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IMPACT OF GROUNDWATER DEPLETION ON SOCIOECONOMIC LIVELIHOOD IN NUSHKI DISTRICT, BALOCHISTAN

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ABSTRACT

Groundwater depletion is a major issue in Nushki District, Balochistan, where arid climatic conditions and insufficient water management have resulted in significant socio-economic impacts on the local communities. This paper examines the causes and consequences of groundwater depletion in the region, using a multidisciplinary approach that incorporates remote sensing data from GRACE and GRACE-FO satellites alongside qualitative socio-economic assessments to demonstrate how over-extraction and the proliferation of unregulated tubewells have contributed to falling aquifer levels, forcing farmers to switch from high-value crops to less profitable drought-resistant varieties, leading to increased economic instability and food insecurity, as well as exacerbating gender inequalities and increasing household vulnerabilities by burdening women with water collection and agricultural management when male labor is no longer available. This research underscores the necessity for stronger governance frameworks for sustainable groundwater management, community resilience, and gender equality, highlighting the importance of integrated water and energy policies, as well as participatory approaches to local governance in order to counteract the negative impacts of groundwater depletion in Nushki District.

Keywords: *Nushki, Balochistan, extended drought, socioeconomic impacts, groundwater depletion, water governance, water policy*

INTRODUCTION

Groundwater is a critical resource for communities around the world, supporting agriculture, drinking water, and other economic activities (Foster et al., 2013; Scanlon et al., 2023). It is the subsurface part of the hydrological cycle and the primary source of water for domestic and agricultural purpose in many countries; particularly in arid and semi-arid regions (Famiglietti, 2014). Groundwater depletion is a growing problem and can have significant social and economic impacts on livelihoods, especially in arid and semi-arid areas (Hoogesteger, 2022; Priyan, 2021).

The economic consequences of groundwater depletion are serious and declining groundwater levels affect agricultural productivity, which can lead to further economic instability (Li et al., 2023). Reduced access to groundwater will reduce cropping intensity, meaning that household incomes will be negatively affected by reduced irrigation access (Jain et al., 2021). Moreover, increased water consumption for intensive agriculture caused by groundwater dependency, coupled with declining groundwater levels, results in higher depletion rates and negative economic consequences including food security (Kumar &

Srinivasan, 2025). This broad economic instability resulting from groundwater depletion is not limited to agriculture and extends to local economies that depend on water-intensive crops. For example, Ashraf et al. (2021) show that excessive extraction in Iran has caused severe agricultural decline and threatened drinking water availability, thereby affecting the economic viability of rural areas. This aligns with the more general review by Fessahaye et al. (2025) that finds that over-extraction anomalies cause decline in agriculture, population migration, and public health risks.

Another aspect of the problem is that groundwater availability strongly affects social structures and community relationships. For instance, a study of rural livelihoods in Zimbabwe by Madya et al. (2024) shows that groundwater depletion directly impacts livelihoods, such as agriculture, reducing food production, increasing food insecurity, and exacerbating poverty. Groundwater depletion can also negatively impact the roles of rural women in water management, an issue that has already contributed to gender inequalities (Swaraj & Maheshwari, 2022). On the other hand, improved water management, such as managed aquifer recharge, has been found to enhance both food security and gender equity by reducing the physical burden on women (Tantoh et al., 2021).

The depletion of groundwater has become a major problem in the arid and semi-arid parts of Pakistan, especially in Balochistan, where groundwater is the main source of water supply and the recharge rate is low due to the low rainfall and high rate of evapotranspiration (Akhtar et al., 2021). Groundwater depletion in Nushki District is high due to over-extraction and poor groundwater management policies (Kakar, 2017; Khair et al., 2014). The region's hydrological imbalance, aggravated by climate change and population pressure, poses severe risks to both agricultural productivity and the livelihoods of local farmers (Kakar, 2017; Rehman et al., 2019).

The satellite gravimetry (GRACE/GRACE-FO) datasets have provided an informative understanding of the terrestrial water storage changes on a broad scale in South Asia; however, these data cannot capture the aquifer processes involved in the region on a district scale without downscaling and local calibration (Sheikh et al., 2025). In this regard, the paper will concentrate entirely on hydrogeological conditions and locally based information of Nushki only to evaluate groundwater trends and socio-economic consequences and mention the research of the region only as the background. Although this is a general trend of water scarcity in Balochistan, present research has been mainly concentrated on the depletion of groundwater in the canal-fed plains in Punjab and Sindh, and thus, the arid areas such as Nushki have been under-researched. Nushki is a case of particular interest requiring individual consideration because of its arid climate, dependence on agriculture and the recent rise of the use of solar-powered tube wells, which has increased uncontrolled extraction. In addition, the socioeconomic organization of Nushki, which is based on small-scale agriculture, transhumant pastoralism, and the division of labor by gender, makes it extremely susceptible to the lack of groundwater.

The study also seeks to come up with realistic policy and community-based governance policies that will make water management in this frontier region more ecologically sustainable and socially resilient.

