical aspect conducted electrical resistivity surveys across selected transects on Bohol Island, with processed data generating 1D and 2D resistivity models. These models provided crucial insights into subsurface geological structures, aquifer properties, and potential saline water zones. Hydrochemical investigations systematically collected and analyzed groundwater samples from strategically located wells, measuring major ion concentrations such as chloride and sodium. This assessment helped gauge current salinity levels and pinpoint potential saltwater intrusion zones. By combining geophysical and hydrochemical data, the study establishes a baseline of Bohol Island's freshwater aquifers, serving as a reference point for assessing future changes due to sea-level rise. The extent of intrusion varies based on sea-level rise magnitude, local geological conditions, and existing water management practices. Identification of key vulnerable areas, such as the western portion of Tagbilaran City and estuarine zones, highlights the study's significance. This integrated research approach lays a solid foundation about the implications of sea-level rise on saltwater intrusion in Bohol Island by understanding hydrogeological processes and water utilization strategies, supporting the development of informed water management practices to safeguard freshwater resources.

Keywords: groundwater, electrical resistivity, sea-level rise, saltwater intrusion, Bohol, Philippines

1. Introduction

Tagbilaran City, the capital of Bohol, Philippines, is experiencing rapid urban development due to its popularity as a tourist destination. With its population growing at an annual rate of 1.57%, the estimated groundwater demand of 58.5 million liters per day in 2010 is projected to increase by about 4-5% per year (Philippine Statistics Authority, 2018; The Asia Foundation, 2014). This rising water demand highlights the need for effective water resource management in the region. Furthermore, the western region of Bohol is characterized by karst landscapes (Urich, 1993; Urich et al., 2001). The karst environment poses significant challenges for water resources due to subterranean drainage systems that limit the storage capacity of carbonate aquifers (Uhlig, 1980; Yuan, 1997; Kiernan, 2011; Ford & Williams, 2007; Gillieson, 2005). The search for groundwater in Tagbilaran City is particularly challenging due to these karst features. Studies by the Japan International Cooperation Agency et al. (1998) indicated that karstic limestone in the area has a small water storage capacity due to highly developed conduit and cave systems. Factors such as continuous dissolution of channels and anthropogenic alterations have impacted the flow direction and velocity of groundwater, as seen in changes in spring discharges. Water quality in these aquifers is also vulnerable to contamination from improper waste disposal, poor sanitation, and urbanization in recharge areas (Fisher, 2009). Over-extraction of groundwater has led to saline water intrusion in coastal areas.

Given the increasing water demand, evaluating the current groundwater in western Bohol is crucial. This study employs electrical resistivity surveys and hydrochemical analysis to investigate the quantity (e.g., thickness, depth, extent) and quality (e.g., anions, cations) of potential aquifers. The primary objectives of this study are to identify potential zones susceptible to saltwater intrusion, quantify the possible depth and extent of saltwater intrusion, provide valuable groundwater baseline data for future research and mitigation efforts, and delineate the groundwater potential zones for future groundwater well construction. The findings will benefit Bohol Island, particularly Tagbilaran City, by providing insights into the implications of sea-level rise on saltwater intrusion, understanding hydrogeological processes and water utilization strategies, and identifying potential sites for future groundwater well construction. Additionally, this study offers a model for addressing groundwater-related problems in other karst environments, supporting the development of informed water management practices to safeguard freshwater resources.

2. Tectonic, geologic and hydrogeologic setting

The Philippine archipelago, an island arc system, is shaped by arc magmatism, ophiolite accretion, and various tectonic processes (Mitchell et al., 1986; Rangin, 1991; Yumul et al., 2008; Aurelio et al., 2013). The Philippine Mobile Belt (PMB) is defined by subduction zones with opposing dips (Fig. 1). East-dipping subduction zones on the western side include the Manila Trench, Negros Trench, Sulu Trench, and Cotabato Trench. Conversely, the eastern side is bordered by the East Luzon Trough and the Philippine Trench, where the west-dipping Philippine Sea Plate (PSP) is subducting. The entire island arc system is traversed by a left-lateral strike-slip fault known as the Philippine Fault (Aurelio, 2000; Barrier et al., 1991). The interplay of oceanic crust subduction, collision processes, and fault movements generates seismic activity within the PMB (Ramos et al., 2005; Yumul et al., 2003). Bohol Island, located in the south-central Visayas, is part of the PMB and is one of the seismically active regions in the Philippines. Local faults and trenches in this area significantly impact the hydrogeological system. The survey area is situated on Bohol Island, between latitudes 9°39'00"N to 9°58'00"N and longitudes 123°50'30"E to 124°8'00"E (Fig. 2).

Western Bohol is predominantly underlain by the Maribojoc Limestone and the Carmen Formation. The Middle Miocene Carmen Formation consists of interbeds of shale, sandstone, conglomerate, and limestone. The sandstone unit contains feldspar-rich clasts set in a clayey matrix with minor amounts of carbonate and chlorite, whereas the shale is calcareous and thinly bedded (Mula & Maac, 1995). The younger Pliocene Maribojoc Limestone, described by Arco (1962), is soft, chalky, non-compact, marly, and coralline. It is poorly bedded and porous, with numerous caverns and sinkholes. However, some portions (e.g., northern areas) mapped as Maribojoc Limestone are underlain by medium- to coarse-grained detrital limestone units with shell fragments, differing from the neighboring highly karstic and coralline lithology.

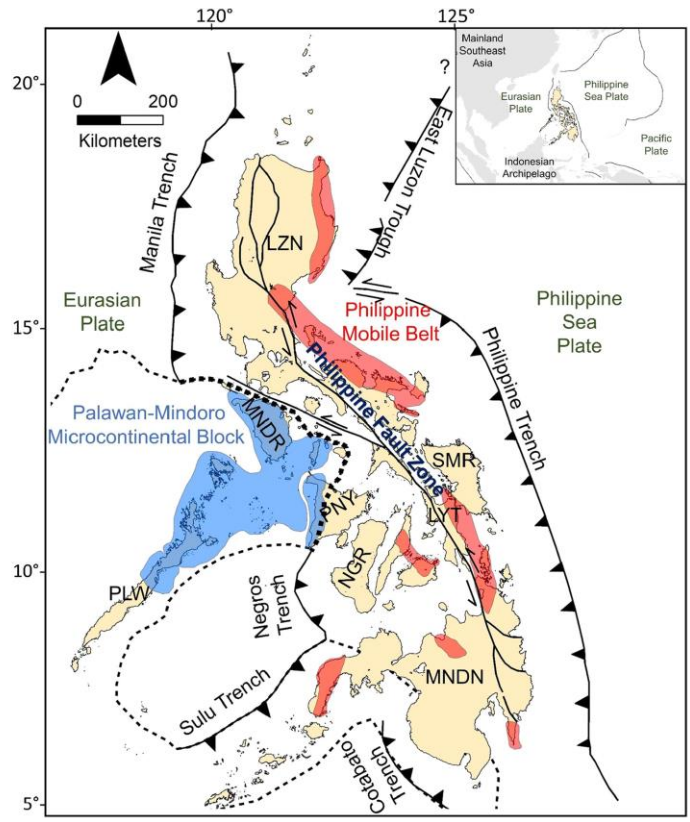

Fig. 1. General tectonic map of the Philippine island arc system illustrating the study area's location *(adapted from Rangin, 1991; Yumul et al., 2008; Casulla, 2022). Labels indicate the major islands: LZN (Luzon), MNDR (Mindoro), PLW (Palawan), PNY (Panay), NGR (Negros), SMR (Samar), LYT (Leyte), and MNDN (Mindanao). The red areas reflect Cretaceous (island arc) metamorphic zones, whereas the blue areas show pre-Cretaceous (continental) metamorphic regions (modified from MGB 2010)*

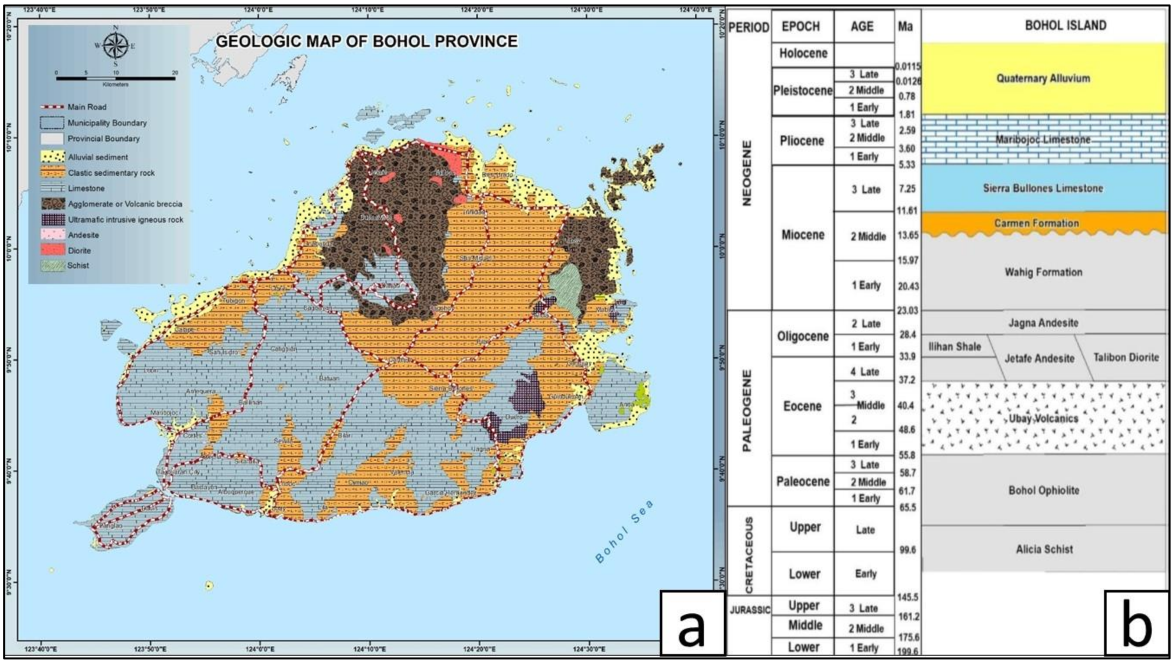

Fig. 2. (a) Geologic Map and (b) stratigraphic column of Bohol Island

Earlier hydrogeologic studies in Bohol Province (Quiazon 1976; NWRC1982) reveal distinct groundwater occurrences in the Maribojoc Limestone and Carmen Formation. The Carmen Formation, a clastic aquifer, has a yield of 0.3 to 5.7 L/s and a shallow water table depth of 1 to 33 meters below ground level (mbgl) (Quiazon, 1976). The sandstone and conglomerate units, with favorable permeability coefficients, show promising groundwater potential compared to the fine-grained shale units. In contrast, the Maribojoc Limestone aquifer yields 0.3 to 9.3 L/s, with deeper and more variable water table depths (1 to 60 m). Quiazon (1976) noted that spring flow direction and velocity are difficult to determine due to the intricate solution channel systems in the limestone. The Maribojoc Limestone also exhibits highly non-homogeneous rock permeability ranging from 0.2 to 120 m/day, with thicknesses of 20 to 120 m based on groundwater well data.

3. Methodology

Electrical resistivity surveys and hydrochemical analyses were conducted to evaluate groundwater potential zones on Bohol Island. Primary groundwater data were collected from municipal waterworks and water districts. Rock units in the area were identified and described based on accessible outcrops, and groundwater levels were assessed through spring and well inventories.

Vertical electrical sounding (VES) surveys were conducted using a Syscal R2 resistivity meter. The Schlumberger configuration, with a maximum half-current electrode spacing (AB/2) of 362 meters, was used to measure resistivity values and delineate subsurface layer thicknesses. The VES method involved injecting current (I) into the ground using two outer current electrodes (A and B) and measuring the potential difference (V) between two inner potential electrodes (M and N). The MN/2 length was set to be less than or equal to 1/5 of the AB/2 distance. The current electrodes were extended from the sounding center at logarithmic distances, while the potential electrodes were fixed to enhance the depth of investigation. When the measured potential difference became very low, the distance between potential electrodes was increased (Telford et al., 1990; Binley and Kemna, 2005; Ernstson and Kirsch, 2006). To check for lateral variations in surface resistivity, two readings with different MN/2 values were taken for some AB/2 values. The instrument automatically computed resistance by dividing the measured potential difference (V) by the injected current (I) for each reading. Resistance was then multiplied by the geometric factor to obtain the apparent resistivity (ρa): $\rho a = GR$, where G is the geometric factor and R is the resistance.

