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The Groundwater-Energy-Food Nexus in Iran's Agricultural Sector: Implications for Water Security

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Abstract: This paper presents the first groundwater-energy-food (GEF) nexus study of Iran's agronomic crops based on national and provincial datasets and firsthand estimates of agricultural groundwater withdrawal. We use agronomic crop production, water withdrawal, and energy consumption data to estimate groundwater withdrawal from electric-powered irrigation wells and examine agronomic productivity in Iran's 31 provinces through the lens of GEF nexus. The ex-post GEF analysis sheds light on some of the root causes of the nation's worsening water shortage problems. Access to highly subsidized water (surface water and groundwater) and energy has been the backbone of agricultural expansion policies in Iran, supporting employment in agrarian communities. Consequently, water use for agronomic crop production has greatly overshot the renewable water supply capacity of the country, making water bankruptcy a serious national security threat. Significant groundwater table decline across the country and increasing energy consumption underscore dysfunctional feedback relations between agricultural water and energy price and groundwater withdrawal in an inefficient agronomic sector. Thus, it is essential to implement holistic policy reforms aimed at reducing agricultural water consumption to alleviate the looming water bankruptcy threats, which can lead to the loss of numerous agricultural jobs in the years to come.

Keywords: food-energy-water nexus; agronomy; water management; sustainability; Iran

1. Introduction

Iran is currently facing extreme water and environmental management challenges [1–8]. The country's technological approach to address water shortages through a large network of dams, inter-basin water transfer projects, and groundwater withdrawal has proven inadequate as water demands keep growing in the face of dwindling natural water supply and newly developed surface water and groundwater resources [1,2]. Consequently, Iran is grappling with a state of "water bankruptcy" [2] that threatens the sustainability of one of the world's most ancient and thriving civilizations. Rising water stress will likely increase the risk of water conflicts [9–13] driven by the country's water management issues. There is widespread evidence of water security becoming a major concern from a national security standpoint, including extensive drying-up of water bodies, frequent sand and dust storms, widespread groundwater table decline, deteriorating water quality, and increasing competition and conflict over limited water resources [1,2]. These problems are rampant to varying levels in the Middle East and North Africa (MENA) region, where prolonged droughts have, in part, been a catalyst of political unrest and social instability in countries like Syria [14]. Likewise, the potential links between drought-induced water scarcity and local conflicts have been a source of concern in Sub-Saharan Africa [15].

Iran's water resources are state-regulated and supplied at a minimal cost. Access to cheap water (surface water and groundwater) and energy has been the backbone of agricultural expansion policies, which are an important support mechanism for rural employment in Iran. Currently, about 20% of the jobs in the country belong to the agricultural sector, which uses more than 90% of Iran's total water withdrawals and contributes approximately 10% of the GDP. Since rural water and energy (electricity and diesel) are very cheap, agricultural activities are effectively only curtailed due to severe water shortages, manifested in the lack of surface water and drastic groundwater table decline as opposed to prohibitive water and energy prices. Water shortages are variable due to diverse climate conditions, which range from arid/semi-arid in the vast majority of the country to subtropical in the Caspian Sea coastal strip (Figure 1). On average, Iran receives less than one-third of the global average rainfall. Most of the country receives less than 100 mm of rain per year, although in small areas the average annual rainfall reaches more than 1000 mm. Consequently, the country relies heavily on groundwater to cope with the intermittency of surface water supply to sustain irrigated agriculture.

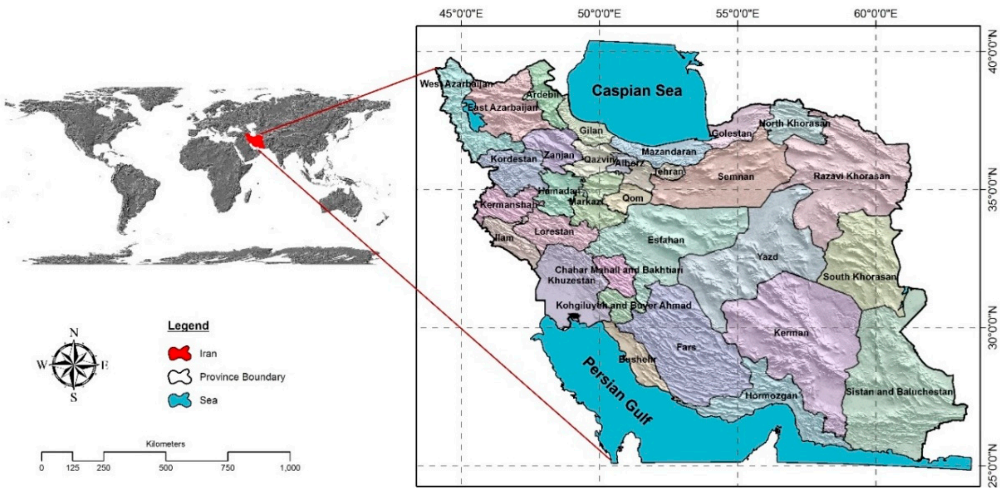


Figure 1. Map of Iran and its 31 provinces.

Iran launched food self-sufficiency initiatives after the Revolution of 1979, especially during the Iran-Iraq war, when food shortages were perceived as a primary national security threat. The push for food self-sufficiency was justified in the postwar era because of lasting economic sanctions that limited Iran's ability to access global markets [1,16]. As a result, self-sufficiency in staple crops (e.g., wheat) has become a strategic goal to ensure food security, encouraging the expansion of the agricultural sector through heavy subsidies despite massive adverse impacts on the nation's water and land resources (e.g., groundwater depletion, soil salinization, and water quality problems). The policy has contributed to increased food production without necessarily creating a more nutritious diet. However, serious concerns about depending on other nations for staple crops persist to this day, making proposals of food and virtual water imports highly controversial.