Study Area and Context

Nushki District is located in Balochistan Province of Pakistan, with Chagai District on the west and Afghanistan on the north (Rehman & Alamgir, 2018). The climate of the region is hyper-arid or arid with an average of less rainfall of about 120-200mm/year (Jamali, 2006; Qazi, 2004). These circumstances result in a long-term water shortage that strongly limits agricultural output and replacement of water tables. The agricultural activities are mainly agrarian by nature and mainly consist of a combination of rain-fed agriculture, assisted by tube wells, and small-scale herding of livestock.

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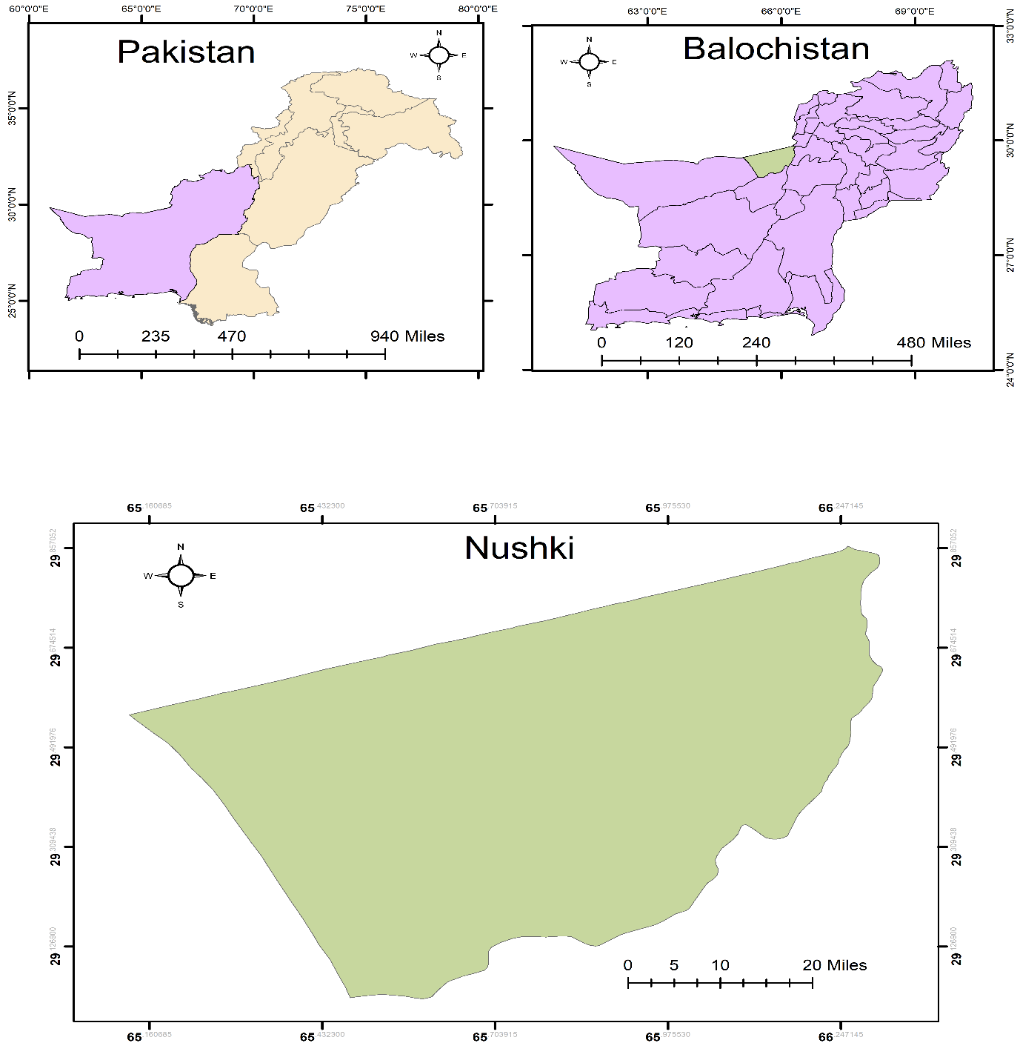

Figure 1 Map of Nushki District

Traditionally, Nushki residents controlled water by using localized and indigenous systems, including karezes (qanats), seasonal earthen dams, and rain-fed agriculture (Jamali, 2006). Until the end of the twentieth century, these ancient systems preserved a sustainable equilibrium between recharge and withdrawal, but with the introduction of deep mechanized tube wells, and in the recent past, solar-operated pumps, the process of groundwater abstraction has become unlimited and uncontrolled (Aftab et al., 2018). This technological change has unlinked extraction to the costs of energy and the rainfall cycle, further hastening the depletion of the aquifers. Government drought reports and reports by relief agencies continue to classify Nushki as one of the most water-strained districts in Balochistan, experiencing frequent droughts and extreme effects on livelihood. Irrigation by groundwater and the ineffective institutional control of the situation make the district a focal point of research on the hydrological and social aspects of the groundwater crisis in dry Pakistan.