Apparent resistivity values were plotted on a bi-logarithmic graph to generate sounding curves for each VES station. These curves were interpreted using the IX1D v2 software (Interpex Limited, 1990). The strata log data (thickness, lithology) from two adjacent Local Water Utilities Administration (LWUA) wells served as the initial model.

The southwestern portion, where available strata log data are present, was used as the calibration area for the VES data. The strata log data from wells BOL-TAG-401 was correlated with VES 12. Well data showing lithologies were used to constrain the geoelectric data interpretation. 1D and 2D geoelectric cross-sections were generated to investigate subsurface lithologies and map the lateral extension of geoelectric layers. These results were used to identify potential sites for future groundwater well construction. Thirty-two sounding data points were used to create resistivity contour maps at depths of 10m, 40m, and 80m, illustrating the estimated spatial extent of saltwater intrusion in the coastal areas of Tagbilaran City.

Groundwater samples were tested on-site in operational wells using a portable water quality instrument. This device measured physical parameters such as temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) directly in the field. Additionally, groundwater samples were collected and sent to the MGB-CO laboratory for analysis of anions (e.g., HCO3-, SO42-, Cl-, PO4-3, SiO2) and cations (e.g., Ca2+, Mg2+, Na+, and K+).

A Piper diagram was generated to graphically represent various principles and critically examine the dissolved elements in the water. This analysis is an effective tool for isolating and visualizing the analytical data. The Piper diagram consists of three sections: two trilinear diagrams at the bottom and one diamond-shaped diagram in the center. The trilinear diagrams represent the concentrations of cations (left diagram) and anions (right diagram) in each sample. In these diagrams, the concentrations of eight key ions—Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}—are grouped by combining K^+ with Na^+ and CO_3^{2-} with HCO_3^-, thereby reducing the number of parameters for plotting to six. Cation and anion concentrations are first converted to milliequivalents per liter, and then the relative percentages of cation and anion species or groups are computed and plotted on the diagram. Each value is displayed on the trilinear and diamond-shaped diagrams (Piper, 1944).

4. Groundwater resources delineated by electrical resistivity survey

A profile labeled A-A' was created to visualize and identify potential sites for groundwater well development in the municipalities of Tagbilaran (A), Corella, and Balilihan (A') (Fig. 3). This profile comprises four distinct geoelectric layers, excluding the surface layer, characterized by variations in lithology and groundwater presence. The profile includes eight Vertical Electrical Sounding (VES) stations: VES-12, VES-17, VES-19, VES-23, VES-31, VES-32, VES-33, and VES-35, spanning approximately 16.5 km (Fig. 4).

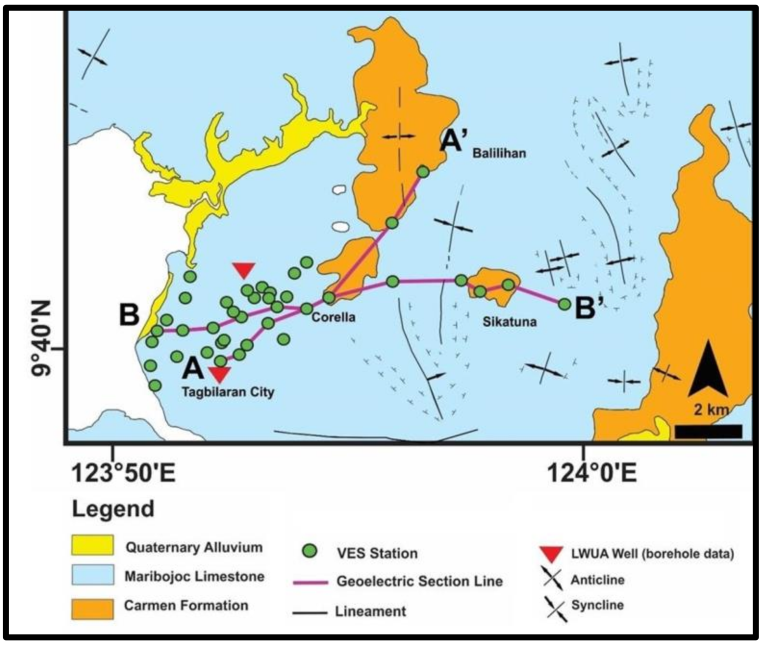

Fig. 3. (a) Location map showing the VES stations and LWUA Well

The uppermost layer (L1) was identified as argillaceous limestone based on the strata log of BOL-TAG-401, likely corresponding to the weathering and deposition of marly limestone. Below this weathered zone lies fresh limestone. This geoelectric layer shows minimal to no groundwater saturation, as indicated by water-table mapping conducted alongside the VES activity. The recorded groundwater depth in this limestone area ranges from 30 to 45 meters and becomes shallower (0.5 to 2 meters) towards the northeast section of the clastic Carmen Formation. The deep groundwater levels in limestone areas are likely due to the highly karstic and permeable nature of the Maribojoc Limestone, which channels water to deeper layers. Conversely, the shallow groundwater level in the Carmen Formation indicates a typical clastic aquifer with sufficient porosity and permeability to store and transmit water. The C1 layer is interpreted as a clayey to silty clastic layer, while higher resistivity values are associated with coarser clastic deposits. Minor clay layers were observed in the upper section on the northeastern side, interpreted as fine-grained clastic layers with resistivity values of 5 to 9 ohm-m. Beneath this C1 layer, a more resistive geoelectric layer corresponds to coarser clastic deposits. The sandy to gravelly facies (C2) of the Carmen Formation, with resistivity values ranging from 44 to 58 ohm-m, is considered the preferable aquifer in this section.

The interpretation results defined the resistivity spectrum of the subsurface layers in the study area. The resistivity values of the interpreted lithologic units are consistent with published values (e.g., Telford et al., 1976; Dhakate et al., 2012; Maury and Balaji, 2014; Kaya et al., 2015; Muhammad and Khalid, 2017).

5. Hydrogeological database

Figure 5 presents the locations and distribution of the 99 groundwater sources sampled throughout the island. Figure 6 displays the results of laboratory analyses for anions, cations, and other physical parameters, summarizing the various hydrogeochemical facies of groundwater in the study area. The majority of the samples (75%) are plotted on the left side of the central diamond-shaped diagram, indicating a calcium-bicarbonate ($Ca-HCO_3$) water type (red cir). This hydrochemical type is observed in groundwater samples from both shallow and deep wells, as well as springs within the study area. 8% of the samples are classified as calcium-chloride (Ca-Cl) water type, while 7% are magnesium-bicarbonate ($Mg-HCO_3$) water type.

The data suggests that most groundwater samples are characterized by alkaline earth metals rather than alkali metals. Due to the groundwater samples being collected from various sources across the study area, which represent different lithologies and aquifer depths, there are two significant groupings in groundwater chemistry. This general data distribution suggests that the $Ca-HCO_3$ water at the central part may represent young/fresh recharge groundwater. On the other hand, the high Mg in the northwestern side of Bohol Island could be due to ferromagnesian minerals in Agglomerate/Volcanic Breccia and Ultramafic rocks. The lithological characteristics of the underlying rocks are major contributing factors to the high magnesium concentrations in the area.

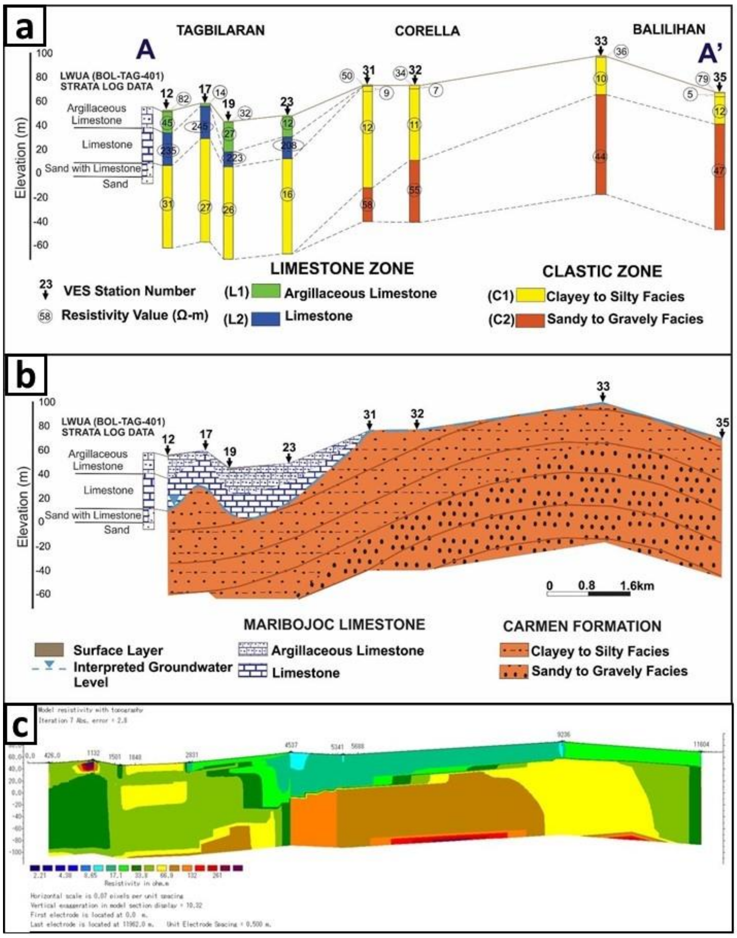

Fig. 4. (a) 1D-inverted VES data and its (b) conceptual model compared to the 2D inverted VES data

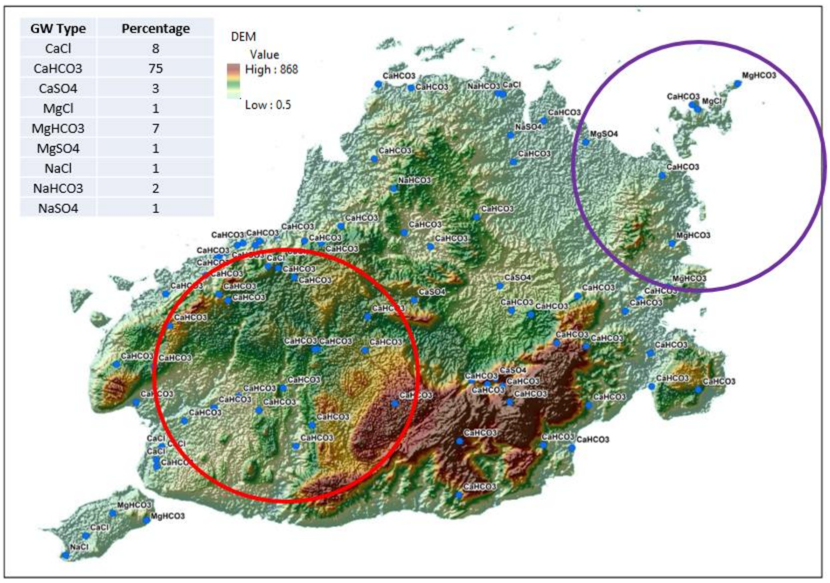

Fig. 5. Location map showing the groundwater sampling points. Red circles indicate areas with calcium-bicarbonate (Ca-HCO_3) water type, while violet circles indicate areas with magnesium-bicarbonate (Mg-HCO_3) water type.