This paper presents the first groundwater-energy-food (GEF) nexus study of Iran's agronomic crops based on national and provincial scale datasets and firsthand estimates of groundwater withdrawal in the agronomic sector. The interlinkages between food, energy, and water (FEW) are increasingly recognized in the fledgling FEW nexus literature [17–24], offering high-level insights into efficient resource use for FEW security. The GEF nexus poses a challenging, yet critical resource management problem that is present in different forms in many countries [25–32]. To date, little attention has been paid to the crippling long-term side effects of inefficient resource management from a GEF nexus perspective. Our ex-post analysis illuminates the ramifications of an unsustainable GEF nexus for Iran's water security, highlighting policy insights to mitigate extensive water shortages and groundwater sustainability concerns across the country. We use province-level data for agronomic crop production, water withdrawal, and electric energy consumption to estimate groundwater withdrawal from Iran's electric-powered agricultural wells. Furthermore, we use crop acreage data along with the estimated agronomic groundwater withdrawal and electric energy consumption to illustrate agronomic productivity in Iran's 31 provinces through the lens of the GEF nexus. Monitoring GEF linkages facilitates an objective assessment of sustainable resource management to safeguard GEF security.

2. Materials and Methods

2.1. Land and Water Requirements of Agronomic Crops

Since it is located in an arid/semi-arid climate, only about 10.5% of Iran's land mass is deemed suitable for agricultural activities, with only 2.6% classified as very good (0.4%) or good (2.2%) agricultural land [9]. The areas under agronomic and horticultural cultivation cover 6% and 1.4% of the country's total area, respectively [33,34]. Over the past three decades, Iran has strived to provide sufficient food for its growing population, which has increased by almost one million per year to reach nearly 80 million in 2017. Based on long-term averages, wheat (200 kg per capita) has persistently dominated the food basket of Iranians, while potatoes (60 kg per capita) and rice (50 kg per capita) constitute the other two major sources of carbohydrates. With a per capita share of 67 kg, tomatoes are among the top vegetables in the annual food basket. Among crops that are mainly used for vegetable oil extraction (20 kg per capita) and as feed for livestock and poultry, grain maize and soybeans have increased substantially in demand over the past 15 years [9]. Also, other fodder products have an important role in feeding livestock and poultry.

We used agronomic crop acreage data for six major categories of crops in Iran including cereals, beans, industrial crops, vegetables, cucurbits, and forage. Because of the importance of rice as a staple food in the country, we considered it separately as a seventh crop category. Agricultural production data also include agronomic crop production and land productivity, defined as production (ton) per unit area of land under cultivation (ha). Figure 2 shows the 2015 province-level distribution of agronomic and horticultural crop acreages in Iran based on data from Ahmadi et al. [33,34]. Over 90% of the cultivated area belongs to the seven categories of agronomic production in five provinces (e.g., more than 99% in Khuzestan Province). There is more horticultural crop acreage than agronomic crops in the three provinces of Yazd, Hormozgan, and Kerman. Twenty-nine and 21 provinces have some level of bean and rice production, respectively. Five other agronomic crops, namely cereals, industrial crops, vegetables, cucurbits, and forage crops, are cultivated in all provinces. Figure 3 summarizes the latest available agronomic production data (2015) for the seven crop categories cultivated over nearly 11.4 million ha [34].

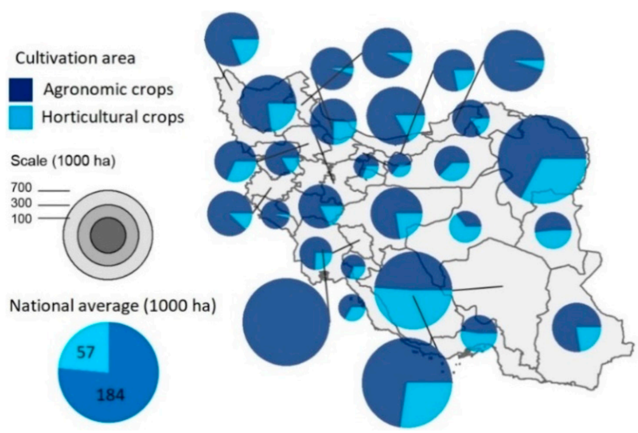


Figure 2. Province-level distribution of agronomic and horticultural crop acreages in Iran in 2015 (Sources of data: Ahmadi et al. [33,34]).

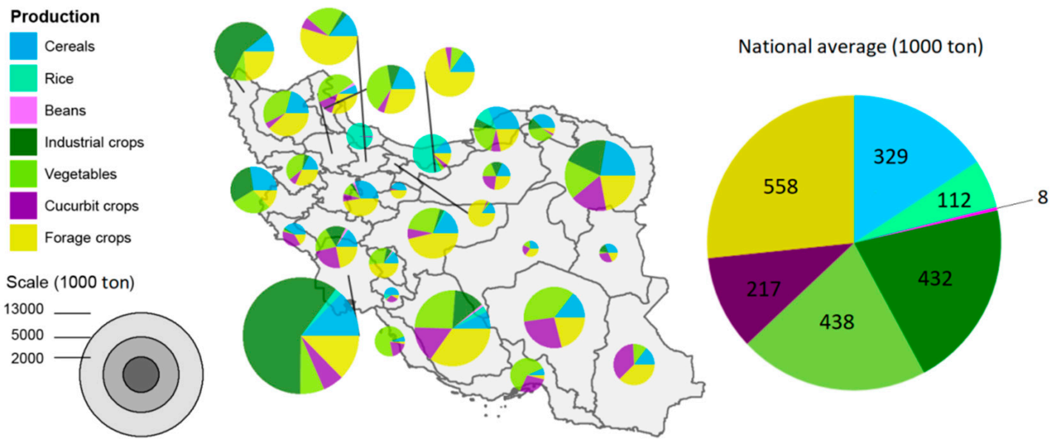


Figure 3. Agronomic production of seven crop categories in Iran in 2015 (Sources of data: Ahmadi et al. [33,34]).

We used the NETWAT crop water calculator [35], Iran's National Water Resources Development Plan, and a survey of provincial extension agents to obtain a dataset of average water demands for different crops in Iran. NETWAT was developed based on Iran's National Water Resources Development Plan, which provides estimates of water demands for a variety of crops produced in different provinces. NETWAT estimates evapotranspiration (ET) for Iran's agricultural crops using the FAO Penman–Monteith equation [36] and a database of available meteorological records in Iran since the 1960s [35]. In cases where crop water demands are unavailable from NETWAT (e.g., barley and industrial crops in some provinces), we used estimates of crop water demand from the National Water Resources Development Plan to obtain a consistent province-scale dataset of crop water demand. Since each province typically consists of several agricultural districts with different crop water requirements, a representative district and associated crop water requirements were identified for each province based on a survey of provincial extension agents, used to characterize average conditions. Responses were received from 25 provincial extension offices, naming one irrigation district as representative of the overall groundwater conditions within their respective provinces. For the six provinces that did not return the questionnaire, we used the average conditions of all irrigation districts within each province to characterize the average groundwater conditions in the agricultural plains. Figure 4 illustrates the average province-level crop water requirements for the seven crop categories examined in this study.