METHODS AND DATA SOURCES

This paper was based on a multidisciplinary methodology to combine hydrological, institutional, and socioeconomic information in an effort to develop a complete socio-hydrological picture of groundwater depletion in Nushki District. Quantitative (remote sensing and hydro-meteorological data) and qualitative (household-level and institutional) data were interpreted in order to comprehend the spatial and temporal patterns of groundwater depletion and its impacts on livelihoods.

GRACE and GRACE-FO satellite mission data were used to determine the change in groundwater storage between the years 2003 and 2023. The data were extracted as monthly terrestrial water storage anomalies based on NASA Jet Propulsion Laboratory (JPL) and Center of Space Research (CSR) gridded data. The least-squares regression was conducted to obtain an estimate of the average rate at which the groundwater storage changes annually as a linear trend. ArcGIS 10.8 was used to compute spatial visualization and mapping, and the Pearson correlation coefficient (r) was used to determine the temporal relationship between the groundwater anomaly computed by GRACE and the recorded precipitation (Pakistan Meteorological Department data). Reports by government agencies and NGOs, including those by the Pakistani Council of Research in Water Resources (PCRWR), UNDP, and OCHA/ReliefWeb, were consulted to get well inventories, and the static measurements of the water level and the performance of small dams. These datasets have served to validate satellite-derived trends; they have also been used in finding spatial clusters of groundwater stress. Differences in data were resolved by comparing with provincial irrigation department archives and recent field evaluations.

GRACE/GRACE-FO satellite data have been found useful in monitoring the change in terrestrial water storage at continental to basin scales, but cannot be used to monitor groundwater change at district or sub-basin scales because of their inherent resolution (typically 300 km). Consequently, the trends of GRACE are mentioned here as a regional background. The quantitative evaluation of the Nushki aquifer is mainly based on the in-situ well monitoring, field survey, and the local reports on hydrology. The analysis does not infer any GRACE-based values of district scale.

The study uses a systematic literature analysis of qualitative research conducted between 2015 and 2025 to extract socio-economic data. The review had clear selection criteria: studies were taken into consideration when (i) they dealt with groundwater-dependent communities in the region of Pakistan's arid areas, (ii) they reported household-level social or economic effects associated with access to groundwater, and (iii) they provided verifiable information on their methods of data collection, data-collection period, and data analysis. This guaranteed methodological comparability and traceability, which overcame previous fears of the lack of survey details. NVivo 14 was used to thematically analyze all the eligible publications to combine household-level experiences (e.g., coping strategies, debt, gendered labor shifts, migration) with hydro-institutional variables (e.g., the intensity of abstraction, irrigation technology, and governance capacity) within an inductive framework of coding.

In order to reflect the policy and technological aspects of groundwater use, new media publications and institutional publications, including Reuters coverage and reviews of solar irrigation and energy transition by the sector, were also coded according to the descriptive content. The triangulated evidence was useful in establishing gaps in governance and regulation that hasten groundwater abstraction. The synthesized dataset, which is summarised in Table 1, is based on remote-sensing, institutional, meteorological, and socio-economic literature to offer a multi-scalar perspective of groundwater stress and adaptation in Nushki. The literature review design was selected to offset the failure of the research to have credible field data at the district level to facilitate a powerful synthesis of peer-reviewed and institutional knowledge without compromising transparency and reproducibility.

Table 1 Summary of data sources and analytical use in the literature-based synthesis.

Source	Type of Data	Time Period	Analytical Use
NASA GRACE & GRACE-FO Missions	Anomalies in the storage of terrestrial water via satellites.	2003–2023	Measure groundwater trends and depletion rates by use of linear regression.
PCRWR, UNDP, OCHA/ReliefWeb	Field-based hydrological data (aquifer monitoring) and institutional (well depth) data.	2010–2024	Check trends of satellites and locate zones of stress.
Pakistan Meteorological Department	Then the data on rainfall and drought index.	2000–2023	Associate variability with groundwater trends.
Peer-reviewed household surveys (Ashraf & Routray, 2013; Khan, 2022; Rehman et al., 2019)	Social, economic, and behavioral data.	2015–2025	Coding of community coping responses thematically.
Reuters, policy reports, and energy reviews	Technological and administrative information.	2016–2025	Test solar irrigation impact on extraction and a policy response.

PHYSICAL EVIDENCE OF GROUNDWATER DECLINE

Regional Trends (Indus Basin and Balochistan)

According to satellite-based analysis, especially of the GRACE and GRACE-FO satellites, the terrestrial water storage in the Indus Basin is decreasing at an alarming pace (Akhtar et al., 2022). The American Geophysical Union (AGU) analyzes that the average rate of loss of groundwater was more than three times higher during the period 2002-2015 and 2015-2022, which can be explained by the fact that the unsustainable rate of abstraction was enhanced by unregulated irrigation and a lack of recharge (Iqbal et al., 2016). These trends also manifest in the peripheral basins such as Balochistan since the province is practically dependent on the slow-recharging fossil water (Amin et al., 2019; Dharpure et al., 2025). GRACE records of time-varying gravitational anomalies reveal extensive shrinkage of aquifers even in underpopulated uplands, demonstrating the basin-wide characteristics of groundwater stress (Watto & Mugera, 2016). The losses in western Pakistan are estimated to be in the form of billions of cubic meters of water, which is more than a few centimeters of water-equivalent depth per year (Ashraf & ul Hasan, 2020; Mehmood et al., 2022).

