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Groundwater Sustainability and Solar Irrigation in Madhesh Province: Status, Challenges, and Integrated Solutions

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Abstract

In pursuit of sustainable agriculture, Madhesh Province is witnessing a rapid transition from diesel and electric pumps to solar-powered irrigation systems. While this shift reduces carbon emissions and energy costs, it raises critical concerns regarding groundwater sustainability. Currently, groundwater levels in the region are not systematically monitored, and the natural recharge rates of extracted water remain uncertain. Without concurrent investments in groundwater recharge infrastructure, restoration of the Chure–Bhabar ecological zone, and regulation of tubewell installation, the widespread adoption of solar irrigation risks exacerbating groundwater depletion. This paper critically reviews the current status of groundwater resources in Madhesh Province alongside the rapid diffusion of solar irrigation technologies. It highlights the gap between renewable energy adoption and sustainable water resource management, underscoring potential long-term risks of unsustainable abstraction. Building on this analysis, the paper proposes integrated, multi-dimensional solutions: combining solar irrigation with strategically designed recharge ponds, reinforcing aquifer recharge through ecological restoration of Chure–Bhabar, and implementing regulatory frameworks for tubewell installation. Furthermore, it explores opportunities for multi-purpose solar utilization to optimize resource use. By synthesizing hydrological data and technology trends, this study emphasizes the necessity of coupling solar-powered irrigation with effective groundwater management to ensure the resilience of Madhesh's water and agricultural systems.

Keywords: Madhesh province, water crisis, solar irrigations, deep tube well sustainability, overextraction of ground water, policy, solutions

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Introduction

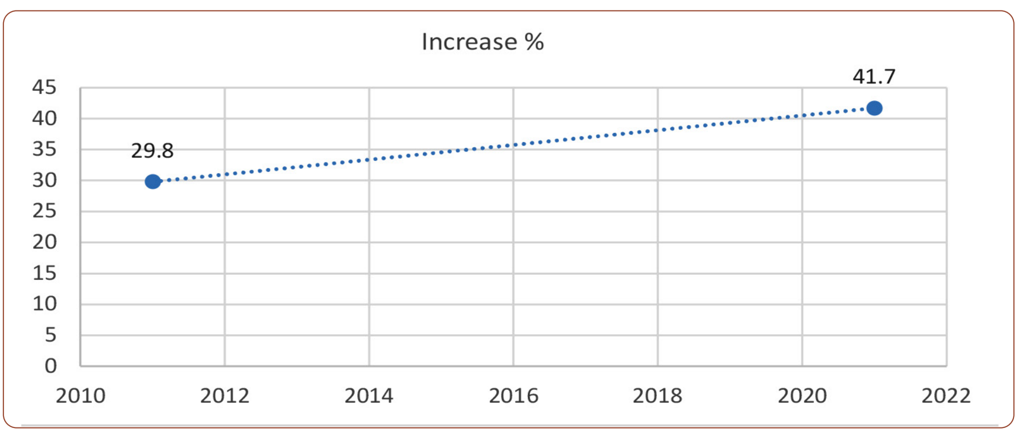
Madhesh Province, encompassing the fertile Terai belt of Nepal, serves as the country's agricultural powerhouse and is often referred to as the "Grain-Basket." This region's agricultural productivity heavily depends on groundwater, supporting over 70% of dry-season cultivation and enabling year-round irrigation of cereal and cash crops (Department of Water Resources and Irrigation [DWRI], 2023). Over the past three decades, the proliferation of shallow and deep tubewells for irrigation has been driven by both public and private sector initiatives (Groundwater Resources Development Board [GWRDB], 2023). In efforts to reduce diesel reliance and promote climate resilience, solar-powered irrigation systems have been scaled up since 2015 (Alternative Energy Promotion Center [AEPC], 2024). However, while these systems offer cleaner energy solutions, their sustainability is often overstated as solar groundwater pumping is rarely monitored for recharge balance, risking aquifer stress (International Centre for Integrated Mountain Development [ICIMOD], 2022). Thus, sustainability calls for a holistic approach incorporating restoration of the Chure–Bhabar recharge zone, regulation of well installations, integration of recharge ponds, and expansion of solar energy use beyond irrigation to include household power, community lighting, and local enterprises.