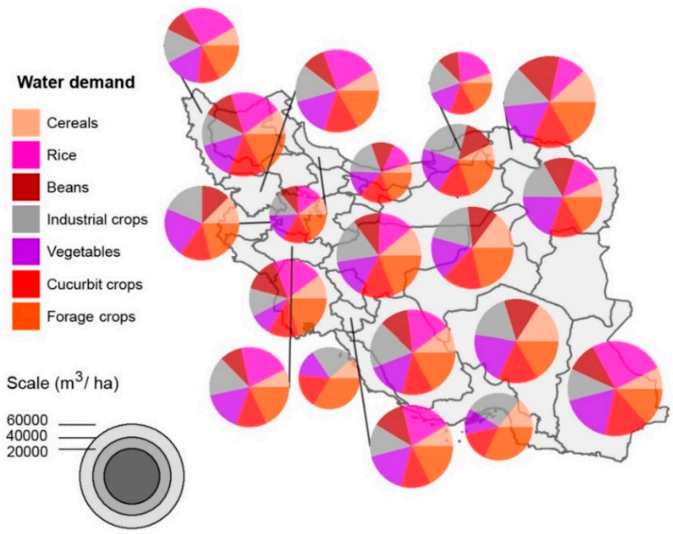


Figure 4. Average province-level crop water demand for the seven crop categories in 2015.

2.2. Groundwater Withdrawal

Groundwater is the primary source of water in the majority of Iran's provinces. According to the provincial water census conducted in 2011, groundwater withdrawal from wells provided approximately 55 billion cubic meters (BCM) of the country's total water supply (about 95 BCM), accounting for about 60% of the total water supply. Twenty-one of 31 Iranian provinces predominantly use groundwater to meet their water demands (Figure 5). Approximately 50% of Iran's groundwater withdrawal occurs in five provinces (i.e., Fars: 14%, Kerman: 12%, Khorasan Razavi: 11%, Isfahan: 8%, and Markazi: 5%), which are located in arid/semi-arid regions (Figure 1). Tehran Province, which has the largest population (about 17% of the country's 79.9 million population in 2017 [37]), ranks sixth in terms of groundwater withdrawal (4.54%) due to extensive surface water development plans to maintain the high reliability of the water supply to support its continuous growth, especially in the metropolitan area of Greater Tehran, the capital. The top five provinces in terms of the percentage of water supply provided by groundwater include Hamedan, South Khorasan, Kerman, Khorasan Razavi, and Zanjan, which, along with Markazi Province, use groundwater to meet more than 80% of their total water demand. In all but four provinces (i.e., two relatively water-rich northern provinces, as well as two provinces in the central plateau of Iran), more than 75% of the groundwater withdrawal is allocated to the agricultural sector, with 20 provinces using up to 85% of their total groundwater withdrawal for agriculture (Figure 6).

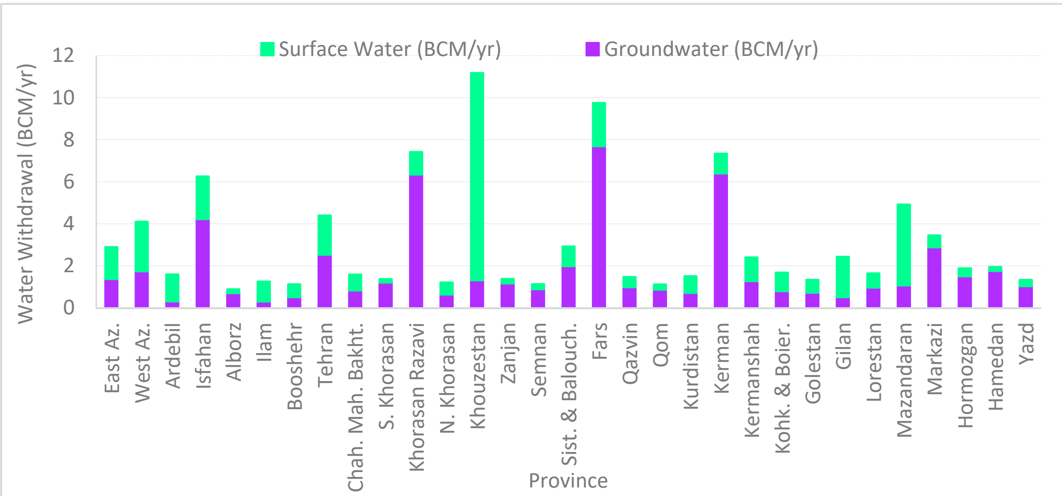


Figure 5. Total surface water and groundwater withdrawal in different provinces in 2011.

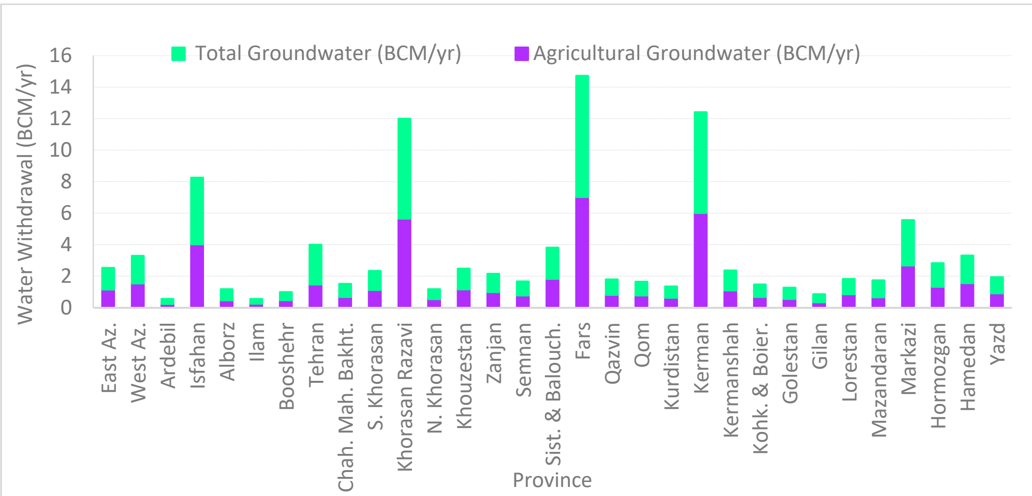


Figure 6. Total and agricultural groundwater withdrawal in different Iranian provinces in 2011.