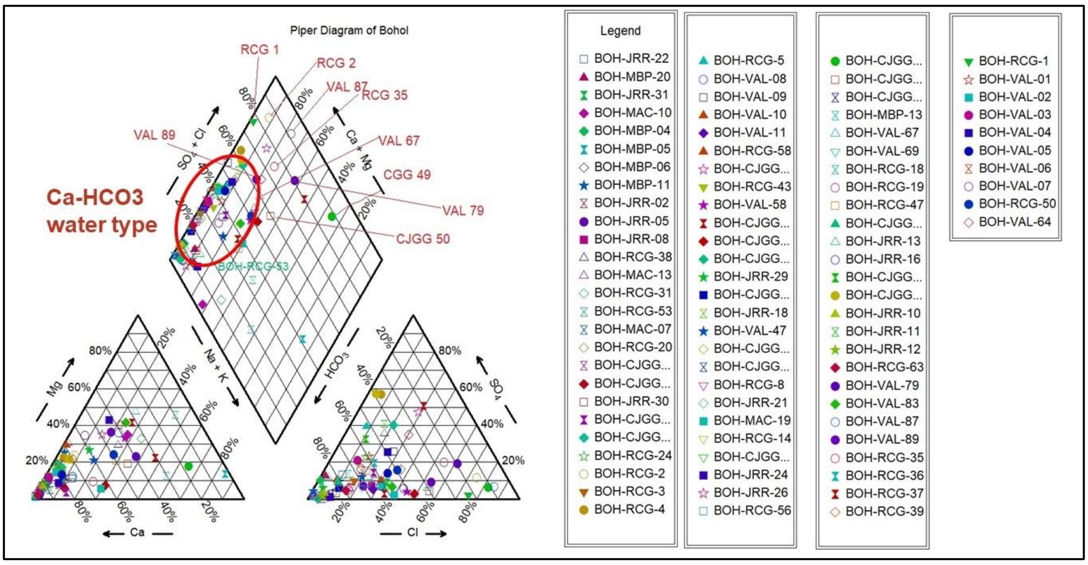

Fig. 6. Piper diagram displaying hydrogeochemical facies in the study area

7. Groundwater problems and future challenges

The risk of saltwater intrusion in Tagbilaran City and northern coastal areas is significant due to the highly karstic and porous limestone, compounded by the over-extraction of groundwater to meet the city's growing demand. Previous studies have documented saltwater intrusion issues in several coastal barangays of Tagbilaran City (JICA et al., 1998; MGB, 2017). This study illustrates the extent of saltwater intrusion by analyzing horizontal variations in groundwater quality and resistivity data.

Figure 7 shows groundwater sources with high electrical conductivity on the northern side of Bohol Island. The northern side has a small watershed, indicating low recharge/river discharge. Low discharge may result in low pressure to maintain the freshwater-saltwater interface. This could explain why many groundwater samples exceed the common drinking standard of 800 microsiemens per centimeter.

Furthermore, based on hydrochemical analysis results, 8 samples are classified as either Na-Cl or Ca-Cl water type. The Ca-Cl type could indicate brine-rock interaction in a carbonate environment. However, this water type does not necessarily indicate saltwater intrusion, as water chemistry depends on local geological conditions and mineral dissolution. Conversely, the Na-Cl type indicates saltwater intrusion in coastal or low-lying areas, particularly in Barangay Panglao, where ocean saltwater infiltrates and mixes with freshwater aquifers.

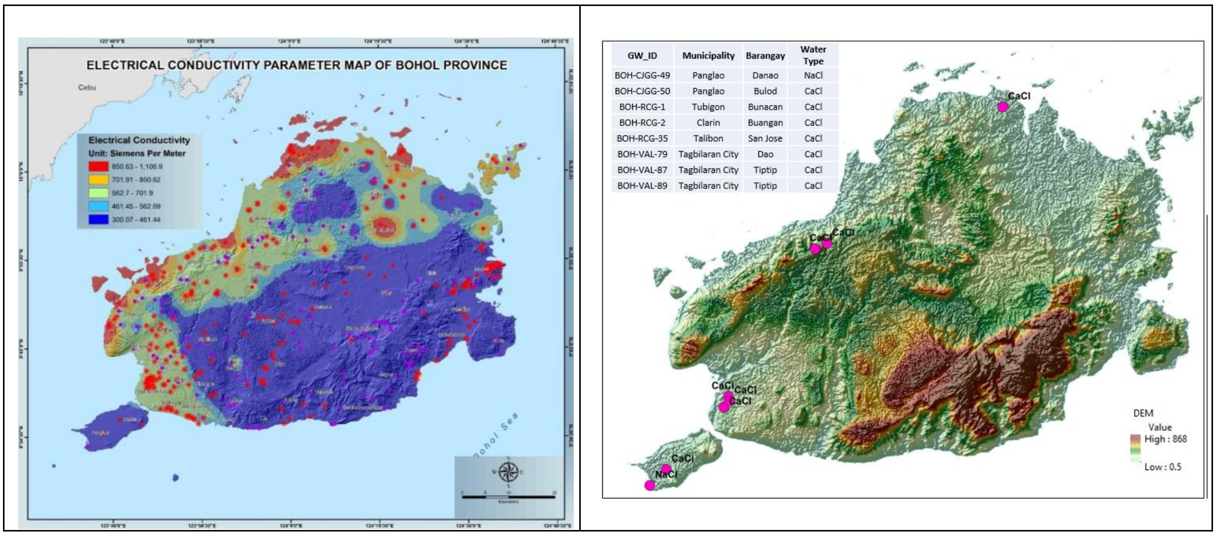

Fig. 7. (left) Groundwater electrical conductivity map showing the locations of all inventoried groundwater sources and (right) location map showing the Na-Cl and Ca-Cl groundwater types

Resistivity contour maps

Resistivity contour maps at various depths were generated to assess the lateral extent of saltwater intrusion. Figure 8 illustrates resistivity maps based on 32 sounding data points from Tagbilaran City's coastal area. These maps reveal a progressive decrease in resistivity with depth, indicating a highly resistive upper layer that overlays less resistive strata.

At a depth of 10 meters (Fig. 8a), the iso-resistivity maps identify two distinct zones: the western side shows very high resistivity values, indicative of unsaturated crystalline limestone, while the eastern side displays low resistivity values, characteristic of the saturated clastic aquifer of the Carmen Formation.

Between depths of 40 meters and 80 meters, very low resistivity values consistently indicate a saline zone on the western side, reflecting high groundwater salinity (e.g., Bernard, 2003; Mtoni et al., 2015). Figure 8b shows resistivity contours at 40 meters depth, with very low resistivity values (0.1 to 5 ohm-m) observed on the eastern side, approximately 1 km from the coastline. This suggests a saline water zone and aligns with previous reports of saltwater intrusion (e.g., MGB, 2017). In contrast, the eastern side's low resistivity values (50 to 20 ohm-m) correspond to clayey and silty layers of limestone and clastic formations. The central area exhibits resistivity values ranging from 30 to 500 ohm-m, indicating regions unaffected by saltwater intrusion, while very high resistivity values (200-500 ohm-m) in the southern and north-central parts signify unsaturated crystalline limestone.

At a depth of 80 meters, the saline zone extends approximately 1.5 km from the coastline, evidenced by low resistivity values (0.1 to 5 ohm-m) at VES Stations 6 and 7 (Fig. 8c), similar to the saline zones observed at 40 meters depth. The central area shows relatively low resistivity zones (5 to 20 ohm-m) due to clayey and silty limestone formations, whereas patches of high resistivity (30 to 100 ohm-m) in the central and easternmost regions indicate freshwater-saturated formations.

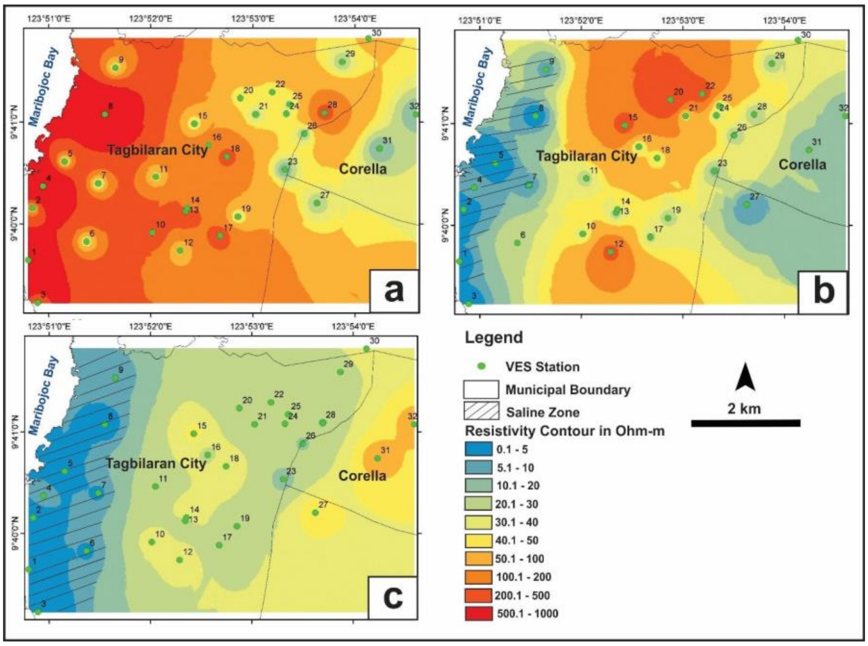

Fig. 8. Iso-resistivity maps at (a) 10 m (b) 40 m and (c) 80 m depths

8. Conclusions

This study identifies specific zones susceptible to saltwater intrusion, primarily driven by sea level rise, local geological conditions, and existing water management practices. Coastal aquifers in the northwestern part of Bohol and the western part of Tagbilaran City, along with estuarine zones at the river mouth of the Abatan Watershed, are particularly vulnerable.

In Tagbilaran City, hydrogeological data indicate that the saltwater-saturated zone extends vertically to approximately 30 meters, as determined by 1D and 2D inversion data. Laterally, this zone reaches up to about 1 kilometer from the coastline, based on iso-resistivity data. It is important to validate these findings through drilling data to ensure accuracy.

To address these challenges, baseline ER and hydrogeological data provide a crucial foundation for understanding the impact of sea level rise on saltwater intrusion, which is essential for developing effective management practices to protect freshwater resources. The sandy to gravelly facies of the clastic Carmen Formation emerges as the preferred aquifer due to its substantial thickness (approximately 15 to 120 meters) and favorable hydraulic properties (transmissivity). To mitigate saltwater intrusion in Tagbilaran City, it is recommended to construct groundwater wells in the eastern municipalities of Corella, Sikatuna, and Balilihan. Utilizing groundwater from the coarse-grained aquifer of the Carmen Formation could significantly aid the water supply in the rapidly growing city of Tagbilaran.

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Assessing hydrogeological characteristics and groundwater potential in Mae Sai, Chiang Rai, Thailand's special economic zone

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Abstract

In 2015, the Thai government designated 10 border provinces as special economic zones to leverage ASEAN's economic potential and enhance safety in border regions. Given the pivotal role of water resources in driving economic development in border regions, effective water management is imperative. This research aims to investigate hydrogeology and assess groundwater potential to support future water demands in Mae Sai, Chiang Rai Province. Methodologies include data collection, field surveys, hydrogeological mapping, and mathematical modeling. The study area is composed of three distinct aquifer types: Flood Plain Deposits (Qfd), Young Terrace Deposits (Qyt), and Old Terrace Deposits (Qot), each exhibiting yields ranging from 10 to 50 cubic meters per hour. There are three types of water chemistry: calcium-bicarbonate, magnesium-bicarbonate, and sodium sulfate. Groundwater predominantly flows from west to east, eventually converging into the Mekong River. While groundwater quality generally maintains a Total Dissolved Solids (TDS) level below 500 mg/L, elevated iron (Fe) concentrations (1-20 mg/L) exceed drinking water standards. Calculations for sustainable groundwater extraction, considering a 10% annual pumping rate over 20 years, suggest a maximum permissible pumping rate of 2,735 and 4,784 million cubic meters per year. Present utilization stands at 7.5 million cubic meters per year, leaving ample capacity (4,776.5 million cubic meters per year) for industrial usage, predominantly in small and medium-sized enterprises (SMEs) and the tourism sector. Encouraging governmental support and investor participation in the special economic zone is recommended, with ongoing groundwater monitoring mandated by the Department of Groundwater Resources to ensure compliance with the Groundwater Act of 1977 and promote sustainable groundwater management practices.