Data from Nepal's National Agriculture Census (2011-2021) indicate that groundwater's contribution to irrigation increased from 29.8% to 41.7%, reflecting its critical role in supporting the agrarian economy (Shreya-Dialouge Earth, 2024). Despite this, the province faces significant water challenges due to climate variability, depleted groundwater levels, and inadequate infrastructure, which have amplified drought impacts and posed serious threats to food security and livelihoods (ICIMOD, 2025; Madhesh Province Government, 2025). The severe drought in 2025 has led to widespread borehole failures and severe reductions in rain-fed agriculture, heightening water scarcity across seven of the eight districts, underscoring the urgent need to improve irrigation systems and groundwater management ICIMOD Report, 2025).

This narrative aligns with broader scholarship on sustainable resource management and development challenges in Nepal's Terai. Mishra and colleagues (2024) emphasize environmental sustainability orientations as key to organizational and community resilience, reinforcing the importance of integrated natural resource governance in agricultural regions. Past studies by Mishra et al. (2017, 2021) also highlight the relationship between infrastructure performance, resource management, and climate vulnerability, providing contextual insights relevant to irrigation and groundwater systems in Madhesh.

Figure 1

Groundwater Contribution in Irrigation in Nepal



Research Objective

To comprehensively assess the status and sustainability of groundwater resources in Madhesh Province by analyzing extraction trends and recharge conditions; evaluate the expansion and impact of solar-powered irrigation systems on groundwater use and agricultural practices; and propose integrated solutions combining solar irrigation, groundwater recharge initiatives, Chure–Bhabar restoration, and multi-purpose solar applications to ensure long-term water and energy security and climate resilience.

Methodology

The study is based on a review of secondary data and institutional reports from national and provincial sources, including the Groundwater Resources Development Board (GWRDB), Department of Water Resources and Irrigation (DWRI), and Alternative Energy Promotion Centre (AEPC). Data from 2010-2023 were taken from the annual reports of Department of water resources and irrigation. Literatures (Publication, report, magazine, records, and data) Problems that are like Nepal's current scenario. Case studies of other countries.

Results and Discussion

Groundwater Status in Madhesh Province

Groundwater is the backbone of Madhesh's agricultural system, supporting paddy, wheat, sugarcane, and vegetable production. As the "Grain -Basket " of Nepal, the groundwater is not only for the drinking, and the household works but does the huge contribution over the irrigation.

The deep tubewell data of the districts considered in present study shows that large number of deep tubewells is drilled in the Terai and Inner Terai region of Nepal (Pathak, 2018).

"Nearly 88 % of households in Madhesh Province rely on groundwater — comprising some 100,780 shallow tube-wells and 60,660 deep tube-wells — underscoring how vital subsurface water is for both domestic and irrigation use" (KC & Khadka, 2025).

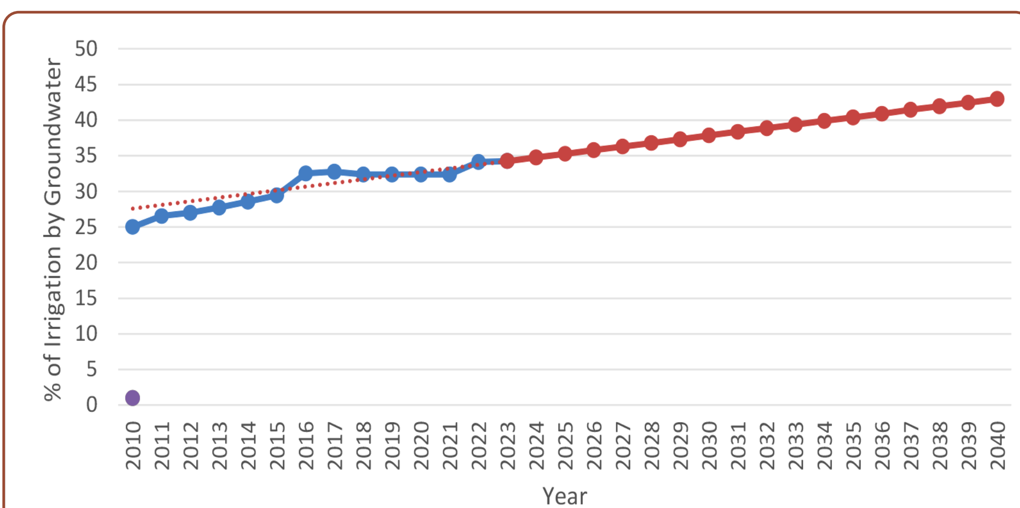
Groundwater contribution in Irrigation in Nepal has increased from 29.8% - 41.7% from 2011 to 2021(Shreya-Dialouge Earth, 2024).