Groundwater sources include deep wells (more than 50 m), semi-deep wells (less than 50 m), qanats (gently sloping underground tunnels (see [38] and the references therein), and springs (Figure 7). In an average year, the majority of the groundwater is extracted from deep wells (about 48%) and springs (25%) followed by semi-deep wells (18%) and qanats (9%). The country is currently undergoing a shift from shallow/semi-deep groundwater sources to deeper wells. In recent years (i.e., from 2002 to 2017), while the amount of water withdrawn from springs, semi-deep wells, and qanats has decreased by 42%, 12%, and 47%, respectively, groundwater withdrawal from deep wells has increased by more than 5% to ease the growing water deficit. On the whole, the country's total groundwater withdrawal has declined by approximately 18% despite population growth and intermittent prolonged droughts during 2002–2017, likely due to a depletion of high-quality groundwater resources and the intrusion of waters of marginal quality. This decline has occurred despite heightened permitted and unpermitted groundwater development by installing more wells (Figure 8). The number of registered deep wells increased from 127,800 in 2002 to about 195,000 in 2017, an increase of more than 52%. Over the same period, the number of registered semi-deep wells increased by more than 80%, rising from 33,000 to about 60,000. There are also a large number of unregistered wells, although the exact number is not known.

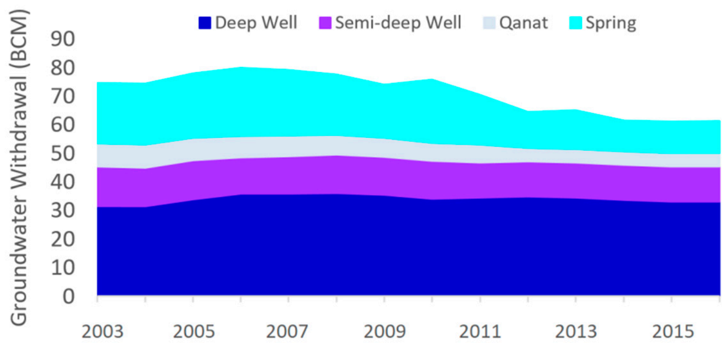


Figure 7. Historical trend of groundwater withdrawal from different sources in Iran.

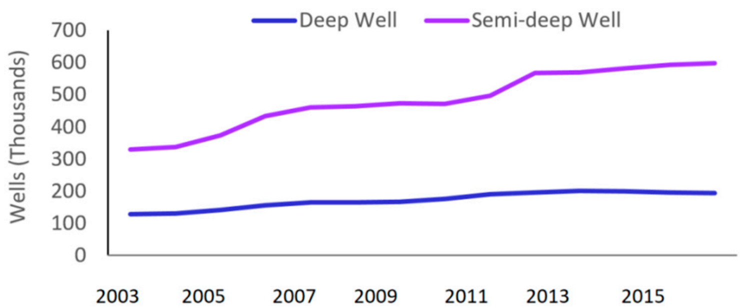


Figure 8. Number of registered deep and semi-deep water wells.

We applied three coefficients to total irrigated agricultural lands under agronomic crop production to quantify the irrigation water supplied from electric-powered wells to meet the agronomic crop water requirement. Our focus on electric-powered wells was motivated by Iran's policy of using electric-powered pumps for all registered groundwater wells, which became effective in 2010. The three coefficients include: (1) the ratio between agricultural groundwater withdrawal and total agricultural water withdrawal; (2) the ratio between irrigation well withdrawals (i.e., excluding groundwater from qanats and springs) and total agricultural groundwater withdrawal; and (3) the ratio between groundwater supplied from electric-powered wells and total agricultural groundwater withdrawal (i.e., both registered and unregistered electric and diesel irrigation wells). In addition, a fourth coefficient was applied to increase irrigation water withdrawal from electric-powered wells in order to account for irrigation water losses before the crop water requirement is fully met. The irrigation water loss coefficient was obtained for each province based on comparing the consumptive water use of crops and the crop water demand met through irrigation.

2.3. Energy Consumption

The energy source for extracting groundwater is electricity or diesel. The number of diesel-powered wells in Iran is decreasing, whereas electric-powered pumps are on the rise. The country's policy of using electric-powered pumps for all groundwater wells currently operating without a permit was voted into law by the Parliament in 2010. As a result, there is currently a push to convert diesel irrigation wells (currently 55% of total irrigation wells) to electric. The effect of this change is observed in an upward trend in the electric energy consumption data (reflecting increasing number of agricultural electric energy customers and sale), and declining diesel consumption for supplying groundwater for irrigation of agronomic crops (Figure 9). The average amount of groundwater extracted from diesel-powered wells from 2014 to 2016 was 57% of the total groundwater withdrawal from wells, which is decreasing because of the reduction in the number of diesel wells. Figure 10a,b shows average groundwater withdrawal from electric and diesel irrigation wells from 2014 to 2016 and the spatial variation in electric energy use in the agricultural sector in each province.