Keywords: groundwater potential, Thailand's special economic zone

1. Introduction

The El Niño phenomenon has significantly influenced several areas, including water used for agriculture, consumption, and socioeconomic development in Thailand. The Special Economic Zone Development Policy Committee was the primary driving force behind these operations. However, this committee was disbanded by the National Council for Peace and Order (NCPO) on July 9, 2015. The newly developed economic areas aim for sustainable and balanced growth. Duty-free zones have been established in Tak, Nong Khai, and Songkhla, along with bonded warehouses in Tak, Mukdahan, Songkhla, Nong Khai, and Chiang Rai, totaling 510 million baht and eligible for customs benefits. Water resources play a crucial role in driving economic activities. Therefore, effective water management is essential to support the increasing future demand. The Department of Groundwater Resources is the main agency to manage groundwater resources in Thailand. Assessing Hydrogeological Characteristics and Groundwater Potential in Mae Sai, Chiang Rai could support border trade, business activities, travel, logistics services, and transportation. Additionally, this assessment can serve as a guideline for sustainable management and conservation of groundwater resource.

2. Methods

2.1 Site description

The study area is located in the northern part of Chiang Rai, Thailand (20°25'41" N, 99°52'59" E), covering approximately 2,300 square kilometers. Mountains bound the basin on the west and north. The basin's altitude varies from +400 to +1,500 meters (MSL) (Fig. 1). The climate is tropical, characterized by an average annual rainfall of 2,500 millimeters. Land use statistics indicate that 60% of the area is dedicated to agriculture, approximately 27% to forests, about 10% to residential areas, with the remaining 2.1% designated for other uses. - Surface water areas account for only 0.9%. As of 2020, water usage in the area amounts to around 7.5 million cubic meters per year, projected to increase to 19 million cubic meters per year by 2030. Our annual usage of surface water is approximately 7 million cubic meters and our groundwater extraction is approximately 12 million cubic meters per year (Department of Groundwater Resources, 2020). However, increased investment in the study area is expected to lead to higher demand for water.

2.2 Hydrogeology

Mae Sai basin, which is known as the Tertiary sedimentary basin (Bal, A. et al., 1992). The basin is bounded by steep and high mountains, forming a contact zone between granite and Carboniferous-Permian metamorphic rocks. Metamorphic rocks are presented from the western to the northern part of the basin, while the Triassic granite and granodiorite are found in the eastern part, as shown in Figure 3.3. The major geological features in this area include Mae Chan Fault, Nam Ma Fault, and unconformity or geological contact. Mae Chan Fault lies in northeastern to southwestern direction from Mae Salong District to Mae Chan District and Chiang Saen District, while Nam Ma Fault lies in northeastern to southwestern direction from Myanmar to Mae Sai District (along the highway No.1). Unconformity, in terms of geological contacts, refers to the thickness of groundwater layer or aquifer in both sedimentary aquifer and metasedimentary aquifer. These sedimentary contacts are primarily found between (1) alluvial sediments and young terrace sediments, (2) young terrace sediment and old terrace sediment, and (3) old terrace sediment and Tertiary rocks, which form the basement layer (Department of Groundwater Resources, 2020).

The hydrogeology of the study area was conducted based on data from a previous project, titled "Geological and Hydrogeological Studies of Limestone Mountain Ranges in Tham Luang-Khun Nam Nang Non Forest Park Project on groundwater exploration and management". It consists of Permian carbonate rock aquifer (Pc), Permian to Carboniferous metasedimentary aquifer (PCms), granitic aquifer (Gr), volcanic aquifer (Vc), old terrace deposits aquifer (Qot), young terrace deposits aquifer (Qyt) and flood plain deposits aquifer (Qfd) (Department of Groundwater Resources, 2012).

- Permian Carbonate rock aquifer (Pc) is a high-potential groundwater aquifer. It consists of thick-bedded limestone at the depth of 20-80 meters, with a discharge rate of 20-30 cubic meters per hour in the general cavities and more than 50 cubic meters per hour in the cave. The hydraulic conductivity is 22.89 meters per day and the transmissivity is 91.71 square meters per day.

- Permian to Carboniferous metasedimentary aquifer (PCms) consists of quartzite and quart-schist at a depth of 30-80 meters, with a discharge rate of 2-5 cubic meters per hour in the cavities and more than 20 cubic meters per hour in fracture zones. The hydraulic conductivity is 28.17 meters per day, the transmissivity is 122.38 square meters per day, and the storativity is 5.36×10^{-5}.

- Granitic aquifer (Gr) and volcanic aquifer (Vc) are located at a depths ranging between 30 and 80 meters. The discharge rate is less than 2 cubic meters per hour in the general cavities and more than 20 cubic meters per hour in fracture and weathering zones. The hydraulic conductivity is 0.09 meters per day (Domenico, P.A. and Schwartz, F.W., 1998)

- Old terrace deposits aquifer (Qot) overlies the basement rock and generally occurs at a depth of more than 60 meters. This aquifer consists of sand and gravel (Øsize 2-5 cm) sediments, with highly sorted and well-rounded shape. The discharge rate exceeds 20 cubic meters per hour. The hydraulic conductivity is 69.12 meters per day, and the storativity is 1.13×10^{-2}.

- Young terrace deposits aquifer (Qyt) lies above the old terrace deposits aquifer and occurs at the depth of 30-65 meters. This aquifer consists of silt, sand, and gravel (Øsize 3-4 mm) sediments interbedded with numerous layers of clay. The discharge rate ranges from 10-20 cubic meters per hour. The hydraulic conductivity is 11.9 meters per day, and the storativity is 8.34×10^{-7} (Sitthisak Manyou, 2010).

- Flood plain deposits aquifer (Qfd) is the youngest aquifer and lies as the topmost layer among all unconsolidated rock aquifers. It mostly exposes in the eastern part of the study area at a depth of 20-30 meters. This aquifer consists of clay, silt, sand, and gravel sediments with a discharge rate of 5-10 cubic meters per hour. The hydraulic conductivity is 0.49 meters per day, and the storativity is 9.89×10^{-9}.

However, only Permian carbonate rock aquifer (Pc), Permian to Carboniferous metasedimentary aquifer (PCms), granitic aquifer (Gr) and Quaternary old terrace aquifer (Qot) are presented in the study area (Fig. 2) .

2.3 Simulation of groundwater potential using groundwater flow model

A groundwater-flow was simulated using MODFLOW-2005 (MODular finite-difference ground-water FLOW model) and Enhanced 3D Visualization. The model domain represents a study area of 670 km2 (with grid sizes ranging from 1,000×1,000 m). The groundwater model domain was discretized into 245 rows and 290 columns, totaling 497,350 grind cells (245x290x7), consisting of 167,444 active cells and 329,906 inactive cells, The model comprises seven different layers: the first (uppermost) layer has relatively low hydraulic conductivity, representing a clayey sand layer; the second to fourth layers are highly permeable, consisting of sand and gravelly sand with varying hydraulic conductivity; the fifth layer is limestone; the sixth layer is a siltstone, sandstone and quartzite; and the seventh layer is a granite (Fig. 4).

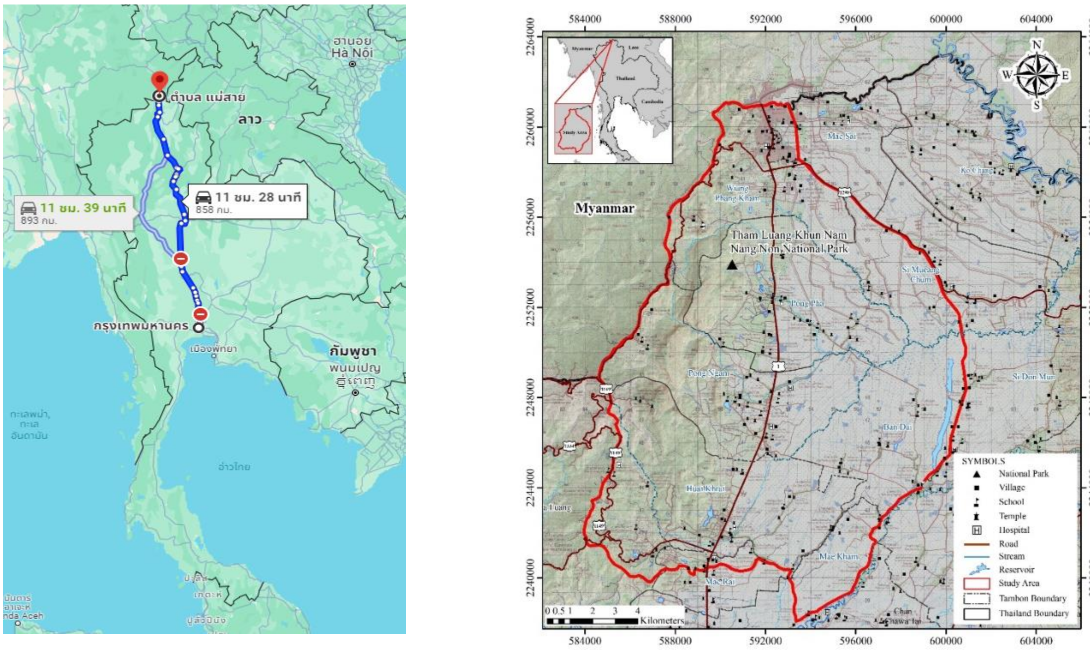


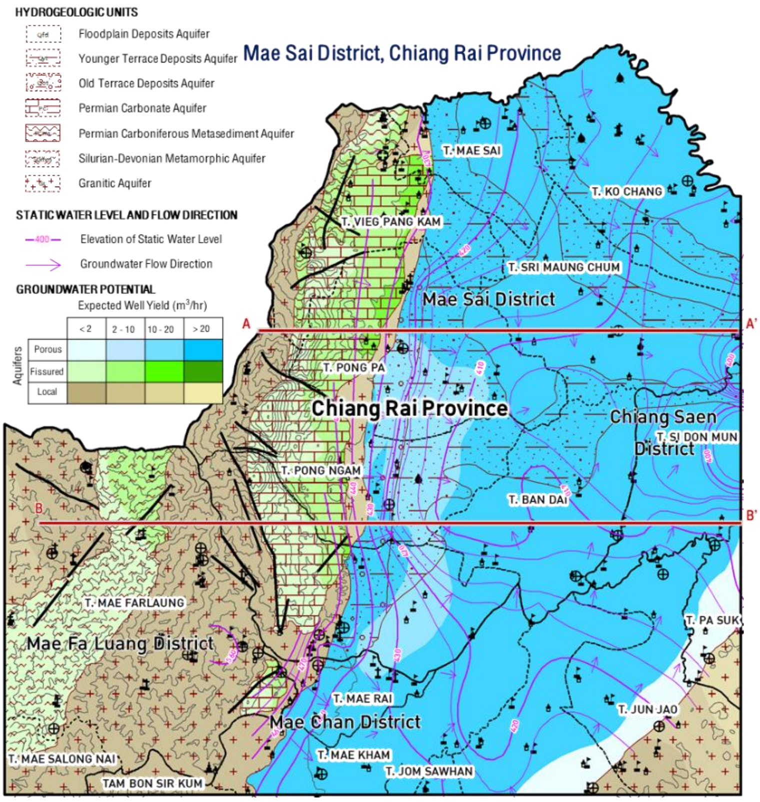
Fig. 1. The maps showing a location of the study area, Mae Sai, Chiang Rai, Thailand's Special Economic Zone

Water balancing of the Mai Sai basin involved many parameters, and groundwater can be simply expressed as follows:

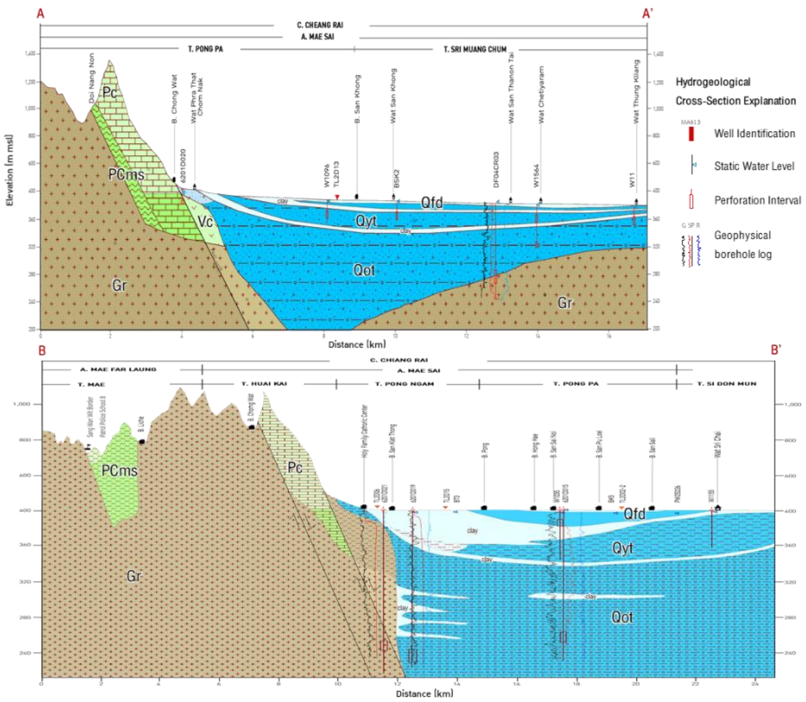
$$\frac{\partial}{\partial x}\left[K_x \frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y \frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_z \frac{\partial h}{\partial z}\right]\pm W = S_s \frac{\partial h}{\partial t}$$

where, K_x, K_y, K_z is hydraulic conductivity along the x,y,z axes, assumed to be parallel to the major axes of hydraulic conductivity [LT-1]; h is piezometric head [L]; W is the volumetric flux per unit volume representing source/sink terms [L3T-1]; S_s is specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material [L-1]; and t is time [T].

