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Sustainable Development and Management Strategies of Groundwater in Arid-Lands

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Abstract— *Sustainable groundwater development efficiently manages existing groundwater resources and addresses the risks associated with aquifer physical qualities, storage capacity, and recovery ability for future generating requirements. Response to future scenario development is essential for sustainable groundwater management in arid lands. This article discusses various development scenarios associated with better management of groundwater. This is to formulate effective and sustainable management strategies and their impact on sustainable groundwater management. The paper also seeks to provide a brief overview of common ideas of sustainability and their application to groundwater resource usage and development. Eventually, sustainable development can be accompanied by policies that stimulate groundwater use and prioritize profit over conservation require being considered. Policies include the establishment and formation of a social identity for collective aquifer storage and recovery, the creation of a legal framework for sustainable groundwater governance, the establishment of social adoption of groundwater pumping technology, and the formation of groundwater cultures at the point of abstraction.*

Keywords— *Arid lands, Sustainable Groundwater, Circular economy, Technology, Policies.*

I. INTRODUCTION

Globally, groundwater is the most abundant freshwater available (NASA 2003) and accounts for 98% of all freshwater on the earth (Velis et al. 2017). It is also the most extracted raw material (Jarvis 2012; Margat and Gun 2013). About 38% of irrigated lands are irrigated by groundwater (Siebert et al. 2010). Agriculture is the most groundwater-consuming sector with 70% of groundwater withdrawn worldwide (NGWA 2023). It is also an important source for humans, where nearly half of all drinking water worldwide is provided by groundwater (Kløve et al. 2011; Smith et al. 2016). The importance of groundwater extends beyond drinking and agriculture but also sustains the ecosystem, by providing nutrients (Dubrovsky & Hamilton 2010; Mullins 2014), buffering temperature (Kaandorp 2019), and supporting biodiversity (UNWWDR 2022).

Global demand for groundwater is rising due to population growth, irrigated agriculture expansion, and economic development. Human activities affect the sustainability of groundwater, many regions pump groundwater above the required without controlling the sustainability levels (WWF 2023), consequently, groundwater has been depleted (Das et al. 2020; Roy & Zahid 2021; Brückner et al. 2021; Negm & Elkhouly 2021). Further, climate variability and change impact groundwater systems, both directly through recharge and indirectly through changes in groundwater use (Taylor et al. 2012). Natural processes like climate change and increasing global air temperature cause a lowering of the piezometric levels of the adjacent aquifer (Sayed et al. 2020; Jannis et al. 2021; Gona et al. 2022). Agroecosystems and land use exert a stronger influence on groundwater, especially the expansion of rain-fed and irrigated agriculture; For example, during multi-decadal droughts in the West African Sahel, groundwater recharge and storage increased rather than declined as farmland replaced savannah, increasing surface runoff through soil crusting and focused recharge in ponds (Leblanc et al. 2008).

Climate trends, hydrogeologic conditions, groundwater withdrawal rates, land use, and management practices in the twenty-first century have all contributed to widespread, rapid, and accelerated groundwater level decreases (Jasechko et al. 2023). Agricultural intensification is also one of the main factors driving groundwater levels to their limit; as a result, groundwater levels have decreased to potentially hazardous levels (Qureshi et al. 2010; Yin et al. 2011). Nonetheless, there are numerous situations where declines in groundwater levels have slowed, stopped, or reversed after intervention, such as adopting regulatory measures (Buapeng and Foster 2008). The global challenge linked with groundwater requires an effective way to offer economic and social advantages while attaining long-term sustainable development (Shah 2005; Filimonau & Barth 2016). Therefore, this study represents the most extensive approaches to saving groundwater levels in many regions. In addition, it establishes a model for the future adoption of sustainable groundwater development practices.