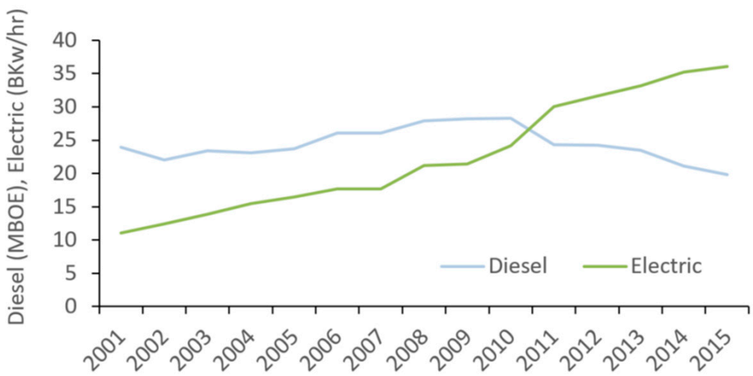
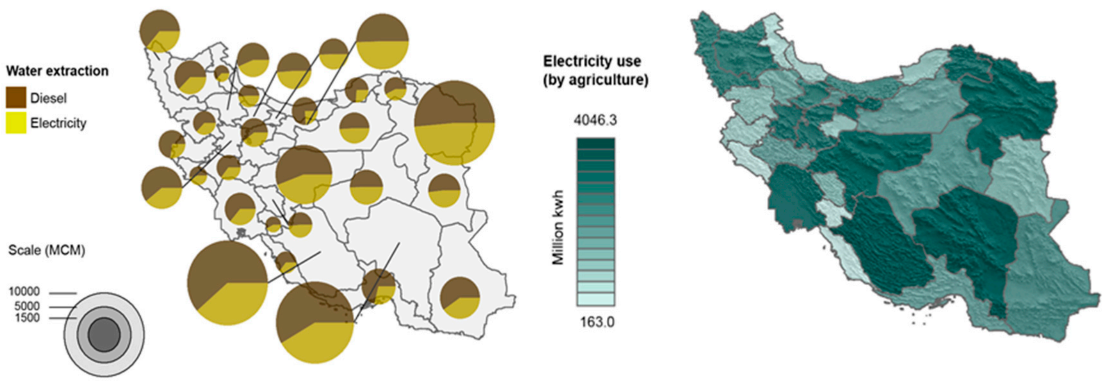


Figure 9. Electric and diesel energy consumption in Iran's agricultural sector.



(**a**) (**b**)

Figure 10. (**a**) Average groundwater withdrawal from electric and diesel irrigation wells from 2014 to 2016; (**b**) spatial distribution of electric energy consumption by province.

2.4. Analysis Metrics

We used three productivity indicators to examine the GEF nexus in the agronomy sector, including land productivity (production per unit cultivated land; kg/ha) for agronomic crop production, groundwater productivity (production per unit groundwater consumption; kg/m^3), and energy productivity (production per unit electric energy consumption; kg/Kwh). Larger values of the indicators show higher productivity with respect to the GEF resources. Since groundwater withdrawals are estimated based on crop water demands, cultivated area, and irrigation efficiency, groundwater productivity essentially represents crop productivity with respect to both cultivated land and groundwater consumption. Likewise, because the estimated electric energy consumption represents groundwater withdrawal, energy productivity characterizes the productivity considering land, groundwater, and electric energy.

We evaluated the impact of groundwater withdrawal for agronomic crop production on the average groundwater drawdown in each province. To this end, we estimated the consequent drawdown in a hypothetical "average virtual aquifer" in each province as an abstract aggregate-level indicator of groundwater status. Iranian water management agencies are run at the provincial level, even though the aquifers do not follow jurisdictional boundaries. The average aquifer is assumed to have a surface area equal to the sum of the areas of all the aquifers within the boundaries of a province. In addition, the average virtual aquifer is assigned the arithmetic average storage coefficient and average drawdown of different aquifers located fully or partially within a province. Relative groundwater depletion is then calculated as a dimensionless index by dividing depleted groundwater volume in each province by total groundwater withdrawal in the country (Equation (1)). The average aquifer status is evaluated during 2009–2016, when measured drawdowns are available for all aquifers. Furthermore, we used a groundwater vulnerability index, calculated as the product of three dimensionless factors, namely relative groundwater depletion, percent groundwater-supplied drinking water, and relative provincial groundwater withdrawal (Equation (2)):

$$RGD_i = (A_i \times S_i \times \Delta h_i)/TGW_i \tag{1}$$

$$GVI_i = RGD_i \times PGDW_i \times RPGW_i \tag{2}$$

where for a province i:RGD = relative groundwater depletion (dimensionless) estimated as the ratio between depleted groundwater volume $(A \times S \times \Delta h)$ and total groundwater withdrawal volume (TGW); GVI = groundwater vulnerability index (dimensionless); $PGDW$ = percent groundwater-supplied drinking water (dimensionless) defined as the ratio between groundwater-supplied drinking water (volume) and total drinking water supply (volume); and $RPGW$ = relative provincial groundwater withdrawal obtained as the ratio between groundwater withdrawal in each province (volume) and total national groundwater withdrawal (volume); A = average aquifer surface area (area); S = average aquifer storage coefficient (dimensionless); Δh = groundwater table drawdown (length) [39].

3. Results and Discussion

Figure 11 illustrates land, groundwater, and energy productivity indicators for the seven categories of agronomic crops produced in different provinces. A different picture of agronomic crop productivity is obtained when the provinces are evaluated based on all three indicators as opposed to considering each indicator individually. It can be seen that the GEF productivity of cereals, beans, and rice is generally small in the majority of the provinces. The three water-rich provinces of Mazandaran, Gilan, and Golestan, which occupy the northern coastal strip of Iran, have better GEF productivity for these crops, especially in terms of electric energy use, likely due to high groundwater tables, followed by the western provinces of Kurdistan, Kermanshah, and Lorestan. The production of industrial crops (cotton, sugar cane, soybeans, sesame, canola, and tobacco) in southeastern and east central provinces of Iran is notably inefficient based on the GEF productivity indicators. The remaining three agronomic crop categories of cucurbits, vegetables, and forage have higher relative GEF-based productivity across Iran, with the northern and western provinces outperforming the rest of the country.

