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Proceedings of the 12TH Groundwater Symposium 2024

Challenges and Opportunities for Sustainable Development and Management of Groundwater

18 March 2024, Kathmandu

Organized by

CREEW

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12th Groundwater Symposium 2024
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Organized by
Center of Research for Environment, Energy and Water (CREEW)
The Small Earth Nepal (SEN)
Kathmandu Valley Water Supply Management Board (KVWSMB), Government of Nepal

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WaterAid Nepal

Editors
Lalit Pathak, Sarad Pathak, Rabin Malla

Cover page photo:
Top Photos: Deep tubewell construction for irrigation at Battar, Nuwakot (2019). The depth is about 120m, and discharge is 10lps. The size of tubewell is 8/6” diameter.

Bottom Photos: Deep tubewell construction for irrigation at Mugitar, Ramechap (2018). The depth of tubewell is about 120m, discharge is about 7lps, and its irrigation command area is 10ha.

These projects were implemented by the Groundwater Resources and Irrigation Development Division (GWRIDD), Kavre, Nepal. Photo credit: GWRIDD.

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ACKNOWLEDGEMENTS

In recognition of our shared accomplishments and solidarity, we extend our deepest gratitude to everyone who contributed to the resounding success of the 12th Groundwater Symposium on "Challenges and Opportunities for Sustainable Development and Management of Groundwater". We express our heartfelt appreciation to the participants, presenters, and distinguished guests whose unwavering dedication and invaluable insights illuminated the symposium, making it a truly notable event. We are profoundly grateful to the dignitaries whose esteemed presence enriched our discussions with their profound wisdom and visionary perspectives.

Our sincere thanks go to the collaborators and partners whose steady support and commitment were instrumental in achieving the vision of this symposium. We extend special recognition to the organizations- Acme Engineering College, Nepal (ACME), Asian Institute of Technology, Thailand (AIT), Centre for Water Resources Studies, Institute of Engineering, Nepal (CWRS, IOE), International Maize and Wheat Improvement Center (CIMMYT), Cereal Systems Initiative for South Asia (CSISA), Environment and Public Health Organization, Nepal (ENPHO), Groundwater Youth Network (GWYN), Himalayan Whitehouse International College, Nepal (HWIC), Interdisciplinary Centre for River Basin Environment, University of Yamanashi, Japan (ICRE - UY), International Water Management Institute (IWMI), Kantipur Engineering College, Nepal (KEC), Kurita Water and Environment Foundation, Japan (KWEF), Nepal Development Research Institute, Nepal (NDRI), Nepal Hydrogeological Association, Nepal (NHA), Stockholm Environment Institute, Asia Centre, Thailand (SEI), Southasia Institute of Advanced Studies, Nepal (SIAS), Smartphones For Water Nepal (S4W-Nepal), Sustainable Mekong Research Network, Thailand (SUMERNET), Transforming Agrifood Systems in South Asia (TAFSSA), United International Federation of Youth for Water and Climate (UNIFY), Universal Engineering and Science College, Nepal (UESC), and WaterAid Nepal.

We also express our heartfelt appreciation to the hardworking members of the organizing committee, the advisory, committee, and scientific committee along with the dedicated office staff, whose tireless efforts ensured the seamless execution of every aspect of this event.

We also extend our gratitude to all participants for their active engagement and spirited contributions during the event. That enthusiasm and passion were the driving force behind the success of the symposium.

As we reflect on the journey thus far, we eagerly anticipate the next symposium in the coming year, where we can once again converge, inspired by the shared pursuit of sustainable groundwater management.

Organizers
Center of Research for Environment, Energy and Water, Nepal (CREEW)
The Small Earth Nepal (SEN)
Kathmandu Valley Water Supply Management Board (KVWSMB), Government of Nepal

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PREFACE

Groundwater constitutes about one-third of the global freshwater supply and is the most abundant source of freshwater on Earth. The United Nations World Water Development Report 2022, "Groundwater: Making the Invisible Visible," highlights that groundwater accounts for approximately 99% of all liquid freshwater on Earth. It provides half of the water withdrawn for domestic use globally and 25% for irrigation, underscoring its indispensable role in human life and ecosystems.

However, the increasing pressures from climate change and other stressors are raising concerns about the sustainability of groundwater resources. Asia, particularly South Asia and Southeast Asia, is at the forefront of groundwater extraction, with significant challenges arising from over-extraction, pollution, and mismanagement. South Asia alone accounts for about 34% of global groundwater usage, with unregulated irrigation pumping leading to rapid declines in water levels. Similarly, Southeast Asia faces extensive issues, including salinity intrusion and sanitation-related contamination, necessitating urgent sustainable management practices.

The Groundwater Symposium was initiated in 2009, and has evolved into a prestigious platform for academicians, researchers, policymakers, and industry experts to discuss and share knowledge on groundwater management. It is dedicated in addressing the critical theme of "Challenges and Opportunities for Sustainable Development and Management of Groundwater." This symposium takes place at a time when the importance of groundwater as a vital resource cannot be overstated. The 12th edition of the symposium extends this discourse to a regional and international scope, reflecting the interconnected nature of groundwater issues.

The Symposium was held at the Hotel Aloft Kathmandu Thamel on March 18, 2024, co-organized by the Center of Research for Environment, Energy and Water (CREEW), The Small Earth Nepal (SEN), and the Kathmandu Valley Water Supply Management Board (KVWSMB). The event featured approximately 150 participants, including 120 in-person and 30 virtual attendees, with 48% female representation. The symposium included sessions on various aspects of groundwater management, with partner sessions focusing on enhancing groundwater governance in Southeast Asia and understanding Nepal's socio-hydrologies of groundwater irrigation. A technical session highlighted innovative approaches to groundwater challenges through science, community engagement, and policy integration. Dr. Kriangsak Pirarai, Director of the Bureau of Groundwater Exploration and Potential Assessment, Department of Groundwater Resources, Thailand, delivered the keynote address, sharing insights from Thailand's journey in groundwater regulation and innovation. His presentation emphasized the importance of proper regulation, conservation measures, and innovative approaches in effective groundwater management.

The first partnership session featured four presentations by esteemed experts in groundwater resource management and governance, providing valuable insights into effective practices and innovative frameworks in Southeast Asia. The second partnership session included eight presentations on the intersection of climate, agriculture, and groundwater resource management, followed by a panel discussion on groundwater issues in Nepal and India. This session also featured a focused panel on "Silent but Long Strides of Groundwater Irrigation in Nepal," where Dr. Dipankar Saha, Dr. Manohara Khadka, and Dr. Maheswor Shrestha shared their experiences and future directions based on their extensive work in the field.

A high-level panel discussion, led by Prof. Dr. Vishnu Prasad Pandey from Tribhuvan University, was a focal point of the event, emphasizing inclusive groundwater development and management in Nepal. Panelists from academia, NGOs, and government bodies discussed strategies to overcome barriers and promote sustainable practices, focusing on inclusivity in the Nepalese context. They highlighted structural and attitudinal challenges, the importance of comprehensive databases, and the role of research. Dr. Manohara Khadka of IWMI Nepal outlined six dimensions of inclusivity: multi-actor involvement, resource accessibility, investments, policy frameworks, knowledge management, and capacity development. Ms. Tripti Rai from Oxfam in Nepal discussed geographical, caste, ethnicity, gender, and disability-related exclusions, stressing the link between resources and power. Prof. Dr. Dinesh Pathak emphasized the need for a single authority to oversee groundwater policy and implementation, while Dr. Dol Prasad Chapagain addressed the interplay between structural and mindset issues. The panel agreed on the necessity of integrating inclusivity from the project's outset, leveraging citizen science, and ensuring community ownership to foster resilient infrastructure and effective groundwater management in Nepal.

The technical session featured five presentations on innovative approaches to groundwater challenges, incorporating scientific, community, and policy perspectives. Topics included a community-centric framework for groundwater governance in Nepal, remote sensing for groundwater monitoring, groundwater-surface water interaction analysis using physio-chemical and stable isotope data, a hydrogeological conceptual model for coastal wetlands, and spring water management in Nepal's mid-hills. Additionally, the session on sustainable water management in Madesh Province included stakeholder mapping for integrated water use in Lahan Municipality. Poster presentations covered groundwater quality in Kathmandu Valley, citizen science-based groundwater level monitoring, global youth engagement in groundwater sciences, and microbiological analysis of Kathmandu Valley River waters.

We hope that the papers presented at the symposium will promote the adoption of sustainable groundwater management practices at local, regional, and national levels. The symposium provided an excellent opportunity for participants to network, share knowledge, and collaborate on future research and development initiatives. We extend our gratitude to all the speakers and participants who made the symposium a success and look forward to continuing this platform in the future. We also hope that future symposiums will build on the achievements of this event, fostering ongoing dialogue and collaboration, and contributing to the sustainable management of groundwater resources for future generations.

Organizers
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KEYNOTE PRESENTATION

Navigating Thailand's Groundwater Challenges: A Journey Through Regulation and Innovation

Navigating Thailand's Groundwater Challenges: A Journey Through Regulation and Innovation

Dr. Kriangsak Pirarai
Director of the Bureau of Groundwater Exploration and Potential Assessment
Department of Groundwater Resources, Thailand

1. Introduction

The evolution of groundwater management in Thailand has been characterized by a journey of innovation and regulation. Early efforts centered on addressing public health concerns through mandatory household septic tanks, inadvertently impacting shallow groundwater quality. The advent of deep groundwater wells from 1907 marked a transition to more structured water supply systems, initially employing bamboo drill rods and later advanced machinery imported from abroad. Collaboration with international experts, particularly from the US Geological Survey in the 1950s, significantly bolstered Thailand's hydrogeological knowledge and infrastructure development. This era witnessed the establishment of the Groundwater Division within the Department of Mineral Resources, later reorganized as the Department of Groundwater Resources in 2002 under the Ministry of Natural Resources and Environment. Legislative milestones such as the 1977 Groundwater Act, universally enforced in 1994, underscore Thailand's commitment to sustainable groundwater management, safeguarding both quantity and quality nationwide.

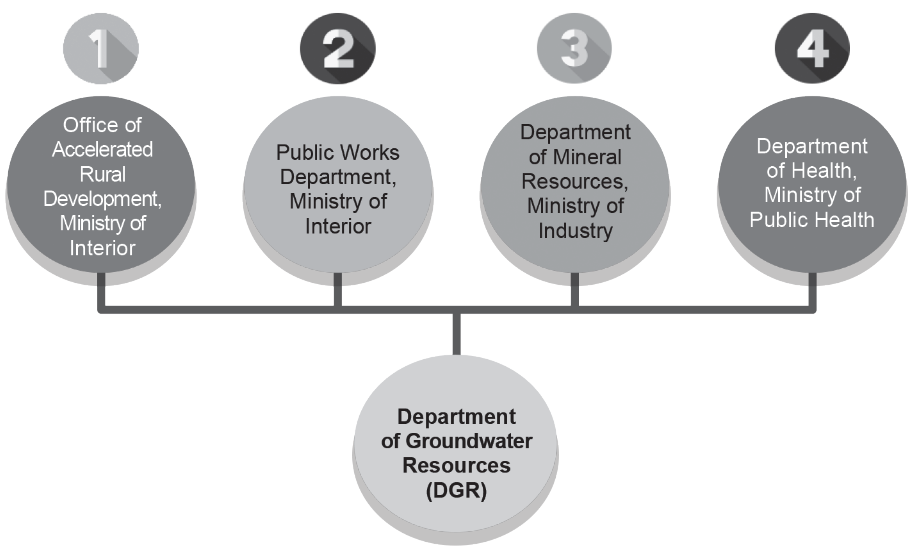

Figure 1: Formation of DGR after Government reform in 2002

The formation of the Department of Groundwater Resources (DGR) through a pivotal 2002 government reform consolidated four disparate organizations into a unified authority, positioning DGR as the central body responsible for Thailand's groundwater resources under the Ministry of Natural Resources and Environment.

2. Groundwater challenges in Thailand

Groundwater challenges in Thailand have historically centered around land subsidence and regulatory frameworks aimed at managing groundwater abstraction. The Groundwater Act of 1977 established the principle that groundwater exploitation is a public concern, necessitating permits for drilling and extraction. This legislation also introduced measures like groundwater tariffs and conservation fees to curb excessive water use and raise awareness about groundwater's environmental significance (Lorphensri et al., 2011). To address issues like land subsidence linked to groundwater depletion, Thailand designated Critical Zones with stringent regulations for both private and public groundwater users. These measures highlight Thailand's proactive stance in balancing water resource management with environmental sustainability.

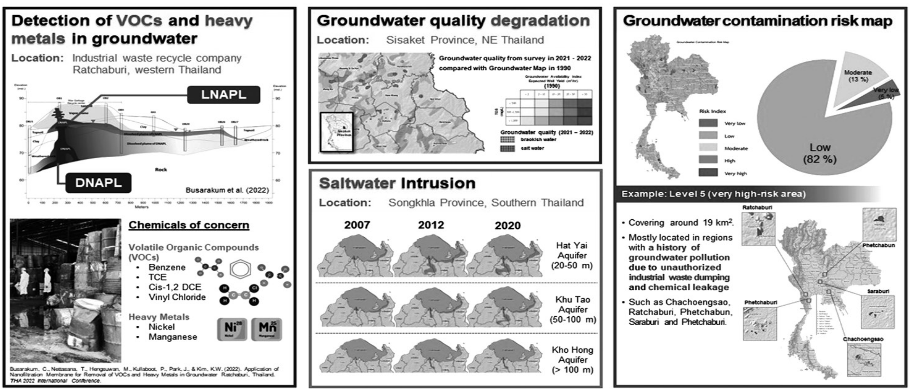

Figure 2: Deterioration of Groundwater Quality

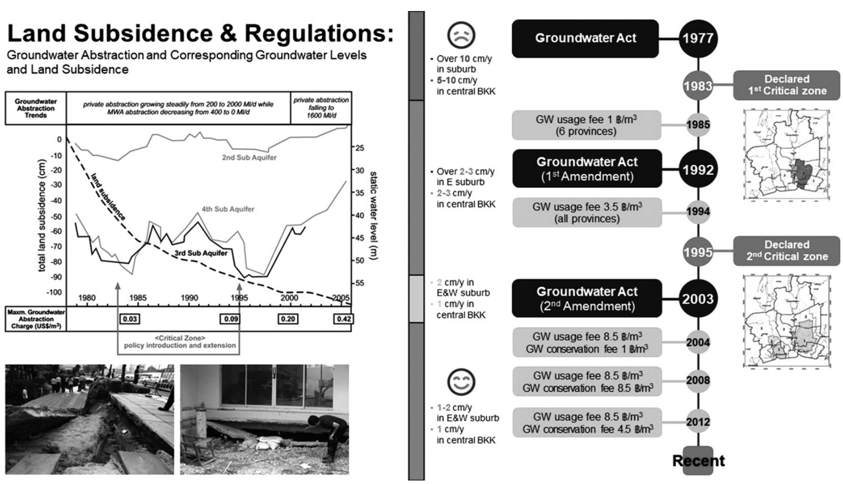

Figure 3: Groundwater Abstraction and Corresponding Groundwater Levels and Land Subsidence

3. Core functions of DGR

The Department of Groundwater Resources (DGR) in Thailand fulfills a pivotal role in managing the nation's groundwater through a series of core functions aimed at conservation, development, and regulatory oversight. Central to their efforts is the meticulous exploration and assessment of groundwater potential using advanced techniques like surface geophysical surveys and borehole logging. These activities are crucial in mapping out groundwater resources across Thailand, ensuring informed decision-making in resource allocation and management. DGR also spearheads groundwater development initiatives, supporting various sectors from agriculture to community water security, particularly in drought-prone or saline-affected areas. Concurrently, the department prioritizes groundwater conservation through rigorous monitoring of water levels and quality, alongside innovative restoration projects such as Managed Aquifer Recharge (MAR). Underpinning these efforts is the Bureau of Groundwater Control, tasked with enforcing national groundwater usage plans and ensuring compliance with the Groundwater Act. This regulatory framework includes collecting tariffs based on usage licenses and managing the Groundwater Development Fund to finance sustainable projects. Through these integrated approaches, DGR strives to balance groundwater exploitation with long-term conservation, safeguarding Thailand's vital water resources for future generations.

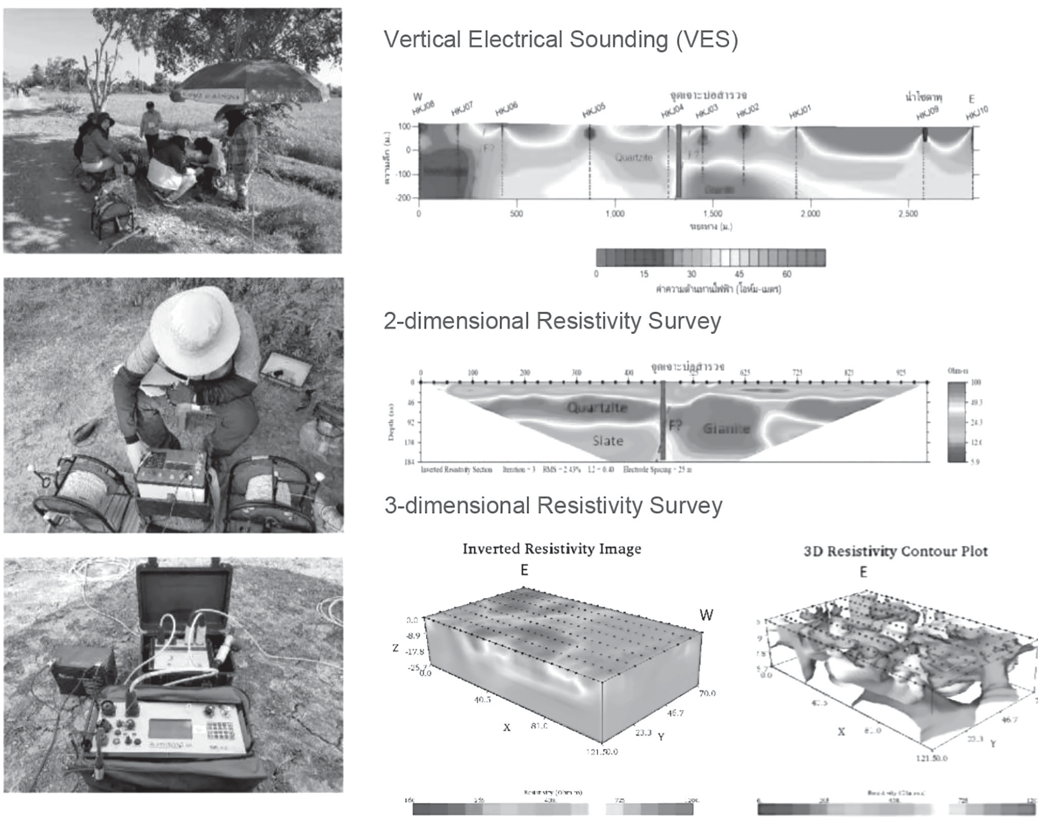

Figure 4: Groundwater exploration by using surface geophysical survey (Electrical resistivity methods)

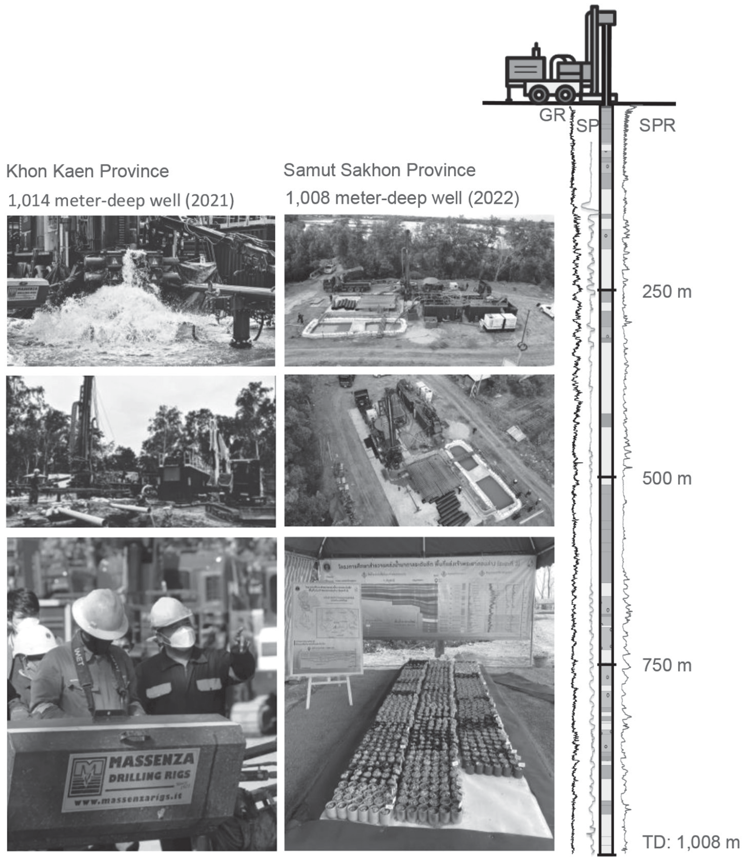

Figure 5: Drilling test and well completion

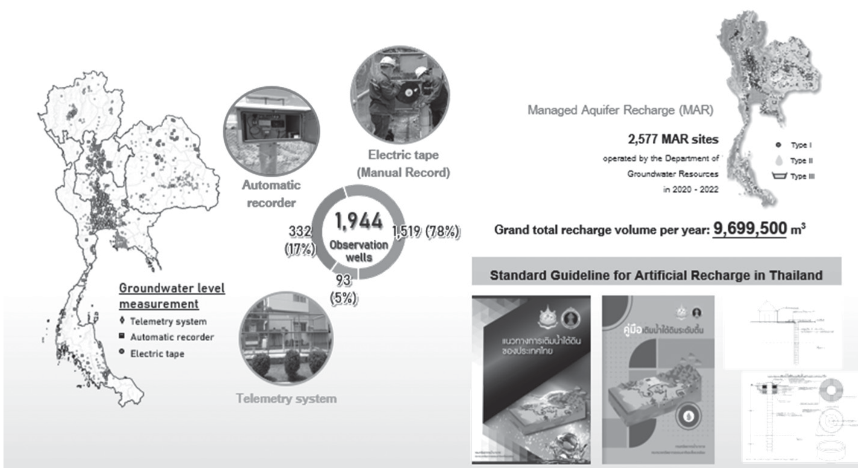

Figure 6: Groundwater Monitoring

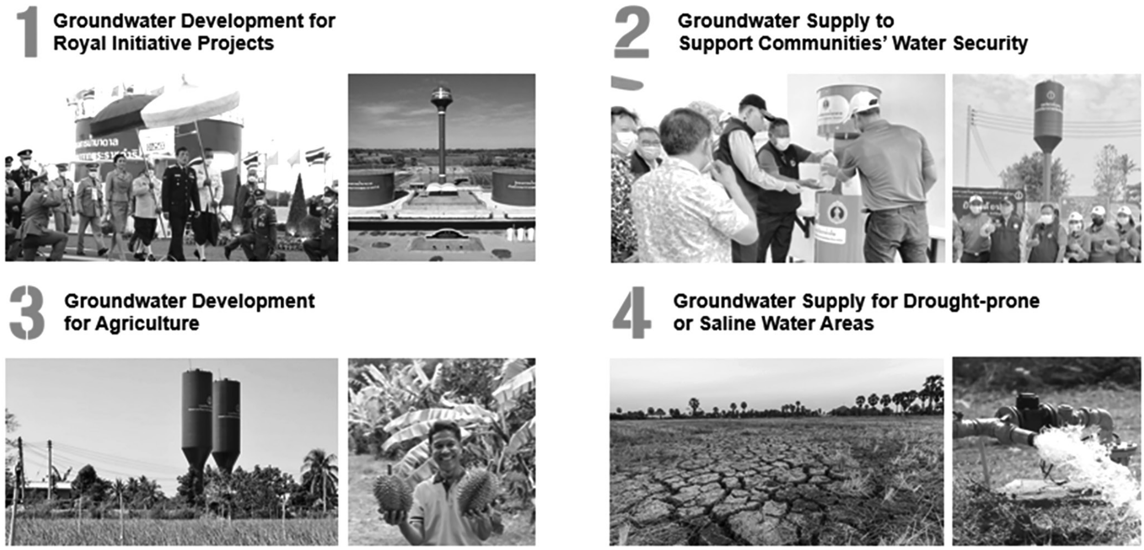

Figure 7: Groundwater Development

4. Conclusion

Thailand's robust approach to groundwater management underscores the critical roles of regulation, conservation, and innovation. Thailand's experience demonstrates the effectiveness of integrating advanced exploration techniques, stringent regulatory frameworks such as the Groundwater Act, and proactive conservation strategies like Managed Aquifer Recharge (MAR) to sustainably manage groundwater resources. These insights offer valuable lessons for Nepal, particularly in enhancing regulatory frameworks, utilizing technology for groundwater assessment, and fostering community involvement in conservation efforts. By adopting a comprehensive approach that harmonizes development with conservation, Nepal can address its own groundwater challenges more effectively, securing water sustainability for its expanding population and diverse ecosystems.