Following the conceptual model, the main input boundaries are located in the west of the Khun Nam Nang Non Mountains. These boundaries are represented by the General-Head Boundary (GHB) package as external boundary conditions. The top model layer involves two external surficial stresses simulated using the Recharge (RCH) and Evapotranspiration (EVT) packages. Recharge was estimated from precipitation based on the CHIRPS dataset, which is the rainfall estimates from rain gauge and satellite observations (Funk et al., 2015). The EVT values at the Doi Tung weather station were obtained from the Mae Fah Luang Foundation under Royal Patronage, based on reference crop evapotranspiration (ETo) and crop coefficient (Kc). Abstraction was simulated by the Well (WEL) package with a negative sign; likewise, recharge wells were calculated using the same package but with the opposite sign.



(A)



(B)

Fig. 2. (A) A map showing a Hydrogeological of the study area and (B) Hydrogeological cross-section line A-A’ and line B-B’

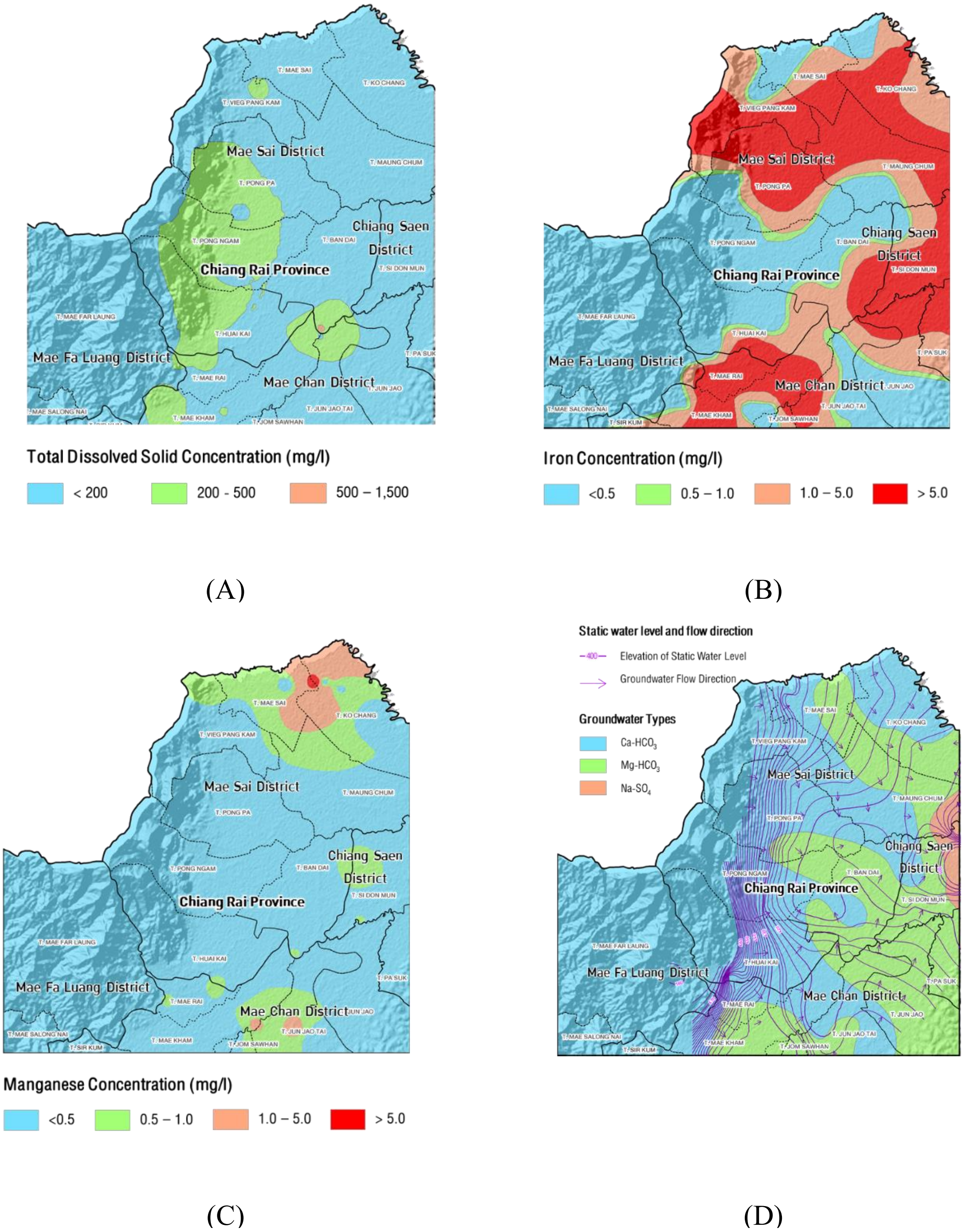


Fig. 3. Maps showing the groundwater quality and hydrochemical types

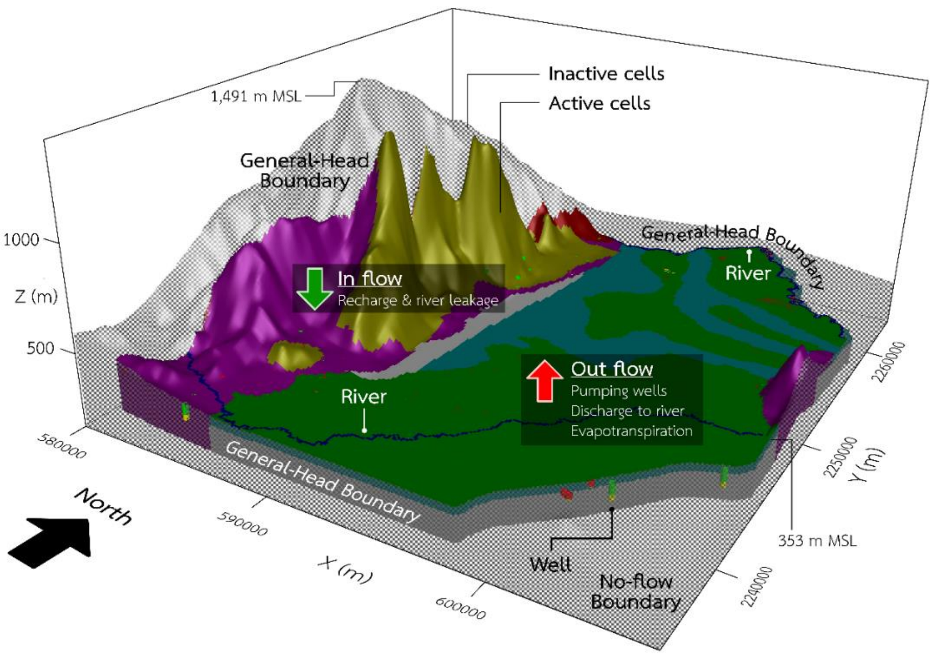


Fig. 4. A schematic diagram representing model layers and MODFLOW packages

Groundwater level was monitored in 150 wells within the model domain. Measurements were taken during two periods: in March 2019 and in August 2019, using an electric tape and an automatic data logger. These data were used to construct head distribution and groundwater-flow direction maps. Afterward, the series of groundwater levels were imported into the model as observed head values for model validation

After the model performance had been acceptable, MODPATH was employed to compute three-dimensional flow paths for imaginary water particles moving through the groundwater system (Pollock, 2016). The program is known as a post-processing module that calculates flow paths from MODFLOW's head and flow output files. In addition to particle paths, MODPATH computes the residence time for particles traveling through the system.

3. Results

3.1 Groundwater flow model

Table 1 displays the water balance for the entire model domain. As illustrated in Fig. 5, the computed results demonstrate an excellent correspondence between simulated heads and observed heads, which were monitored at 150 observation wells distributed across the study area. The normalized root mean square error (NRMSE), a common statistical metric, was used to assess the model's performance. The analysis revealed that the outflow from the area is greater than the inflow, with the pilot simulation's NRMSE standing at 7.79% (Fig. 5 and Fig. 6).

Table 1. Volumetric budget for the entire model at the end of 1-year simulation

Cumulative volume (m3)		Cumulative volume (m3)	
IN:		**OUT:**	
Storage	31,482,368.0000	Storage	158,329.0000
Wells	0.0000	Wells	42,050,262.0000
River leakage	16,667,767.0000	River leakage	63,585,868.0000
Head dep bounds	191,745,632.0000	Head dep bounds	97,431,360.1406
Recharge	2,957,394.0000	Recharge	0.0000
Evapotranspiration	0.0000	Evapotranspiration	39,634,232.0000
Total in	242,853,161.0000	Total OUT:	242,860,051.1406
IN - OUT	-6,890.1406		
Percent discrepancy	-0.00		

The allowable output of aquifers is determined by evaluating five different scenarios, where the pumping rate is increased annually by 5%, 10%, 20%, 30%, and 40%. This results in a continuous groundwater flow to the basin, known as the "Head-Dependent Flux Boundary". These estimates led to the specification of the initial pumping rates as 2,735 and 4,784 million cubic meters, under a pumping rate drop of less than 10%, and a drawdown of less than 25 meters. The results of these calculations are listed in Table 2 for each of the districts. (Fig. 7)**.**