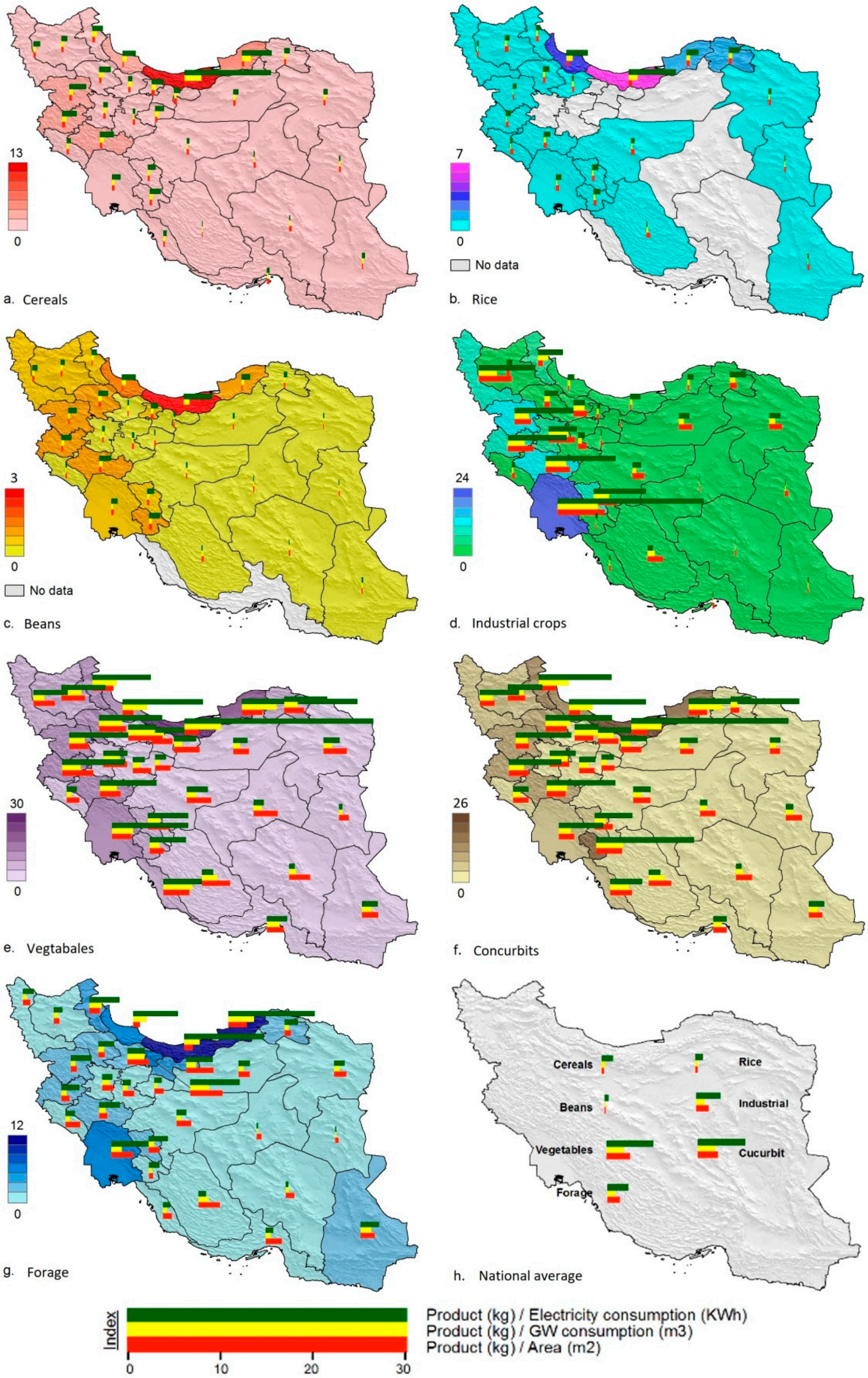


Figure 11. Provincial (**a**–**g**) and national (**h**) agronomic crop productivity based on GEF productivity indicators. Darker shades illustrate higher energy productivity (kg/Kwh) as a surrogate for GEF-nexus-based agronomic productivity.

Growing and relatively stable agronomic crop cultivation has been made possible at the expense of depleting groundwater resources, which until recently were managed as an unlimited resource exploited with very cheap energy. Figure 12 shows the estimated groundwater withdrawal for the production of the examined agronomic crops and horticultural crops, along with the reported groundwater withdrawal and the amount of groundwater that is available for use based on the Ministry of Energy's guidelines, designating up to 75% of renewable water considered as allowable withdrawal in each province. Two important observations can be made: (i) reported agricultural groundwater withdrawal in all the provinces exceeds allowable groundwater withdrawal for agricultural and non-agricultural purposes; and (ii) estimated groundwater withdrawal for agricultural crops is larger than the reported withdrawals in all provinces, except a few provinces such as those located in water-rich regions and Isfahan.

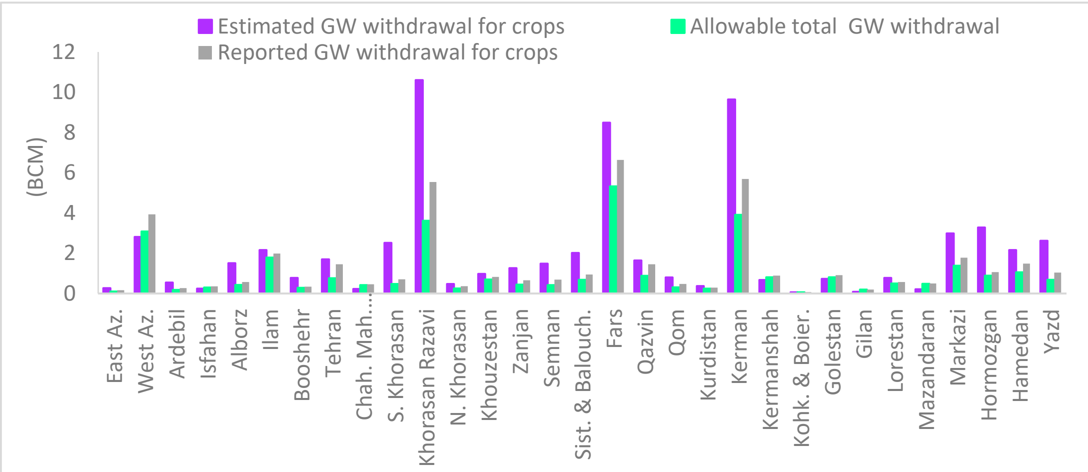


Figure 12. Comparison of estimated, reported, and allowable agricultural water withdrawal at the provincial level.