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(This article is based on the keynote presentation/slides by Dr. Kriangsak Pirarai at the Groundwater Symposium 2024)

PARTNER SESSION I

Strengthening Groundwater Governance and Management in Southeast Asia: Insights and Cross Learning for Evidence-based Decision-Making (AIT-SEI)

Mapping Groundwater Resilience to Climate Change and Human Development in Asian Cities

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Abstract

Groundwater resources in major Asian cities, including Bangkok, and Kathmandu Valley are under immense pressure from a variety of stresses, including climate change and human development. Groundwater resources are depleting because of over-extraction, causing social, environmental, and economic problems. Therefore, this study aims to investigate the effect of climate change and human development on groundwater resources and assessing the groundwater resiliency of two Asian cities which can aid in developing strategies for sustainable groundwater management. The methodology incorporates model-based analysis of climate and land use change, groundwater recharge, groundwater level and resiliency. The results suggests that both the Asian cities are expected to be warmer in future and will receive more rainfall under both RCPs. Groundwater recharge is expected to decline in both Asian cities under the high urbanization scenario and both RCPs, whereas it is expected to rise under the low and medium urbanization scenarios and both RCPs scenarios. Similarly, both the Asian cities will encounter maximum reduction in groundwater level under high urbanization scenarios. The outskirts part of both Asian cities is resilient to climate change and human development whereas, the center area or the urban areas are not resilient.

Keywords: *Groundwater resiliency, Climate change, Human development, Asian cities*

1. Introduction

Groundwater makes up 94% of the world's freshwater supplies and is portrayed as the true hidden wealth of the planet (Koundouri and Groom, 2010). The most ideal resource of water supply is groundwater as it is less susceptible to drought and quality deterioration than surface water (Schwartz and Ibaraki, 2011). Major Asian cities' sustainable growth depends heavily on groundwater. Future climate change and human development (population growth and urbanization) are projected to have a greater impact on groundwater availability for the city's water supply. Therefore, it is crucial to evaluate the groundwater's resilience to climate change and human growth to strategically plan and manage the city's water supplies.

The overall objective of the study is to develop groundwater resiliency map under climate change and human development scenarios in Asian cities.

The specific objectives are:

1) To evaluate regional climate model (RCMs) for future climate change projection in Asian cities.
2) To analyze the future climate scenarios and project future land use and land cover in Asian cities.

3) To estimate the spatiotemporal distribution of groundwater recharge under climate change and human development scenarios in Asian cities.

4) To estimate future water demand (agricultural, industrial, and domestic) in Asian cities.

5) To estimate the groundwater level of the aquifers under climate change and human development scenarios in Asian cities.

6) To develop groundwater resiliency indicator under climate change and human development scenarios and to generate groundwater resiliency map in Asian cities.

2. Materials and methods

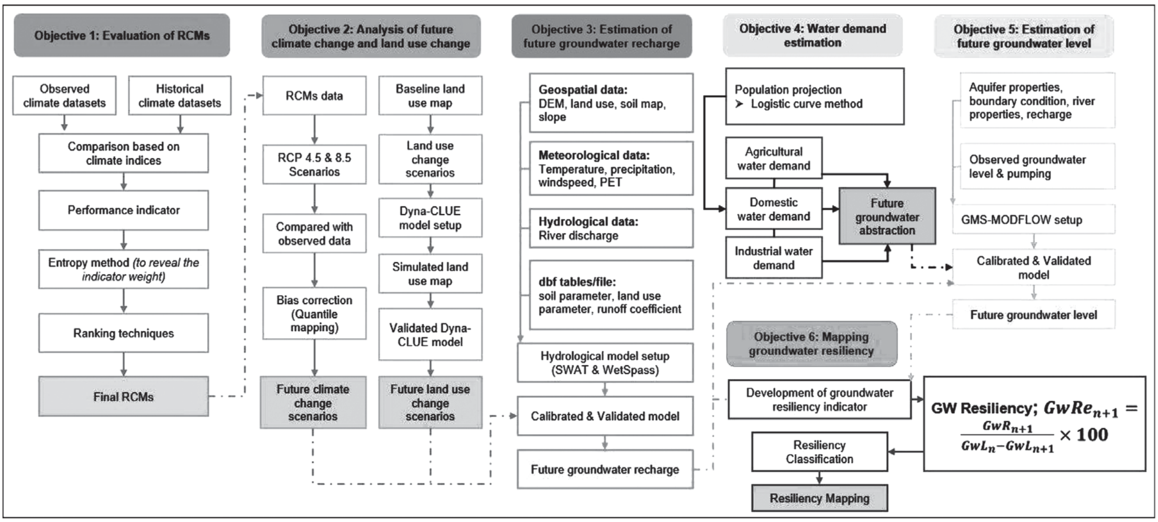

Figure 1: Overall Methodological Framework of the Study

3. Results and discussion

3.1 Evaluation of regional climate models (RCMs)

The evaluation of Regional Climate Models (RCMs) in each city was done based on their ability to replicate the observed climate datasets. This study assesses the capacity of the 21 RCMs from the CORDEX data portal to simulate climate extremes in the rapidly developing Asian cities (Bangkok and its vicinity and Kathmandu valley) which are highly vulnerable to climate change. The RCMs were evaluated to simulate the six climate indices; CDD, SDII, R50mm, RX1day, TX mean and TN mean. The performance indicators employed were CC, NRMSD, ANRMSD and AARD. To reveal the weightage of each performance indicator Entropy method was used and finally to rank the RCMs weightage average techniques were employed. The RCMs: WAS44_SMHI_RCA4_IPSL_CM5A_MR, and WAS44_IITM_REGCM4-4_CSIRO_MK3-6-0 are the top ranked RCMs for Bangkok and its vicinity and Kathmandu respectively.

3.2 Future climate and land-use projection

The future climate of two Asian cities (Bangkok and its vicinity and Kathmandu valley) was projected using the top five better performing RCMs obtained from the evaluation study under intermediate concentration scenario RCP 4.5 and high-end concentration scenario RCP 8.5 for three future period: near future (2010-2039), mid future (2040-2069) and far future (2070-2099) relative to baseline period (1976-2005) using quantile mapping technique.

According to the study's findings, both Asian cities would be warmer in the future under both RCP scenarios. For Bangkok and its vicinity, by the end of the twenty-first century, the average yearly maximum temperature is expected to increase by 0.4 to 1.5 °C in RCP 4.5 and 0.5 to 3.1 °C in the RCP 8.5 scenario. Similarly, the average yearly minimum temperature is forecast to increase by 0.8 to 2 °C in RCP 4.5 and 0.9 to 4.3 °C in RCP 8.5. Likewise for Kathmandu valley, by the end of the twenty-first century, the average yearly maximum temperature is expected to increase by 0.22 to 2.44 °C in RCP 4.5 and 0.60 to 5.38 °C in the RCP 8.5 scenario. Similarly, the average yearly minimum temperature is forecast to increase by 0.48 to 3.52 °C in RCP 4.5 and 0.57 to 5.60 °C in RCP 8.5.

As for rainfall, both the Asian cities are expected to receive more rainfall in future. Maximum increase in future rainfall is higher in Bangkok and its vicinity as compared to Kathmandu valley. The relative increase in future rainfall for Bangkok and its surroundings varies from 6.79% to 56.17% under RCP 4.5 and 11.64% to 80.72% under RCP 8.5. The maximum increase in future rainfall by 49.1% and 75.1% in the far future and RCP 4.5 and RCP 8.5 respectively is expected in Kathmandu valley.

Future land-use change in both the Asian cities was projected using Dyna-CLUE model. Three land use scenarios (high urbanization, medium urbanization, and low urbanization) were developed for Bangkok and its vicinity, Thailand, and Kathmandu valley to analyze its impact on groundwater. For Bangkok and its vicinity, in high urbanization scenario, agricultural land decreases from 69% of total land area to 33% from 2015 to 2099. Whereas built-up area increases from 15% to 52% of total land area. For medium urbanization scenario, built up area increases from 15% of total land area to 25% from 2015 to 2099 and in low urbanization scenario, forest area increases from 7% to 25% of total land area from 2015 to 2099 whereas, built up area is constant in all the future period. Likewise for Kathmandu valley, in high urbanization scenario, agricultural land decreases from 10% of total land area to 2% from 2015 to 2099. Whereas built-up area increases from 21% to 51% of total land area. For medium urbanization scenario, built up area increases from 21% of total land area to 25% from 2015 to 2099 and in low urbanization scenario, forest area increases from 62% to 75% of total land area from 2015 to 2099 whereas, built up area is constant in all the future period.

3.3 Estimation of future groundwater recharge and groundwater level

For both the Asian cities, the groundwater recharge for the baseline period 2001-2005 (Bangkok and its vicinity) and 1979-2005 (Kathmandu valley) and three future time periods: near future (NF) (2010-2039), mid future (MF) (2040-2069) and far future (FF) (2070-2099) were estimated annually as well as seasonally (wet season May-October and dry season November-April). In the high and medium urbanization scenarios, groundwater recharge is predicted to decrease, whereas it will rise in the low urbanization scenario in both RCP scenarios. The increase in future groundwater recharge is expected to be higher in the dry season. The decline in future groundwater recharge is expected to be significant in the wet season.

The impact of climate change and human development (land-use change, population growth and groundwater abstraction change) on groundwater level in both the Asian cities was investigated using a groundwater model called GMS-MODFLOW. Three groundwater abstraction scenarios (same as land-use change scenarios): high urbanization, medium urbanization, and low urbanization were developed for both the Asian cities to analyze its impact on groundwater level.

For Bangkok and its vicinity, the result suggests that for high urbanization scenario, groundwater abstraction increases from 551.2 MCM/yr in 2009 to 753.3 MCM/yr in 2095 which is pessimistic scenario. For medium urbanization scenario, the groundwater abstraction decreases from 551.2 MCM/yr in 2009 to 319.1 MCM/yr in 2095, which is same as the business as-usual rate and similarly for low urbanization it decreases to 200.3 MCM/yr in 2095 which resembles the safe-yield pumping rate as described by Department of Groundwater Resources (DGR), Thailand. For Kathmandu valley, the result suggests that for high urbanization scenario, groundwater abstraction increases from 22.91 MCM/yr in 2001 to 223.9 MCM/yr in 2095, which is pessimistic scenario. For medium urbanization scenario, the groundwater abstraction increases from 22.91 MCM/yr in 2001 to 112.9 MCM/yr in 2095, which is same as the business as-usual rate and similarly for low urbanization it decreases to 56.2 MCM/yr in 2095 which resembles the optimistic scenario.

The impact of climate change and land use change on groundwater level was projected for four future periods: 2035, 2055, 2075 and 2095 under two RCPs scenario (RCP 4.5 and RCP 8.5) and three land-use change scenarios (high, medium, and low urbanization) after comparison with baseline (2001). Three abstraction scenarios (like land-use scenarios) were also analyzed to calculate future groundwater abstraction and subsequently used to calculate future groundwater level in all the aquifer layers. For Bangkok and its vicinity, the result reveals that average groundwater level is projected to decrease under high urbanization scenarios and all RCPs scenarios. Whereas, for medium and low urbanization scenario and both RCPs scenarios it is projected to increase in future. For Kathmandu valley, on average, the groundwater level will decrease in future for all three pumping scenarios: high, medium, and low urbanization and both RCPs scenarios. The average decrease in groundwater level was higher for high urbanization than medium and low urbanization scenario.

3.4 Groundwater resiliency

Groundwater resiliency map of the Asian cities was developed using the result of groundwater recharge from hydrological model and groundwater level from the groundwater model. In this study groundwater resiliency is defined as the percentage recovery over total depletion.

The groundwater resiliency map of both Asian cities was developed for four time periods (2035, 2055, 2075 and 2095) under RCP 4.5 and RCP 8.5 scenario and three land use and pumping scenarios (low, medium, and high urbanization scenario). For Bangkok and its vicinity, the results show a projected increase in percentage of area under “very highly resilient class”, for medium and low urbanization scenarios and for high urbanization scenario, there is projected decrease in percentage of area under “very highly resilience class" while the area under "not resilient class" is increasing and this is valid for all climate change scenario and all three aquifer layers. For Kathmandu valley, results show a projected decrease in the percentage of area under "very highly resilient" class and a projected increase in the "not resilient" class, towards the future periods. The decrease in the area classified as "very highly resilient" and an increase in the area under "not resilient" was significant and higher for high urbanization than medium and low urbanization.

4. Conclusion

Groundwater resources play a very crucial role in sustainable development of main Asian cities. The over extraction of groundwater caused by rapid growth in population, rapid expansion in urban land, economic development, tourism development alongside with climate change may lead to extensive reduction of groundwater level causing social, environmental, and economic problems. Therefore, this study objects to examine the resilience of groundwater system to climate change and anthropogenic development in Asian cities: Bangkok and its vicinity, and Kathmandu Valley, Nepal, which eventually helps in the management and protection of groundwater resources as well as to develop strategies for sustainable use. A unified methodology was used to conduct the study. According to the findings and variance in climate change and human development, it is possible to conclude that groundwater supplies in both Asian cities are threatened by climate change and human growth. As a result, appropriate groundwater monitoring and adaptive development are vital for the sustainable management of groundwater resources in Asian cities.

Assessing Groundwater Infrastructure Sustainability in the Special Economic Zone (SEZ) of Thailand: A Case of Tak SEZ

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Abstract

Groundwater serves a vital role in ensuring water security but faces increasing strain due to factors like urbanization, population growth and climate change. Meanwhile, governmental initiatives such as Special Economic Zones (SEZs) aim to foster economic growth but are likely to limit equal access, potentially sparking conflicts within sectors. This imbalance in groundwater uses and management within SEZs could lead to disputes affecting vulnerable communities. This study assesses groundwater sustainability at the SEZs of Thailand using the Groundwater Sustainability Infrastructure Index (GSII) framework. The GSII comprises four dimensions: Groundwater Sustainability Indicators (GSI), Social Sustainability Indicators (SSI), Economic Sustainability Indicators (ESI), and Institutional Sustainability Indicators (ISI), along with 17 indicators that identify gaps in current groundwater governance and policies in SEZs and transboundary aquifers. The GSII is scored on a range from 0 to 1, where 0 represents a very poor state and 1 represents an excellent state. The study found that the GSII value of Tak SEZ is 0.48, which is in an acceptable state. However, the scores of some indicators related to groundwater monitoring reflect a poor state of sustainability. Therefore, the analysis of GSII highlights areas for improvement in groundwater monitoring, and information dissemination, guiding appropriate policymaking for sustainable groundwater management.

Keywords: *Tak SEZ, Groundwater, Governance, Sustainability, Transboundary*

1. Introduction

Groundwater is the world's largest freshwater resource. It is reliable during the dry season where there is less surface water available, and less treatment is required. Groundwater accounts for around 33% of the freshwater consumed by humans on average, but in some parts of the world, this figure can reach 100% (USGS, 2020). Nonetheless, many studies show that groundwater resources are under stress from climate change, rapid economic development, land use and land cover change, as well as population growth. Consequently, groundwater resources are becoming degraded over time, affecting their quality, quantity, or both (Hossieeini et al., 2019)

Groundwater plays a crucial role in water security and has been stressed due to unprecedented population growth, rapid urbanization, changes in lifestyle, land use and climate change. Meanwhile, government initiatives like Special Economic Zones (SEZs) are expected to foster economic growth but are likely to limit equal access to water leading to sectoral conflicts. Furthermore, the transboundary nature of groundwater, its partial knowledge and absence of proper bi-lateral frameworks, plans, and governance mechanisms have emerged as an immediate threat to water supplies and competition over limited resources heightening the tension between neighboring countries. Thus, the imbalance uses and ineffective groundwater management for development in SEZs are likely to bring sectoral scuffles and conflicts with vulnerable and marginalized people.

The project "Assessment of Groundwater Sustainability in the Special Economic Zone of Thailand for Operational Groundwater Management," also known as Groundwater Infrastructure Sustainability Assessment (GISA), is supported by Stockholm Environment Institute (SEI) under the program SUMERNET 4 All. The project's major objective is to assess groundwater sustainability at the SEZ of Thailand and recommend strategies to enhance the guidelines and policies for improved operational groundwater management in SEZs. The joint-action project with the Department of Groundwater Resources, Ministry of Natural Resources and Environment (MoNRE), Thailand shall apply the Groundwater Sustainability Infrastructure Index (GSII) developed under "Enhancing the Groundwater Management Capacity in Asian Cities through the Development and Application of Groundwater Sustainability Index in the Context of Global Change" (APN-2013-2015). The GSII provides an assessment of the groundwater sustainability infrastructures (economics, social, institutional, environmental, and mutual social trust) identify gaps of current groundwater governance and policies in SEZs and transboundary aquifers. The two-year joint-action project selects Tak SEZ (Tak Province), Thailand, to assess the groundwater sustainability in SEZs with the proven GSII. This project aims to identify and replicate suitable guidelines and policies in other emerging SEZs under multiple stresses and social dimensions. Furthermore, the application of GSII in the SEZ gives a clear idea of current groundwater sustainability with gaps and a way forward to fill those gaps.

2. Materials and methods

2.1 Study area

The study area of this study is Tak Special Economic in Tak province, the west of Thailand which consists of 14 sub-districts along the border of Thailand-Myanmar in Maesot, Phop Phra, and Mae Ramat districts which contain eight sub-districts (Maesot, Mae Tao, Tha Sai Luat, Phra That Pha Daeng, Mae Kasa, Mae Pa, Mae Ku, Mahawan) of Maesot District, three sub-districts (Phop Phra, Chong Khaep, Wale) of Phop Phra District and three sub-districts (Mae Charao, Mae Ramat, Khane Chue) of Mae Ramat. It is situated on the Salawin river basin and Tak aquifer which is also part of trans-boundary river and aquifer basin name of the same name as Salween as seen in figure 3The topography of the Tak SEZ is mostly mountainous, except for only a small area on the west side plain. The climate statistics are calculated from the daily rainfall data of TMD for the period 1981–2019. The wet season starts from May to October with peak rainfall of around 350 mm in July, while the dry season starts from November to April.

2.2 Methodology

The study develops inclusive framework for evaluating and quantifying groundwater sustainability in special economic zone area of Thailand using an indicator-based approach. The Groundwater Sustainability Infrastructure Index (GSII) is developed under "Enhancing the Groundwater Management Capacity in Asian Cities through the Development and

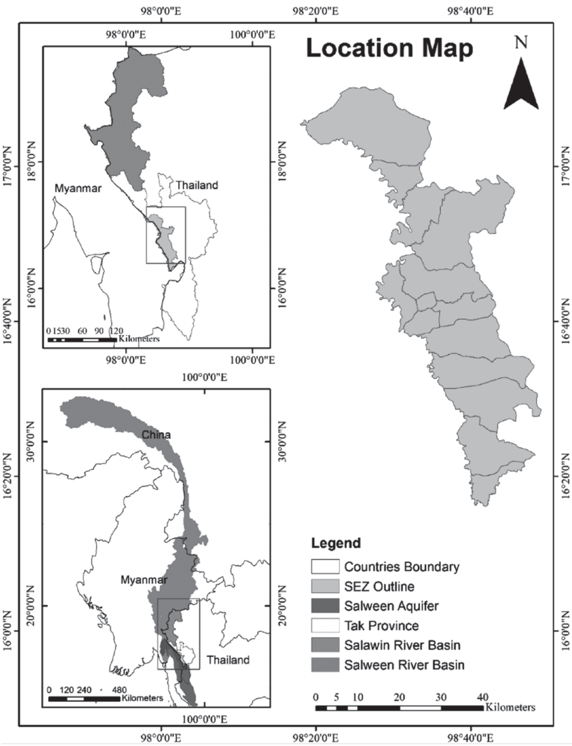

Figure 1: Location Map of Tak Special Economic Zone

Application of Groundwater Sustainability Index in the Context of Global Change" (APN- 2013-2015). The GSII provides an assessment of the groundwater sustainability infrastructures (economics, social, institutional, environmental, and mutual social trust) identify gaps of current groundwater governance and policies in SEZs and transboundary aquifers.

The selection of dimensions and 17 indicators has been done based on the GSII framework developed for the Kathmandu valley (Pandey et al., 2011). The dimensions and indicators are chosen in such a way that they can reflect most of the general situation of groundwater components in any special economic zone (SEZ) of Thailand. The mathematical equation for aggregating these framework elements provides a holistic index value known as Groundwater Sustainability Infrastructure Index (GSII) which provides a general overview of the current state of groundwater sustainability and a detail diagnosis of strength, gaps, and areas of improvements for sustainable groundwater management to the decision makers, managers, and related actors.

The groundwater sustainability framework consists of four dimensions i.e. groundwater sustainability, social sustainability, economic sustainability, and institutional sustainability. There are 17 indicators within these dimensions which are rated on range of 0-1, where 0 is very poor state and 1 represents excellent state of the measured indicators (Table 1). The indicators chosen are qualitative, however the rating of each variable within an indicator is quantitative based on a dimensionless rating. Furthermore, after aggregation of all the elements, the final index value range is assigned.

Table 1: Groundwater sustainability framework indicators rating scale

Class	Score
Very poor	0.00
Poor	0.25
Acceptable	0.50
Good	0.75
Excellent	1.00

3. Results and discussion

3.1 Contextualized GSII framework

The GSII Framework is contextualized within four dimensions and 17 indicators which reflects the current scenario of groundwater management in Tak SEZ. The dimensions of Groundwater Sustainability Indicators (GSI) highlight the significance of groundwater resource availability and the necessity of monitoring its quality and quantity, along with factors such as monitoring well density and fundamental hydrogeological data. Social Sustainability Indicators (SSI) dimensions emphasize the impact of social factors on the sustainable management of groundwater, including community attitudes towards monitoring, groundwater pricing, regulatory measures, and their involvement in policy formulation. Economic Sustainability Indicators (ESI) highlight the importance of industrial water efficiency in the sustainable management of groundwater, particularly in specialized economic zones. Institutional Sustainability Indicators (ISI) highlights the significance of a regulatory framework, coordination across sectors, and gender-inclusive roles in policy development to achieve sustainable groundwater management (Table 2).

Table 2: Elements of Groundwater sustainability framework with description of the framework indicators

Dimension		Indicators	Description
Groundwater Sustainability Indicators (GSI)	GSI1	Renewable groundwater resources per capita	Annual amount of renewable groundwater resources (m3 per year) per capita, people using groundwater. (def renewable)
	GSI2	Ratio of total groundwater abstraction/ Groundwater recharge	The ratio of total withdrawal or use of groundwater from a given aquifer over the total yearly addition of water to the aquifer.
	GSI3	Groundwater Quality	The overall water quality status.
	GSI4	Basic hydrogeological information	Availability of information on hydrogeological maps, aquifer type, aquifer properties e.g. water level, water quality, hydraulic conductivity, porosity, storage coefficient, groundwater storage volume, specific yield, specific retention, specific capacity. important variable
	GSI5	Density of monitoring well	Groundwater monitoring ability to measure groundwater levels and fluctuations due to different pressure sources in the aquifer.
Social Sustainability Indicators (SSI)	SSI1	Minimum water satisfactory	Ratio of residents who can use at least the unit water demand of the minimum required L/capita/day to the total population of the study area.
	SSI2	Groundwater contamination	The ratio of residents who have risk of consuming the groundwater nitrogen contamination to the total population.
	SSI3	Knowledge management	Disseminations of the information regarding groundwater tariff and rates
	SSI4	Recognition of 'stakeholder's participation' in policy/law	Level of involvement of different stakeholder in groundwater policy/ law.
	SSI5	Gender inclusiveness	Provision of gender inclusiveness in groundwater development and management.

Dimension		Indicators	Description
Economic Sustainability Indicators (ESI)	ESI1	Industrial Water Productivity	The total revenue of the industrial sector over the total industrial abstraction.
	ESI2	Percentage of people who could own a production well with a license	The ratio of the ppl who could afford to own a production well with a license from the total population.
Institutional Sustainability Indicators	ISI1	Regulatory and Institutional Framework	
	ISI2	Provision and Availability	Availability of human resources, information, and education.
	ISI3	Cross-sector coordination	Provision for coordination between different sector (domestic, agriculture, industrial and governmental agencies) involving groundwater usage and management.
	ISI4	Community Aquifer Management Organization	Provision of groundwater rights at local level to water use.
	ISI5	Levees on Polluters	The existence of policy and mechanism to punish polluters
	ISI6	Gender Responsible policies and agencies	The existence of gender responsible policies

3.2 Groundwater sustainability infrastructure index

The groundwater sustainability infrastructure index (GSII) is analyzed based upon four dimensions i.e. groundwater sustainability, social sustainability, economic sustainability, and institutional sustainability. and 17 indicators. The indicators aggregated and analyzed on scale from 0 to 1, representing the poor state to excellent state of sustainability.

The overall assessment of GSII reveals that groundwater sustainability in Tak SEZ is moderately satisfactory, with a score of 0.48. However, evaluation of individual dimensions shows that the social, groundwater, and institutional aspects are generally acceptable or good, whereas the economic dimension score is poor. This highlights the necessity for collaborative action from policymakers, local governance bodies, and communities to strengthen groundwater sustainability and management. It is imperative to prioritize addressing economic indicators, particularly the issue of high tariff fees affecting businesses reliant on groundwater extraction. Furthermore, there is a crucial need to enhance the dissemination of information and knowledge management among residents concerning groundwater sustainability and management practices.