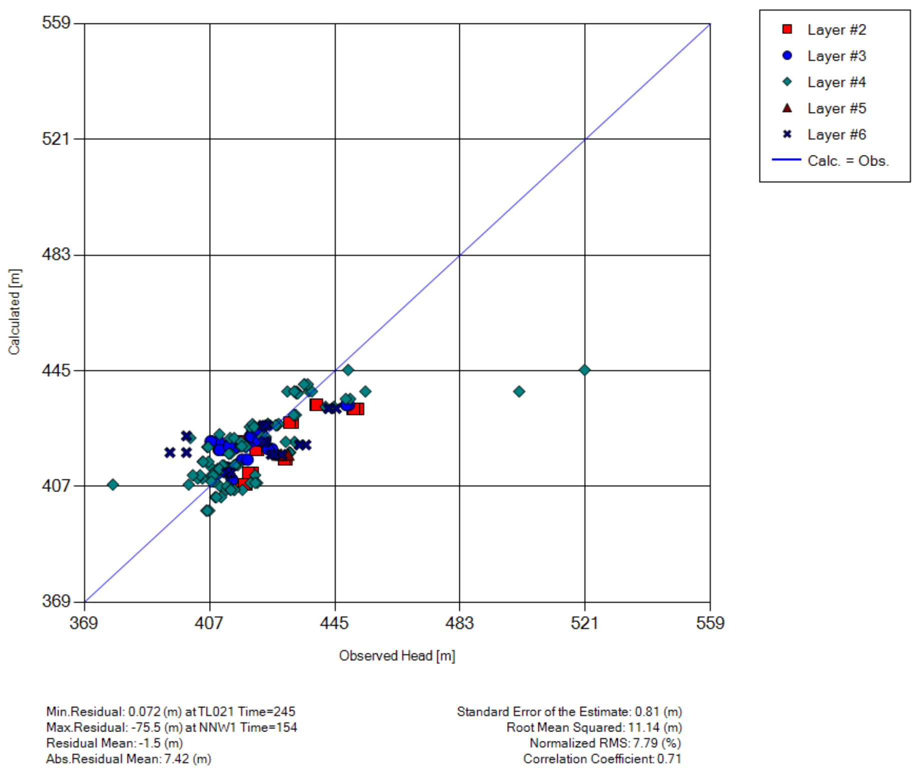


Fig. 5. Comparison between calculated heads and observed heads

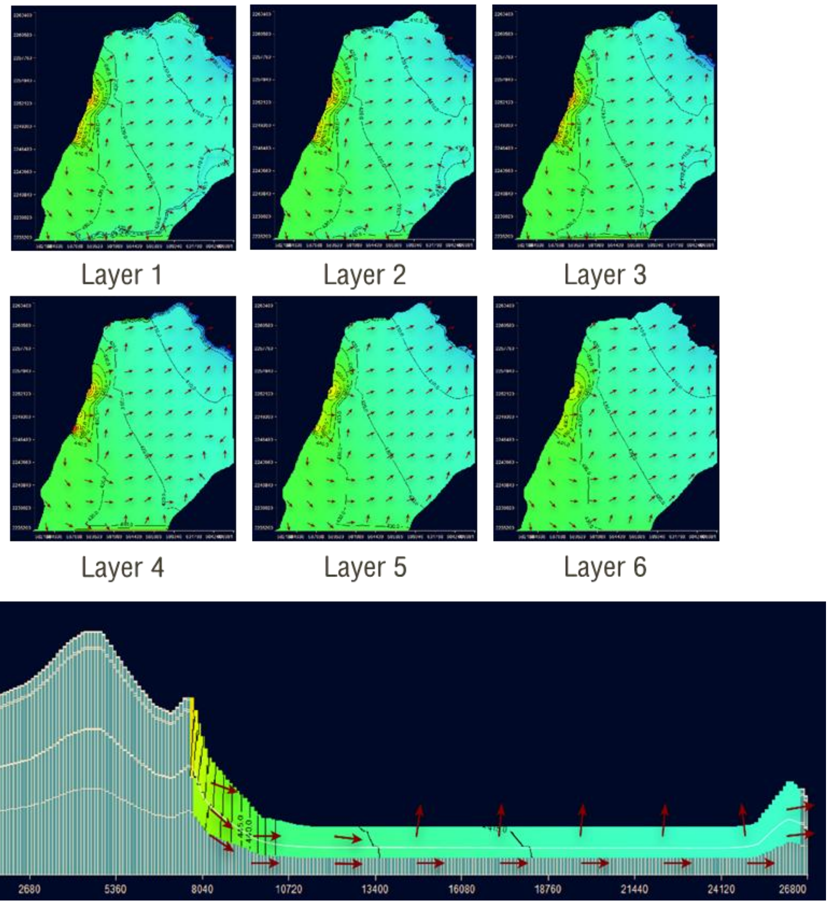


Fig. 6. A Steady-State Model to Simulate Groundwater Flow

Table 2. Permissible Yield based on pumping rate

	Pumping rate (20 year)				
	5%per year	**10%per year**	**20%per year**	**30%per year**	**40%per year**
Inflow to the system (MCM)	5,716	7,528	18,082	55,284	178,491
Permissible Yield on pumping rate (MCM)	2,735	4,784	15,739	53,276	176,769
drawdown (m.)	20	25	200	500	2,000

MCM = Million Cubic Meters
m.= meter

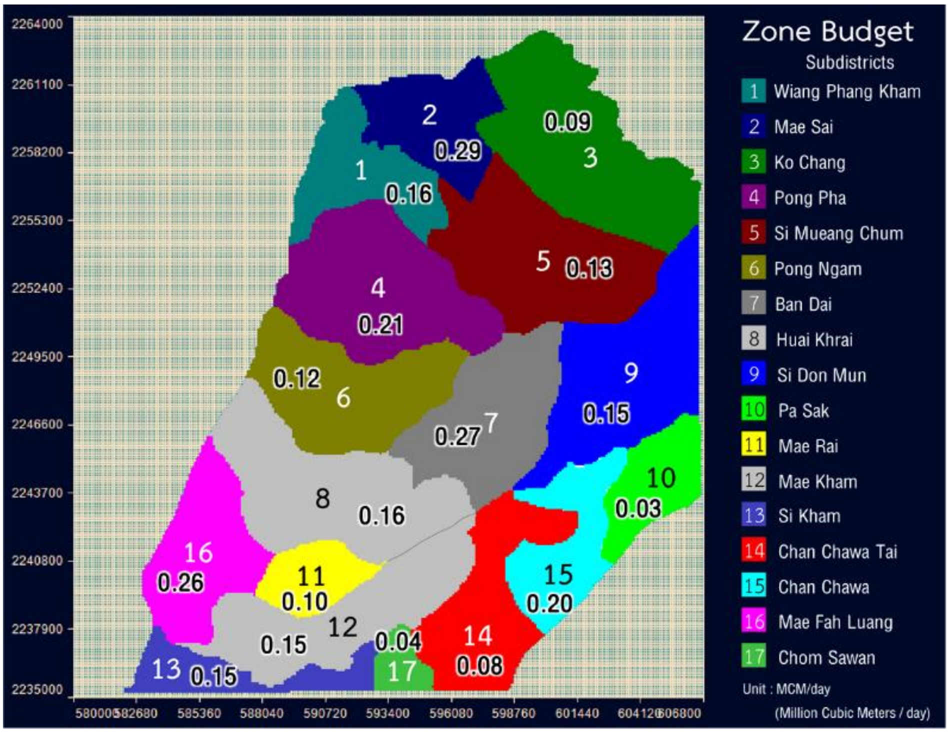


Fig. 7. The zone budget module of permissible yield was computed separately for each district of the aquifer basin

4. Conclusions

The emergence of El Niño is affecting water scarcity in Thailand. Given the presence of a Special Economic Zone, effective water management is crucial for driving the economy. The Department of Groundwater Resources, therefore, conducted a study on the hydrogeological characteristics and groundwater potential in Mae Sai, Chiang Rai, part of Thailand's Special Economic Zone. The study classified the area into 7 hydrogeological units: 3 units for unconsolidated aquifer and 4 units for hard rock terrain aquifer. The groundwater quality showed total dissolve solid less than 500 mg/L, but with Fe-content and Mn-contents exceeding 5 mg/L. Therefore, water treatment is necessary before consumption. By utilizing this constraint, the transient MODFLOW model was used to simulate sustainable groundwater extraction with an annual pumping rate of 10% over 20 years. The model recommends a maximum permissible yield of 2,735 and 4,784 million cubic meters per year. A groundwater model with a zone budget module computed the sustainable yield on a district-by-district basis. Even though it is still in the early stages, the current modeling study provides policymakers with an initial tool for managing sustainable groundwater resources in the basin in the future. The current of water usage is 7.5 million cubic meters per year, indicating a significant available groundwater capacity of more than 4,700 million cubic meters per year for industrial processes, especially for small and medium-sized enterprises (SMEs) and the tourism industry. To enhance the success of the special economic zone, it is suggested to encourage governmental support and investor participation, and to enforce regular groundwater monitoring by the Department of Groundwater Resources. This should comply with the Groundwater Act of 1977 and support sustainable groundwater management practices.

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Hydrogeological information and groundwater usage of the Hanoi city, Vietnam

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Abstract

Hanoi, the political and economic hub of Vietnam, relies heavily on groundwater as its primary water resource. With three major aquifers (Holocene, upper Pleistocene, and lower Pleistocene) and significant reserves, groundwater demands for drinking water, industrial production, and daily consumption. However, rapid urbanization has intensified challenges such as overextraction, pollution, salinity intrusion, and land subsidence, threatening both water quality and availability. This study reviews Hanoi's hydrogeological conditions, groundwater resources, utilization patterns, and the pressing environmental challenges posed by urban development. The findings underline the importance of sustainable management practices, monitoring networks, and protective measures to ensure the long-term security of Hanoi's groundwater resources.

Keywords: groundwater, aquifers, monitoring network, Hanoi

1. Introduction

Hanoi, the political, economic, and cultural hub of Vietnam, is located at the heart of the Red River Delta within the Northern Delta's key economic region. As one of the most densely populated areas in the country, Hanoi has a thriving industrial, agricultural, and service sector, driving a substantial demand for water for drinking, daily use, and production.

Uniquely, Hanoi benefits from abundant groundwater reserves, replenished year-round by surface water sources primarily the Red River as well as shallow aquifers widely distributed across the delta. These favorable conditions allow for convenient groundwater exploitation through large diameter wells, making it the city's sole water supply source for over a century.

However, Hanoi's rapid urbanization has significantly altered environmental conditions, including its groundwater resources. Declining groundwater quality and quantity, including issues of pollution and depletion, have been observed in certain areas, adversely affecting both livelihoods and economic activities. In the city's central urban areas, decades of intensive groundwater extraction, compounded by poorly planned well locations far from recharge sources, have created extensive groundwater depression cones covering hundreds of square kilometers. This overextraction has amplified negative environmental impacts, including groundwater depletion, increased contamination, and land subsidence.

2. Hydrogeological information of the Hanoi area

The Hanoi area features three porous aquifers (Holocene - qh, Upper Pleistocene - qp_2, and

Lower Pleistocene - qp_1) and 16 fissured aquifers. These aquifers vary in their distribution, hydrogeological characteristics, supply zones, movement, drainage patterns, and hydraulic relationships with surface water and between aquifers. This information serves as the foundation for analyzing and proposing solutions to protect groundwater resources. Key features of the aquifers are summarized below:

Holocene aquifer (qh):

This aquifer covers much of the southern Red River Delta, with medium to high water content and shallow distribution depths, making it suitable for rural water exploitation. The qh aquifer has a close hydraulic connection with surface water sources. Its shallow location, including areas of direct exposure, makes it highly susceptible to contamination. Moreover, areas with hydrogeological windows are at significant risk of polluting the primary aquifers being exploited in the region.