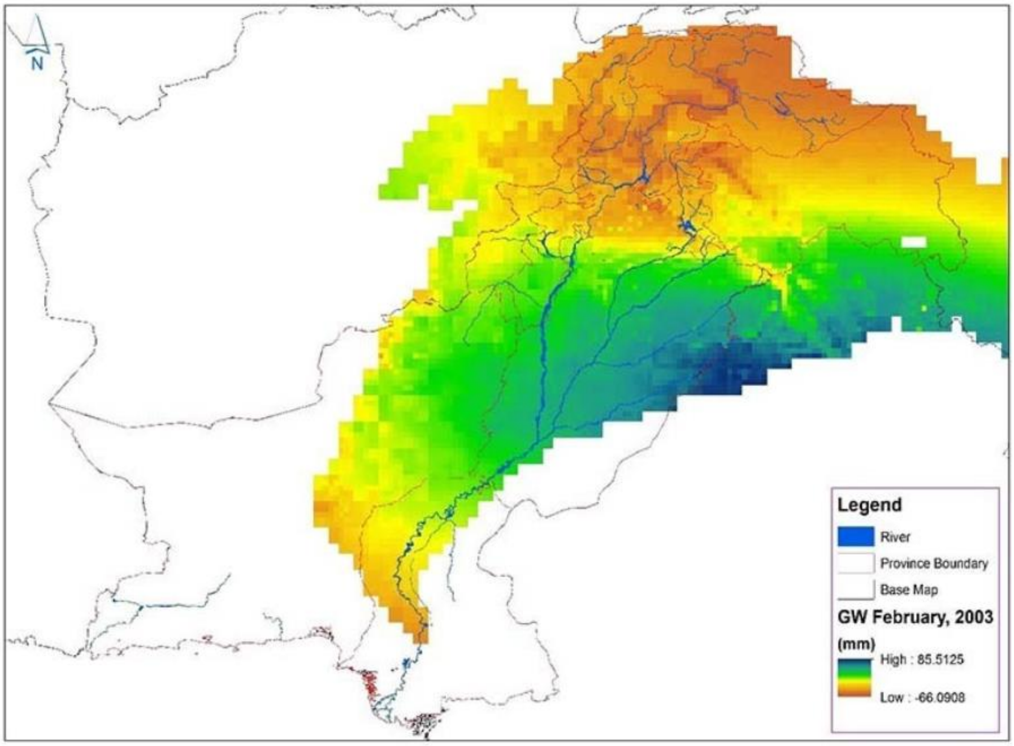

Figure 2 This map represents the monthly changes in groundwater of the Indus River Basin as generated using NASA GRACE satellite data by Pakistan water managers. Orange and yellow colors represent where the groundwater may be exhausted, and blue and green colors. Credit: Pakistan Council of Research in Water Resources These regional patterns illustrate the necessity of connected water management, which integrates provincial water management and satellite monitoring in order to absorb transboundary aquifer stress (Ahmed et al., 2021).

Local Observed Impacts and Monitoring

Pakistan Council of Research in Water Resources (PCRWR) and provincial irrigation departments confirm an acute decline of groundwater in Nushki through ground-level monitoring. It is observed that the level of water is decreasing several meters annually, especially in locations where deep tube wells are widely employed (Akhtar et al., 2022). High irrigation practices and livestock rearing, coupled with low rainfall, have decreased the natural recharge, and intense drilling of tube wells has led to localized cones of depression. The extraction of groundwater in Nushki relies on the main source, i.e., the private tube wells, as the situation is generally arid in Balochistan. The official statistics are not complete, yet the estimates, provided by the Agriculture Department Nushki, there are more than 2000 tubewells in the district, but there is no officially confirmed district-wide record. The old systems of karez usage and shallow wells are dried up, and farmers have to use deeper boreholes, which are energy-consuming (Ahmed et al., 2021; Rehman et al., 2019). These deeper wells raise the cost of operation and household debt, which makes the socioeconomic vulnerable even more. In the last ten years, according to Water Extension, the underground water level has dropped to 100 to 130 feet in different union councils of Nushki District. UC Kishingi is adversely affected, where water level has dropped to 700 feet in the last two decades.