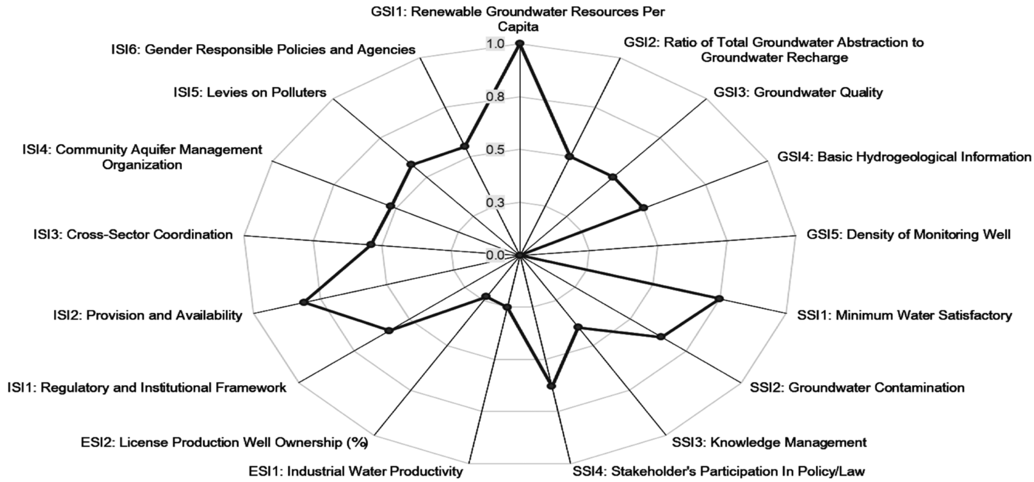

Figure 2: Spider Plot for GSI

4. Conclusion

This research study contextualizes the groundwater sustainability framework by examining the impact of multiple groundwater resources in Tak SEZ, studying the current institutional situation of Tak SEZ for groundwater management, identifying the current situation of groundwater and its management through community surveys, and finally calculating the GSII based on groundwater, social, economic, and institutional sustainability. The findings reveal that the GSII for Tak SEZ scores at 0.48, indicating an acceptable state. However, challenges such as inadequate knowledge management, information dissemination, and data monitoring at the local level hinder sustainable groundwater management. There's a pressing need for extensive awareness initiatives among locals regarding groundwater tariffs, licensing, and permits. The institutional framework for groundwater management comprises formal laws, informal norms, and organizational structures crucial for effective governance. The government bodies, local and regional governments play a pivotal role, spanning from national to local levels, ensuring regulatory adherence and efficient resource management.

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Outlook of Groundwater Governance in the Lower Mekong Region

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Abstract

Groundwater resources are essential for millions globally, particularly in regions like the Lower Mekong Region (LMR), where reliance on groundwater is significant amidst increasing anthropogenic pressures and environmental changes. Effective groundwater governance ensures the region's water security and sustainable development. This study develops a pragmatic framework to assess groundwater governance in four rapidly urbanizing LMR cities: Vientiane, Khon Kaen, Siem Reap, and Can Tho of Lao PDR, Thailand, Cambodia and Vietnam, respectively. The framework comprises thirty benchmarking indicators across four dimensions, rated (0: Non-Existent; 1: Incipient; 2: Acceptable; 3: Optimum) based on the adequacy of provisions and institutional capacity. The rated two variables are aggregated using several equations to obtain the current state of groundwater governance from non-existent to the optimum level, named the Groundwater Governance Index (GGI). Results reveal varying states of groundwater governance, with GGI values of 0.90, 1.16, 0.78, and 1.23 for Vientiane, Khon Kaen, Siem Reap, and Can Tho, respectively. Lao PDR and Cambodia exhibit early-stage governance provisions, while the other countries show acceptable states. However, all four urban centres lack the provisions and capacities for inclusive groundwater governance and management. The outlook provides an opportunity for improved collaboration among stakeholders, including governments, communities, and international organizations, to enhance sustainable groundwater management. This study underscores the urgency of effective governance frameworks to address critical groundwater issues in the LMR.

Keywords: *Water security, Groundwater management, Sustainability, Rapid urbanization, Inclusive governance*

A Generic Framework for Assessing the State of Transboundary Groundwater Governance in Internationally Shared Aquifer Systems

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Abstract

Despite constituting only 30% of global freshwater, groundwater fulfills significant domestic, agricultural, and industrial demands worldwide. However, rapid urbanization, climate change, and mismanagement have heavily stressed global groundwater resources. Many transboundary aquifer systems globally are under substantial threat, mainly due to inadequate governance mechanisms rather than physical constraints. Since managing anything that cannot be measured is arduous, the assessment of the current state of groundwater governance is vital. This research has developed a comprehensive framework for quantitatively assessing the state of groundwater governance at the transboundary aquifer level.

Recognizing the absence of a ready-to-use tool, this research aims to fill the gap in existing qualitative frameworks to facilitate effective governance strategies for transboundary groundwater resources. This comprehensive framework has a four- layered structure comprising four dimensions, twenty-seven benchmarking indicators, two variables, and two sub-variables. The sub-variables, when rated on the formulated scale and aggregated into variables, indicators, and dimensions, culminate into the Transboundary Groundwater Governance Index (TGGI). The TGGI, measured on a scale of 0 to 3, is interpreted into different states of transboundary groundwater governance. This robust framework can help assess the state of associated actors, information availability, and the policy, legal, and regulatory frameworks, contributing to the sustainable utilization of groundwater and enhancing resilience and water security.

Keywords: *Groundwater governance, Transboundary aquifers, Assessment framework, Sustainability, Water Security*

1. Introduction

Groundwater, a critical component of the global water cycle, serves as a vital resource for a wide range of human activities and ecosystem functions. Groundwater constitutes approximately 30% of the global freshwater volume, while glaciers and ice caps comprise around 69%, and surface water constitutes merely 1% of the total freshwater resources (Shiklomanov, 1993). It also accounts for a substantial portion of the global freshwater needs, meeting approximately 36%, 42%, and 27% of the respective demands for the domestic, agricultural, and industrial sectors (Döll et al., 2012). However, groundwater resources are highly stressed owing to rapid population growth, urbanization, climate change, industrialization, and commercialization (Hutchins et al., 2018; Vörösmarty et al., 2010; Wen et al., 2017). The impact of these anthropogenic and natural stressors, along with overexploitation and mismanagement, has exacerbated the impact on the quality, quantity, and distribution of groundwater. Given the substantial reliance and heightened vulnerability, there is an increased imperative for sustainable management and effective governance of these resources (Closas & Villholth, 2020).

Many aquifer systems globally are under substantial threat mainly due to inadequate governance and management (Wijnen et al., 2012). Usually, sustainable groundwater utilization is not primarily impeded by physical constraints. Instead, it is ineffective groundwater governance systems that tend to impact the sustainability of this resource (Mukherji & Shah, 2005). Groundwater governance, often interchangeably used with groundwater management, is the comprehensive system of rules, regulations, and customs related to using groundwater that shapes how we manage groundwater and utilize underground aquifers (Megdal et al., 2015). Governing groundwater is often complex, firstly because it is an invisible resource unlike surface water, and secondly because it is associated with a diverse range of stakeholders and decision-makers, with conflicting objectives. Consequently, governance of such a resource is also associated with various uncertainties due to limited data and information, complexities in policies and regulatory structures, varying roles and duties of different stakeholders, and associated jurisdictions (Mukherji & Shah, 2005). The management of transboundary aquifer systems, which extend across two or more independent nations, is notably intricate.

Considering the importance of internationally shared aquifer systems and the stresses associated with them, it is essential to assess the state of their groundwater governance. State assessment based on the actors associated, policies, legal and regulatory frameworks, and the state of information and knowledge can pave the path for sustainable utilization of this priceless resource. In hindsight, this contributes to the resilience and water security of the region in the face of future challenges.

While there are several frameworks designed to assess the governance of water resource systems conceptually or qualitatively, there exists no assessment framework that quantitatively evaluates the state of groundwater governance at the transboundary aquifer level. The major objective of this study is to develop a generic transboundary groundwater governance framework that can be deployed to quantitatively assess the state of groundwater governance in any transboundary setting. The framework can be a robust assessment tool that can address existing challenges and assist stakeholders in comprehending the intricacies of governance, pinpointing potential conflicts arising from legal and institutional policies, cross-sectoral coordination, and information gaps.

2. Materials and methods

The generic, indicator-based framework that can evaluate the state of transboundary groundwater governance through an index, namely the Transboundary Groundwater Governance Index (TGGI), will be formulated based on the methodological framework as shown in Fig 1.

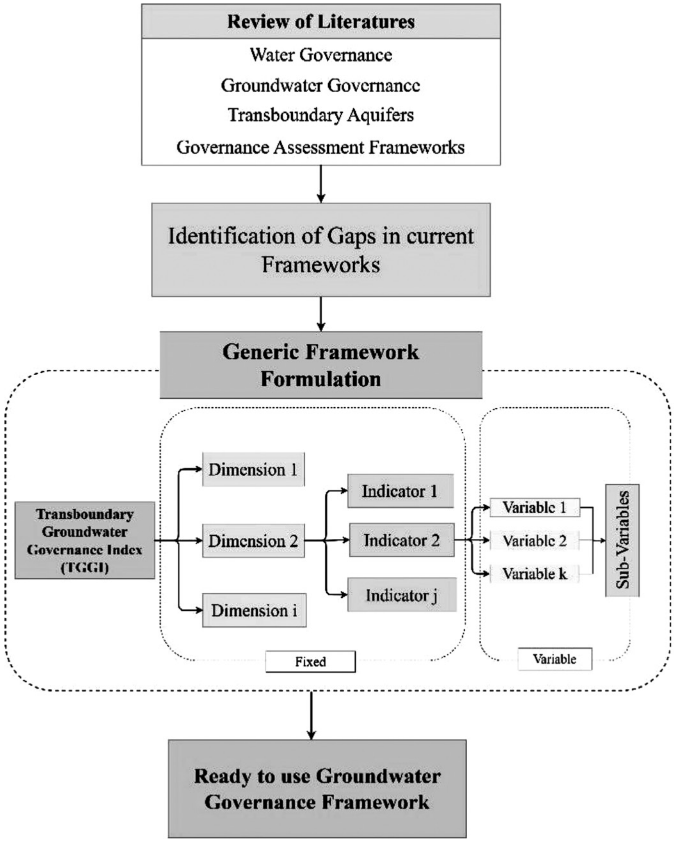

Figure 1: Methodological framework of TGGI framework

2.1 Choice of framework components

The generic framework would consist of four major components: namely Dimensions, Indicators, Variables, and Sub-Variables (Context of Application). Since quantifying groundwater governance is challenging, the dimensions, indicators, and variables need to be carefully selected. The selection of these components is primarily based on the available literature on groundwater governance. Reference to relevant frameworks, concepts, and theories has been made to finalize the choice of components. Additionally, the inadequacy of prevailing frameworks and concepts in addressing aspects such as stressors of groundwater resources and inclusiveness, among others, has been considered while selecting the framework constituents.

2.2 Rating of the framework variables

As the selected sub-variables will quantify the various indicators and, consequently, their dimensions, they will be assigned numeric values to calculate the final TGGI. The sub-variables will be given a dimensionless rating. These ratings will be assigned on a fixed scale, eliminating the need for normalization, which can be determined based on the chosen rating model.

2.3 Aggregation of variables, indicators, and dimensions

To obtain a final TGGI, the quantified sub-variables, variables, then the indicators, and finally, the governance dimensions need to be aggregated. Two types of aggregation models will be applied to the various components of the framework.

If, D = Dimension of the framework; i = Total number of dimensions; j = Total number of indicators within each dimension; k = Total number of variables within each indicator

The sub-variables, variables, and indicators will be aggregated by assigning an equal weightage or priority to each component. However, the dimensions would be aggregated based on the following model to obtain the Transboundary Groundwater Governance Index (TGGI), as shown in Equation 1.

$$\mathrm{TGGI} = \sum_{i=1}^{n} W_i * D_i$$

Where, n = Total number of dimensions; TGGI = Transboundary Groundwater Governance Index; Wi = Weightage of the ith dimension

Following the aggregation of the variable, a dimensionless value of the TGGI will be obtained. The framework suggests a certain threshold to interpret the index computed. The threshold has been ranged on different scales, which translates to a certain state of governance, with a description provided.

2.4 Weightages

To aggregate the dimensions, specific weights must be assigned to each of them. In this study, the Analytic Hierarchy Process (AHP) will be employed. Developed by Saaty (1990), AHP is a tool that aids in determining the relative weightage of individual alternatives through pairwise comparison. AHP can facilitate the translation of individual preferences into a ratio-scaled weight, which, when combined, provides linear additive weights for the alternatives.

3. Results and discussion

3.1 Elements of the groundwater governance framework

The framework illustrated in Table 1 comprises four major components, namely: Dimensions, Indicators, Variables, and Sub-Variables (Context of Application). The dimensional component of the framework pertains to the overarching categories used to assess the state of transboundary groundwater governance. Similarly, the indicators are specific, measurable components within each dimension that provide more granular criteria for assessing the dimension. A single dimension contains numerous non-overlapping indicators for detailed evaluation. Moreover, variables are quantifiable parameters that help measure the dimensions and their respective indicators. The performance of each indicator can be evaluated through a set of precise common variables. To contextualize the fragmented nature of groundwater governance and management efforts, the variables will be quantified at both the national and transboundary (interstate) levels, also referred to as sub-variable classes.

The Transboundary Groundwater Governance Index (TGGI) quantifies the current state of groundwater governance in transboundary aquifer systems, based on a formulated framework with four dimensions:

I. *Technical:* This dimension evaluates scientific and technical aspects, assessing indicators related to groundwater data collection, modeling, and monitoring.

II. Legal and Financial: This dimension evaluates legal and financial frameworks for transboundary groundwater governance, including policies, preventive measures, economic incentives, gender-responsive provisions, legal agreements, and dispute resolution mechanisms for equitable and sustainable aquifer management.

III. Institutional: This dimension assesses institutional structures responsible for transboundary groundwater governance, including groundwater monitoring and regulatory institutions, provisions for community-based management, and formal institutions for transboundary cooperation and financing.

IV. Operational: This dimension emphasizes the practical implementation of policies, focusing on transparency and collaboration.

Table 1: Transboundary groundwater governance Framework

Dimensions	S.N.	Code	Indicators	Variables			
				AoP		IC	
				NC	TBC	NC	TBC
Technical	1	T1	Existence of basic transboundary hydrogeological information (data, maps, reports)				
	2	T2	Existence of groundwater level monitoring network and data				
	3	T3	Existence of groundwater quality monitoring network and data				
	4	T4	Regional numerical groundwater flow models				
	5	T5	Provisions for information and knowledge dissemination on transboundary groundwater aquifer systems				
	6	T6	Presence of publications (guide) addressing Gender and Vulnerable & Marginalized (V&M) groups				
Legal and Financial	7	LF1	Existence of integrated groundwater policies and laws considering various stressors of groundwater resources				
	8	LF2	Prevention mechanisms on illegal water well construction and operation				
	9	LF3	Land-use control mechanisms on potential groundwater recharging areas				
	10	LF4	Prevention mechanisms on groundwater polluting activities				
	11	LF5	Provisions of economic instruments and incentives to promote groundwater management				
	12	LF6	Existence of dedicated fiscal mechanisms to support groundwater management				
	13	LF7	Existence of policies on conjunctive use and management of groundwater and surface water resources				
	14	LF8	Existence of Gender Equality, Disability, and Social Inclusion (GEDSI) responsive groundwater policies and legal provisions				

Dimensions	S.N.	Code	Indicators	Variables			
				AoP		IC	
				NC	TBC	NC	TBC
Legal and Financial	15	LF9	Existence of Memorandum of Understandings (MOUs) or legal agreements on the transboundary aquifer system				
	16	LF10	Existence of coordinated cross-sectoral groundwater policies (environmental, energy, agriculture, industry, health, tourism, and spatial planning and land use)				
	17	LF11	Existence of transboundary water dispute or conflict resolution mechanism				
	18	LF12	Provisions for equitable groundwater extraction based on land area and population				
Institutional	19	I1	Existence of groundwater investigation and monitoring institutions				
	20	I2	Existence of groundwater regulatory and management institutions				
	21	I3	Provisions for formal or informal community-based inclusive groundwater utilization and management entities				
	22	I4	Presence of formal transboundary groundwater cooperation and coordination institution				
	23	I5	Presence of transboundary groundwater financing institutions				
Operational	24	O1	Transparency in groundwater services for all consumers				
	25	O2	Existence of groundwater-management action plan				
	26	O3	Notification mechanism for transboundary impacts				
	27	O4	Arrangements for collaborative governance dynamics between the resource-sharing transboundary states				

Note: Variables: AoP – Adequacy of Provisions; IC Institutional Capacity to implement the provisions Sub-Variables (Context of Application): NC – National Context; TBC – Transboundary Context

The sub-variables will be rated on a scale of 0 to 3, as illustrated in Figure 2. A rating of 0 signifies a 'non-existent' state, while the highest rating of 3 indicates the 'optimal state' of provisions and institutional capacity related to transboundary groundwater governance.

Rating	State
0	Non-existent
1	Incipient
2	Acceptable
3	Optimal

Figure 2: Rating scale for the sub-variables of the framework

Following the rating of the sub-variables, the framework elements need to be aggregated. The aggregation model discussed above will be utilized for this purpose. Ultimately, the weighted aggregation of various dimensions within the framework will generate the TGGI. Since variables are assessed in both national and transboundary contexts, the computed index allows for both a disintegrated assessment (through the national context) and a holistic assessment (through the transboundary context) of the state of groundwater governance. The interpretation of the TGGI is described in Table 2.

TGGI	State of Transboundary Groundwater Governance	Description
0	Non-existent state	At this level, all aspects of transboundary groundwater governance face a significant absence of foundational elements with gaps in addressing the complex challenges associated with the sustainable governance of the transboundary aquifer system.
0 < TGGI <= 1	TGGI closer to 1 refers to an incipient state, while a value between 0 and 1 indicates a position that is toward the incipient state.	Stepping into the early stages, this state reflects limited efforts toward good groundwater governance and a phase of budding developments in transboundary groundwater governance.
1 < TGGI <= 2	TGGI closer to 2 refers to an acceptable state, while a value between 1 and 2 indicates a position that is towards the acceptable state.	This state reflects a moderate level of development across all dimensions of transboundary groundwater governance representing a satisfactory baseline for comprehensive transboundary groundwater governance.
2 < TGGI <= 3	TGGI closer to 3 refers to an optimal state of transboundary groundwater governance, while a value between 2 and 3 indicates a position that is towards the optimal state.	This state reflects optimal development and efficiency across all dimensions and an exemplary standard for the sustainable governance of the transboundary aquifer system.

The framework will undergo validation/ verification with global and local experts working in the field of groundwater governance before its deployment to assess the state of transboundary groundwater governance. This comprehensive framework builds upon various previous frameworks and concepts related to water governance and groundwater governance. The dimensions, indicators, and variables of this framework have been selected by referring to numerous existing literatures in the domain, such as research articles, project reports, case studies from various internationally shared aquifers, and the UN's Draft articles on the Law of Transboundary Aquifers. Some notable references include the Groundwater Governance conceptual framework (Foster et al., 2010), Global Diagnostic on Groundwater Governance (FAO, 2016), Methodology for the GEF Transboundary Waters Assessment

Programme (UNESCO-IHP, 2011), Gender-responsive monitoring and water assessment, indicators for reporting (Miletto et al., 2019).

4. Conclusion

The objective of this study was to develop a generic, indicator-based framework for transboundary groundwater governance. The formulated framework can be used to quantitatively assess the state of groundwater governance in internationally shared aquifer systems. This comprehensive framework, built upon concepts of water governance, particularly groundwater governance, has been developed by referencing numerous related frameworks, research findings, policy briefs, and case studies. The unique structure of this framework consists of four major components: Dimensions, Indicators, Variables, and Sub-variables (Context of application). The overarching Dimensions align with the components of water governance. Similarly, the 27 specific, measurable benchmarking indicators under various dimensions offer a detailed assessment of groundwater governance. The variables and the context of the application (sub-variables) are the quantifiable parameters in the framework. The scaled rating of the sub-variables, under the formulated scale, provides a quantifiable value for the current state of groundwater governance in the aquifer system, which can be interpreted into different states of transboundary groundwater governance. The framework is crucial for promoting effective management of shared aquifer systems, providing a structured approach to evaluating legal, financial, and policy aspects, and ensuring equitable and sustainable use of groundwater resources across borders. With further improvement of various aspects of the framework, it can streamline the identification of strengths and areas needing improvement, enabling policymakers to develop cohesive strategies, plans, and initiatives focused on addressing water insecurity, strengthening governance, and fostering inclusivity.

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PARTNER SESSION II-A

Navigating the Invisible: Emerging Sociohydrologies of Groundwater Irrigation in Nepal (CGIAR initiative on TAFSSA, CSISA, IWMI and CIMMYT)

Piloting and Implementation of Digital Groundwater Information System: A Case Study of Nepal's West Terai

Saral Karki
International Maize and Wheat Improvement Center (CIMMYT)

Abstract

Groundwater monitoring and data are crucial for keeping groundwater use within planetary boundaries. This study provides an overview into the approaches used for groundwater monitoring and sharing data such that it can be used to inform decision makers for sustainable groundwater management practices. It tries to build on and optimize the on-going groundwater data collection in Nepal carried out by Ground Water Resources Development Board.

Three different digital approaches were experimented in the Banke area to recommend a pragmatic and sustainable approach for data collection and management. The three systems included, firstly, data collection with tablets using ODK based form, secondly, digital data collection using a diver with USB data logger and finally telemetric digital data collection that uploads the data via mobile network and cloud-based storage. The dashboard allows users to quickly visualize the location of the monitoring wells and browse and download the dataset for further use. Though the initially generated data may be lacking in several aspects, these interactions support a transition towards sustainable groundwater management by both empowering the lead agency – the Groundwater Resources Development Board in the case of Nepal – through building capacity and exposure.

Keywords: *Groundwater monitoring; Digital data collection; Data visualization dashboard; Groundwater governance; Nepal*

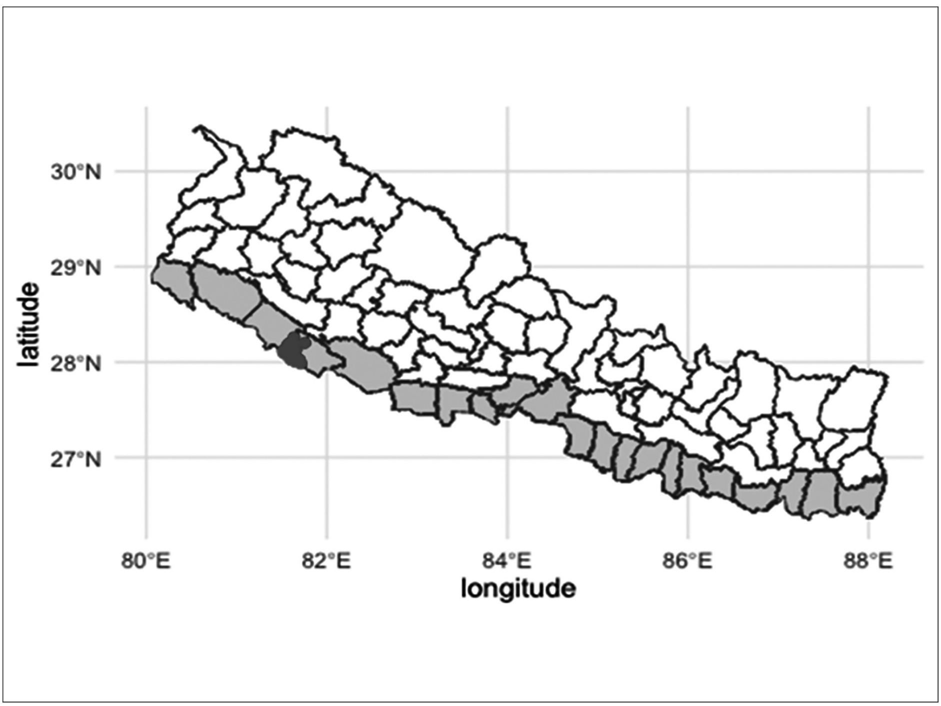
1. Introduction

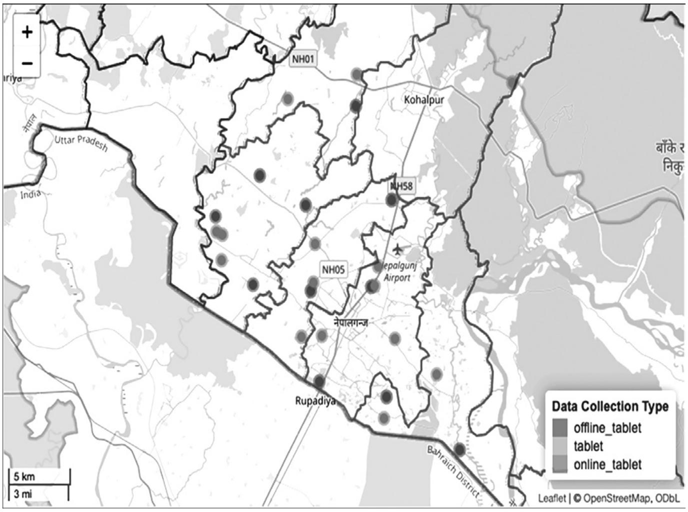
Groundwater monitoring and data are crucial for keeping groundwater use within planetary boundaries. The unmeasured and the unsustainable use of these invisible resources poses great sustainability challenges especially impacting low-income countries with poor groundwater governance. Even in countries that monitor and collect groundwater data, most countries report that the data usage is negligible. To sustainably manage groundwater use, it is crucial to measure what you manage. However, in most low-income countries, financial resources and technical capacity for groundwater monitoring tends to be low. This study, therefore, provides an overview into the approaches used for groundwater monitoring and sharing data such that it can be used to inform decision makers for sustainable groundwater management practices. It tries to build on and optimize the on-going groundwater data collection in Nepal carried out by Ground Water Resources Development Board.