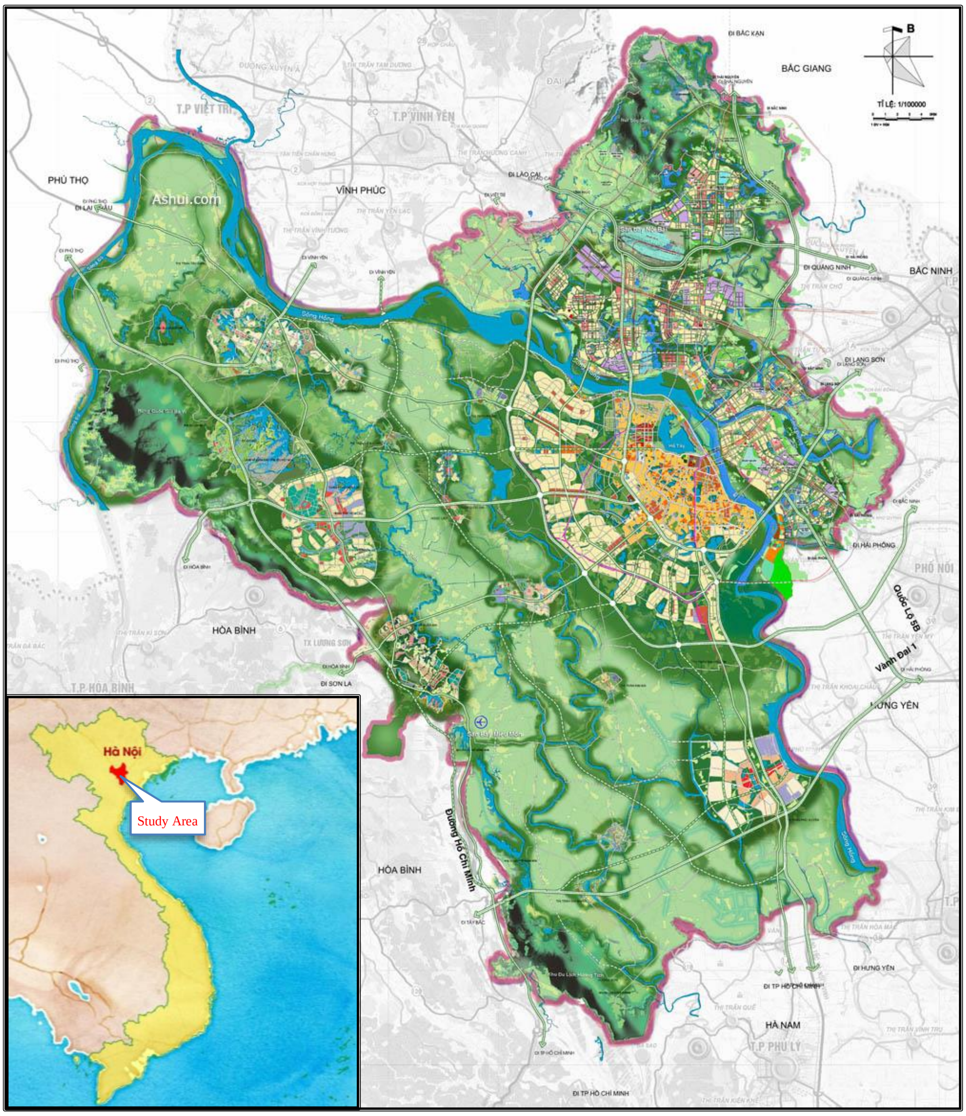

Fig. 1. Map of the study area location

Upper Pleistocene aquifer (qp_2):

This aquifer spans a large portion of the study area, featuring medium to high water content and strong hydraulic connections with the Holocene (qh) and Lower Pleistocene (qp_1) aquifers. In many locations, the qp_2 and qp_1 layers share a single hydraulic system, emphasizing the importance of protecting water quality in hydrogeological window areas, as they are critical points of potential contamination. The qp_2 aquifer also interacts with surface water sources.

Lower Pleistocene aquifer (qp_1):
As the primary and most critical aquifer for meeting Hanoi's water needs, the qp_1 aquifer is characterized by a large distribution area, significant thickness, and medium to high water content. Located beneath the porous aquifers, it is better protected from contamination by overlying separating layers. However, hydrogeological windows in this layer are vulnerable to infiltration of polluted surface water from upper aquifers, posing a risk to its quality.

Fissured aquifers:
Among the fissured aquifers (fractured, karst aquifers) in the region, the Vinh Bao, Dong Giao, and Na Vang formations are the most notable due to their superior water storage capacity and significant potential for exploitation. However, the limestone fissured aquifers of the Dong Giao and Na Vang formations are particularly vulnerable to contamination because they are largely exposed at the surface, and their interconnected fracture systems facilitate pollutant infiltration.

3. Major water resources and water utilization ways

3.1. Major water resources

Groundwater resource potential:

The summary of the calculation results for the groundwater resource potential of Hanoi shows that the total potential groundwater resource is 11,025,947 m^3/day, including:

- Stored water resources: 2,813,914 m^3/day;
- Natural recharge: 2,840,094 m^3/day;
- Maximum recharge from the Red River: 5,371,939 m^3/day.

Exploitable groundwater reserves:

The calculated exploitable groundwater reserves for the three aquifers: Holocene (qh), upper Pleistocene (qp_2), and lower Pleistocene (qp_1) based on groundwater flow model results, are determined to be 3,819,617 m^3/day, distributed as follows:

- Holocene aquifer (qh): 672,122 m^3/day;
- Upper Pleistocene aquifer (qp_2): 1,013,701 m^3/day;
- Lower Pleistocene aquifer (qp_1): 2,133,794 m^3/day.

For freshwater areas (TDS <1.5 g/L), the exploitable reserves are 3,291,798 m^3/day, including:

- Holocene aquifer (qh): 618,016 m^3/day;
- Upper Pleistocene aquifer (qp_2): 838,251 m^3/day;
- Lower Pleistocene aquifer (qp_1): 1,835,531 m^3/day.

For brackish and saline water areas (TDS ≥1.5 g/L), the exploitable reserves are 527,819 m^3/day, including:

- Holocene aquifer (qh): 54,106 m³/day;
- Upper Pleistocene aquifer (qp_2): 175,450 m³/day;
- Lower Pleistocene aquifer (qp_1): 298,263 m³/day.

The exploitable freshwater groundwater reserves in Hanoi amount to 4,076,365 m³/day, including:

- Exploitable groundwater reserves in porous aquifers: 3,291,798 m³/day;
- Exploitable groundwater reserves in fissured aquifers: 784,567 m³/day.

3.2. Water utilization ways

Groundwater in Hanoi is exploited and utilized for various purposes, primarily industrial production and domestic consumption. The utilization methods are categorized into the following forms:

3.2.1. Concentrated exploitation

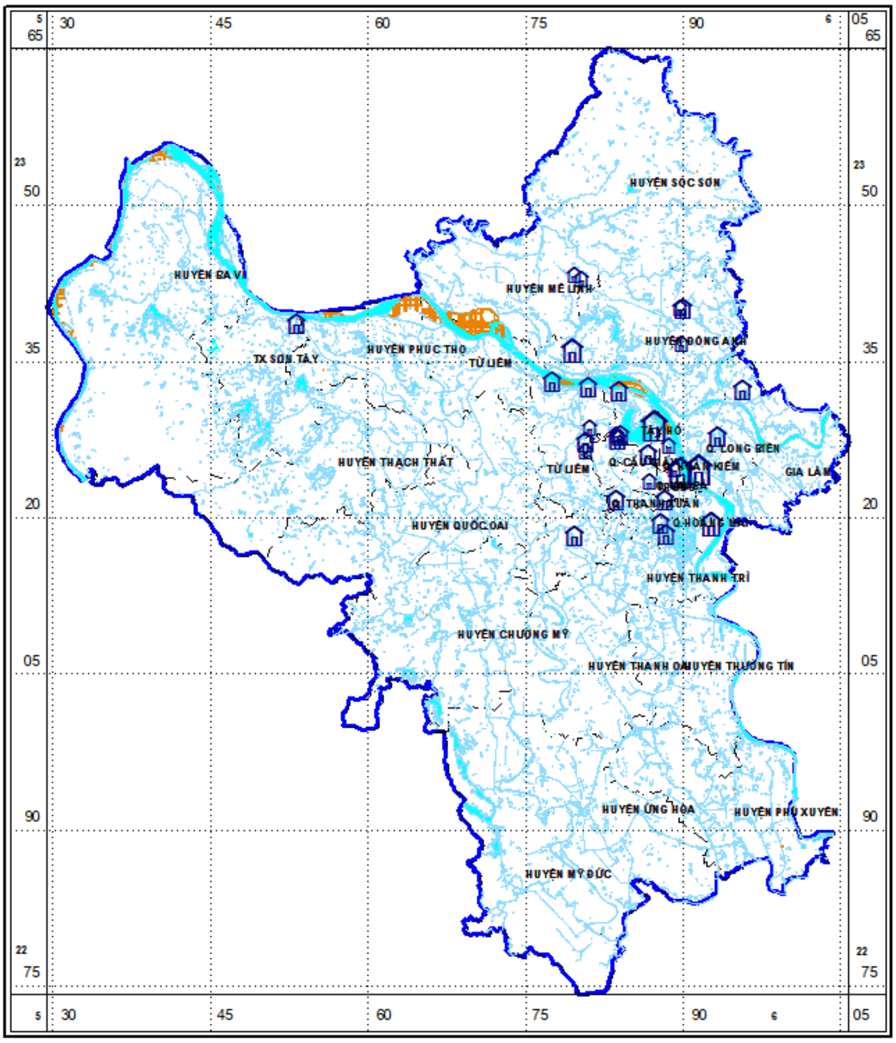

Fig. 2. Map of the locations of centralized water plants and stations in Hanoi

Concentrated groundwater exploitation in Hanoi primarily serves water plants for drinking, daily consumption, and industrial production, with drinking and domestic use being the primary focus. These centralized water plants are connected to the citywide water supply network. Currently, Hanoi has 24 water plants and supply stations with a total of 308 exploitation boreholes, operating across 17 districts. The total exploitation volume from these centralized facilities is approximately 693,581 m^3/day.

3.2.2. Single exploitation

Single exploitation involves groundwater extraction by individual entities, such as clean water supply stations, production facilities, businesses, hospitals, schools, and military units. This type of exploitation occurs across most districts, excluding Hoan Kiem District. There are 725 exploitation boreholes under this category, collectively extracting about 124,540 m^3/day.

3.2.3. Rural exploitation

Rural groundwater exploitation is widespread across 21 districts, predominantly in suburban and rural areas. These works are generally drilled by households and individuals for daily living, farming, small-scale production, and business. According to surveys and local data, Hanoi has 752,484 rural groundwater exploitation boreholes, with a combined extraction volume of approximately 429,913.6 m^3/day.

4. Hydrological database (groundwater monitoring network)

Hanoi places a strong emphasis on sustainable development and environmental protection, with water resource monitoring and protection being critical priorities. Currently, two water resource monitoring networks operate in the city:

The National monitoring network managed by the National Center for Water Resources Planning and Investigation (under the Ministry of Natural Resources and Environment).

The Hanoi City monitoring network, overseen by the Monitoring Center (under the Department of Natural Resources and Environment).

Although these networks operate independently, there is regular collaboration and information exchange to support effective water resource management. The national monitoring network provides Hanoi with monthly bulletins, forecasts, and warnings to facilitate local decision-making.

a. Objectives of monitoring

Ensure the national water resource monitoring network operates according to its design, delivering high-quality, reliable monitoring data.

Enhance data quality to provide timely monitoring, supervision, and forecasts related to the quantity and quality of surface water and groundwater.

Detect fluctuations in water resources promptly and inform state management agencies to guide inter-provincial and international water resource management decisions.

b. Tasks of monitoring

Monitor and update databases on water resource parameters at surface water and groundwater monitoring sites.

Forecast water resource trends, including groundwater level fluctuations and groundwater quality changes.

Assess and document changes in water resources to produce bulletins, forecasts, warnings, and annual reports.

Maintain and ensure the functionality of water resource monitoring infrastructure.

c. Monitoring points and infrastructure

The regional monitoring network in Hanoi was established between 1989 and 1995 and has since expanded throughout the Northern Delta. The Hanoi area features 39 monitoring points**,** including 37 groundwater monitoring points and 2 surface water monitoring points**,** positioned along a transect spanning the city from its northeast to southwest edges.

At each groundwater monitoring site, separate wells are installed to observe key aquifers, including the Holocene, Pleistocene, Neogene, and Triassic aquifers. According to the "Report on the Planning of the National Natural Resources and Environment Monitoring Network for the Period 2016-2025, with a Vision to 2030," Hanoi has 37 monitoring points with 68 works in total.

d. Monitoring methods

Manual monitoring (Portable electric measuring wires): Rainy Season (May-October): Measurements are taken 10 days per month and for dry Season (November-April): Measurements are taken 5 days per month.

Semi-automatic monitoring (Water levels): Devices record data every 2 hours, Data collection and validation occur twice monthly.

e. Water quality analysis parameters

Water sampling is conducted twice annually during critical periods: Dry Season: March-April, when water levels reach their lowest. Rainy Season: August-September, when water levels are at their highest.

Unified analytical parameters across the monitoring network include:

Comprehensive samples: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, CO_3^{2-}, CO_2, NH_4^{+}, Al^{3+}, NO_3^{-}, NO_2^{-}, pH, hardness, dried residue, and physical properties.