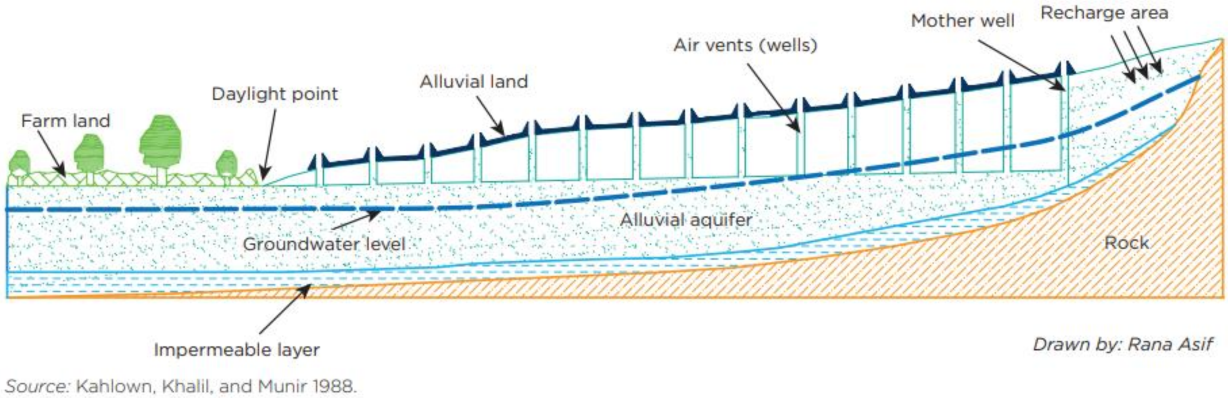

Figure 3 Schematic Diagram of a Typical Karez (Adopted from Ashraf & ul Hassan, 2020)

The recession impacts agriculture and access to domestic water. Communities are becoming more reliant on common boreholes and water supplied by tankers, which increases expenses and creates social conflicts when there is a lack of water (Akhtar et al., 2021; Shah et al., 2025; Sheikh et al., 2025). The rate of extraction in Nushki is currently much higher than the recharge rate, thus showing that there is a great demand for regulation measures and community sensitization to control the further degradation of the aquifer.

Major Drivers of depletion in Nushki

The factors that contribute to the depletion of groundwater in the Nushki District are a combination of technological, climatic, and institutional factors. These factors interact with one another, creating a feedback loop that increases the stress in the aquifer and poses a risk to the long-term water security. The major driver is the introduction of large-scale mechanization of tube wells, especially since the beginning of the 2000s. Agricultural subsidies and private investments in agriculture made farmers shift towards the use of deep boreholes instead of the traditional irrigation methods, including karezes. It is estimated that thousands of unregistered tube wells are currently in operation in Nushki, with a variety of them using either diesel power or solar-powered energy (Shahid, 2025). These wells are mostly unregulated, and this allows rates of extraction that are way above natural recharge rates. Although tube wells can have short-term positive economic effects, such as increased crop production and increased irrigation control, it has long-term costs that are extremely high: a falling water table, decreasing yields with time, rising operating expenses, and broken well infrastructure (Rehman et al., 2017).

The recent proliferation of solar-driven irrigation systems in Balochistan has altered the availability of groundwater and the economics of energy services, but little is recorded on a district basis. Thousands of solar tube wells have been installed all over the province through national programs like the Kissan Package by the Prime Minister and the Balochistan Solar Irrigation Initiative, which have been subsidized. Locally-based information indicates that 28,000 tube wells currently run on solar energy in Balochistan, although consistent records of the number in Nushki cannot be found, as the people use it informally (Tahir & Shahid, 2024). According to field interviews and stakeholder consultations, there is a gradual increase in solarisation with fuel price volatility as the driving force behind solarisation, as opposed to environmental issues. Therefore, solar energy minimizes the operating cost, but without pumping control, there is a danger of additional groundwater depletion, which supports the energy-water paradox found in dry areas. This technological change, coupled with unregulated tube wells, is one of the major anthropogenic factors that cause groundwater decline. The issue is aggravated by climatic stress. The dry climate of Nushki is marked by the large evapotranspiration rates, low precipitation rates per year, and multi-year drought periods (UNDP, 2015). Longer periods of dry weather lower the rate of natural aquifer recharge, and even average extraction becomes the mining of centuries-old fossil groundwater (Iqbal et al., 2024). The low recharge rates and large extraction rates have caused a gradual decrease in the water table and a decrease in the resilience of shallow and deep aquifers. Lack of oversight and governance has resulted in uncontrolled extraction, severely diminishing aquifer levels (Khair et al., 2014; Rehman & Mengal, 2025).

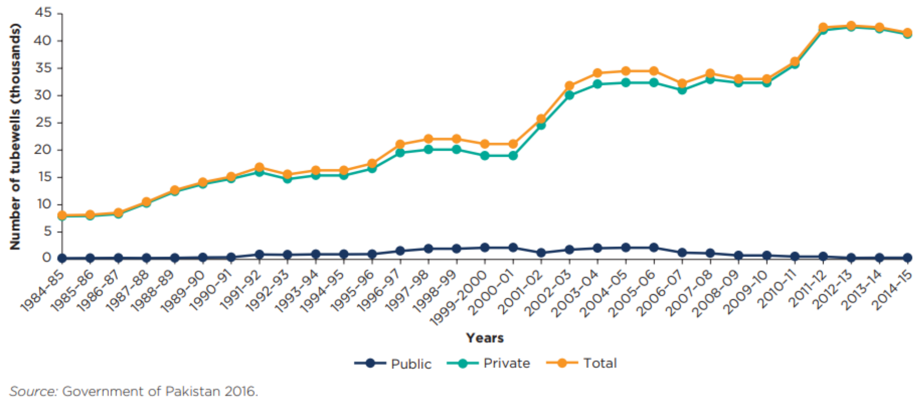

Figure 4 Increasing Numbers of Tubewells in Balochistan (1984-2014) (Adopted from Ashraf & ul Hassan, 2020)