These observations lead to two critical insights. First, based on the comparison of reported and allowable groundwater withdrawal, it is clearly necessary to reduce agricultural water withdrawal to mitigate groundwater depletion and safeguard the sustainability of water resources and long-term food production. Second, the discrepancy between estimated and reported agricultural water withdrawals potentially indicates widespread underreporting of agricultural groundwater withdrawals in Iran, which necessitates better monitoring and regulation of groundwater resources. This is particularly important in provinces where there is a large difference between the estimated and reported groundwater withdrawal for agronomic crops, including S. Khorasan, Khorasan Razavi, Fars, Kerman, Markazi, Hormozgan, and Yazd. These provinces generally have a larger number of wells, including unregistered wells, making groundwater withdrawal monitoring a major challenge that contributes to the large difference between estimated and reported water withdrawal.

Iran's recent crop acreage data do not reflect the impact of recent droughts, indicating weak feedbacks between acreage and renewable water availability, energy costs, and agronomic production. Despite significant annual variability in renewable water, which is governed by wet and dry cycles [40], the land under cultivation of the seven agronomic crops is relatively stable (Figure 13). This is made possible through increasing groundwater pumping in a conjunctive agricultural water management scheme, common in arid/semi-arid regions of the world. There was only one incident of significant crop production decline in the 2008 drought because of a loss of crops in rainfed agricultural land. The total area of farmland shows only a slight overall decline due to the downward trend in the acreage of cereals, beans, and industrial crops as opposed to the mild upward trend of the acreage of cucurbits, vegetables, and forage (Figure 14). Land management is an effective adaptation strategy to mitigate groundwater depletion in arid and semi-arid areas where profit margins of agricultural production are affected by energy costs or concerns about groundwater sustainability and deteriorating groundwater quality [41]. As groundwater tables decline due to the increasing stress on Iran's groundwater resources [42,43], the energy cost of lifting deeper groundwater should normally increase as a balancing feedback to prevent groundwater depletion. Heavily subsidized, cheap agricultural electric energy essentially removes the negative feedback signal, allowing agronomic crop production to continue to the point that the sustainability of the country's groundwater resources is severely compromised. Figure 13 shows the upward trend of total energy consumption in the agricultural sector, calculated as the sum of diesel and electric energy. The accelerating electric energy consumption, due to a combination of switching diesel irrigation pumps to electric pumps and extracting groundwater from larger depths, shows that the positive trend of total agricultural energy consumption is governed by the significant increase in electric energy consumption.

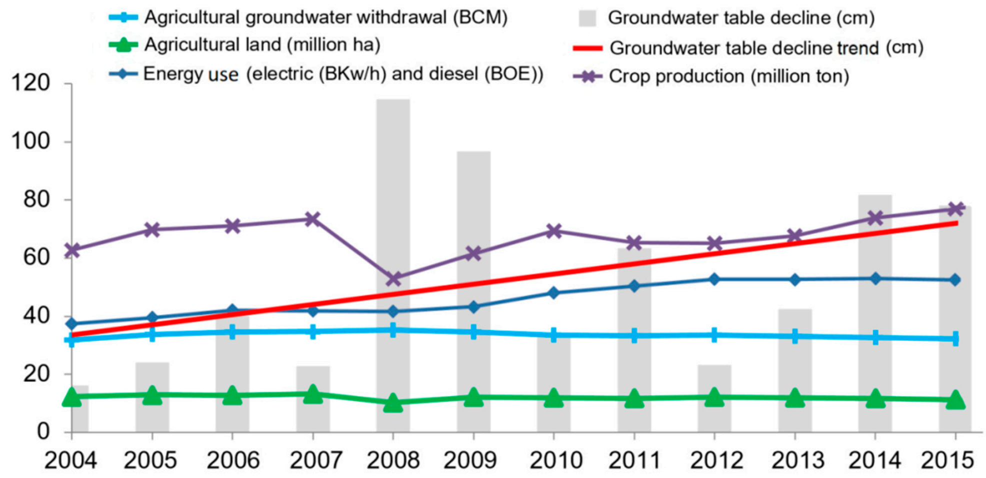


Figure 13. National agricultural GEF resource use, cultivated lands, and crop production in Iran.

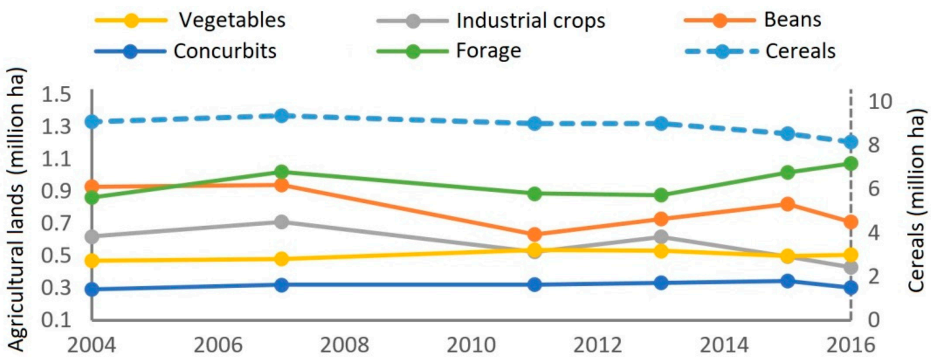


Figure 14. Acreages of agronomic crops in Iran. Rice acreage is included in cereals.

The dramatic groundwater drawdown in vast areas of Iran is an important sign of "water bankruptcy," associated with unsustainable GEF management policies, which has critical implications for long-term water security if the current management paradigm persists. The declining groundwater withdrawal trend (Figure 13), despite an increasing number of wells (Figure 7), indicates growing water scarcity and reduced groundwater availability. Figure 15 illustrates varying levels of groundwater vulnerability across the Iranian provinces. The groundwater tables are declining throughout the country. This has important implications for water security through increasing the competition over allocating limited water between urban and agricultural areas [44–46], especially under heightened hydroclimatic stress and continuous development [47]. More than one-third of the provinces are experiencing an average annual groundwater decline of 0.6 m, indicating severe to extreme groundwater vulnerability. The situation is particularly dire in the central and eastern provinces, especially Tehran, Isfahan, Fars, Kerman, and Khorasan Razavi, where the average decline is about 1 m per year. The continuation of this trend into the future should be a source of major concern, taking into account projections of warmer and drier climate in vast areas of Iran [48,49], which are expected to reduce renewable water availability and increase water stress throughout the 21st century.