Figure 2

Ground Water Extration

Figure 3

Annual Data of % of Groundwater Irrigation Per Year and its Forecasted Data Up to 2040



From above figure, line indicates a clear upward trend in reliance on groundwater for irrigation over the past decade. Suggests a continued gradual rise of 0.5–0.6 percentage points per year in groundwater's contribution to irrigation. From 2010 to 2040, groundwater irrigation share is projected to increase from ~25% to over 40%, a rise of about 15 percentage points.

This indicates growing dependence on groundwater for irrigation, which could imply higher pressure on aquifers unless recharge and sustainable management are prioritized

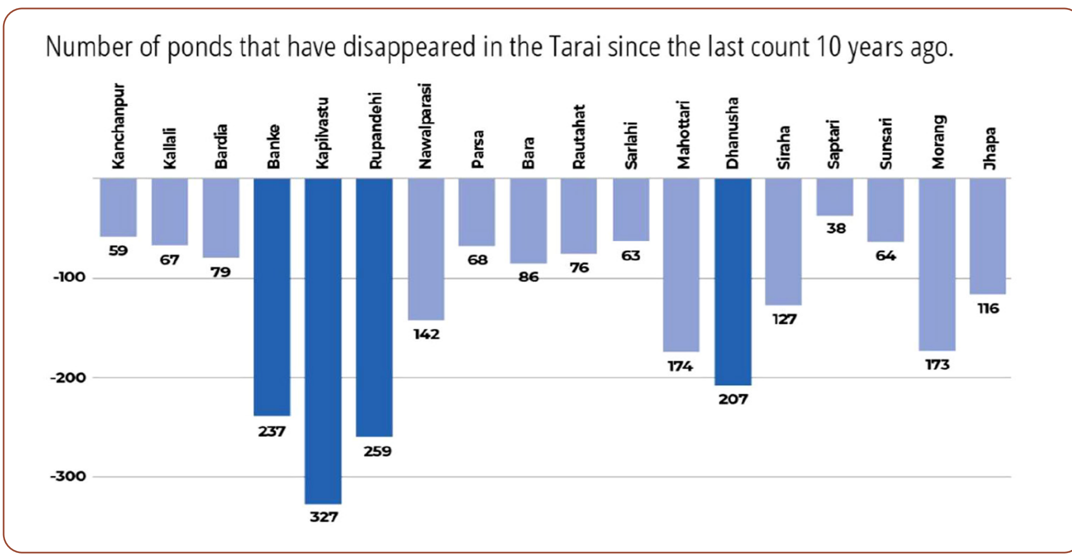
However, groundwater extraction has outpaced natural recharge. Studies by the GWRDB (2023) show a declining water table of 0.15–0.25 meters per year in central and western districts such as Dhanusha, Mahottari, and Sarlahi.

Recharge from rainfall and river percolation has been declining due to the degradation of the Chure–Bhabar region, which serves as the province's main infiltration zone (Provincial Policy and Planning Commission, 2024). Deforestation, sand mining, and haphazard infrastructure development in this fragile belt have disrupted the natural recharge processes.

The most recent survey 10 years ago showed that this number has shrunk dramatically to only 626, mainly because of encroachment and most of them in the Tarai, where 53% of Nepal's population lives. Many more lakes and ponds have probably disappeared in the past decade (Mainali, 2024).

Figure 4

Depleted Ponds



Expansion of Solar Irrigation Systems

Growth and Distribution

The Alternative Energy Promotion Centre (AEPC) began large-scale solar irrigation promotion around 2015 with support from development partners such as the World Bank, GIZ, and ICIMOD. By 2024, over 2,500 solar irrigation systems had been installed across Madhesh Province (AEPC, 2024).

Table 1

Solar Irrigation Systems Installed in Madhesh Province by District

District	Solar Systems Installed (Approx.)	Implementing Partners
Saptari	300	AEPC, ICIMOD, Practical Action
Siraha	250	AEPC, HELVETAS
Dhanusha	400	AEPC, IWMI, GIZ
Mahottari	320	AEPC, private vendors
Sarlahi	450	AEPC, World Bank (KISAN II)
Rautahat	280	AEPC, UNDP
Bara	350	AEPC, cooperatives
Parsa	200	AEPC, Practical Action

Note. (AEPC, 2024; World Bank, 2023)

While these installations reduce dependence on fossil fuels, most projects lack groundwater monitoring mechanisms. As AEPC focuses on energy access indicators (kW capacity and systems installed), water-use data remains poorly documented (AEPC, 2024).