Global and Local Groundwater Characteristics

This section shows global annual freshwater withdrawals as a percentage of internal resources, as shown in Fig. 1, as well as, shows an example of groundwater depletion in Egypt, as shown in Table 1. Total water withdrawals, not counting evaporation losses from storage basins. Withdrawals also include water from desalination plants in countries where they are a significant source. Withdrawals include extraction from nonrenewable aquifers and desalination plants for agriculture (irrigation and livestock production and for direct industrial use) and for domestic uses (drinking water, municipal use or supply, and use for public services, commercial establishments, and homes). The annual freshwater withdrawal is increasing which implies the necessity to better manage water resources, in particular groundwater.

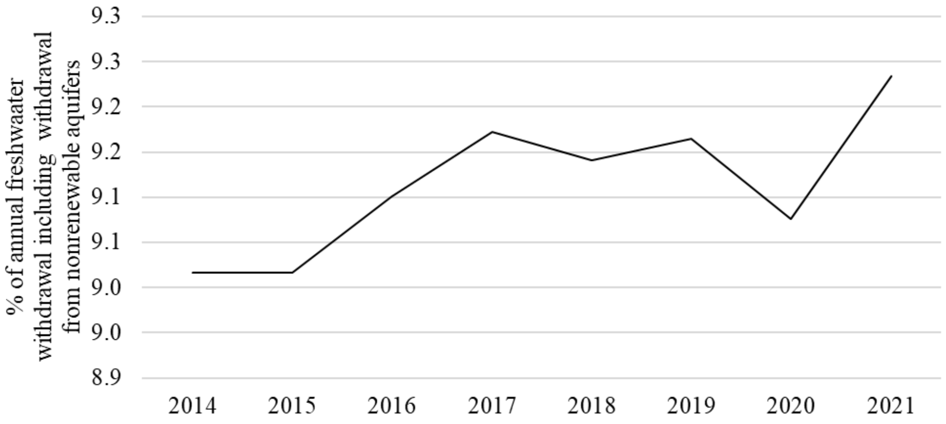

Fig 1. Annual freshwater withdrawals, total (% of internal resources) (Source: FAO-AQUASTAT)

Table 1. An example of inventory data of some wells tapping Wadi Araba in Egypt (Source: Authors, Freeg et al. 2023).

Location		Total depth (m)	Well yield $m^3 hr^{-1}$	Static water depth m	Dynamic water depth m	Transmissivity $m^2 day^{-1}$
Upstream	BNS-B	1200	200.0	111.4	155.5	400
	BNS-D	450	197.0	109.7	137.6	340
Midstream	BNS-C	1448	100.0	78.0	173.6	49
	ED-2	858	45.0	68.4	206.2	10
	Araba-2	300	97.0	35.2	150.8	50
Downstream	Araba-1	300	45.0	81.8	156.0	20

In Egypt, where freshwater resources are limited, the country relies on groundwater in some parts, like the Wadi Araba region. Table 1 shows an example of inventory data of the drilled wells in the aquifer subject to groundwater characteristics. The transmissivity of upstream wells BNS-B and BNS-D implies the higher extraction potentiality of groundwater from the aquifer upstream, which is classified as moderate potentiality. Regarding midstream and downstream wells, the transmissivity implies weak extraction potentiality of groundwater from the aquifer at midstream and downstream. For more information see *Appraisal of multilayer aquifer system for sustainable groundwater management in Wadi Araba, Eastern desert, Egypt.* Therefore, the global and local challenges of groundwater resources require the formation and creation of sustainable groundwater management strategies. Policies that encourage groundwater use and promote profit over conservation must be considered while pursuing sustainable development.

Sustainable Development and Management Strategies

Groundwater and Circular Economy

The circular economy aims to save resources through closed-loop usage. The circular economy can be applied to water through water footprint which counts water in both quantity and quality and both direct and indirect water usage that must consider circularity (Sauvé et al. 2021). The virtual water and water footprint concepts emphasize the importance of considering the entire water supply chain when consuming (Aldaya et al. 2011). To evaluate the sustainability of water consumption, analyzing the water footprint is significant by further subdividing water allocation into three groups: blue, green, and grey (Hoekstra and Mekonnen 2012). This demonstrates how the same product or consumer good can have a drastically varied water footprint and level of sustainability or circularity depending on where it came from and what source of water was used in its manufacturing. Further, establishing an intensive production system, such as poultry, seasonal crops, animals, and trees, is critical for transitioning farmers from agriculture to agro-industries based on agricultural raw material processing (IFAD 2014; FAO 2014; Freeg et al. 2023). This allows groundwater-based communities to transition from agriculture to agro-industries based on agricultural raw material processing activities, hence conserving water supplies.