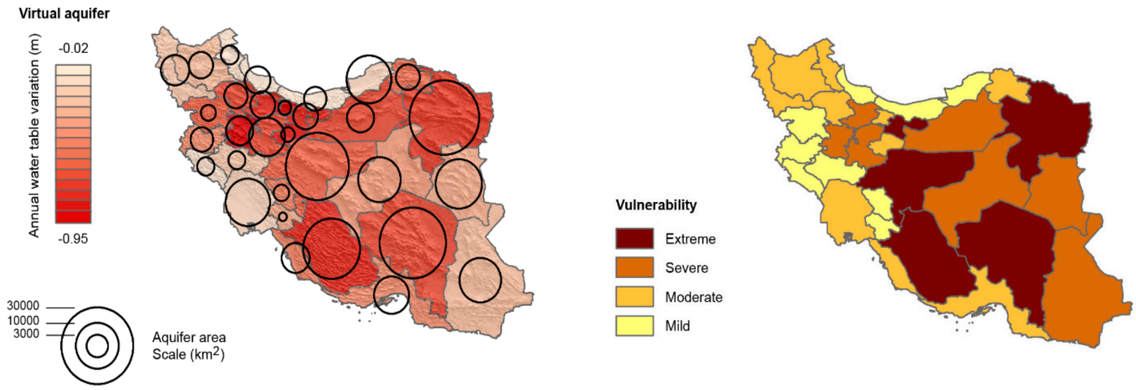


Figure 15. Representative (virtual) aquifer and groundwater vulnerability in each province (mild vulnerability: GVI = 0–0.21, moderate vulnerability: 0.21–0.83, severe vulnerability: 0.83–2.98, extreme vulnerability: GVI = 2.98–10 [39]).

The combination of Iran's attempt to switch to electric energy as the major energy source for the agronomic sector and the grave status of groundwater resources poses critical resource management policy challenges. If the current practice of providing the agronomic sector with heavily subsidized energy continues, as is expected to be the case, the widening financial gap of larger energy requirements will not be sensed at the farm level, eliminating incentives for reducing water consumption. Likewise, the groundwater tables can be expected to continue to drop under the status quo. In the absence of groundwater conservation, the significant average annual groundwater table drawdown (increase in groundwater pumping head) means that more energy is needed to sustain agronomic production. This would result in larger total subsidies being paid by the government in the short to medium term. This will likely increase the vulnerability of the electric power industry, which should prepare to absorb the additional agricultural energy load. In addition, increased electricity production is likely to be associated with increased greenhouse gas emissions (as observed in other parts of the world, e.g., California [50]). From a long-term sustainability perspective, however, it is critical to recognize the extensive and widespread groundwater table decline as a serious warning signal to implement adaptive agricultural water management measures to mitigate, or better yet, prevent future socioeconomic repercussions (e.g., job losses) associated with exhausting high-quality or marginal-quality groundwater.

Monitoring GEF linkages and trends offers a framework for the objective assessment of water sustainability in the broader context of the country's development trajectory. This ex-post analysis of the agronomic sector from a GEF nexus perspective documents groundwater resource sustainability challenges with looming consequences for Iran's economic and food production stability. Agricultural crops play a major role in feeding the population of Iran, like in other developing countries, and about 80% of cultivated area and water use can be attributed to the agronomic sector. As such, Iran is faced with difficult agricultural policy choices affecting its water and food security. Implementation of command-and-control policies (e.g., fallowing agricultural lands in vulnerable areas) in hopes of curbing the accelerating groundwater depletion will be difficult due to the socioeconomic ramifications of unemployment in farming communities. At a minimum, such policies will require effective government compensation programs in the face of a generally fragile national economic condition. It is essential to implement programmatic reforms that enable the farming communities to increase the efficiency of agricultural water and energy use to mitigate groundwater table decline and/or reestablish the aquifer water balance in agricultural plains. Such reforms require facilitating the modernization of the agricultural sector through technology transfer and extension programs, along with enforcing supplementary policies and regulations to improve groundwater monitoring and management. Failing to do so will aggravate the pernicious impacts on the country's groundwater resources, possibly causing the loss of numerous agricultural jobs, ecosystem damage, land subsidence, sinkholes, and food security issues in the years to come due to excessive groundwater stress and depletion in vulnerable provinces. To this end, the provincial scale of the present analysis allows us to locate the most vulnerable areas and prioritize mitigation programs. The GEF nexus analysis approach is transferrable to other regions experiencing groundwater table decline and allows for identifying weak links in natural resource management policies and taking corrective action in a timely fashion.

4. Conclusions

In this paper, we examined the groundwater-energy-food (GEF) nexus to shed light on the root causes of Iran's most pressing and prevalent water security threat, i.e., extensive groundwater table decline. The ex-post analysis of agronomic crops was based on national and provincial scale datasets of land use, crop production, and electric energy consumption along with firsthand estimates of groundwater withdrawal in the agronomic sector. The GEF analysis demonstrates a great need for increasing agronomic productivity with respect to water and energy use. Stable and/or growing agronomic crop cultivation and production in Iran has been made possible at the expense of depleting groundwater resources, which until recently were managed as an unlimited resource exploited with cheap energy. Currently, the reported agricultural groundwater withdrawals in all Iranian provinces exceed the allowable groundwater withdrawal for agricultural and non-agricultural purposes combined, although estimated crop water demands are generally much larger than reported withdrawals. The discrepancy between estimated and reported agricultural water withdrawals indicates potential widespread underreporting of agricultural groundwater withdrawals, which necessitates better monitoring and regulation of groundwater. The dramatic groundwater drawdown in vast areas of Iran is an important sign of water bankruptcy associated with unsustainable GEF management policies, which has critical implications for long-term water and food security if the current management paradigm persists. It is essential to implement programmatic reforms that empower farming communities to increase the efficiency of agricultural water and energy use with the ultimate goal of mitigating the groundwater table decline and/or reestablishing the aquifer water balance in agricultural plains. Such reforms require facilitating the modernization of the agricultural sector through technology transfer and extension programs, along with enforcing supplementary policies and regulations to improve groundwater monitoring and management. Failing to do so will aggravate the pernicious impacts on the country's groundwater resources, possibly leading to the loss of numerous agricultural jobs in the years to come due to excessive groundwater stress and depletion in vulnerable provinces.

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