Iron samples: Fe^{2+}, Fe^{3+}.

Contamination indicators: NH_4^{+}, NO_3^{-}, NO_2^{-}, PO_4^{3-}, COD, Eh.

Trace elements: Arsenic (As), mercury (Hg), selenium (Se), chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), manganese (Mn).

f. Utilization of monitoring data

Groundwater dynamics monitoring has been conducted continuously since 1996, with results stored in the National Center for Water Resources Planning and Investigation. These results are published in annual groundwater dynamics reports and summarized every five years (e.g., 2000, 2005, 2010). Data is regularly disseminated through government publications and websites, including those of the Ministry of Natural Resources and Environment and the Department of Water Resources Management.

The monitoring data encompassing water levels, quality, and temperature serves various purposes, such as:

Studying hydraulic relationships between surface water and groundwater.

Mapping groundwater dynamics.

Understanding the formation of chemical compositions in groundwater.

In conclusion, the results from both national and municipal water resource monitoring networks are critical for water resource forecasting, warning, and management, ensuring sustainable development and environmental protection for Hanoi.

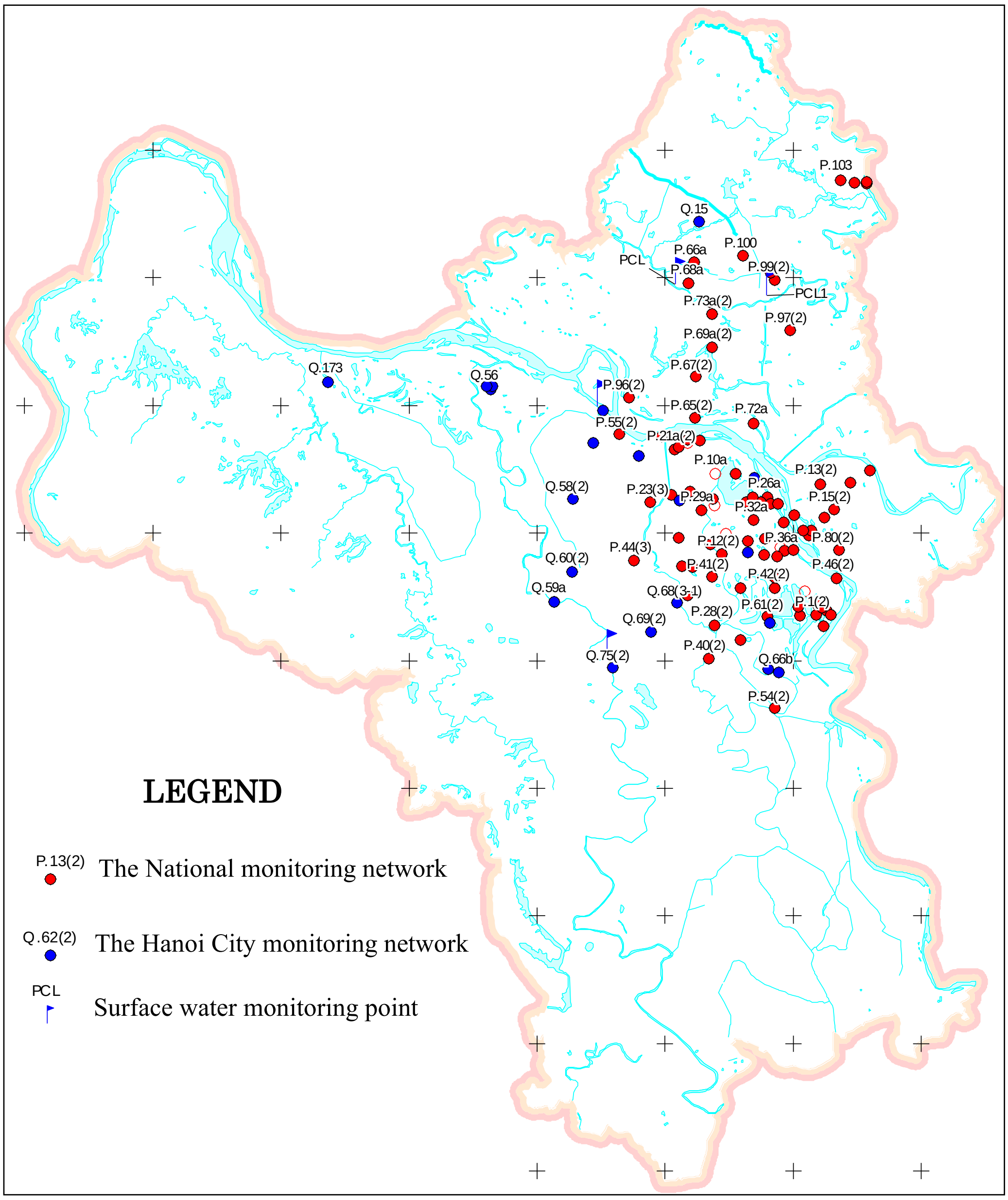

Fig. 3. Distribution map of groundwater dynamics monitoring points in Hanoi area

5. Major problems and future challenges

5.1. Risk of groundwater depletion

a) Holocene aquifer (qh)

Monitoring data from the national and Hanoi networks indicates a clear trend of declining water levels in the qh aquifer in recent years. The expansion and deepening of water level depression funnels are of particular concern. In certain areas, groundwater levels have dropped below -10 meters. Key observations include:

- In 2016, the total area where water levels in the qh aquifer fell below -5 meters reached 313.6 km^2**,** an increase of 90.8 km^2 compared to 2015.

b) Pleistocene aquifer (qp_1 and qp_2)

The Pleistocene aquifers faces increasing pressure from rising groundwater exploitation to meet the growing demands of domestic use, services, production, and business activities in Hanoi. This rise in demand is largely driven by rapid socio-economic development, as surface water resources can only fulfill a fraction of the city's needs.

If groundwater extraction continues unchecked, it could lead to several severe consequences, including:

- Depletion of aquifers.
- Land subsidence and structural damage.
- Reduced drainage capacity in urban areas, increasing flood risk.

Monitoring data from the southern part of the Red River highlights significant changes in water level depression funnels over time. These observations include:

Seasonal Variation:

The area impacted by groundwater exploitation (with water levels below 0 meters) decreases during the rainy season and expands during the dry season. This seasonal fluctuation has been observed to intensify over time.

Expansion of strongly affected areas:

Areas with water levels below -8 meters increased from 46 km^2 in February 1993 to 182.84 km^2 in May 2015, reflecting an average annual growth of 6.22 km^2**.**

The maximum affected area in 2015 surpassed the corresponding area in 2014 by 8.56 km^2**,** potentially due to adjustments in water plant extraction during the dry season.

Expansion of very strongly affected areas:

Regions where water levels dropped below -14 meters grew significantly, from 3 km^2 in 1993 to 93.69 km^2 in November 2015. This area also exceeded the maximum value recorded in 2014.

The continued expansion of these severely impacted zones underscores the urgent need for effective groundwater management policies to prevent resource depletion and mitigate associated risks.

5.2. Pollution

a) Holocene aquifer

The Holocene aquifer faces significant pollution risks, particularly in areas with hydrogeological windows, which are natural zones of vulnerability for groundwater contamination. Key findings include:

Three high-risk pollution zones have been identified, covering an area of 390.4 km², equivalent to 26% of the aquifer's distribution area.

These high-risk zones are concentrated in:

- The hydrogeological window area between the Hong (Red) River, Duong River, and the Holocene aquifer.
- River sections contaminated by polluted wastewater, such as the Nhue, To Lich, and Set rivers.

These areas are characterized by weak self-protection capacity of the aquifer and proximity to pollution sources.

b) Pleistocene aquifer (qp_1 and qp_2)

The Pleistocene aquifer is also at risk of pollution, particularly in regions where it is hydraulically connected to the Holocene aquifer. Research highlights include:

- Three high-risk pollution zones have been identified, spanning 212 km², which represents 10.6% of the aquifer's distribution area.
- High-risk zones are concentrated in:
  - Areas along both sides of the Red River.
  - Hydrogeological windows between the Holocene and Pleistocene aquifers, particularly where the Holocene aquifer is already polluted.
  - Specific locations include Minh Khai and Que Cat communes in Dan Phuong District, and Thanh Van and Hien Giang communes in Thanh Oai District.

c) Limestone aquifers (Dong Giao, Na Vang, and Vinh Bao aquifers)

The limestone aquifers, such as the Dong Giao, Na Vang, and Vinh Bao aquifers, are among the most important in the region. However, these aquifers are highly susceptible to pollution due to their characteristics:

- Many of these aquifers are exposed at the surface, with interconnected crack systems that allow contaminants to easily infiltrate.
- High-risk pollution zones for these aquifers are distributed in My Duc, Chuong My, and Ba Vi Districts, covering a total area of 105.3 km².

5.3. Groundwater salinity

a) Holocene aquifer

In the southern part of Hanoi, the Holocene aquifer has a saline boundary, with saline water distributed patchily in a leopard-print pattern. The Pleistocene aquifer's saline boundary is primarily located in the southern areas of Hanoi, specifically in Phu Xuyen and Ung Hoa Districts. These observations indicate that the saline boundary of the Pleistocene aquifer is dynamic, likely influenced by nearby groundwater extraction activities, particularly in freshwater zones.

5.4. Land subsidence

Hanoi has established 10 monitoring stations to observe land subsidence caused by changes in groundwater levels. These stations are located at water plants and booster stations managed by Hanoi Clean Water Trading Company No. 2. The objective is to study the relationship between groundwater exploitation and land subsidence in these areas.

- **Mechanism of subsidence**:
  - Increased groundwater extraction lowers the water table, leading to a reduction in pore pressure within soil and rock layers.
  - This triggers the consolidation of soil, which, in turn, causes land subsidence.
  - Subsidence is more pronounced in areas with weak soil structures compared to those with dense clay layers.

Monitoring efforts aim to assess and mitigate the risks associated with excessive groundwater extraction and its contribution to land deformation across Hanoi.

6. Conclusions

Hanoi’s groundwater resources are vital for its socio-economic development, yet they face numerous challenges due to growing demand and environmental pressures. This study highlights the following key conclusions:

1. **Groundwater resources and usage**:
   - Hanoi possesses significant groundwater reserves distributed across three primary porous aquifers (Holocene, upper Pleistocene, and lower Pleistocene) and several fissured aquifers.
   - Groundwater exploitation is categorized into centralized, single, and rural systems, collectively supporting the city’s water supply needs.
2. **Major challenges**:
   - **Depletion**: Overextraction has caused widespread groundwater depression funnels, particularly in the Holocene and Pleistocene aquifers, with water levels dropping significantly over the years.
   - **Pollution**: Pollution hotspots have been identified, particularly in hydrogeological window areas and regions impacted by wastewater discharge. These issues threaten both water quality and the ecosystems dependent on these resources.
   - **Salinity intrusion**: Saline boundaries in southern Hanoi aquifers, particularly the Holocene and Pleistocene, pose risks to freshwater availability. Monitoring has shown dynamic shifts in salinity levels, influenced by groundwater

extraction and other factors.

- **Land subsidence**: Excessive groundwater extraction has contributed to land subsidence, especially in areas with weak soil structures, further complicating urban development and infrastructure stability.

3. **Monitoring and management**:
   - Hanoi operates two groundwater monitoring networks to assess resource trends, water quality, and environmental impacts. These networks provide critical data for policy-making and resource management.
   - Continuous monitoring and updates to databases are essential to track groundwater dynamics and address emerging challenges.

4. **Recommendations**:
   - Implement stricter regulations on groundwater exploitation to prevent overuse and depletion.
   - Strengthen pollution control measures, particularly in areas near hydrogeological windows and polluted surface water sources.
   - Expand and enhance monitoring networks to provide comprehensive data for forecasting and decision-making.
   - Promote the use of alternative water sources, such as treated surface water, to reduce pressure on groundwater reserves.
   - Increase public awareness of sustainable water usage practices and the importance of groundwater conservation.

By addressing these challenges through integrated management and proactive measures, Hanoi can ensure the sustainability of its groundwater resources, securing the city's water supply and supporting its long-term development goals.

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