Adoption of Groundwater Pumping Technology

The adoption of groundwater pumping technology is important for long-term sustainable development. For example, the negative influence of submersible pumps on groundwater levels and quality has led to legislation in many countries to control abstraction (Jones 2012). Groundwater pumping technology also includes the mobilization of solar and wind turbines. Solar and wind turbines were introduced in the late 1970s (Ward and Dunford 1984), and since then, many countries have set ambitious plans and initiatives to use solar and wind turbines widely. India's first solar-powered water pumping systems were launched in 1993-1994 as part of the government's non-conventional energy sources promotion program, to install 50,000 units within five years (Purohit and Michaelowa 2005). In the United States, a study examined hybrid wind and solar-powered center-pivot groundwater irrigation. It demonstrates that it might be economically viable on the High Plains of Northern Texas if used to irrigate two crops yearly (Vick 2010). However, applying solar-based groundwater pumping technology for irrigation showed positive impacts on saving groundwater resources from depletion, as well as, offering a cost-effective and sustainable energy solution (Closas 2017; Mostafaeipour et al. 2021). Technology can be expanded to combine the pumping system and the irrigation method in the field, such as modern irrigation systems of sprinklers, subsurface, and drip irrigations. The replacement of traditional surface irrigation methods with modern irrigation systems, including horizontal sprinklers, central pivots, surface drip, and subsurface drip, sustains groundwater resources. A study conducted in the Nile Delta of Egypt showed when those techniques were applied, the drawdown of groundwater reached 2.60 m, 4.20 m, and 6.50 m, respectively (Abd El-Aty et al. 2023).

II. POLICIES AND GROUNDWATER

The aim of the groundwater vulnerability assessment is determined by several elements, including the organization's groundwater policy goal, technical concerns, and institutional issues (Pandian et al. 2023). The scope, forms, and settings for governance at the point of groundwater abstraction must be addressed from the perspective of the primary stakeholders—regulators, users, and suppliers (Jones 2012). This necessitated the importance of jointly sharing the groundwater source between all beneficiaries, otherwise, in the long run, groundwater markets may prove socially unstable and divisive unless a new governance paradigm is devised (Jarvis 2011). Policies require a good grasp of the key links between groundwater systems and surface water, land use, and other sectors (Foster and Chilton 2017). However, some policies have recently emerged, such as I) Integrated approaches to land and water resource management (including surface water, aquifers, and recharge zones), II) Pricing water use, land tenure reform, and water allocation systems based on consumptive use (Duda 2017), III) Encourage and sustain stakeholder engagement in groundwater governance (Valizadeh et al. 2022), IV) Establish economic mechanisms, behavior, and incentives for groundwater management (Koundouri et al. 2017), and V) Establish a legal framework for sustainable groundwater governance (Mechlem 2016). Eventually, multiple frameworks and transdisciplinary skill-building circumstances must be included to improve groundwater and aquifer collaboration.

III. CONCLUSIONS

This article discusses various development scenarios associated with better management of groundwater. This is to formulate effective and sustainable management strategies and their impact on sustainable groundwater management. This study highlighted a wealth of opportunities for the combination of integrated approaches in groundwater management. It is simultaneously recognized that community mobilization and stakeholder organization around a common vision of resource sustainability are necessary prerequisites for developing and implementing groundwater management plans. They must be based on a comprehensive understanding of the important connections between groundwater systems and surface water, land use, and other sectors. Eventually, integrated groundwater policy creation and management planning are essential components of effective governance in managing the 'required transformation process'.

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