People deplete weakly governed and poorly regulated areas. Inadequate well registration, limited monitoring of pumping, and the absence of extraction limits lead to a setting where technology and climatic pressures cannot be checked. By overlapping policy loopholes and high-tech abstraction, a self-reinforcing cycle develops: the more the aquifer is used up, the deeper the wells are sunk or the more efficient the pumps are installed, which further decreases the aquifer (Rana et al., 2020). The relative relevance of these drivers may be conceptualized in the following ways: unregulated mechanized tube wells become the most important cause, solar pumps increase the extraction pressures, climate variability limits natural recharge, and in a weak institutional framework. These causes combine to create a vicious cycle of water draining and socioeconomic susceptibility. Unless Nushki aquifers are properly managed, their depletion will become irreversible, not only to agricultural livelihoods, but also to water security in the region in the long run.

SOCIOECONOMIC IMPLICATIONS

Reduction in groundwater in Nushki District caused a series of socioeconomic effects, which included agriculture, livestock, household income, migration patterns, and gender dynamics (Jamali, 2006; Rehman et al., 2017; Rehman et al., 2019). The intensive use of groundwater by the district in crop production and animal rearing makes it very susceptible to hydrological shocks, and long-term drought worsens the situation, as well as unregulated groundwater extraction (Khair et al., 2014). The impact is both direct, in the form of low agricultural productivity, and indirect, in the form of increased indebtedness, livelihood pressures, and increasing social inequalities. These overlapping stressors demonstrate that the highly arid areas cannot possibly suffer environmental degradation and be socioeconomically vulnerable at the same time.

Agricultural Impacts

The depreciation of groundwater has led to the shrinkage of the irrigated area and a significant decrease in crop production. Tube wells are either drying or becoming economically unviable, and farmers have to replace high-value crops like vegetables, melons, and wheat with low-income but drought-resistant cereals like barley and millet (Kakar, 2017; Mustafa & Qazi, 2007). In accordance with relief assessments, during years of serious drought, the yields of cereals and vegetables decreased by approximately 40 and 50 percent, respectively (Islamic Relief, 2019). This agricultural crisis lowers the household earnings, local market supply, and impairs downstream economic processes, including transportation, storage, and food processing, are impaired. The transition to low-value crops also reduces cash flow, which weakens the ability of the community to invest in adaptation mechanisms or farm upgrades. As water becomes increasingly scarce, farmers are compelled to shift to less water-intensive crops or abandon agriculture altogether, leading to economic displacement and loss of livelihoods (Rehman & Mengal, 2025).

Livestock and Rural Economy

The livestock industry, which is a part of the arid economy of Nushki, is also under the same pressure. A drop in groundwater decreases the levels of fodder and water, leading to high mortality levels in livestock, mostly goats and sheep, during prolonged droughts (Rehman & Alamgir, 2018). It is estimated that livestock deaths in some union councils had reached 25 percent because of the effects of dehydration and shortages of food (Durrani et al., 2021; Rehman & Alamgir, 2018). The high interest rates often force households to borrow or sell productive assets and trigger a debt dependency cycle and making them less resilient (Akhtar et al., 2021). The burden of the extravagant expense of buying tanker water to supply to households ranging between PKR 3,000 and 5,000 a month to supply domestic water aggravates poverty and the economic vulnerability even further (Durrani et al., 2021).

Migration and Labor Dynamics

Lack of groundwater has also contributed to increased migration due to a lack of water (Jamali, 2006; Rehman et al., 2017). Remittances do stabilize short-term incomes, but male outmigration causes more burdens to the rest of the family, especially females, and undermines the community. This is also due to the rural brain drain, which is caused by the loss of working-age males, and youth are moving away more and more from agricultural livelihoods (Shah et al., 2025). Child labor can also substitute formal schooling when families are trying to compensate for the lost income, and this makes intergenerational poverty a reality, and the adaptive ability of the future generation becomes low.

Gendered Impacts

Social costs of the depletion of groundwater are disproportionately experienced by women and girls. They travel longer to fetch water (Jamali, 2006). Due to the drying of wells or the greater distance between the wells and the settlements, they use three to four more hours a day than ten years ago in order to bring water (Islamic Relief, 2019). This time load minimizes the chances of education, income-making, and involvement in local governance. The migration of men leaves women with more tasks of managing the household and looking after the livestock, yet without access to decision-making venues or credit options. This creates a cycle of poverty and marginalization within the district, deeply entrenching social inequalities (Rehman & Mengal, 2025). Such feminization of rural hardship not only harms the welfare of women but also reduces the adaptive capacity of households, which points to the nexus between environmental stress and deep-rooted gender inequality.