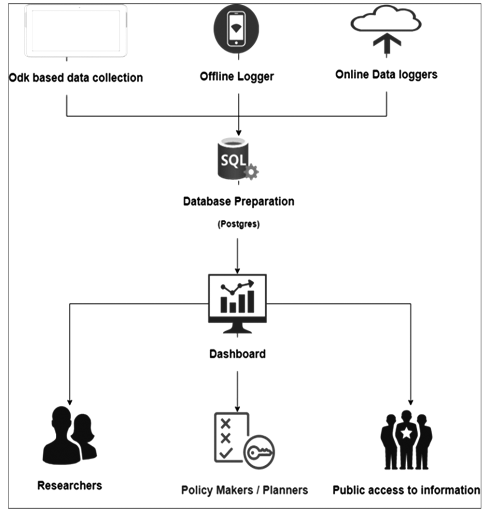
Three different digital approaches were experimented in the Banke area to recommend a pragmatic and sustainable approach for data collection and management. The three systems included, firstly, data collection with tablets using ODK based form, secondly, digital data collection using a diver with USB data logger and finally telemetric digital data collection that uploads the data via mobile network and cloud-based storage. Upon completion of the pilot, and careful examination of various costs (operational, maintenance, training), and other carefully identified features, the data collection using the ODK based tool was recommended for further scaling. The cost ODK based tool was significantly less than the other two methods over time whilst still producing robust groundwater depth data. Furthermore, to complement the data collection using the tablets, the database was managed, and data visualized via a dashboard for efficient data dissemination. The dashboard allows users to quickly visualize the location of the monitoring wells and browse and download the dataset for further use. Though the initially generated data may be lacking in several aspects, these interactions support a transition towards sustainable groundwater management by both empowering the lead agency – the Groundwater Resources Development Board in the case of Nepal – through building capacity and exposure.

2. Materials and methods

As part of the CSISA III project, initial discussion about potential interest in digitizing the GWRDB's groundwater monitoring system was held in Kathmandu in 2019. Based on invitation of the GWRDB a participatory pilot activity was then designed to digitize and groundwater data collection and link these to an online dashboard for visualization and download. The







GWRDB as the key agency responsible for groundwater monitoring in Nepal's Terai and lead the implementation through its field office in Nepalgunj, Banke district. This district was chosen due to the availability of legacy datasets and logistical convenience as both GWRDB and CSISA maintain offices in the district.

Three systems were introduced as a part intervention to groundwater monitoring, the first was tablet based digital collection, with dashboard for data visualization, and download. The second was using an offline data logger – i.e. a submersible USB data logger, the third was a telemetric online data logger synced to the cloud. The methods, therefore, were manual, semi-automatic and fully automated system respectively. The idea was to test the three methods to identify which could and would be sustainably adapted into the existing monitoring system.

Key Results

1. Fifty-year cost comparison of the three different systems to identify the cost effectiveness and recommended the use of ODK system accordingly.
2. Assessment of the maintenance and repair and other logistical risk of the devices.
3. Assessment of the technical expertise required to operate and maintain the system.

Application of the Water Table Fluctuation Method to Characterize Groundwater Recharge in the Banke District, Nepal

Pratik Bhuju
International Maize and Wheat Improvement Center (CIMMYT)

Abstract

Banke district in Nepal has undergone significant transformations, marked by a notable increase in the number of wells and expansion of irrigated land areas. Shifts in climatic conditions, characterized by reduced precipitation levels, have raised concerns regarding the sustainability of groundwater resources in the region.

Despite these pressing issues, the absence of recent and accurate assessments of groundwater recharge further increases the challenge of effective water resource management. To address these gaps, this study endeavours to provide updated insights into groundwater recharge dynamics in Banke district.

Our approach integrates advanced estimation techniques with recent data on groundwater level and precipitation data employing a combination of field observations and data analysis to estimate the groundwater recharge rates and patterns. In this study the water table fluctuation method (WTF) is used. To calculate recharge using this method, the specific yield (Sy) of the fluctuation zone must be estimated. The analysis incorporates 22 years of groundwater monitoring data, plotting rainfall values against water table rises for individual recharge events.

Based on the estimation of specific yield, annual groundwater recharge rates are computed. These results will be compared with the recharge rates derived from effective porosity, assuming a 15% porosity for Banke's alluvial aquifer. The comparison between recharge estimates derived from the water table fluctuation method and those based on effective porosity offers insights into the reliability and accuracy of each approach. Additionally, discussing any discrepancies observed between the two methodologies can illuminate factors influencing groundwater recharge dynamics in the Banke district. Moreover, addressing the implications of these findings for groundwater management strategies and the sustainability of irrigation practices will be crucial for informed decision-making and resource allocation in the region.

Keywords: *Water table fluctuation method (WTF), Specific yield (Sy), Groundwater Monitoring data, Effective porosity, Alluvial aquifer*

1. Introduction

With increasing demand of groundwater uses for irrigation in Banke district, it is important to understand the groundwater status and recharge dynamics for sustainable extraction practice. Previous estimates of groundwater recharge, as documented in the UN report of March 1992, utilized methodologies such as Duba's estimate, conservation estimates based on rainfall, and calculations considering factors like effective porosity and aquifer material composition(Shallow GW Resource of the Terai Banke District (TR19), n.d.). However, the reliance on these outdated estimations has left a significant research gap, particularly on the substantial changes in agricultural land use and climatic conditions since 1992.

Since the publication of the UN report, Banke district has undergone significant transformations, marked by a notable increase in the number of wells and expansion of irrigated land areas. Shifts in climatic conditions, characterized by reduced precipitation levels, have raised concerns regarding the sustainability of groundwater resources in the region. Despite these pressing issues, the absence of recent and accurate assessments of groundwater recharge further increases the challenge of effective water resource management.

To address these gaps, this study endeavors to provide updated insights into groundwater recharge dynamics in Banke district. Building upon the methodologies outlined in the UN report, our approach integrates advanced estimation techniques with recent data on groundwater level and precipitation data. Specifically, we aim to employ a combination of field observations and data analysis to estimate the groundwater recharge rates and patterns.

However, it is important to acknowledge the limitations inherent in our study. The interpolation of groundwater monitoring data from 2001 to 2023 introduces uncertainties, and the monthly monitoring frequency may not capture short-term variations adequately. Despite these challenges, our research seeks to contribute valuable insights that inform sustainable water management practices and support the long-term viability of groundwater resources in Banke district.

2. Materials and methods

In this study the water table fluctuation method (WTF) is used which is based accepting that the rises of water table are due to the recharge water reaching the groundwater. To calculate recharge using this method, the specific yield (Sy) of the fluctuation zone must be estimated. A graphical procedure is utilized, correlating groundwater level rises with precipitation. The analysis incorporates 22 years of groundwater monitoring data, plotting rainfall values against water table rises for individual recharge events.

3. Results and discussion

Based on the estimation of specific yield, annual groundwater recharge rates are computed. These results will be compared with the recharge rates derived from effective porosity, assuming

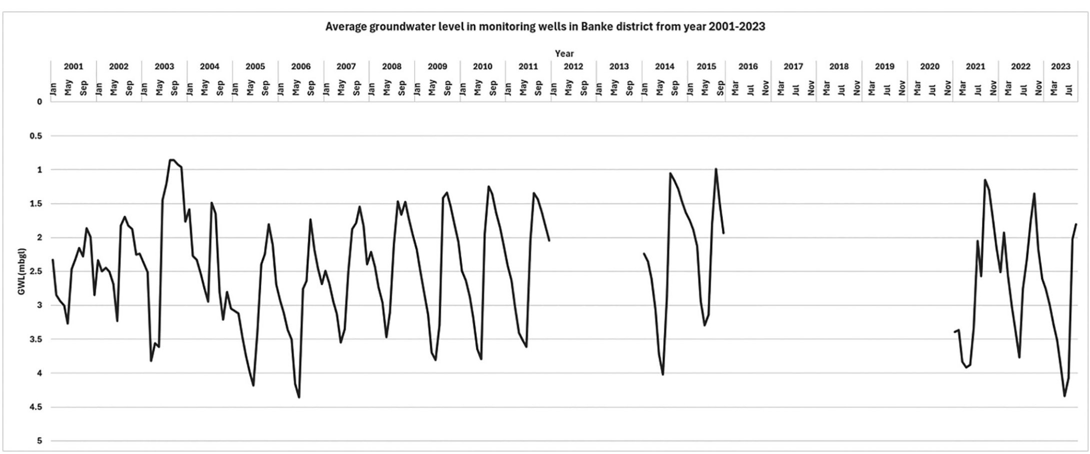


Figure: Average Groundwater level in monitoring wells in Banke district from year 2001-2023.

a 15% porosity for Banke's alluvial aquifer (comprising of sand and gravel).

The comparison between recharge estimates derived from the water table fluctuation method and those based on effective porosity offers insights into the reliability and accuracy of each approach. Additionally, discussing any discrepancies observed between the two methodologies can illuminate factors influencing groundwater recharge dynamics in the Banke district. Moreover, addressing the implications of these findings for groundwater management strategies and the sustainability of irrigation practices will be crucial for informed decision-making and resource allocation in the region.

Energy Technologies for Pumped Groundwater Irrigation – Spread, Opportunity, and Challenges

Shisher Shrestha
International Water Management Institute (IWMI)

Abstract

According to Kansakar (2006), only 18% of Tarai farms used GW irrigation. However, this number rose to 30% in the 2011 Agriculture Census and 41.7% in the most recent Agriculture Census. Enormous energy is needed to pump the GW to the surface.

According to WECS, water pumping in the Tarai region accounts for the highest energy consumption in the country's agricultural sector, with diesel accounting for an 84% share (WECS, 2023). Lack of energy access in the farms and the requirement for upfront costs to construct the pumping infrastructures are the leading causes of low coverage GW-based irrigation.

To compare various energy technologies, such as diesel pumps (DP), electric pumps (EP), and solar irrigation pumps (SIP), for groundwater abstraction for irrigation in Nepal, this paper combines a review of the literature with on-the-ground experience. The literature review focused on the Terai region, abstracting GW from shallow and deep aquifers through individual and community projects.

For the widespread adoption of different technologies for GW irrigation, we consider and compare them against key parameters such as costs (both operational and upfront), performance, usability, supply chain, and impact on GW resources. The EP receives a subsidized electricity tariff for agricultural use, while SIPs receive upfront capital subsidies. In addition to the detrimental environmental effects, diesel pumps are costly to operate, making them impractical for water-intensive crops. Although EPs have relatively low running costs and reasonable upfront costs, farms must be within the grid's coverage area to access EPs. Also, in areas with access to the grid, the quality of the grid and frequent power outages in rural areas are major concerns. Most smallholder farmers cannot afford the high upfront cost of SIP, and the GoN's subsidy budget is insufficient to meet the high demand.

Keywords: *Groundwater, Irrigation, Energy, Technology; Subsidy, Solar irrigation pumps, Smallholder farmers*

1. Introduction

There are 2.2 million hectares of arable land in Nepal, and the Tarai plains contain nearly 78% of this land (ADB, 2013). About 70% of the command area typically is covered by surface irrigation, but only half of the coverage area can have year-round irrigation. Nepal's Tarai region boasts abundant groundwater (GW) resources with an estimated GW recharge rate of 8,800 MCM annually with multiple layers of suitable aquifers. It is estimated that only 1312 MCM/year of GW resources are currently utilized (Shrestha et al., 2018). GW-based irrigation can help farms without access to surface irrigation swiftly expand their irrigation coverage areas and offer year-round irrigation. The government of Nepal (GoN) plans to increase year-round irrigation to 80% by 2030 (NPC, 2020).

According to (Kansakar, 2006), only 18% of Tarai farms used GW irrigation. However, this number rose to 30% in the 2011 Agriculture Census and 41.7% in the most recent Agriculture Census. Enormous energy is needed to pump the GW to the surface. According to WECS, water pumping in the Tarai region accounts for the highest energy consumption in the country's agricultural sector, with diesel accounting for an 84% share (WECS, 2023). Lack of energy access in the farms and the requirement for upfront costs to construct the pumping infrastructures are the leading causes of low coverage GW-based irrigation. Furthermore, GW-based irrigation can have up to 1.5 times the infrastructure cost and 4.5 times higher maintenance costs than surface irrigation (IMP, 2019).

2. Materials and methods

To compare various energy technologies, such as diesel pumps (DP), electric pumps (EP), and solar irrigation pumps (SIP), for groundwater abstraction for irrigation in Nepal, this paper combines a review of the literature with on-the-ground experience. The literature review focused on the Terai region, abstracting GW from shallow and deep aquifers through individual and community projects.

3. Results and discussion

GW's use for irrigation in Nepal can be traced to the early 1970s when diesel pumps were utilized. (Nepal & Thapa, 2009) suggest that the intensification of utilizing diesel pumps started after the inception of the Agriculture Perspective Plan (APP) in 1995, as there were limited options for utilizing other forms of energy. Apart from diesel pumps, kerosene and petrol operated pumps are common (Foster et al., 2019). According to a study by (Urfels et al., 2020), GW abstraction grew by 15% in the Tarai region between 2011 and 2016. This timeline also coincides with the introduction of Solar irrigation in Nepal through several pilot projects funded by USAID, ICIMOD, iDE, etc. (Shrestha & Uprety, 2021). In 2016, SIP adoption became widespread after the government's subsidy program for solar irrigation was introduced. The mid-2010s saw dramatic shifts in the energy sector, with the national utility service provider ending decade-long load-shedding as several large hydropower projects were commissioned and connected to the grid. The rapid grid expansion since the early 2020s saw calls to increase energy consumption, leading to rapid grid expansion in rural areas. Farmers utilizing NEA's grid for irrigation are the second highest category of NEA consumers, with a 4.34% share. The figure below shows the gradual increase in energy sales for NEA in the water supply and irrigation sector.

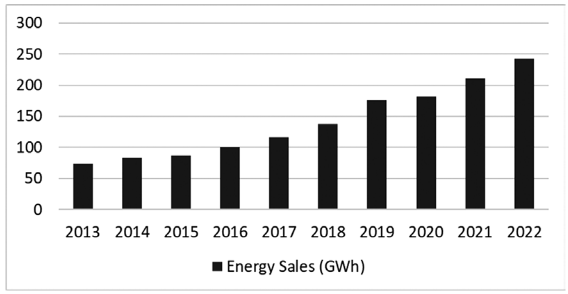


Figure 1 Energy Sales of NEA for Water Supply and Irrigation (GWh) (Data Source: NEA)

Agriculture consumes 10.5% of diesel imported into the country (WECS, 2010). There are approximately 170,000 pump sets in Nepal (Foster et al., 2021), and around 80% of these pumps are DP (Justice & Biggs, 2013). It is estimated that there are 3,129 SIPs installed for irrigation and drinking water (WECS, 2023), which is only 1.8% of the total installed pumps. Solar energy contributes to only 0.42% of the total energy consumption in the agriculture sector but is expected to grow in the future (WECS, 2023). (Sarkar & Ghosh, 2017) suggest replacing a single 1 kW diesel pump in Bangladesh with a solar PV pump with a net annual GHG reduction of 0.9 tCO_2. Additionally, there are no operational costs associated with SIPs, while farmers utilizing DPs to irrigate make their water-intensive crops uneconomic (CGIAR-WLE, 2014).

For the widespread adoption of different technologies for GW irrigation, we need to

Table 1 Comparison between Electric Pump, Diesel Pump, and Solar Irrigation Pump

Parameter	Electric Pump	Diesel Pump	Solar Irrigation Pump
Upfront Cost			
Operational Cost			
Performance			
Ease of Use			
Supply Chain			
Impact on GW			

consider and compare them against key parameters such as costs (both operational and upfront), performance, usability, supply chain, and impact on GW resources. Table 1 compares EP, DP, and SIP with the abovementioned parameters.

For these parameters, the type (individual or community projects) and scale of projects adopting EP, DP, and SIP technologies may have some implications for comparison. For this paper, we consider small individual systems for simplicity of comparison. In the market, the upfront and operational costs of a commonly used 5HP DP range between NPR 20,000 and 30,000 (Foster et al., 2019). A good quality 2HP EP costs between NPR 20,000-50,000. However, a typical 2HP SIP installation can cost between NPR 2-3 lacs, which is nearly ten times more than a typical DP or EP.

The operational cost of DPs is the highest, with the cost of irrigating one hectare of land reaching NPR 3,425 (Foster et al., 2019), and farmers renting DPs must pay NPR 300 per hour plus fuel costs per use. Farmers receive subsidies for electricity tariffs for agriculture meters, which cost NPR 2.3 per unit. There is no cost to operate the SIP. Farmers with access to EP and SIP preferred SIP (due to no operational costs) and used EP only to supplement additional water required during peak season.

The DP and EP provide consistent performance based on motor ratings and can be operated for as many hours as needed to meet irrigation water demands. However, the performance of SIP depends on solar radiation and is affected by cloudy days. Aside from that, off-grid SIPs can only operate at full capacity for 3-4 hours per day on sunny days. EP and SIP are easy to use and typically installed as a stationery system. Even farmers with little training can use them efficiently by turning on the switch. Many SIPs are kept turned on, and the pump operates in accordance with the available solar radiation. DPs, on the other hand, are quite heavy, require mechanical force to start, and necessitate some skill to operate after making temporary electrical and plumbing connections.

DP and EP use AC pump technology and have established a supply chain and local repair and maintenance facilities. SIPs, on the other hand, are a relatively newer technology that often employs DC pump technology, which is challenging to repair locally and lacks locally available technicians. Regarding GW sustainability, DP and EP have limited operating hours due to high costs and limited solar radiation, respectively. In contrast, EP has unlimited hours of inexpensive pumping, which may impact GW's sustainability.

4. Conclusion

GoN intends to replace the number of DPs with SIPs and EPs to meet its 2030 emission reduction target of reducing GHG emissions by 28% in 2030. The EP receives a subsidized electricity tariff for agricultural use, while SIPs receive upfront capital subsidies. In addition to the detrimental environmental effects, diesel pumps are costly to operate, making them impractical for water-intensive crops. Although EPs have relatively low running costs and reasonable upfront costs, farms must be within the grid's coverage area to access EPs. Also, in areas with access to the grid, the quality of the grid and frequent power outages in rural areas are major concerns. Most smallholder farmers cannot afford the high upfront cost of SIP, and the GoN's subsidy budget is insufficient to meet the high demand.

STW and DTW have increased over time, and they are not well-regulated. There have been calls to reduce or eliminate electricity tariffs for agriculture meters and increase access to SIPs. Exploring grid-connected SIP allows farmers to sell surplus solar energy to the grid. This provides farmers with additional opportunities while incentivizing them not to overuse groundwater resources. GoN must strategize to concurrently improve access to SIP and EP rather than promoting one technology in isolation. GW sustainability must be prioritized, and geographical areas with reach aquifers and underutilized GW resources should be targeted. Furthermore, the overall implementation of GW-based irrigation projects must be improved to ensure their longevity through improved monitoring.

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Groundwater Governance in a Federal Nepal: Examining the Government Ecosystem

Labisha Uprety
Lee Kuan Yew School of Public Policy

Abstract

Despite groundwater commanding significant interest both from government agencies and development partners in Nepal, existing research focus has been largely limited to better understanding the more 'technical' parameters of this resource. Besides limited interjections on the lack of groundwater laws, explorations of mechanisms that govern groundwater and its existing policy landscape have been mostly absent. Nepal recently transformed into a federal structure post the Constitution of 2015, and each level of government has been awarded substantial powers and jurisdiction over water and natural resources, making this an exciting time to study the new governance universe that makes up the 'groundwater government' in the country. While groundwater governance is not solely within the remit of government alone but includes various actors at different scales such as farmers, communities, and water markets, this research intends to study formal institutions and rules concerning groundwater which is the least investigated aspect of the groundwater ecosystem. The paper asks whether the institutional and legal framework with a multiplicity of actors of the current groundwater governance status in Nepal is best suited to face the challenges in a context of increased use.

Using a qualitative methodology based on key informant interviews and policy

document reviews, the study aims to draw lessons and identify key institutional bottlenecks for sustainable water governance in a politically transitioning economy.

Keywords: Groundwater governance, Groundwater policy, Institutions, Nepal, South Asia

(Note: this abstract and presentation is a reproduction of a paper by the authors already in publishing pipelines)

PARTNER SESSION II-B

Silent but Long Strides of Groundwater Irrigation in Nepal (CGIAR initiative on TAFSSA, CSISA, IWMI and CIMMYT)

Implementing Conjunctive Management of Water Resources for Sustainable and Inclusive Irrigation Development in Western Nepal

Nirman Shrestha
International Water Management Institute (IWMI)

Abstract

Climate variability and insufficient irrigation are primary constraints to stable and higher agricultural productivity and food security in Nepal. Agriculture is the largest global freshwater user, and integration of surface and groundwater use i.e. conjunctive management is frequently presented as a strategy for increasing efficiency as well as climate change adaptation. However, conjunctive management (CM) planning often ignores demand-side requirements and a broader set of sustainable development considerations, including ecosystem health and economics of different development strategies. While there is generic understanding of conjunctive use, detailed technical knowhow to realize the CM is lacking in Nepal.

This paper presents a holistic framework through literature reviews, stakeholders' consultations and expert interviews for assessing CM and implementation prospects from a systems-level perspective. We demonstrate the framework through a case study in Western Nepal, where climatic variability and a lack of irrigation are key impediments to increased agricultural productivity and sustainable development.

Results show that knowledge of water resources availability is good and that of water demand low in the Western Terai. Additional and coordinated investments are required to improve knowledge gaps as well as access to irrigation. There is therefore a need to assess water resources availability, water access, use and productivity, to fill the knowledge gaps to pave pathways for CM.

Keywords: *Climate change, Conjunctive use, Conjunctive management, Groundwater, Water policy*

1. Highlights

- Customized framework development for assessing prospects for conjunctive management.
- Conjunctive management status in western Nepal assessed by applying the framework.
- Knowledge on water availability and demand are moderate and low, respectively.
- Additional and coordinated investments required in adaptive technology prioritization, robust data systems, and expansion of irrigation and agricultural value chains to improve access to irrigation.

(Note: this paper and abstract is drawn from its published version –

Pandey, Vishnu Prasad, Nirman Shrestha, Anton Urfels, Anupama Ray, Manohara Khadka, Paul Pavelic, Andrew J. McDonald, and Timothy J. Krupnik. "Implementing conjunctive management of water resources for irrigation development: A framework applied to the Southern Plain of Western Nepal." Agricultural Water Management 283 (2023): 108287.)

Constraints and Opportunities in Groundwater use in Rice Rroduction Systems: Farmer Perspectives from Nepal

Emma Singh Karki
International Maize and Wheat Improvement Center (CIMMYT)

Abstract

Despite being rich in water resources, lack of access to affordable and timely irrigation faced by Nepali farmers has limited their agricultural productivity (Bhandari and Pandey, 2006). In areas where there is no access to surface irrigation, farmers in Terai depend on groundwater for supplemental irrigation to overcome rainfall deficits. However, recent research finds that most farmers do not recognize the link between delayed irrigation and yield outcomes and consider irrigation as a crop saving mechanism rather than a productivity-enhancing investment (Urfels et al., 2020). Gaps in farmers knowledge regarding irrigation practices can be attributed to a largely ineffective extension system.

There has been little qualitative exploration of the constraints farmers face while making decisions about their groundwater irrigation management practices at the local level. This research utilizes the "Decision-making Dartboard" (DmD) framework that divides critical decision-making processes into six stages spanning four asset categories (Brown et al., 2021, p. 257). The DmD framework unpacks decision making processes into four asset categories across six levels which are then combined to examine the various factors individuals evaluate to arrive at their final classification.

The study was conducted in Kailali and Banke districts in the Western Terai region of Nepal. Our study findings revealed distinct location specific trends regarding current irrigation practices and physical, financial, information, and human resources related opportunities and constraints for

Various agencies are promoting the use of groundwater irrigation but are operating in silos which leads to unplanned construction of STWs and duplication of beneficiaries. While the current policy promotes group ownership of shallow tube wells, there is a demand for individual ownership which might lead to an unsustainable use of groundwater in the future. Future policies must evaluate the use and effectiveness of current subsidy programs to ensure the promotion of sustainable and equitable use of groundwater to avoid overexploitation.