DISCUSSION

The case of the groundwater crisis in Nushki District can be viewed as the complex interplay of the technological, institutional, and environmental factors that are characteristic of arid and semi-arid areas of Pakistan. The case, based on the socio-hydrological theory, demonstrates that when the governance and recharge processes are poorly organized, even the intervention to decrease scarcity (e.g., mechanized tube wells and solar irrigation) can lead to increasing vulnerability in the long-term (Khair et al., 2014; Pahl-Wostl et al., 2013). Nushki is therefore a mini world to learn about the structural forces of hydrological risk in the frontier districts.

Institutional failure has dominated groundwater over-pumping in Nushki. The unregistered tube wells and unmetered solar pumps run without much supervision, leading to a tragedy of the commons situation at the local level. Similar cases of governance failures have been reported in India and Iran, where poor enforcement of the regulation promoted aquifer overuse despite the socioeconomic benefits initially (Aliabadi et al., 2020; Shah et al., 2021). These cases explain why local institutional arrangements, when put together with regional hydrological monitoring, are needed to apply sustainable water extraction limits. A range of technological inventions aimed at enhancing access to water have had undesirable side effects. The increase in the solar-powered irrigation pumps not only lowered the operational costs but also increased accessibility, accelerating the process of aquifer depletion, establishing a technological paradox of climate-friendly solutions causing greater environmental pressure (Baig et al., 2020). The same trends exist in the North African nations, where subsidized pumps enabled overpumping in Morocco and Tunisia (de Fraiture & Giordano, 2014). The results highlight that the implementation of technology should be accompanied by governance, monitoring, and recharge management to avoid cases of maladaptation.

In addition to its agricultural impact, groundwater depletion also initiates significant social and economic stress, including increased indebtedness among farming households. The findings align with global research that highlights how groundwater scarcity contributes to rural economic vulnerability and can precipitate social inequalities, where wealthier individuals capitalize on the ability to extract deeper groundwater while poorer households face market entry barriers (Wada et al., 2012). The social effects of the degradation of groundwater are very unequal. Smallholders and pastoralists who use shallow wells are more vulnerable than the rich farmers who have the capability of deep drilling (Mustafa & Qazi, 2007). Falling water tables and consequent lower crop production, animal deaths, and growing household debt burden women and children as more labor and food insecure groups (Hussain et al., 2023).

Furthermore, groundwater depletion in Nushki has gendered implications. As water scarcity worsens, women shoulder a disproportionate burden of collecting water, often from farther distances and for domestic uses, which can compromise their physical health and limit their education and income-earning prospects, perpetuating entrenched gender inequalities. While men leave to seek better livelihoods due to agricultural failures, adding to the workload of women, who take on more responsibility for the household and livestock without corresponding increases in decision-making power or access to resources. More inclusive water management strategies could address these gendered impacts and increase community resilience by ensuring that both men and women have a voice in governance processes.

The interaction between groundwater depletion and migration patterns also merits attention. In the face of increasing water scarcity, many families resort to migration, further straining community cohesion and exacerbating rural brain drain as younger generations leave agricultural livelihoods (Xu & Famiglietti, 2023). Effective policy responses must therefore consider the relationship between environmental stress and long-term societal trends, including migration and the sustenance of community ties.

The scale of noticed groundwater decline, in combination with the growing costs of energy and water access, is an example of a feedback loop as physical scarcity increases socio-economic susceptibility. To overcome this imbalance, it is necessary to have integrated water-energy governance and local governance, depending on community management appropriate to the arid hydrogeological context of Balochistan.

Policy Framework

The metering, well registration, and managed aquifer recharge (MAR) have been broadly approved as fundamental instruments of demand and supply management of groundwater. Their operationalization in Nushki needs a feasibility study based on hydrogeological, institutional, and socio-political realities. As demonstrated through empirical studies on Balochistan and other similar arid systems (PCRWR, 2021; van Steenbergen et al., 2015), interventions tend to fail when developed without considering local enforcement capacity, complexity of tenure, and the cost of monitoring dispersed users. Under the conditions of Nushki fractured aquifers, small fiscal space, and traditional water rights, where a universal metering of water rights is mandatory, the policy may not be viable or economical. An institutionally and technologically feasible route would then be to follow a staged management architecture, where (i) a georeferenced well registry, hydrogeological database is inserted as the underlying monitoring layer; (ii) metering pilots on high-discharge wells are deployed and linked to the telemetry-enabled data collection to measure extraction rates; and (iii) site-specific MAR pilots are based on mapping of aquifer transmissivity, soil permeability, and recharge potential. It is possible to embed these measures in the context of participatory water-user associations and to match incentives with energy-policy instruments in order to improve compliance and adaptive capacity. This kind of evidence-based, calibrated approach can transform generic policy prescriptions into a spatially manifested model of governance of groundwater that incorporates hydrological constraints with socio-institutional feasibility necessary to meet long-term aquifer sustainability and livelihood resilience in Nushki.

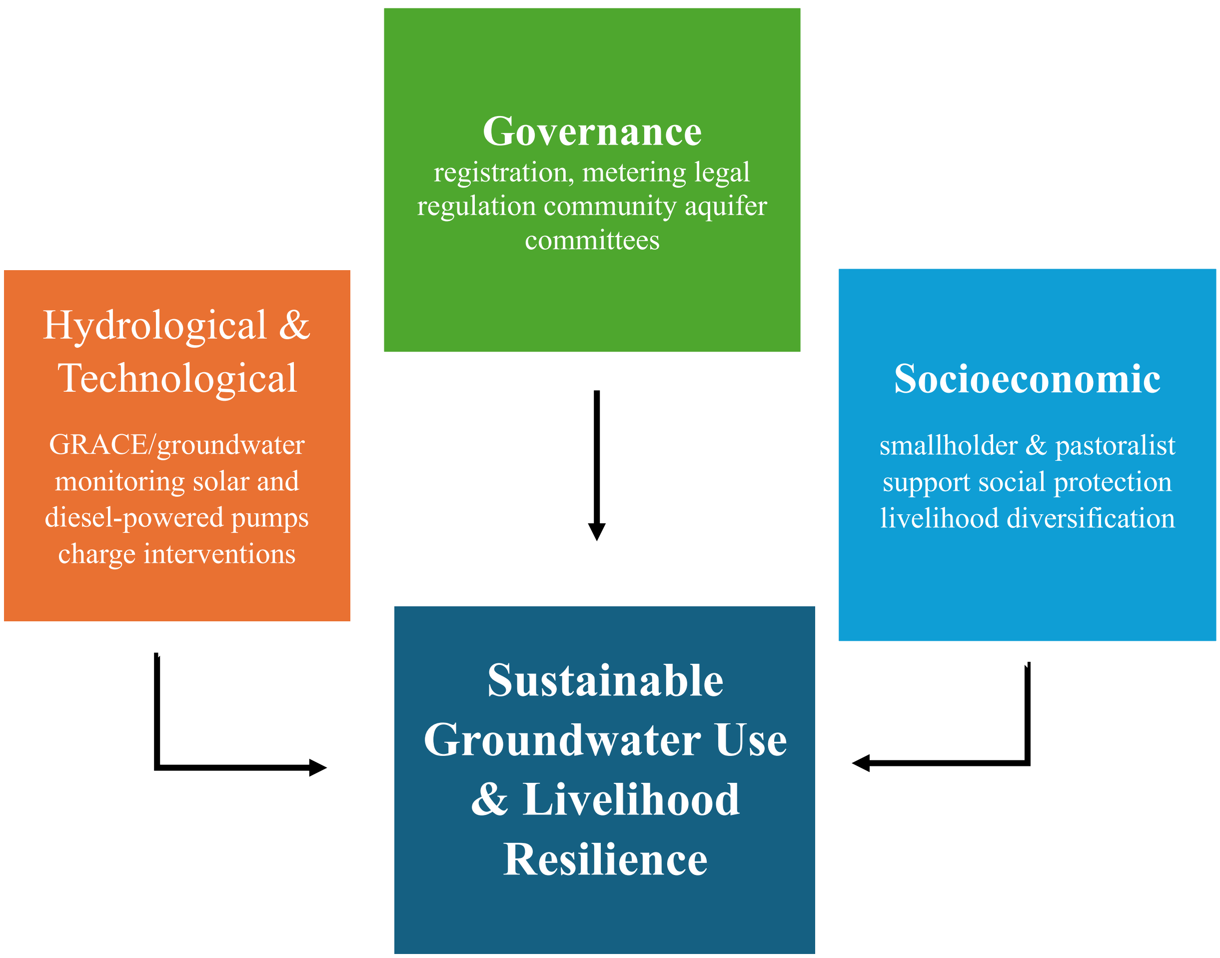

Figure 5 Proposed Integrated Socio-Hydrological Policy Framework for Nushki District

CONCLUSION

It has been revealed from this study that the groundwater depletion in the Nushki District is a deteriorating, interconnected process that directly increases the vulnerability on socioeconomic levels. It is necessary to respond to this crisis with a multi-scalar approach. First, systematic mapping, constant monitoring of groundwater levels, and transparent reporting mechanisms are all fundamental interventions that must be provided on the basis of data. Secondly, it should enact governance reforms to subject the solar-powered extraction to well registration, licensing, and regulation to avoid unsustainable extraction. Third, ecosystem-related interventions like recharge programs of aquifers, small-scale dams, and watershed management are essential to having hydrological balance. Lastly, the social protection should focus on the most vulnerable families to mitigate against livelihood shocks and avoid forced migration. Immediate areas of research need involve a quantification of the decline rate of an aquifer in various extraction conditions, the effectiveness of recharge interventions, and the modeling of socio-economic consequences in various policy settings. The policy level needs the concerted efforts between the provincial governments, local communities, and development agencies in ensuring that the district is not brought into a self-perpetuating cycle of groundwater depletion and livelihood erosion. Unless such efforts are made, remediation will grow costly in terms of financial as well as social aspects.

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