Keywords: *Household decision making, irrigation practices, sustainable intensification, Nepal*

1. Introduction

Despite being rich in water resources, lack of access to affordable and timely irrigation faced by Nepali farmers has limited their agricultural productivity (Bhandari and Pandey, 2006). In areas where there is no access to surface irrigation, farmers in Terai depend on groundwater for supplemental irrigation to overcome rainfall deficits. However, recent research finds that most farmers do not recognize the link between delayed irrigation and yield outcomes and consider irrigation as a crop saving mechanism rather than a productivity-enhancing investment (Urfels et al., 2020). The CSISA survey (2016) found that farmers produced 368 kg/ha more rice, on average, when irrigating a first, second or third time (SE 34 kg) (Urfels et al., 2020).

One of the key constraints in accessing groundwater is the high cost of purchasing or renting diesel pumpsets (Foster et al., 2021, Urfels et al., 2020). Foster et al. (2021) found that farmers often use more expensive and fuel inefficient pumpsets because they are often unaware of fuel consumption of different pumpset designs. In addition, there is a lot of heterogeneity in the cost of groundwater irrigation which was mostly attributed to pumpset ownership (Foster et al. 2019) and monopolies in shallow tubewell and pumpset rental markets (Sugden, 2014). They also suggest that farmers lack knowledge about the best irrigation scheduling practices and call for guidelines for farmers about profitable irrigation scheduling practices (Foster et al., 2021).

Gaps in farmers knowledge regarding irrigation practices can be attributed to a largely ineffective extension system. The limited research on groundwater irrigation and information source and mechanisms are largely based on survey data. There has been little qualitative exploration of the constraints farmers face while making decisions about their groundwater irrigation management practices at the local level. Using qualitative methods, the study aims to delve into the following research questions:

What are farmer's current irrigation management practices?

What key factors determine current irrigation management decisions? Who is involved in the decision-making process?

What are the constraints and opportunities farmers face in current groundwater irrigation management practices? Is information a constraint?

2. Materials and methods

This research utilizes the "Decision-making Dartboard" (DmD) framework that divides critical decision-making processes into six stages spanning four asset categories (Brown et al., 2021, p. 257). The DmD framework unpacks decision making processes into four asset categories across six levels which are then combined to examine the various factors individuals evaluate to arrive at their final classification. The DmD is based on the Livelihoods Platforms Approach. This work applied the DmD framework, a semi-structured question schedule designed to be adaptive to the respondent's irrigation classification, with the overarching goal to determine their typology and what is required to progress towards increased irrigation intensity.

The study was conducted in Kailali and Banke districts in the Western Terai region of Nepal. In each district two villages are selected based on their responsiveness to irrigation intensity. In Kailali district, Prithvipur, Kailari Municipality and Mainpokhari, Joshipur municipality were selected and in Banke district, B Gaun, Khajura Municipality and Bhanghotana, Duduwa Municipality were selected. Data was collected using village resource mapping exercises, and semi-structured interviews (SSIs). One village resource mapping exercise was conducted in each village totaling 4 village maps. In addition, 14 SSIs were conducted in each village using a snowball sampling method to capture diverse farmer's perspective based on their current irrigation management practices and pumpset ownership/usage. Participant selection was based on three typologies of farmers who practice varying irrigation intensities (high, medium, low), totaling 56 SSIs. Some selected farmers participated in both village mapping and SSI exercises, but new participants were selected to limit bias and ensure a wider perspective of the current practices in each village.

3. Results and discussion

Our study findings revealed distinct location specific trends regarding current irrigation practices and opportunities and constraints for irrigation led intensification.

Physical Resources

- ❖ Overall, all locations indicated increased access to ground water irrigation has led to changes in their farming practices, with less time allocated for transplanting in comparison to rainfed irrigation.
- ❖ Use of larger pumpsets is still common in Kailali which limits opportunities for supplemental irrigation due to lack of road access to plots.
- ❖ In locations with electricity access on their agricultural plots, farmers are more likely to irrigate more using electric pumpsets and krishi meters. The cost of supplemental irrigation is quite low but farmers face issues with irregular power supply and voltage fluctuations.
- ❖ In plots with limited access to electricity, farmers tend to invest in setting up eletrical lines to their respective plots close to the main supply using their own resources.

Financial Resources

- ❖ Increased access to groundwater irrigation due to the subsidy provided by different agencies on shallow tubewells and electrical motors but farmers had a mixed perception on the effectiveness of the subsidy critera for communal use.
- ❖ Liquidity issues during lean periods a constraint to supplemental irrigation, espeically for those using deisel pumpsets.
- ❖ Lack of storage facilities and credit access limits farmers from storing paddy to sell during favorable market conditions.
- ❖ Variations in the irrigation rental market among the study locations for electric pump set use offsets the opportunity to lower production costs

Information Resources

- ❖ General awareness on the benefits of supplemental irrigation but high fuel costs and limited profitability in the current agricultural systems remains a key constraint
- ❖ Farmers with the exception of lead farmers, have limited access to formal extension services
- ❖ Use of digital tools to access weather related information common amongst lead farmers
- ❖ Awareness among farmers regarding the frequency of irrigation based on the plot specific soil type.

Human Resources

- ❖ In locations with greater use of diesel pumpsets, men are more likely to take responsibility of irrigation management.

4. Conclusion

Farmer household decisions regarding irrigation management practices are largely based on traditional practices and with limited access to formal extension sources to support irrigation led intensification. Overall, farmers in both Banke and Kailali districts indicated a preference for electric pumpset use to lower production costs and transplant in a timely manner. However, the lack of profitability in the current agricultural system and unfavorable market conditions adds an additional layer of complexity to intensify current irrigation management practices.

Various agencies are promoting the use of groundwater irrigation but are operating in silos which leads to unplanned construction of STWs and duplication of beneficiaries. While the current policy promotes group ownership of shallow tube wells, there is a demand for individual ownership which might lead to an unsustainable use of groundwater in the future. Future policies must evaluate the use and effectiveness of current subsidy programs to ensure the promotion of sustainable and equitable use of groundwater to avoid overexploitation.

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Understanding Access and Barriers in Groundwater Development in Nepal: Navigating from Macro to Micro-perspective

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Abstract

The comparison of groundwater uses for irrigation in two consecutive national agriculture censuses between 2011 and 2021 shows that groundwater irrigation coverage of total irrigated area was 29.8% in 2011 and reached to 41.7% in 2021 (Chakraborty et al., 2023). This shift towards groundwater (GW) irrigation signifies a significant transformation in Nepal's irrigation sector and overall agriculture sector. However, unlike surface water irrigation, groundwater use is mostly privately invested, and its access is strongly linked with households' socio-economic characteristics. If groundwater development continues without deeper considerations of equity and access issues, it may widen disparities in irrigation access and create issues of sustainability in the long run. This study brings macro and micro perspective of overall irrigation development in Nepal giving particular focus to groundwater development.

This study aims to unravel the equity considerations and barriers to access to groundwater development at macro-level which is further validated with micro-level case studies. Understanding the complex interplay of socio-economic factors contributing to irrigation access and equity is essential for developing effective policies and interventions for promoting equitable, efficient, and sustainable groundwater development in Nepal. To bring a macro-perspective of GW irrigation development, this study uses district level data of consecutive National Agriculture census conducted in 2011 and 2021. For the micro-perspective, this paper brings the case of Rani Jamara Kuleria Irrigation Project (RJKIP), a World Bank funded irrigation project of Western Nepal. This case study uses both primary and secondary information collected through desk-based literature review and on-site field visits.

Keywords: *Groundwater irrigation, Access, Equity, Smallholder, Marginalized, Sustainability*

1. Introduction

The comparison of groundwater use for irrigation in two consecutive national agriculture censuses between 2011 and 2021 shows that groundwater irrigation coverage of total irrigated area was 29.8% in 2011 and reached to 41.7% in 2021 (Chakraborty et al., 2023). This shift towards groundwater (GW) irrigation signifies a significant transformation in Nepal's irrigation sector and overall agriculture sector. Insights gained from decades of groundwater development trends in the South Asian region, we can expect that groundwater use may further increase in future and have implications for resource sustainability, quality, and agricultural productivity. However, unlike surface water irrigation, groundwater use is mostly privately invested, and its access is strongly linked with households' socio-economic characteristics. If groundwater development continues without deeper considerations of equity and access issues, it may widen disparities in irrigation access and create issues of sustainability in the long run. This study brings macro and micro perspective of overall irrigation development in Nepal giving particular focus to groundwater development.

2. Materials and methods

This study aims to unravel the equity considerations and barriers to access to groundwater development at macro-level which is further validated with micro-level case studies. Understanding the complex interplay of socio-economic factors contributing to irrigation access and equity is essential for developing effective policies and interventions for promoting equitable, efficient, and sustainable groundwater development in Nepal.

Method: To bring a macro-perspective of GW irrigation development, this study uses district level data of consecutive National Agriculture census conducted in 2011 and 2021 which gave the broader understanding of irrigation development in Nepal national and province levels. To further shed light on broader research questions considered in this study, we also analyzed secondary dataset at household level collected by the World Bank dataset Household Risk and Vulnerability Survey 2018. This dataset consists of 6051 households distributed across 50 districts in Nepal, consisting of three ecological zones: Mountain, Hill, and Terai.

For the micro-perspective, this paper brings the case of Rani Jamara Kuleria Irrigation Project (RJKIP), a World Bank funded irrigation project of Western Nepal. This case study uses both primary and secondary information collected through desk-based literature review and on-site field visits to the RJKIP command area, Focus Group Discussions (FGDs) with a mixed group of male and female farmers, in-depth interviews, and Key Informant Interviews (KII) with various stakeholders.

3. Results and discussion

The results revealed key insights into groundwater use patterns and their socio-economic determinants. The terai belt has the highest percentage of households with year-round access to irrigation (61%) of which over 2/3rds of the households depend on groundwater irrigation. Initial results also indicate that households engaged in groundwater irrigation is accessed by households that show better access to roads, markets, and banking facilities compared to those relying on surface or rain-fed agriculture. Households with better access to agriculture inputs such as fertilizers, pesticides, and improved seed were also found to depend more on groundwater irrigation. Additionally, the economic value of land with access to groundwater is higher, as indicated by higher rental rates compared to land irrigated by canals or dependent on rain-fed agriculture. As highlighted earlier, tenants have to pay higher rent for the parcels which have access to groundwater irrigation.

The case study from RJKIP further validates the findings revealing from the field that groundwater access for irrigation faces multiple barriers and challenges, significantly impacting smallholder farmers, marginalized communities, and women. One of the barriers faced by smallholder farmers is substantial upfront investments required in groundwater extraction for digging, pipe installation, and buying pumps. Policy barriers also add complexities in accessing groundwater. For example, existing water policies do not address groundwater ownership separately, dissuading farmers without landholding to make investment due to the risk of eviction or replacement by landowners.

Energy cost associated with groundwater extraction is another barrier for making groundwater accessible for smallholder farmers. Solar and electric pumps are cheaper options. However, slow field electrification and unreliable power supply add challenges. Likewise, the mandatory requirements of citizenship, land ownership certificates, recommendation from ward office create barriers for tenant farmers and farmers without citizenship in applying for agriculture meter upon which farmers receive subsidized electricity for irrigation purpose. Women farmers lack guidance, knowledge and information to navigate through the application processes hindering their access to state services and subsidies.

Smallholder farmers often depend on boreholes/wells of neighboring fields and engage in informal agreements with varying pricing structures for fuel, pumps, and water transaction with borehole/well and pump owners. Pricing disparity widens the resource access gap, disproportionately affecting smallholders, women, and marginalized farmers who lack voice, power and have no alternative means. Gender and social barriers further compound the issue. Women in agriculture face multiple challenges, including restricted access to technical training, information, and government subsidies. Lack of land entitlement excludes women farmers from state services and subsidies. Social norms hinder women's mobility and interaction; In Terai women have limited access to media compared to men and language barriers further exacerbate disparities. Consequently, women farmers also lack access to information on new technology in irrigation such as solar pumps. Additionally, irrigation technology and infrastructure are not gender friendly (Khadka et. al., 2021) exacerbating the challenges in groundwater access and overall agricultural productivity.

4. Conclusion

This study found the critical role of infrastructure, market access, access to agricultural inputs and financial services in facilitating GW use suggesting the need for targeted policy interventions. The policies should aim to improve accessibility and encourage private sectors and financial institutions to provide essential services which encourages GW irrigation practices.

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TECHNICAL SESSION

Innovative Approaches for Addressing Groundwater Challenges: Integrating Science, Community and Policy

Navigating Water Security: A Pragmatic Community-Centric Framework for Groundwater Governance in Nepal

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Abstract

Groundwater, a common-pool resource, represents a significant freshwater reservoir characterized by abundance, albeit subjected to over-exploitation. The resource's governance entails a soft approach to foster sustainability and water security and ensure effective management within the community. Diverse natural and anthropogenic pressures are concurrently worsening global strain on the resource, constraining its accessibility and optimal utilization. Therefore, community participation is essential at various stages of its governance and management. In Nepal, the recent implementation of federalism has added new horizons, yet there is some complexity in the regulatory mechanism of this vital resource. Therefore, this research develops a community-centric groundwater governance framework to identify strengths, gaps and challenges for urgent call-to-action. The framework introduces the Groundwater Governance Index (GGI) as a metric for evaluating the present condition of groundwater governance. The GGI encompasses four dimensions, comprising twenty-six indicators, each assessed against two variables: the adequacy of provisions and the institutional capacity to implement said provisions. The framework adopts a comprehensive approach, analyzing indicators through various perspectives and lenses. By employing this methodology, stakeholders can effectively identify and prioritize critical issues pertaining to groundwater governance, thereby contributing to the assurance of water security in Nepal.

***Keywords:** Water governance framework, Aquifer management, Assessment methodologies, Groundwater governance index*

1. Introduction

Groundwater is the preeminent global freshwater reservoir, constituting approximately 50% of the world's potable water supply and contributing to 40% of the global irrigation water resources (UN Water, 2022). Several studies have clarified an escalating pressure on groundwater reservoirs attributable to a combination of anthropogenic and natural factors, including climate change, excessive extraction, increasing reliance, contamination, and intrusion of seawater (Cherubini & Pastore, 2011; Gleeson & Wada, 2013). In Nepal, cities such as Kathmandu and Birgunj are facing rapid groundwater level decline due to over-abstraction and decline in recharge areas (Baranwal, 2023; Shrestha et al., 2018), whereas this resource is underutilized in many places of Nepal with only 22% of the total dynamic groundwater recharge being utilized (Shrestha et al., 2018).

Effective management and the promotion of sustainable utilization of this shared common-pool resource hinge upon the collaborative efforts of both governmental entities and local communities. Studies have shown that state-centric groundwater governance is usually ineffective (Molle & Closas, 2020). Several assessment frameworks such as Organization for Economic Co-operation and Development (OECD) principles on water governance, Groundwater governance: a conceptual framework for assessment of provisions and needs (GW-MATE, World Bank) have been developed; however, a dedicated community-centric framework for the quantitative visualization of current provisions and needs is still absent. This framework should offer a comprehensive overview that considers multiple societal perspectives. Therefore, there is a need for a community-centric groundwater governance assessment framework which incorporates community in every step of planning and decision-making.

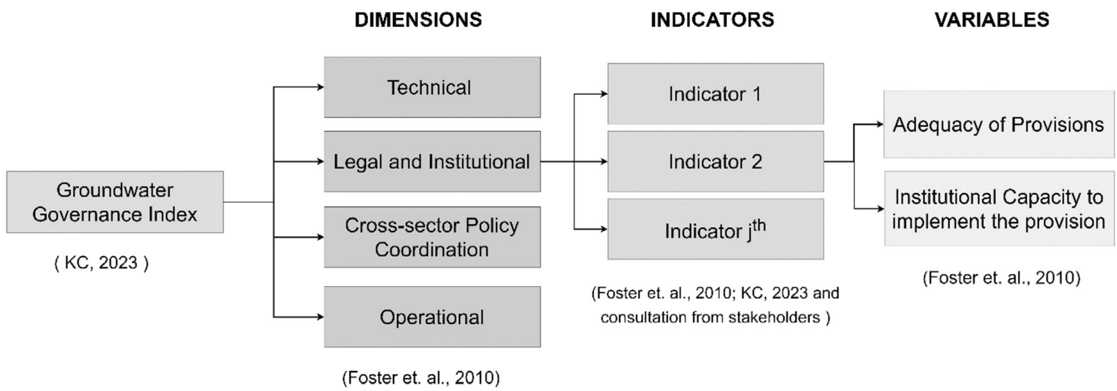

Figure 1: Components of Groundwater Governance Framework

2. Materials and methods

This study builds on the existing groundwater governance frameworks (Foster et al., 2010; KC, 2023; Miletto et al., 2019) and uses the Groundwater Governance Index (GGI) to quantify groundwater governance. GGI value ranges from 0 to 3, where 0 is the non-existent state of governance, whereas 3 refers to the optimum state of groundwater governance. The framework adopts four dimensions: technical, legal and institutional, cross-sectoral policy coordination, and operational. Each dimension consists of several indicators, and each indicator is assessed based on two variables (adequacy of provision and institutional capacity to implement the provision), as seen in Figure 1 (Foster et al., 2010; KC, 2023). The values for the variables within each indicator are obtained from experts and community-based surveys.

3. Results and discussion

The study presents 26 indicators with 7 technical, 9 legal and institutional, 5 cross-sectoral policy coordination, and 5 operational dimensions indicators. Most indicators have been derived from existing literature on groundwater governance frameworks (Foster et al., 2010; KC, 2023; Miletto et al., 2019). Similarly, other indicators have been derived from case studies of groundwater governance and other groundwater-related studies. Indicators within the framework offer the capability to assess existing provisions comprehensively and needs from various perspectives, including those of the state, community, market, and accessibility.

The overall framework is presented in Figure 2. The study uses Equation 1 to derive a quantitative value for each indicator, and within each dimension, the aggregation of indicator values is performed using the method specified in Equation 2. Assigning equal weightage to each indicator, subsequently, the GGI is computed using a composite index method mentioned in Equation 3.

In Figure 2, D = Dimensions; I = Indicators; V = Variables; i,j,k = number of dimensions, indicators within each dimension, and number of indicators within each dimension respectively; Di = Aggregated value of ith dimension; wj = weightage of jth indicator within the dimension; Iij = Aggregated value of jth indicator in ith dimension; GGI = Groundwater Governance Index, TE = Technical, LI = Legal and Institutional, CS = Cross-sectoral Policy Coordination, OP = Operational dimensions.

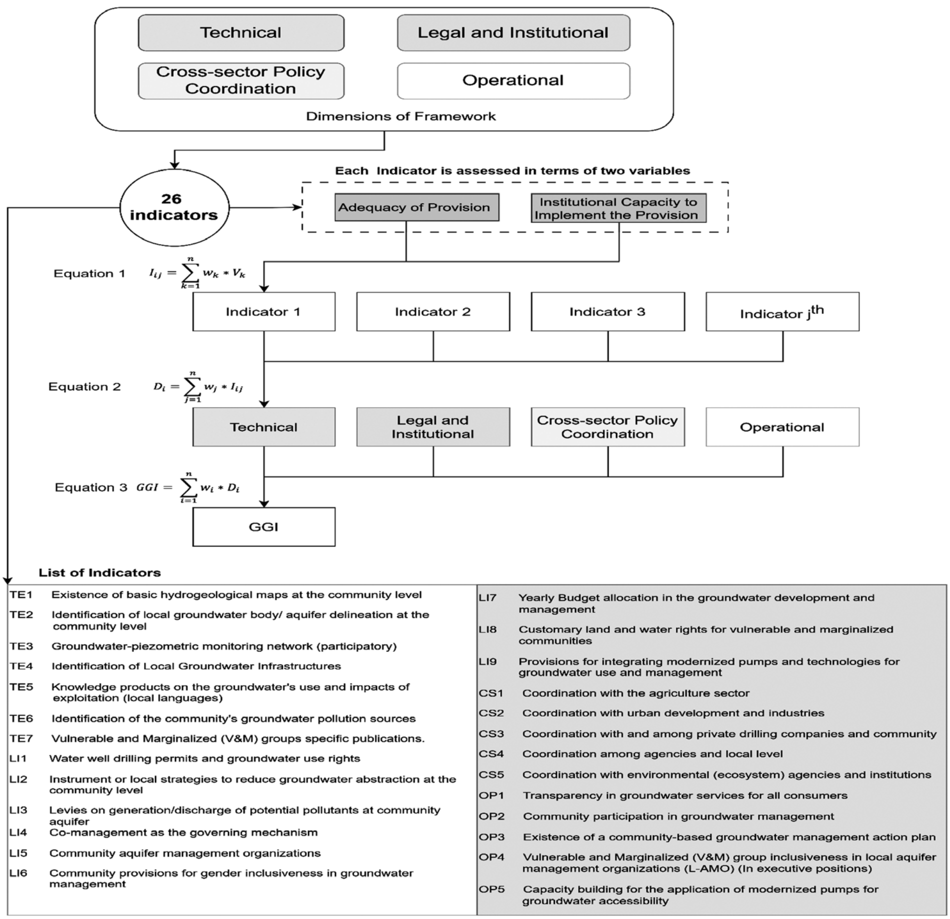

Figure 2: Description of Groundwater Governance Framework

4. Conclusion

The abundance of groundwater and its increasing withdrawal have seriously impacted its sustainable management. Various groundwater stresses affect access, quality, and management, risking conflicts. So, assessing groundwater governance is a soft way to ensure sustainable resource management. The study provides a community-centric groundwater governance framework to identify an urgent call for action and enhance participation in groundwater governance and management. It comprises four dimensions and twenty-six indicators, each rated with two variables. The indicators aim to capture critical aspects of the groundwater governance process and provide a quantitative figure known as the Groundwater Governance Index (GGI). The GGI values range from 0 to 3, providing the current state of groundwater governance. The framework further provides a way for analyzing through multiple lenses, including the community, state, and market perspectives; the framework facilitates the identification of strengths and gaps within the existing governing mechanism of the resource. By highlighting the pressing issues, the stakeholders and policymakers will find a helpful framework to prioritize the efforts. This comprehensive approach driven by community needs and aspirations ensures the improvement of groundwater governance, which ultimately adds to water security in Nepal.

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Ground Truth from Above: Bridging the Gap in Groundwater Monitoring with Remote Sensing

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Abstract

Groundwater is a crucial resource, supplying half of the world's domestic water demand and balancing surface water fluctuations. Its depletion can lead to permanent loss of storage capacity and ground surface subsidence, impacting infrastructure. Monitoring groundwater changes is vital for sustainable management. Conventional methods include electronic and physical inquiries, leveraging wells and equipment for localized measurements. Satellite data offers cost-effective, real-time surveillance of groundwater storage variations, aided by missions like GRACE and sophisticated models. Numerical modeling predicts future scenarios, optimizing resource management decisions. However, accuracy depends on quality point-based measurements, necessitating ongoing research. Combining GRACE's satellite perspective with numerical modeling enhances efficiency and accuracy in groundwater assessment, highlighting the importance of leveraging newer technologies.

Keywords: *Satellite-based monitoring; GRACE, Groundwater monitoring, Water resource management, Groundwater depletion, Sustainable water management*

1. Introduction

Groundwater constitutes 30% of the world's freshwater, crucial for agriculture, industry, and sustaining river flows during droughts (Masood et. al. 2022). Population growth exacerbates reliance on groundwater, leading to over-extraction and dropping water tables, affecting food production and ecological balance. Proper management is vital to avoid socio-economic stresses. Dynamic changes in groundwater storage require comprehensive monitoring for sustainable management (Hertig and Gleeson, 2012). Enhanced understanding of groundwater movement and age is crucial for addressing scientific, technical, and legal questions, especially in transboundary contexts. Global initiatives like the EU Water Framework Directive underscore the importance of groundwater monitoring. Voss et al. stress the need for international cooperation to manage transboundary water resources effectively. This paper presents a comprehensive overview of methods and tools for monitoring groundwater fluctuations, including point-based measurements, satellite-based monitoring, and numerical modeling. Technological advancements have revolutionized groundwater monitoring, ensuring accurate assessment and management of groundwater resources.

Regions with low groundwater recharge relative to total runoff are particularly vulnerable to precipitation variability and pollution. From point-based monitoring at field to studying the fluctuation using numerical models, estimation of groundwater storage is being carried out following various methodologies. The use of remote sensing and GIS is one of the groundwater monitoring methods has increased exponentially. Recent advances in satellite data related to water cycle involve less parameterization and effective computation over larger spatial and finer temporal scales. The satellite covers the issue of cost, time, and labour by providing its free data for some areas/regions, which can be used to assess groundwater evaluation efficiently at a global, regional, or national level. Combinations of other satellite products, computational tools, GIS techniques, and hydro-climate models have proved most effective so far. In this research article, the various categories of groundwater modelling have been discussed briefly, stressing the advantage of remote sensing technique for monitoring groundwater fluctuation.

2. Point-based groundwater modelling

Groundwater estimation methods have evolved, from traditional rope measurements to advanced instruments like pressure transmitters and piezometers. Freeman et al. (2022) highlights their use in Managed Aquifer Recharge, ranging from basic setups to complex sensor arrangements. Observation wells track annual groundwater level changes, while piezometers sample water quality reliably. The gravity method detects gravitational field changes, useful for near-surface groundwater investigations (Chandler, 1994). Electrical resistance surveys, integrated with lithological details, map resistivity distribution to identify freshwater zones (Mohamaden, 2008). Environmental isotopes offer insights into groundwater geochemistry and aquifer characteristics, with nitrate presence indicating agricultural influence on shallow aquifers (Kendall and Aravena, 2000).

3. Satellite-based groundwater modelling

Remote sensing plays a prominent role in acquiring data and assessing the data to obtain desirable results. Recent advances in satellite data related to water cycle involve less parameterization and effective computation over larger spatial and finer temporal scales. The satellite covers the issue of cost, time, and labour by providing its free data for some areas/regions, which can be used to assess groundwater evaluation efficiently at a global, regional, or national level. The summary of satellites which provide data for modelling groundwater potential and water storage are listed in Table 1.1.

Table 1: Summary of the Satellites mentioned in the literature.

Satellite	Resolution	Comments
SRTM DEM	90 m and 30 m	Captures elevation data of an area
Sentinel-2	10-20 m	Land use and land cover data of the area; soil, water, and vegetation cover. It offers water, soil, and vegetation cover information for inland waterways, land, and coastal regions.
IRS-LISS 3	24 m	Land and water resource management data is provided with this satellite.

MODIS	250 m, 500 m and 1 km	Data related to precipitation, meteorological data, and land use and land cover data. enhances understanding of global processes like atmospheric profiles, clouds, evapotranspiration, and more (Jioa et al., 2015). While not directly evaluating groundwater resources, MODIS data aids in groundwater modeling by providing inputs.
Landsat	30 m	Data related to land cover, vegetation and water resources. The Landsat satellite is a useful tool for assessing groundwater as well, although compared to MODIS, it has a higher resolution of 30 m (Elmahdy *et al.,* 2020)
GRACE and GRACE FO	300 km	Gravity Recovery and Climate Experiment provide groundwater depletion and storage change (Mohanasundaram et al., 2021). Developed collaboratively by the US and German space agencies (DLR and NASA), the GRACE twin-satellite mission was launched on March 17, 2002. With spatial scale of 50,000 km^2 aligning with in-situ runoff data and hydrological model outputs, despite its coarser geographical resolution (300 km).

4. Regional groundwater estimation through numerical modelling

Groundwater, a critical element of the Earth's hydrological cycle, plays an essential role in maintaining ecosystems, supporting agriculture, and fulfilling human water requirements (Foster and Chilton, 2003). Nevertheless, comprehending and managing groundwater resources pose significant challenges due to their intricate interplay with geological formations, surface water bodies, and human activities (Gorelick and Zheng, 2015). In this context, numerical modeling emerges as a potent tool for estimating regional groundwater resources by simulating the complex hydrological processes governing groundwater flow and transport (Rushton, 2004).

4.1 Spatial interpolation models

Groundwater level data are crucial for understanding regional groundwater resources. However, acquiring direct measurements across an entire area can be impractical due to terrain ruggedness, lack of access, or financial constraints. In such cases, interpolation techniques estimate groundwater levels at unmeasured locations based on known data points (Biernacik et al., 2023). Kriging, a widely used method, calculates a weighted average of nearby measurements, considering spatial correlation (Mueller et al., 2023). It provides uncertainty metrics, aiding decision-making (Cressie, 1986). Inverse Distance Weighting (IDW) allocates weights based on distances from measured points, with closer points receiving higher weights (Chen and Liu, 2012). While interpolation offers insights, numerical modeling provides a comprehensive understanding of groundwater dynamics (Rushton, 2004).

4.2 Hydrological budget-based models

Quantifying groundwater resources involves understanding the hydrologic budget equation tailored for groundwater systems (Ahamed et al., 2022). Methods for determining groundwater levels include calibrated models, volumetric budget analyses, or analytical techniques (Konikow, 2011). Static modeling compares groundwater recharge rates with abstraction estimates, identifying areas of concern for depletion (Gururani et al., 2023). Transient modeling offers a dynamic approach, useful for rapid depletion detection, especially where lateral flows are significant (Osiadacz, 1996). Challenges in global real-time monitoring include limited data sharing and sparse monitoring wells. Collaboration and advanced technologies like remote sensing and satellite imagery are essential for improving monitoring accuracy and timeliness (Gururani et al., 2023).

4.3 Available numerical models for groundwater analysis

The geostatistical or hydrologic budget equation forms the fundamental framework for developing groundwater surface models across entire basins, with a plethora of GIS-capable software tools available to facilitate this task (David, 2004). Some notable examples of such software tools are listed in table 2:

Table 2: Numerical models for groundwater analysis

Model	Description
USGS Modular Groundwater Flow Model (MODFLOW)	Developed by the United States Geological Survey (USGS). MODFLOW is an extensively employed numerical modeling software for simulating groundwater flow in aquifers.
Finite Element Subsurface Flow System (FEFLOW)	FEFLOW, developed by the Danish Hydraulic Institute (DHI), is a versatile software tool for simulating groundwater flow and transport in both saturated and unsaturated subsurface environments.
Groundwater and Surface-water FLOW (GSFLOW)	GSFLOW is a joined surface-water-groundwater flow model developed by the USGS. It integrates MODFLOW with the Precipitation-Runoff Modeling System (PRMS) to simulate groundwater and surface water interactions.
PHREEQC and HST3D (PHAST)	PHAST, developed by the USGS, is a software package for simulating geochemical reactions, solute transport, and groundwater flow in aquifers. It integrates the PHREEQC geochemical modeling program with the HST3D groundwater flow and transport model.
Saturated-Unsaturated Transport (SUTRA)	SUTRA is a solute transport and finite element groundwater flow model developed by the USGS. It is capable of simulating both saturated and unsaturated flow processes in porous media.
SWAT-MODFLOW (SWATmf)	It stands out as a semi-coupled model used for assessing future streamflow patterns, reservoir storage, and groundwater levels under various management practices and climate scenarios.
FREEWAT and ModelMuse	Open-source tools like FREEWAT and ModelMuse significantly support groundwater modeling efforts.

5. Conclusion

Conventional groundwater monitoring, reliant on on-site measurements and models, is costly and time-consuming. Spatial interpolation introduces errors, especially in distant areas, leading to inaccuracies. Satellite technology offers a more economical alternative, providing robust estimations of groundwater storage variations.

Satellites like GRACE offer free data for certain regions, enhancing accessibility for global evaluation. Integration with computational tools, GIS techniques, and models like GLDAS and WGHM improves resolution and assessment capabilities. Despite advancements, reliance on point-based measurements persists for accuracy. Integrating satellite-based models with point-based investigations can enhance policymakers' understanding. Emphasizing the importance of point-based measurements and adopting cost-effective detection technologies are crucial. In conclusion, a balanced approach incorporating both satellite and point-based measurements maximizes accuracy in groundwater assessment and management.

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Analysis of Groundwater and Surface Water Interaction through Physio-chemical and Stable Isotope δ18O and δD in Bara and Rautahat, Nepal

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Abstract

Lowlands of Terai are generally considered as huge potential of groundwater. Groundwater is the major source for domestic and agricultural activity in this area which is extracted through dug well sand pumps. This study assesses the hydro geochemistry and stable isotope δ18O and δD for groundwater surface water interaction in the region of Lal Bakaiya river. Altogether 28 samples were collected from surface water and groundwater along the region in dry season. The hydrochemical analysis-gibbs plot of Total Dissolved Solids against cation and anion presents interaction between deep and shallow groundwater only but absence of interaction of both aquifers with surfacewater. This is further validated by isotopic analysis of δ18O and δD which shows distinct isotopic characteristics and does not overlap with the other two aquifers. This result provides the need for istopic analysis for development of water policy as there is close interaction between different aquifers in the areas.

Keywords: *Terai lowlands, Groundwater hydrogeochemistry, Surface water interaction, Stable isotopes*

1. Introduction

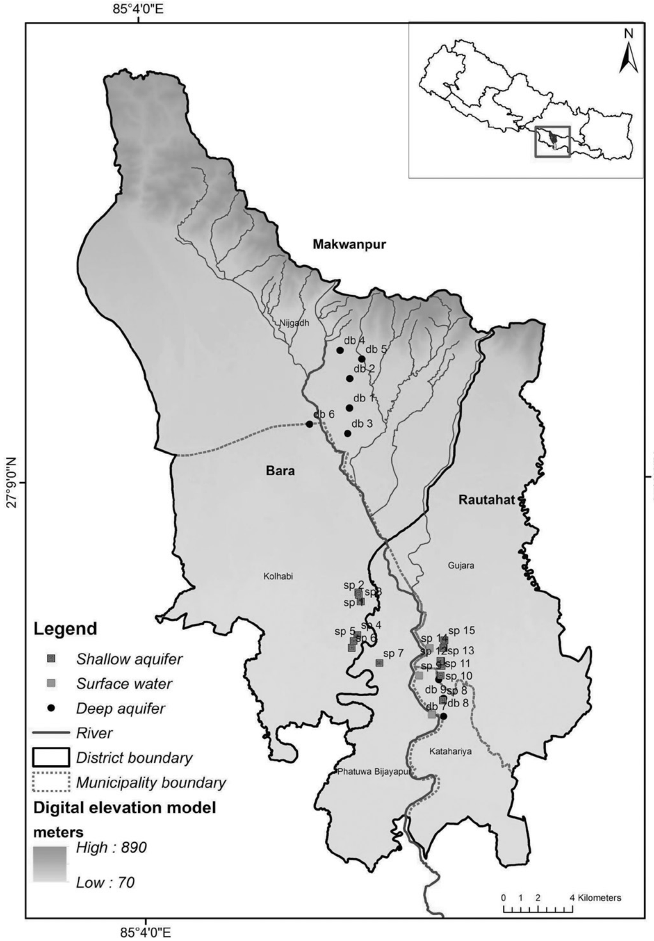
Groundwater is a crucial and cost-effective natural water source in Nepal, providing a reliable supply for domestic and irrigation needs for most of the population. Despite contributing over 50% to the overall water demand, groundwater faces significant pressure due to extraction rates exceeding recharge rates (Awale, 2017; Saha, 2018). Nepal, divided into eight physiographic regions, features the Siwalik range with a low water table and the Terai region with abundant groundwater, including both shallow and deep aquifers (Kansakar et al., 2004). Shallow aquifers are predominantly unconfined, while deep aquifers remain confined. The Bhabar zone, characterized by permeable sedimentary rocks, serves as the primary recharge zone, significantly contributing to groundwater recharge (Pathak, 2016). There is unmonitored extraction of groundwater in Terai, despite the depletion of water table more groundwater is being extracted leading to change in water chemistry and quality.

This research focused on groundwater-surface water interaction in the terai region using physio-chemistry and stable isotopic techniques, in particular δ18O and δD to identify the interconnection between stream and aquifers. The stable isotopic ratios of water (δD and δ18O) have been useful in identifying the environmental processes during groundwater recharge as well as identifying the mixing of various groundwater sources (Nakamura et al. 2007; Weyhenmeyer et al. 2002)

2. Materials and methods

2.1 Study area

The study area is Lal Bakaiya river basin (27˚15’00” N to 85˚20’00” E) located in Madhesh Province, central southern part of Nepal which flows from Bara to Rautahat covering a total basin area of 868 sq km. The initial point of the study area lies in middle siwalik and lower siwalik and maximum area lies in recent geology.



2.2 Methodology

Twenty-eight samples were collected from three sources; shallow aquifer (n=15), deep aquifer (n=10) and surface river water (n=3) based on convenient sampling within the buffer of 4 km from the river. Sampling was done from Feb 25 - Feb 27, 2019, covering a stretch of 25 km. The water samples were collected in 1 liter PET bottle for ion analysis and 60 ml narrow mouth HDPE bottle for isotope analysis by initially rinsing with sample water. The groundwater was first allowed to run for 2 minutes before sample collection and water was filled up to the brim by filtering with by 0.45 µm mill pore nitrocellulose filter to separate the suspended sediment to prevent bubbles formation. The samples were placed in boxes after collection to stop fractionation and later preserved in refrigerator.

2.3 Analytical method

For the analysis of all the ions standard procedures Trivedi & Goel (1986) and APHA (2005) were followed. Volumetric titration was conducted for the analysis of calcium and magnesium whereas, flamephotometer and spectrophotometer were utilized for the analysis of Sulphate, Nitrate, Sodium and Potassium respectively.

Stable isotope analysis ($\delta^{18}O$, δD) was performed in National Institute of Hydrology of India (NIH), Roorkee using Dual inlet isotope ratio mass spectrometer (DI-IRMS) (GV Instrument). The analyses were standardized with secondary standards developed by NIH correlated with 3 international references by IAEA; Vienna Standard Mean Ocean Water (V-SMOW), SLAB and GISP.

Isotope ratios are expressed in per mil (‰):

$\delta^{18}O$, δD = (R sample - R standard/R standard) X 1000(%)

The deuterium excess (d-excess) was obtained as d-excess = $\delta 2H - 8 \times \delta^{18}O$ (Dansgaard, 1964)

3. Results and discussion

3.1 Origin of Water

Gibbs plot showing TDS vs. anions and Cations

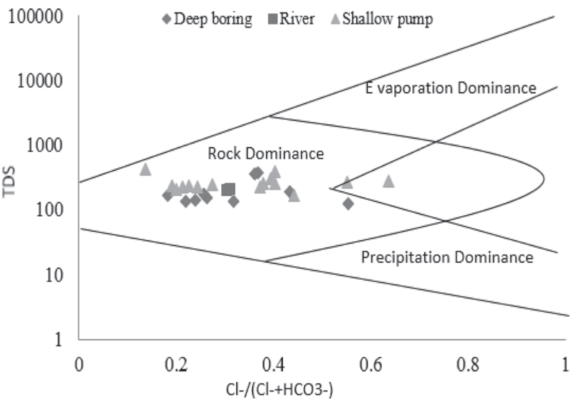


Figure 2: Gibbs plot showing TDS vs. anions

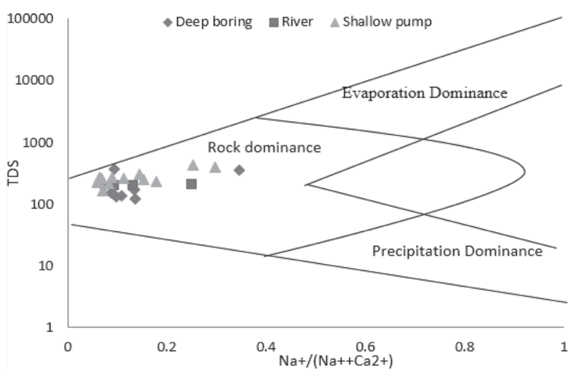


Figure 3: Gibbs plot showing TDS vs. cations

The Gibbs plot of both Total Dissolved Solids (TDS) against the concentration of Anions and Cations clearly indicates that all samples from the study region lie within the Rock dominance section. The cations range from 0.05 to 0.34, while the anions range from 0.13 to 0.63. Consequently, the origin of all three sources of water is primarily rock dominated. Specifically, the Lalbakaiya River originates from the Chure Hills, providing ample time for water to interact with the rock formations, thereby influencing its composition and characteristics.

Alternatively, it may suggest that the interaction between the shallow aquifer, surface water, and deep aquifer has led to similar TDS levels among them.

Cations vs. anions for rock weathering

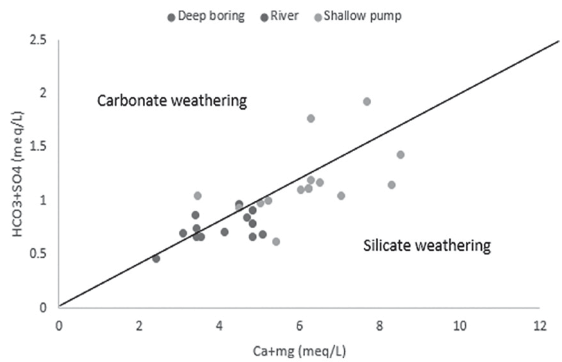


Figure 4: Cations vs. anions for rock weathering

The cations and anions found in the sample, as observed in the plot, exhibit a predominant inclination towards silicate weathering. In the case of shallow water sources, the data depicting cation versus anion concentrations appear scattered. This scattering may indicate the presence of multiple distinct unconfined aquifers or potential external chemical contamination of water within the shallow aquifer.

3.2 Groundwater processes using stable isotopic studies

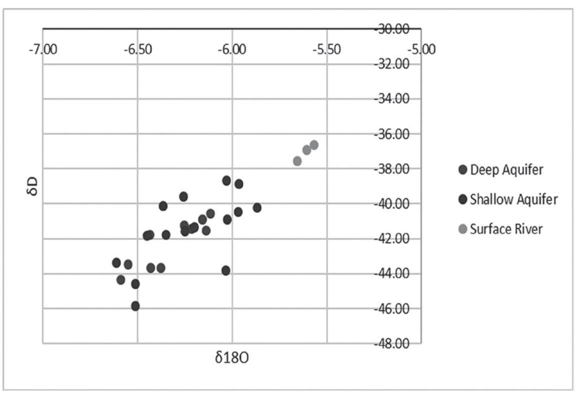


Figure 5: Isotope interaction of δ18O and δD between 3 different sources

Deep Aquifer: The $\delta^{18}O$ values range from -6.12 to -6.59, and δD values from -40.54 to -44.37. Shallow Aquifer: The $\delta^{18}O$ values range from -5.87 to -6.61, and δD values from -38.68 to 45.88.

Surface River: The $\delta^{18}O$ values range from -5.57 to -5.66, and δD values from -36.65 to -37.54. Given these ranges, it appears that the isotopic compositions of the Deep and Shallow Aquifers overlap, suggesting potential interaction or mixing between these two sources. However, the Surface River's isotopic composition is distinct and does not overlap with the other two sources. This could indicate that the Surface River water does not interact with the Deep and Shallow Aquifers, at least not significantly.

This lack of interaction could be due to various factors such as differences in local geology, separate groundwater flow paths, different recharge rates, or distinct climatic and environmental conditions influencing the isotopic compositions.

3.3 Limitations

- Limited samples from the river and absence of rainfall data restrict comprehensive analysis.
- Duration required for interaction between surface and deep water remains undetermined.
- Data collection during low water table conditions (dry season) may not capture potential interactions; comparison with wet season data could offer more insights.
- Surface water data collected solely from the southern Chure region, with similar lithological conditions.
- Only three sets of surface water data are available for comparison.

4. Conclusion

Hydrogeochemistry and isotopic analysis methods were applied to investigate the interaction between groundwater and surface water in the study area. The analysis revealed a visible interaction between the shallow and deep aquifers, indicating a dynamic exchange of water between these geological formations. However, the interaction with surface water was found to be limited, which may be attributed to the scarcity of surface water samples available for comparison, particularly when compared to the extensive data collected from the deep and shallow aquifers.

Moreover, the sampling was conducted during the dry season, which overlooked the potential influence of precipitation on the hydrological system. This oversight might have impacted the interpretation of the study's findings, as seasonal variations in rainfall can significantly affect the movement and behavior of water within the aquifer system.

The study suggests that contamination, such as agricultural runoff or leaching, present in the shallow aquifer has the potential to contaminate the deep aquifer due to their close interaction via groundwater flow pathways. Conversely, contamination in the deep aquifer could also affect the shallow aquifer through similar mechanisms. The scattered data on rock weathering in the shallow aquifer further hints at the possibility of external chemical contamination, which underscores the importance of understanding and mitigating potential sources of pollution in the region.

Additionally, the presence of excess deep groundwater in the area could have repercussions on the local shallow water sources. The imbalance in groundwater levels may lead to changes in the hydrological regime, potentially impacting water availability and quality in the shallow aquifer.

Given these findings, the study recommends further research utilizing stable isotopes to provide a more comprehensive understanding of groundwater dynamics and interactions in the Terai region. Such insights are crucial for informing the development of effective water management policies and strategies aimed at safeguarding water resources and mitigating the risks of contamination in the region.

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Understanding Groundwater-Surface Water Interaction and Potential Pathways through a Hydrogeological Conceptual Model at a Coastal Wetland

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Abstract

Marton Park wetland is a coastal wetland located on the Kurnell Peninsula in NSW, Australia. A hydrogeological conceptual model (HCM) was developed to understand the interaction of surface water and groundwater.

To gain a better understanding of the wetland, field data was gathered through the installation of monitoring wells and a three-month monitoring program. The monitoring program included continuous salinity and water level measurements using data loggers and water quality sampling for groundwater and surface water, hydraulic testing, and surface water flow measurements.

The HCM showed that groundwater levels are generally shallow, and above the base of the wetland, indicating groundwater–surface water interaction is taking place. Limited groundwater-surface water interaction is observed during periods of low rainfall, while more interaction is observed during periods of higher rainfall when groundwater levels come close to the ground surface. Groundwater is likely to contribute significant inflow to the wetland during high rainfall events.

This study demonstrated the complex interaction of surface water with groundwater and tides at the wetland. The improved hydrogeological understanding of the wetland resulting from this study will help inform future management of the wetland including managing potential contaminant migration via wetlands to down-gradient sensitive environmental receptors.

Keywords: *Hydrogeological conceptual model, Groundwater-surface water interaction, Wetland monitoring, Salinity dynamics, Wetland management*

1. Introduction

Marton Park wetland is a coastal wetland located on the Kurnell Peninsula in NSW, Australia. It feeds into Quibray Bay and the Towra Point Nature Reserve, a RAMSAR protected wetland and the largest of its kind within Greater Sydney. A hydrogeological conceptual model (HCM) was developed to understand the interaction of surface water and groundwater, providing insight into potential contamination migration pathways.

2. Materials and methods

Over the years, urbanization has shaped Marton Park wetland. Previously a saltwater system, development has restricted tidal influence and the wetland's connection to Quibray Bay (Molino Stewart Pty Ltd 2009). Currently residential and industrial areas surround the wetland and lie within its catchment area. Potential contaminants from surrounding industrial areas may enter the wetland via surface water and groundwater.

The wetland overlies the Botany Sands, a highly permeable aquifer system. The shallow groundwater levels surrounding Marton Park and the transmissive nature of the aquifer suggest strong surface water-groundwater interaction. The wetland is a potential contaminant sink, filtering pollutants before they enter the downstream RAMSAR protected reserve via an outlet drain (Molino Stewart Pty Ltd 2009).

To gain a better understanding of the wetland, field data was gathered through the installation of monitoring wells (shown on Figure 1) and a three-month monitoring program. The monitoring program included continuous salinity and water level measurements using data loggers and water quality sampling for groundwater and surface water, hydraulic testing, and surface water flow measurements at the inlet (MP01) and outlet of the wetland (MPSW01).

Figure 1: Site location, monitoring locations and cross-section

Field data was analysed and combined with a review of publicly available information to create a HCM, presented in Figure 2. The HCM is a summary of the current understanding of the groundwater system and the influences on it, including ‘natural’ processes, such as recharge and discharge as well as man-made stressors. The HCM will assist in understanding possible future changes to the wetland as a result of groundwater-surface water interaction.

3. Results and discussion

The HCM in Figure 2 shows that groundwater levels are generally shallow, and above the base of the wetland, indicating groundwater–surface water interaction is taking place. The groundwater and surface water hydrographs show a clear response to rainfall with groundwater levels taking somewhat longer to return to baseline levels (Figure 3). Long-term groundwater levels measured at a government monitoring bore at Marton Park showed a maximum seasonal fluctuation between 0.87 and 1.68 metres Australian Height Datum (mAHD) from April 2002 to May 2021. Limited groundwater-surface water interaction is observed during periods of low rainfall, while more interaction is observed during periods of higher rainfall when groundwater levels come close to the ground surface as observed in the hydrograph of PMW03 (higher than surface water level at MPSW01). Groundwater is likely to contribute significant inflow to the wetland during high rainfall events.

The major ion chemistry pie charts (Figure 2) show the relative concentrations of major ions and can be used to determine water type and discern processes affecting water samples including precipitation or dissolution, mixing and ion exchange. The results show a clear difference in water types between surface water and groundwater. The dominant ions for groundwater are bicarbonate (HCO3) and calcium (Ca), while the dominant ions for surface water vary somewhat across the monitoring locations with sodium (Na) and chloride (Cl) dominance at the outlet of the wetland and an increase in bicarbonate dominance at the centre of the wetland (MP06) and the northeast monitoring location (MP01). The salinity of groundwater is lower than surface water. The relatively higher salinity of surface water in the wetland may be related to the subtle and slow inflow of brackish water through the outlet drain of Marton Park wetland during high tide. The invert level of the outlet drain is lower than the high tide level, but very close to the surface water level at MPSW01 (Figure 3). A strong tidal influence was not observed in the hydrographs, however the salinity graphs at MPSW01 and PMW03 showed a salinity increase occurring at the same time as the highest monthly tides. The higher salinity of surface water at Marton Park may also be related to evapo-concentration.

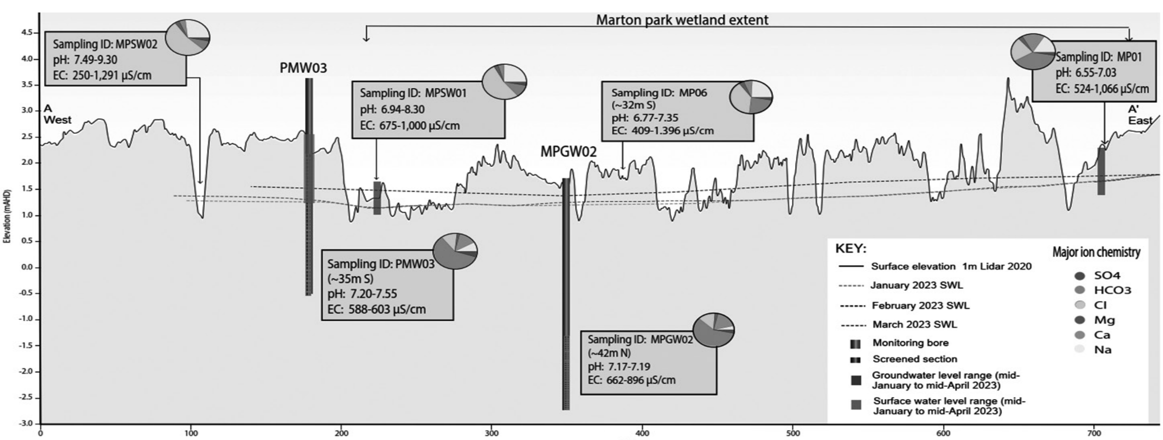

Figure 2: Conceptual hydrogeological cross-section A-A'

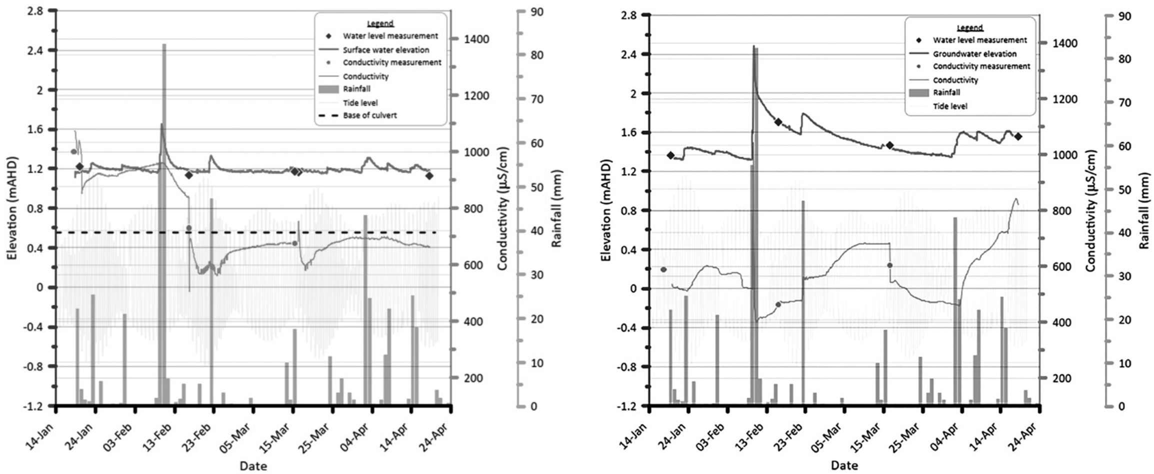

Figure 3: Hydrographs for PMW03 (groundwater well) and MPSW01 (surface water monitoring location)

4. Conclusion

This study demonstrated the complex interaction of surface water with groundwater and tides at Marton Park wetland. The improved hydrogeological understanding of the Marton Park wetland resulting from this study will help inform future management of the wetland including managing potential contaminant migration via wetlands to down-gradient sensitive environmental receptors.

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Springwater Management, Agriculture, and Resilient Livelihoods in the Midhills of Nepal (SPAN)

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Abstract

Natural springs serve as the mainstay of life and livelihood in Nepal, and are the primary sources for drinking needs, irrigation and livestock. However, the significant decrease in available springwater resources have raised serious concerns about the sustainability of mountain agriculture, particularly springwater-fed agriculture and local livelihoods in Nepal. The project (2024-2028) aims to improve springwater management in the midhills of Nepal for inclusive and resilient rural livelihoods. The broader benefits of the project are improved federal, provincial and local government capacity to promote socially inclusive and gender-aware springwater management and agricultural livelihoods. The project intends to achieve this by piloting participatory socio-technical solutions, participatory learning, generating transdisciplinary knowledge, exploring governance options, building stakeholder capacity, and mainstreaming springshed management into public policy and development planning. The project will contribute to the end-of-project outcome to promote socially inclusive and gender-aware springwater management and agricultural livelihoods through enhancing holistic knowledgebase of innovative and inclusive springwater management pathways, supporting public policy and development planning, and empowering communities. With enhanced capacity and an inclusive approach, governments will be better equipped to address the water management challenges in the Nepali midhills and support rural development.

Keywords: *Springshed management, Agricultural livelihoods, Sustainable agriculture, Inclusive governance, Capacity building*

Sustainable Water Management in Madesh Province: "Stakeholders mapping on Integrated Water use in Lahan Municipality"

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Abstract

Nepal had sectoral policies on use of water, such as- policies on hydropower (2001), irrigation (2013), water supply and sanitation (2014) and water induced disaster management (2015), it lacked an integrated policy to guide the use and management of these sectors. To fulfill this gap, the government of Nepal (GoN) issue the National Water Resources Policy in July 2020. Water security is a critical issue in many regions around the world, including Mahesh Province in Nepal. As looking through the role and responsibility of different stakeholders in 3 layers of government by small scale study in local level government, it is noticed that major role and responsibilities on different stakeholders and also requirement of require policy and guideline for strengthening on WASH specially Water Security outcomes in all three tiers of government.

Water security in Nepal is a critical issue that involves multiple tiers of government, namely the federal, provincial, and local levels. Analyze water security concerns and the roles of each tier of government in addressing them.

Overall, effective collaboration and coordination among the federal, provincial, and local governments are essential for addressing water security challenges in Nepal and ensuring equitable access to clean and sustainable water resources for all citizens.

Keywords: *Water security, WASH policy, WASH stakeholders*

HIGH LEVEL PANEL DISCUSSION

Towards Inclusive Groundwater Development and Management in Nepal: Addressing the Barriers

High Level Panel: Towards Inclusive Groundwater Development and Management in Nepal: Addressing the Barriers

Moderator: Prof. Dr. Vishnu Prasad Pandey, *CWRS, IOE, TU*
Panelists:
Ms. Tripti Rai, *Country Director, Oxfam in Nepal*
Dr. Manohara Khadka, *Country Representative (Nepal), IWMI*
Dr. Dol Prasad Chapagain, *Deputy Manager, KUKL*
Prof. Dinesh Pathak, *Department Head, CDGLTU; President, NHA*

Introduction:

The panel discussion on inclusive groundwater development and management in Nepal convened a diverse group of experts from academia, government, and development organizations. Led by Prof. Vishnu Prasad Pandey, the session delved into the complexities and challenges surrounding groundwater management in Nepal, emphasizing the imperative of inclusivity in decision-making processes. It was one of the focal points of the Groundwater Symposium 2024. This session brought together experts from academia, government, and development organizations to delve into the complexities and imperatives of groundwater management. Key themes such as inclusivity in decision-making processes, the interconnectedness of structural and mindset challenges, and the role of academic institutions in research and capacity building were thoroughly examined. The insights shared during this discussion underscored the critical need for comprehensive data, differentiated solutions, and institutional coordination to foster sustainable groundwater management practices in Nepal.

Key Discussions:

Understanding Inclusivity: Dr. Manohara Khadka, Country Representative IWMI-Nepal, emphasized six key dimensions for ensuring inclusive groundwater development and management in Nepal during the discussion. She highlighted the critical importance of involving diverse actors, including marginalized groups such as women, LGBTQ+ individuals, and smallholder farmers, in decision-making and planning processes related to groundwater resources. Dr. Khadka stressed the need to ensure equitable access to resources and decision-making power among all stakeholders involved in groundwater management, including considerations of access to technology and information. Moreover, she emphasized the necessity of dedicated investment in capacity-building activities to enhance understanding of social challenges and promote inclusive groundwater development projects. She also underscored the importance of explicit policies dedicated to groundwater management that address complexities and ensure the inclusion of voices typically marginalized in planning and decision-making processes. Additionally, she emphasized the integration of social, technical, and institutional knowledge to address groundwater issues from interdisciplinary perspectives, including engineering, social sciences, and gender and social inclusion. Finally, Dr. Khadka emphasized the crucial role of empowering local governments in groundwater management, advocating for their empowerment through scientific evidence, capacity-building, and strong relationships with local communities and institutions. She stressed the significance of multi-stakeholder partnerships involving private sectors, research institutions, and community organizations to foster a commitment to inclusivity in groundwater governance. Throughout her remarks, Dr. Khadka highlighted the importance of commitment to inclusivity, noting that behavioral issues could hinder progress even in the presence of regulations and policies.

Dr. Manohara Khadka also highlighted the importance of developing a collaborative platform akin to the N-WASH for inclusive groundwater management in Nepal. She emphasized the need for such a platform to engage various stakeholders, including state and non-state actors, academia, research institutions, and the private sector. Dr. Khadka underscored the importance of government leadership and ownership to ensure the reliability and trustworthiness of the platform, similar to N-WASH. She suggested learning from existing multi-stakeholder platforms at the local government level for groundwater management and data collection.

Factors Contributing to Exclusion: Ms. Tripti Rai, Country Director of Oxfam in Nepal, provided insights into the status of inclusivity in groundwater management from a practitioner's perspective. She highlighted three key factors contributing to exclusions in Nepal: geography and topography, ethnicity and caste, and socio-demographic factors such as gender, age, and disabilities. Ms. Rai emphasized that these factors intersect to exacerbate marginalization and hinder meaningful participation in decision-making processes related to groundwater management. She also underscored the link between resources and power dynamics, stating that without understanding the political economy of decision-making, barriers to inclusion will persist. Ms. Rai stressed the importance of developing strategic plans to address the layers of exclusion faced by different groups and implementing intentional strategies for inclusive groundwater management. When asked to quantify the current state of inclusivity in groundwater management, Ms. Rai expressed that, based on her experiences working with communities in various regions of Nepal, inclusivity remains at a very minimal level. She cited examples of communities lacking access to safe water and facing challenges in influencing policies or investments related to groundwater management, indicating a significant gap in institutional mechanisms for regulating groundwater at the local level. Overall, Ms. Rai's assessment suggests that Nepal still has a long way to go in achieving meaningful inclusivity in groundwater management practices.

Regarding the issue of mindset of the actors in terms of inclusion, Dr. Rai identified two angles: ignorance and preconceived notions. She emphasized the importance of organizing issues that communities prioritize to foster meaningful engagement. Dr. Rai shared experiences from working with vulnerable communities, highlighting the need for awareness-building around water quality issues and affordability of piped water supply. She also noted the role of policy and institutional frameworks, emphasizing the need for political will to address regulatory gaps and ensure transparent management of groundwater resources. Her insights provided a clear message based on practical field experiences, advocating for collaborative platforms and proactive measures to address mindset barriers and promote inclusive groundwater management in Nepal.

Structural and Mindset Issues: Dr. Dol Prasad Chapagain, Deputy Manager at KUKL, emphasized the interconnectedness of structural and mindset issues in hindering inclusive groundwater development and management policies. He acknowledged the critical role of stakeholders' mindsets, including policymakers, in shaping groundwater management policies and practices. Dr. Chapagain highlighted that both structural issues, such as institutional and policy gaps, and mindset issues, including social values and norms, contribute to barriers in achieving inclusivity. He emphasized the importance of addressing these gaps through a feedback loop system between structural and mindset issues to ensure effective implementation of policies. Additionally, Dr. Chapagain suggested establishing a comprehensive groundwater monitoring system, implementing digital systems, increasing investment in the sector, and strengthening governance and inclusive policies. He underscored the need for further research to differentiate between mindset and instrumental issues affecting policy implementation. In response, the moderator acknowledged Dr. Chapagain's insights, highlighting the importance of considering policies not only from a technical viewpoint but also in addressing mindset issues through capacity building and other measures at the policy level.

Academic Role in Groundwater Management: Prof. Dinesh Pathak, Department Head at CDGL-TU and President of NHA, highlighted the crucial role of academic institutions in addressing challenges related to groundwater management through research, education, and capacity building. He emphasized that academic institutions cannot function effectively without proper institutional arrangements. Prof. Pathak stressed the need for an authorized government body responsible for monitoring, policymaking, and evaluation in groundwater management. He highlighted the lack of comprehensive data on groundwater resources nationwide and the need for continuous data production based on scientific and professional standards. Prof. Pathak emphasized the importance of differentiated solutions based on location-specific hydrogeological systems and the necessity for developing guidelines for groundwater management tailored to different regions. He also underscored the fragile nature of groundwater exploitation in mountainous areas and the potential disturbances caused by drilling activities. When asked about the status of data availability and research, Prof. Pathak indicated that while there is sufficient information available for the southern region, data availability is limited in mountainous areas. He emphasized the importance of conducting investigations at representative locations to improve understanding and management of groundwater resources in these regions. Overall, Prof. Pathak highlighted the critical need for comprehensive data, research, and differentiated solutions to address the complexities of groundwater management effectively.

Similarly, Prof. Dinesh Pathak highlighted two implementable solutions for inclusive groundwater management. Firstly, he suggested a top-down approach, where organized and authorized bodies facilitate the transfer of inclusive groundwater management policies from higher levels to lower levels, such as municipalities or rural municipal levels. This approach would involve representation from user groups or local bodies to ensure inclusivity in policy formulation and implementation. Secondly, Prof. Pathak proposed a bottom-up approach, where the demand for groundwater evaluation originates from local communities and is communicated to higher levels for policy revision and implementation. In this approach, there would be a need for studies, understanding, and database preparation, which could be facilitated by top-level institutions like universities or academic institutions. Prof. Pathak emphasized the importance of addressing local demands and leveraging the expertise of various organizations, including non-governmental organizations and academic institutions, to achieve inclusive groundwater management.

Key Messages:

The panel discussion on inclusive groundwater management underscored the importance of proactive measures and enablers to address structural and mindset challenges. Fundamental elements such as database research and capacity building were identified for effective intervention design and implementation. Early attention to inclusivity in project design, coupled with comprehensive understanding of available resources, was emphasized through hydrogeological mapping and groundwater accounting. Utilizing citizen science approaches and fostering community involvement were highlighted as essential strategies for achieving inclusivity and sustainability. Elevating the profile of groundwater on political and economic agendas, along with prioritizing community needs through dedicated policies and institutions, emerged as critical steps toward achieving inclusive groundwater management. Ultimately, the key takeaway was the collective commitment to collaborative efforts and community-centered approaches in advancing groundwater management practices.

Conclusion:

The panel discussion provided valuable insights into the complexities of inclusive groundwater development and management in Nepal. It underscored the need for multi-dimensional approaches that address structural, attitudinal, and policy-related barriers. Moving forward, collaborative efforts among stakeholders from academia, government, NGOs, and communities will be crucial in fostering sustainable groundwater practices and ensuring inclusivity in decision-making processes. This discussion concluded with a comprehensive exploration of actionable solutions and key considerations put forward by each panelist. Prof. Dinesh Pathak advocated for both top-down and bottom-up approaches, stressing the importance of organized bodies facilitating the transfer of inclusive policies while also considering local community demands. Dr. Dol Prasad Chapagain emphasized community-based approaches and the need for equitable infrastructure, highlighting the inadequacy of current groundwater indicators. Ms. Tripti Rai, proposed innovative solutions, including citizen science approaches and the integration of indigenous knowledge, to enhance inclusivity and address urgent climate-related challenges. Dr. Manohara Khadka underscored the importance of designing projects with inclusivity in mind, stressing interdisciplinary cooperation and capacity building among stakeholders. Overall, the discussion highlighted the significance of proactive measures, policy support, and community engagement in achieving sustainable and inclusive groundwater management practices.

POSTER PRESENTATION

Assessing the Groundwater Quality in Kathmandu Valley through the Water Quality Index

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1. Introduction

Groundwater is a reliable source of drinking water in the Kathmandu Valley (Valley). Rapid population growth and swift urbanization have placed a significant stress on the groundwater resources of the Valley. Currently, groundwater accounts for 50-70 % of the overall water supply in the Valley (ICIMOD, 2007). However, natural and anthropogenic activities such as disposal of waste and chemicals, direct sewage contamination, and inappropriate agricultural techniques have deteriorated the quality of groundwater. As such, accessing the status of the groundwater quality and quantity is vital for sustainable water resource management. The Water Quality Index (WQI) emerges as an effective approach for monitoring groundwater quality, as it condenses diverse and intricate sets of water quality parameter data into a singular numerical value (Das and Choudhary, 2021). Likewise, analyzing the pattern of groundwater level fluctuations is applicable in inspecting the degree of stress posed on the groundwater source within a certain geographical area (Long et al., 2020). Therefore, this study aims to analyze the groundwater level fluctuation and simultaneously evaluate the groundwater quality status by employing WQI during the dry period in the Valley.

2. Methodology

2.1. Study area

Kathmandu Valley is situated in the eastern part of Nepal, with coordinates ranging from 27°42′14″ - 27°42’14″ N latitude and 85°18′31″ - 85.30861°E longitude. The valley ranges in elevation from approximately 1350 m in the city center to 2800 m in the surrounding hills elevation (Shrestha et al. 2016). The fertile soil and diverse topography of the valley support a wide range of agricultural activities, which is further benefited by the warm and temperate climate with substantial rainfall in the monsoon season (Prajapati et. al, 2021). Approximately 60% of the water demand out of 472 MLD is fulfilled by groundwater in the Valley. However, the centralization in the Valley has overexploited the groundwater resources deteriorating both its quality and quantity. Emphasizing the groundwater, it is crucial to study the status of groundwater in the Valley.

2.2 Data collection

Groundwater samples were collected from the 59 spatially located shallow wells in the Valley during pre-monsoon season (April-May) in 2023. The laboratory analysis was performed at the High-Powered Commission for Integrated Development of Bagmati Civilization (HPCIDBC). Various physicochemical water quality parameters, including pH, turbidity, total alkalinity, total hardness, chloride, ammonia, nitrate, phosphate, iron, manganese, and a microbiological parameter - fecal coliform, were determined. Likewise, the groundwater level from respective wells in the Valley was measured using a measuring tape (m) . Apart from this, a land use map of 2019 prepared by ICIMOD was also used to assess the groundwater quality status in different land use.

2.3 Data analysis

2.3.1 Groundwater level

A color-coded map was created using the Quantum Geographic Information System (QGIS). Then, the variations of water levels within different geographical regions were compared based on land use.

2.3.2 Water quality analysis

The parametric values obtained from laboratory analysis of these water quality parameters were compared with the guidelines set by the National Drinking Water Quality Standard (NDWQS), 2005, published by the Ministry of Physical Planning and Works, Nepal and the World Health Organization. (2017). Guidelines for Drinking-water Quality, 4th Edition.

Table 1: Concentration limits for various water quality standards

S.N.	Parameter	Units	Standard limit	Recommending agency	Unit weightage
1	pH		6.5 - 8.5	NDWQS	0.1
2	Turbidity	NTU	5 (10)	NDWQS	0.1
3	Total Alkalinity	mg/l	500	NDWQS	0.1
4	Total Hardness	mg/l	500	WHO	0.1
5	Chloride	mg/l	250	NDWQS	0.1
6	Ammonia	mg/l	1.5	NDWQS	0.1
7	Nitrate	mg/l	50	NDWQS	0.1
8	Phosphate	mg/l	5	WHO	0.1
9	Iron	mg/l	0.3 (3)	NDWQS	0.1
10	Manganese	mg/l	0.2	NDWQS	0.1
11	F. Coliform	CFU/100 ml	0	NDWQS	0
	Total weightage				1

The Weighted Arithmetic Index method (Brown et al., 1972) was used for the calculation of WQI. For the calculation, equal weightage was assigned to each parameter due to the absence of the standard weightage parameters in the context of the Valley. The water quality status of monitoring wells was categorized into five ranks: Excellent (0 - 25), Good (25 - 50), Poor (50 - 75), Very Poor (75 - 100), and Unsuitable for drinking (above 100). This categorization simplifies the assessment of overall water quality.

3. Results and discussion

3.1 Groundwater level

The groundwater level within the valley was seen to fluctuate between 0.24 m to 12.16 m, with an average depth of 4.27 m in the month of April-May. Approximately 71% of the wells had water levels shallower than 5 m, while three wells; at Tokha, Nakkhipot, and Sahidpark, had depths exceeding 10 m. Notably, most of the wells located in the cropland areas were shallow, while those in the build-up region were deeper. Specifically, 13 out of 17 wells with depths greater than 5 m were within the built-up areas.

The increased depth of groundwater level in the central built-up land use can be associated with sealed ground cover, which hinders groundwater recharge (Prajapati et al., 2021). Moreover, the escalating demand for water in urban centers has led to excessive groundwater extraction, placing significant pressure on groundwater resources (Lamichhane and Shakya, 2020).

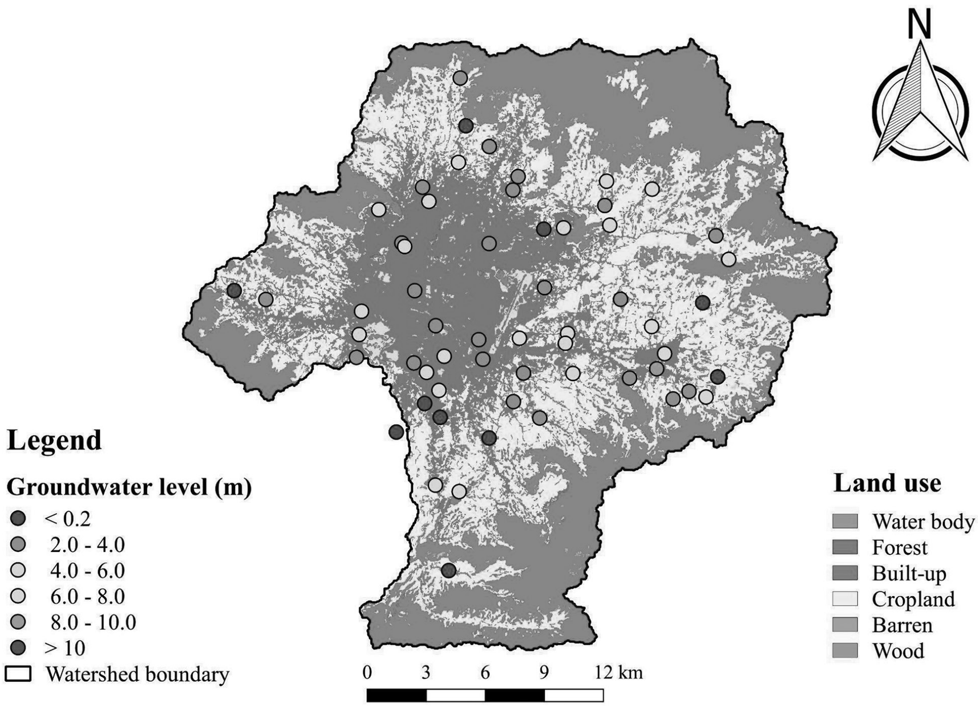

Figure 1: Depth of groundwater below the ground surface

3.2 Comparing water quality with NDWQS/ WHO standards

Out of the 59 wells examined, only two (at Thecho and Kupondole) met all of the NDWQS/ WHO standards during the study period. Water quality parameters such as pH, total hardness, chloride, and nitrate were within the acceptable limits for drinking water purposes. However, turbidity (33%), total alkalinity (2%), ammonia (24%), phosphate (2%), iron (41%), manganese (25%), and fecal coliform (80%)

exceeded the water quality standards in the Valley.

In built-up regions, 79% of the wells (n=38) exceeded the NDWQS standard for fecal coliform. The direct interaction with the poorly managed drainage system and interaction with the contaminated streams create favorable conditions for the proliferation of fecal coliform (Pant, 2011; Warner et al., 2007). The Valley experiences high anthropogenic intervention leading to increased organic waste disposal and subsequent higher concentrations of ammonia, manganese, total alkalinity, and phosphate (Shrestha et al, 2023).

Likewise, in the cropland region, the major pollutant of groundwater pollution is nitrogen-based chemical fertilizers used to enhance crop productivity. Khadka (1993) and Krapac et al. (2002) suggest that nitrogen-based compounds such as nitrate, nitrite, and ammonia originate from chemical fertilizers and domestic effluents. Additionally, fecal contamination from livestock and its direct use as fertilizer promotes the growth of fecal coliforms (Malla et al., 2018) in agricultural areas.

High turbidity was observed in approximately 35% of the wells (both agricultural area and built-up area). High turbidity is associated with suspended matter (Bright et al., 2020) and is caused due to clay content (Fahimah et al., 2023). Similarly, elevated concentrations of iron were mostly found in the deeper wells (> 5m) regardless of the land use type. Reduced oxygen availability in the deep aquifer increases the amount of reduced iron (Pant, 2011). Prolonged exposure to iron can lead to various health issues such as liver, heart, and lung diseases as well as diabetes mellitus, hormonal abnormalities, and a dysfunctional immune system (Gurzau et al., 2003).

Similarly, for one well in the forest area, all parameters met the standards of NDWQS/ WHO except for ammonia (2.5 mg/l) and iron (1.17 mg/l).

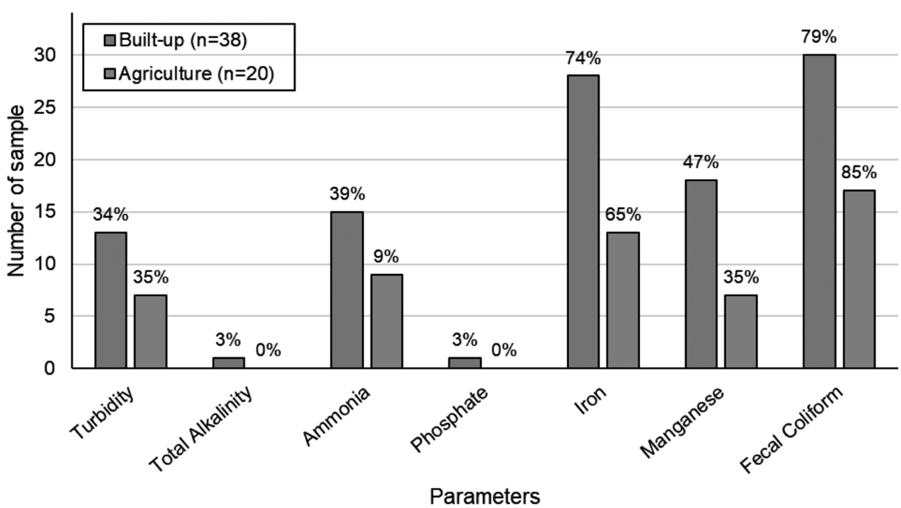

Figure 2: Number of samples exceeding NDWQS/ WHO standards for drinking water

3.3 Water quality index

The values of the Water Quality Index (WQI) indicated that the groundwater from most of the studied wells in the central and eastern regions of the Valley was not suitable for drinking purposes, irrespective of their geography and depth. Likewise in the northern part of the Valley, the water quality ranged from good to poor, except at Tokha (unsuitable for drinking) and at Nagarkot and Thali (very poor). The differences in the water quality status are likely due to the thinly populated northern region than the densely populated central region. According to Khatri and Tyagi (2014), anthropogenic influences lead to increased concentrations of heavy metals, mercury, coliforms, and nutrient loads in groundwater.

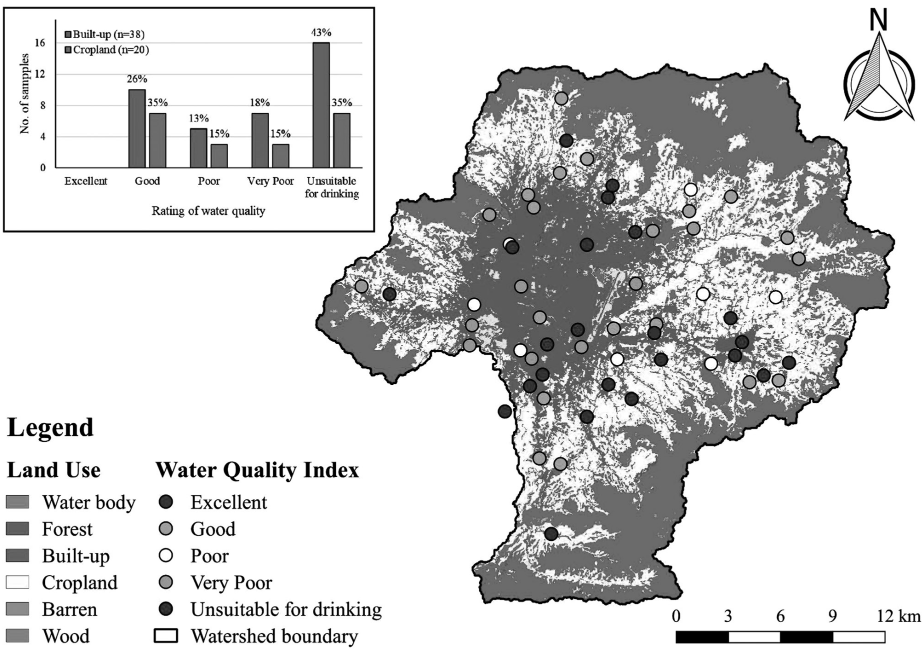

Figure 3: Water quality status (WQS) of groundwater samples of the study area. a) Bar graph showing the number of samples with different water quality status b) Spatial map showing the variation of WQS

4 Conclusion

The study provides an overview of the groundwater status during the pre-monsoon period in the Valley. The groundwater levels tend to be deeper in the built-up areas (meaning depth of 4.63 m compared to 3.49 m in croplands) due to human interference. The water quality index of the examined wells showed the following distribution: Excellent - 0%, Good - 24%, Poor - 10 %, Very Poor - 14%, and Unsuitable for drinking purposes - 32%. Seven out of eleven water quality exceeded the acceptable limits of NDQWS/WHO guidelines for drinking water.

High concentrations of ammonia, iron, and manganese were observed, along with poor turbidity and the presence of fecal coliform. This degradation in water quality is attributed to increasing organic waste disposal including improper irrigation techniques.

The findings of the study highlight the need for the adoption of sustainable agricultural practices, filtration, and chemical treatments, as well as the promotion of community-based water management to mitigate groundwater contamination and improve water quality for safe drinking purposes. Likewise, there are many other parameters to be considered to ensure purity of drinking water, hence the findings underscore the need for further detailed studies. Therefore, there is an urgent need to implement effective groundwater strategies to prevent further deterioration and potentially purify groundwater resources.

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Citizen Science-based Groundwater Level Monitoring in Kathmandu Valley: Investigating Citizen Scientist Performance and Groundwater Level Fluctuations

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1. Introduction

Groundwater resources play a pivotal role in ensuring livelihood security worldwide, offering a dependable source of high-quality water for human use (UNESCO, 2012). Groundwater, being deep percolated water through soil pores, stands out as a reliable alternative to irregularly tapped water supply systems, often free from pollutants. Effective and sustainable management of these resources holds the key to addressing prevalent water scarcity issues in Kathmandu Valley. However, rapid population growth, excessive extraction, significant land-use changes, and sewage contamination have heightened groundwater vulnerability, leading to a drastic lowering of water tables and deterioration in quality. According to ICIMOD (2007), approximately 79% of the Valley's water demand (60-70% in the dry season) is met by groundwater, exacerbating pressure on these resources and resulting in declining water tables. Despite these challenges and the critical importance of groundwater, monitoring efforts in the region have been sporadic, impeding effective management. Therefore, employing citizen science, a participatory and feasible approach, could significantly enhance groundwater monitoring and address associated issues. As such, Smartphones For Water Nepal (S4W-Nepal) has taken an initiative by mobilizing citizen scientists to monitor groundwater in Kathmandu Valley. This study evaluates the consistency and efficacy of the citizen science approach in groundwater level monitoring. Concurrently, it aims to explore spatial and temporal fluctuations in groundwater levels across Kathmandu Valley and determine its relationship with land use patterns.

2. Materials and methods

2.1 Study area

Kathmandu Valley, the urban center of Nepal, is an intermontane basin located between 85°11′31″ to 85°31′38″ East longitude and 27°32′13” to 27°49′10″ North latitude (Dahal et al., 2019). This bowl-shaped Kathmandu Valley spreads over an area of 664 square kilometers (km2) (Dahal, 2019). In Kathmandu Valley, the groundwater basin covers an area of 327 km2 and has an average elevation of 1340 meters above mean sea level. The mean annual precipitation is 1533 mm per year, and Kathmandu Valley receives more than 80% of the annual precipitation in the monsoon season.

As per the census of 2011, the total population is about 2.5 million (Gautam and Prajapati, 2014). Approximately 60% of Kathmandu Valley's population depends on groundwater to fulfill their water requirements (Shrestha et al., 2020). The status of groundwater resources management is inferior in Kathmandu Valley as there are no regulations for groundwater usage and no interventions for groundwater management (Pandey et al., 2011). There is a critical need to monitor and manage the groundwater in Kathmandu Valley, considering the increasing demand for groundwater.

2.2 Data Collection

The monthly groundwater level data, depth below the ground surface, was collected for four years (2020 - 2023) using a measuring tape. Citizen scientists were mobilized to take the measurements using an Android application called Open Data Kit Collect. The data generated by the citizen scientists were quality-controlled by comparing the entered groundwater level values with their corresponding photographs to correct errors in the manual python-based webapp. The two 'Quality Control flags' i.e., 'Checked good' represents the measurements in which the photograph and entered value match, and 'Checked corrected' are the ones in which measurement values have to be corrected based on images uploaded. Furthermore, the land use map of 2020, from the ICIMOD data portal, was also procured for understanding land use linkage to groundwater.

2.3 Data analysis

2.3.1 Evaluation of the performance of the citizen scientists

The performance of the citizen scientists was determined by evaluating the regularity and error percentage. The regularity of the citizen scientists was measured by using the following formula:

$$Regularity\ of\ citizen\ scientists$$
$$= \frac{Total\ number\ of\ measurements\ taken}{Total\ number\ of\ expected\ measurements} \times 100\ \%$$

The error percentage of the citizen scientist measurements is determined by the following formula:

$$Error\ percentage$$
$$= \frac{No.of\ checked\ corrected\ measurements}{Total\ of\ measurements\ taken} * 100\%$$

2.3.2 Spatial and temporal variation of shallow groundwater level

The spatial and temporal, i.e. monthly, seasonal, and annual variation of the groundwater levels of Kathmandu Valley was analyzed using the collected data. The monthly variation of the groundwater level was determined by preparing the heat map using Python. Likewise, the seasonal and annual variation of the groundwater level was evaluated by preparing interpolated maps in QGIS.

2.3.3 Linkage between land use and groundwater

Based on the land use map of 2020, the land use surrounding each monitoring well was determined using buffering techniques in ArcGIS. The zone of contribution for recharge was defined as a radius of 200 meters, within which the dominant land use was identified as the land use corresponding to the respective wells. In order to understand the relationship between land use and groundwater, a box plot was generated using Python.

3. Results and discussion

3.1 Performance of the citizen scientists

Figure 3 (a) illustrates the percentage regularity of citizen scientists involved in monitoring. The graph displayed a high interquartile range of 68% in 2020, followed by approximately 30% in 2023, indicating significant variability in regularity. The COVID-19 pandemic notably impacted data regularity among citizen scientists in 2020. In 2021 and 2022, motivational approaches such as reminder texts, follow-up calls, and acknowledgment texts led to an increase in regularity (average data regularity > 91%). Additionally, improved data dissemination and the distribution of water quality reports from monitoring wells further encouraged citizen scientists. However, in 2023, regularity decreased once again (average data regularity = 83.46%), possibly due to decreased motivation among previous citizen scientists. To address such decline, citizen scientists' motivation approaches should be undertaken regularly. Likewise, figure 3 (b) depicts the error percentage of citizen scientists that sent incorrect data, which was corrected during quality control by S4W-Nepal members i.e., 'Checked correct' ones. There was an increase in the percentage of citizen scientists sending incorrect data from 2020 to 2021. The increase in error percentage could be attributed to newly recruited CS sites added in those years. To address this, follow-up calls for instructing the citizen scientists properly regarding the data collection process were performed on a regular basis. As a result, the error percentage has decreased from 2022 to 2023. The main errors made by the citizen scientists included measurements with errors ranging from ± 0.1 to 1 m. Blurred and missing images of the measurements in the ODK forms also hindered the quality control of the data. Overall, the error percentage is very low (<8%), which shows that the data collected by the citizen scientists is reliable.

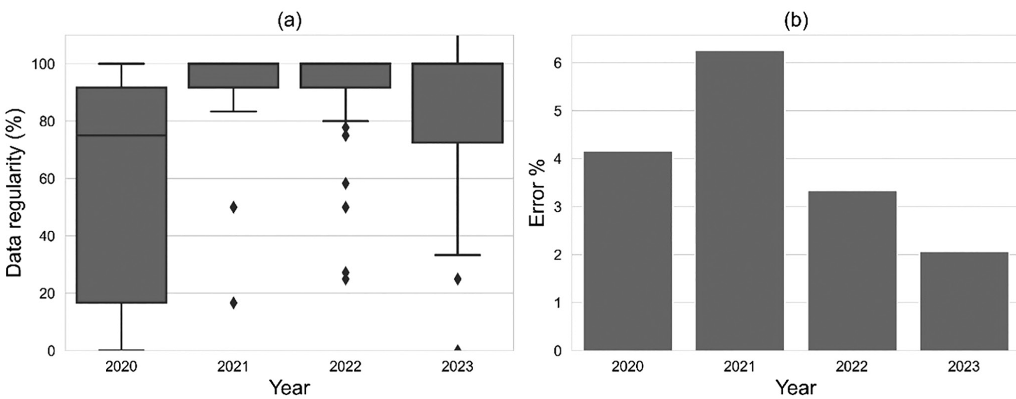

Figure 3: Regularity of citizen scientists (a) and error percentage of CS (b) from 2020–2023.

3.2 Spatial and temporal variations of the groundwater level

3.2.1 Monthly variations

From 2020 to 2023, depth below ground surface in the shallow groundwater monitoring wells of S4W-Nepal exhibited significant variability, ranging from -0.380 to 15.882 meters. The mean groundwater depth across this period was recorded at 3.798 meters, with a standard deviation of 2.530 meters. Notably, these measurements signify the depth of groundwater from the ground surface, where lower values indicate higher groundwater levels and higher values denote lower groundwater levels. The monthly fluctuations in groundwater levels across 64 monitoring wells of S4W-Nepal are depicted in the heat map (Figure 4). A discernible pattern emerges, revealing shallow groundwater levels during the monsoon months, depicted by hues tending towards blue. As the monsoon season recedes, the groundwater levels gradually decrease; however, this decline is moderated by substantial recharge, which persists into the post-monsoon months, particularly October and November (Prajapati et al., 2021). During the winter months (November, December, and January) and early pre-monsoon periods, there is a noticeable deepening of groundwater levels, illustrated by colors shifting toward red on the heat map. Similar results i.e., the higher influence of monsoon rainfall and its role in groundwater recharge were also found in the studies conducted by Lamichhane and Shakya et al., (2020); Abdullahi and Garba, (2015); Palanichamy, (2017); Tesfaldet and Puttiwongrak, (2019). It is noteworthy that the groundwater depth in three monitoring sites - GW001, GW016, GW029, GW038, and GW041 - remained consistently below 3 meters in the 85th percentile of the month. These sites are predominantly situated in areas dominated by agriculture. Conversely, in one well, GW012, the groundwater level exceeded 8.5 meters in the 85th percentile of the month. Notably, this well is located in low-built-up areas. However, the primary reason for the declining groundwater level is attributed to over-extraction by the local community.

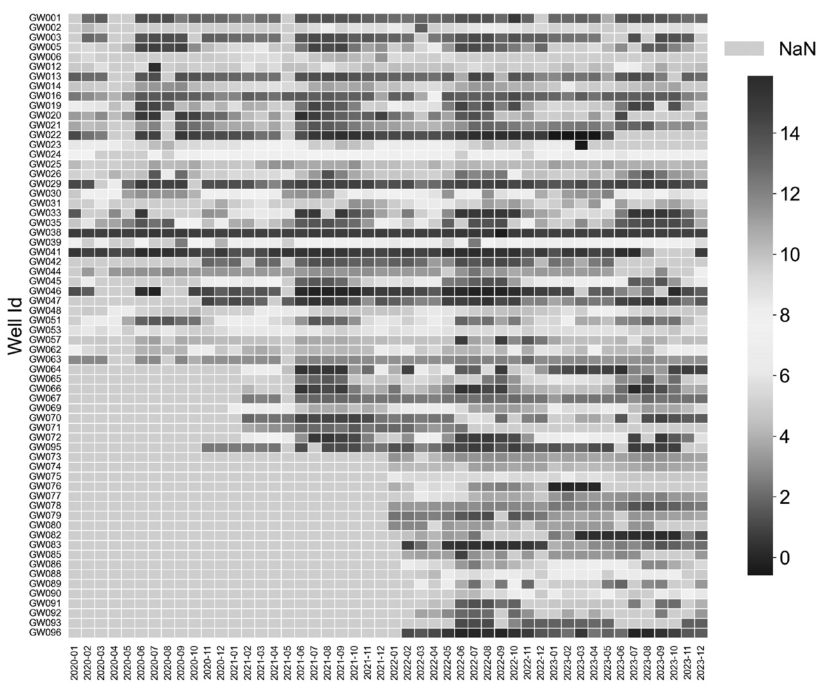

Figure 5: Heat map showing monthly fluctuations of groundwater levels

3.2.2 Seasonal variations

Figure 3 illustrates the spatial and seasonal dynamics of groundwater levels over the four-year period. Throughout Kathmandu Valley, groundwater levels remained shallow during the monsoon season in all four years, with few exceptions noted in central areas. Conversely, greater depths were observed during the pre-monsoon period. This phenomenon underscores the significant impact of monsoonal rainfall on groundwater recharge in Kathmandu Valley. The Kathmandu Valley experiences abundant rainfall during the monsoon season, averaging more than 1000 mm, leading to a high recharge rate and shallow groundwater depths. Even during the post-monsoon period, when rainfall is considerably lower (less than 100 mm), groundwater depths remain shallow, indicating effective aquifer replenishment during the monsoon, sustaining abstraction through the post-monsoon period (Prajapati et al., 2021). However, as winter sets in, groundwater tables gradually decline due to increased extraction, influenced by reduced water supply from the KUKL and a lack of alternative recharge sources (Prajapati et al., 2021). The average annual groundwater level ranged from 0.432m to 10.30m over the study period, with an average of 3.81m. The spatial variation of groundwater levels reveals consistent shallowness in the southern, southeastern, and western parts of Kathmandu Valley throughout all seasons, potentially due to the dominance of natural land uses in these areas. In contrast, the central parts of Kathmandu Valley consistently exhibit deeper groundwater levels across all seasons, possibly indicative of extensive groundwater extraction and low recharge resulting from surface sealing due to the concretization in these regions. Similar results were observed by Gautam and Prajapati, (2014) and Lamichhane and Shakya, (2020) i.e., the central groundwater district experienced the maximum drawdown during the observation period, as most of the urban population relies on groundwater due to the lack of alternative water supply sources, leading to rapid urbanization and correlated groundwater lowering.

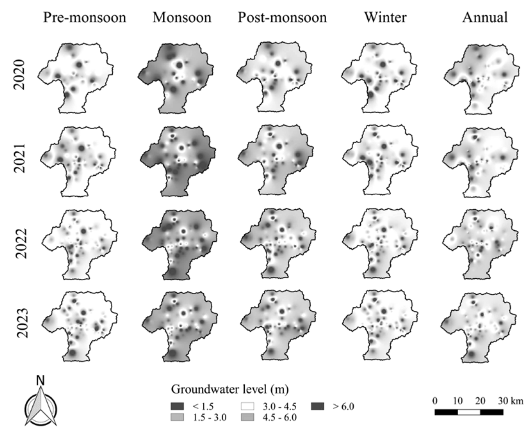

Figure 6: Spatial variation of groundwater levels in Kathmandu Valley

3.3 Linkage of groundwater level and land use

The figure illustrates groundwater level dynamics in two primary land use categories: agriculture-dominated and built-up areas. In agriculture-dominated land use, the median and mean groundwater levels were recorded at 2.48 and 3.028 meters, respectively. Conversely, within the built-up area, these levels were notably higher, measured at 3.79 and 4.244 meters, respectively. These findings highlight a significant contrast in groundwater levels between the two land use types, suggesting a substantial potential for recharge from agricultural land compared to built-up areas (Lamichanne and Shakya, 2019). However, it’s important to note that groundwater recharge depends on various other factors as well, including rainfall, infiltration capacity, lineament density, lithology, and so on (Yeh et al., 2008).

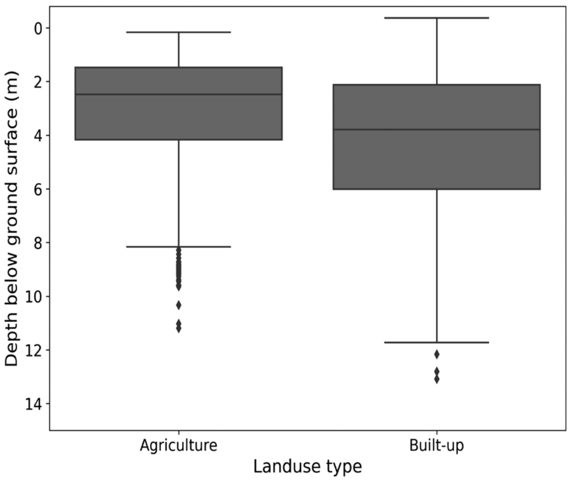

Figure 7: Groundwater levels distribution in the two predominant land use types

4. Conclusion

In conclusion, this study conducted a comprehensive analysis of groundwater dynamics in Kathmandu Valley using citizen-science groundwater monitoring, highlighting the pivotal role of citizen science-based monitoring in sustaining water resources. Overall, the findings underscore the necessity for higher regularity and motivational approaches to ensure high-quality citizen science-based groundwater monitoring data. The study revealed that groundwater levels in Kathmandu Valley ranged from -0.38 to 15.882 meters, with levels heavily influenced by monsoonal patterns. Additionally, groundwater levels were found to be shallower in agricultural areas and deeper in built-up land use. Ultimately, these findings emphasize the importance of proactive and collaborative approaches in safeguarding groundwater resources for the well-being of both present and future generations in e Kathmandu Valley and beyond.

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Global Youth Engagement in Groundwater Sciences: Insights from the UNESCO Groundwater Youth Network (GWYN)

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Abstract

The UNESCO Groundwater Youth Network (GWYN) is a global youth-led network with over 1400 members. The network was founded by UNESCO-IHP, to form a coordinating hub for existing youth organizations that are concerned with groundwater. Youth engagement in groundwater sciences is paramount for sustainable water management in the face of escalating global water challenges. The GWYN serves as a dynamic platform fostering collaboration, knowledge exchange, and capacity building among young professionals in the field. In this contribution, we present key experiences and outcomes from GWYN initiatives, highlighting its role in empowering youth to address pressing groundwater issues worldwide. Through various activities such as workshops, conferences, webinars, and advocacy campaigns, GWYN facilitates skill development, promotes interdisciplinary dialogue, and nurtures leadership qualities among its members. Furthermore, GWYN's emphasis on inclusivity and diversity ensures the participation of voices from diverse backgrounds and various countries, enriching discussions and fostering innovative solutions. By harnessing the energy and creativity of young people, GWYN aims to contribute to advancing groundwater research, policy, and sustainable practices on the global level. Thus, the importance of youth engagement in groundwater sciences highlights GWYN as a model for empowering the next generation of groundwater leaders. In this sense, it is important to highlight the first-ever Youth Declaration on Groundwater, presented at the UN-Water Summit on Groundwater in Paris in December 2022.

Keywords: *Hydrogeology, Youth participation, Research, Advocacy*

Microbiological Analysis of River Waters of Kathmandu Valley

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Abstract:

The unchecked disposal of wastewater from residential, hospital, and industrial sources, notably pharmaceutical and chemical industries, has led to increased pollution levels which is detrimental to both human and animal health. This study aimed to observe microbial diversity and assess the antimicrobial susceptibility pattern of microorganisms within the river waters of Kathmandu valley. A total of 17 sampling sites were selected along the Bagmati, Bishnumati, Manohara, Balkhu, and Dhobikhola rivers. The collected samples were then processed for the isolation and identification of microorganisms using standard microbiological procedures. The results showed a total of 107 bacterial isolates, with Escherichia coli being the most prevalent (15.89%), followed by Klebsiella pneumoniae, Pseudomonas aeruginosa, and Staphylococcus spp., each accounting for 13.08%. Coliforms represented the majority with 53 isolates, while Gram-negative bacteria and Gram-positive bacteria comprised 39 and 15 isolates, respectively. Notably, Chloramphenicol (94.3%) and Meropenem (96.2%) were the most effective antibiotics against Coliforms whereas Ampicillin (16.9%) was the least effective. Among the 24 isolates screened positive for extended-spectrum beta-lactamase (ESBL) production, 10 were confirmed as ESBL-positive. Additionally, out of the 14 Staphylococcus isolates tested for methicillin resistance, 4 were confirmed as methicillin resistant. The detection of multiple drug resistance, methicillin-resistance and the presence of ESBL producing organisms in the water samples indicate a substantial reservoir of antibiotic resistance in the river water and can pose a potential risk for the silent spread of these resistance into the environment.

Keywords: *Bagmati, Wastewater disposal, microbial diversity, Antibiotic resistance, Extended spectrum beta lactamase*

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ENPHO Creating Eco Societies

ICRE University of Yamanashi

Unify for Water and Climate

SIAS Southasia Institute of Advanced Studies

GWYN Groundwater Youth Network

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