Sustainability Concerns

Solar wells can pump water throughout daylight hours at zero cost, which may increase extraction and reduce incentives for conservation (ICIMOD, 2022). The shift to solar-powered irrigation pumps presents an environmental paradox: while it provides zero-carbon energy, the near-zero marginal cost of pumping can diminish the incentive to conserve groundwater, potentially worsening aquifer depletion unless other controls are in place (Shah , 2022). There is evidence of this paradox from Western India, where farmers with solar pumps were observed to pump longer hours than those with costly diesel, sometimes even over-irrigating because there is no fuel cost (Bassi, 2018).

This is particularly an issue in areas where groundwater resources are already overexploited, and recharge rates are slow. Globally, non-renewable groundwater abstraction contributes nearly 20 percent to gross irrigation water demand (Wada, 2012). In India, about 30 percent of aquifers are considered at critical status (Central Ground Water Board, 2014).

Case studies

Pakistan

In Pakistan, particularly in the province of Punjab, the rapid proliferation of private and largely unregulated tube-wells has been identified as a leading driver of groundwater depletion. According to the (Pakistan Council of Research in Water Resources [PCRWR], 2023), groundwater levels in Lahore are falling by approximately 0.92 m per year due to extensive abstraction via tube-wells. Field reports indicate that Punjab's overall extraction rate now exceeds natural recharge by about 142%, with groundwater tables declining at rates of 0.5–1.0 m annually (Wattoo & Ashraff, 2025). The increasing use of solar-powered irrigation has further complicated the situation, as renewable energy—while reducing emissions—can enable longer pumping hours without cost constraints, intensifying aquifer drawdown. This "green paradox" has already led to wells running dry or requiring deeper drilling in major agricultural belts such as Faisalabad, Multan, and Bahawalpur (Pakistan Council of Research in Water Resources [PCRWR], 2023).

India

In India, heavy dependence on groundwater-based irrigation, especially in the northwestern states of Punjab and Haryana, has triggered serious depletion of aquifers. Approximately 60% of India's irrigated agriculture now relies on groundwater abstraction (Pati, 2024). Between 2003 and 2020, Punjab and Haryana together lost about 64.6 billion m³ of groundwater, one of the largest regional declines observed globally (Pati, 2024). Studies show that tube-well density, coupled with subsidized electricity and the dominance of water-intensive crops such as rice and wheat, are key drivers of this depletion (Tripathi et al., 2016). The Punjab Preservation of Subsoil Water Act (2009) intended to delay paddy transplantation and curb pre-monsoon pumping—temporarily slowed groundwater decline, yet more than 80% of the state's administrative blocks remain "over-exploited" (Tripathi et al., 2016).

Integrating Solar Irrigation with Groundwater Recharge

Recharge-Oriented Approaches

A sustainable solar irrigation model must include recharge ponds and rainwater harvesting structures alongside each solar well. Pilot projects in Sarlahi and Rautahat districts have demonstrated that a 50 m² recharge pond can restore local water tables by 10–15 cm annually (ADB, 2024).

Policy and Regulation

The DWRI (2023) and Provincial Policy and Planning Commission (2024) recommend regulating new tubewell installations, making recharge structures mandatory, and strengthening local groundwater user committees. Enforcing aquifer zoning and annual water audits at the municipal level could ensure equitable and sustainable groundwater use. By implementing smart policies that integrate community-led governance with technological and energy-based incentives, we can move toward groundwater markets that not only keep crops alive and farmers prosperous but also keep aquifers healthy for future generations. The challenge now is collective action to achieve the vision of a water-secure and climate-resilient agriculture in the energy-digital age.

Establish a water accounting system (Batchelor, 2016) that provides quantitative estimates of the physical water balance (sources, diversions and withdrawals, consumption, return flows, changes to storage, etc.

Multi-Purpose Solar Utilization

Solar systems should not be limited to irrigation. The same photovoltaic capacity can support street lighting, household power, small enterprises, and community water supply. This multipurpose use enhances socio-economic benefits and optimizes solar investment.

In Siraha and Sarlahi, AEPC-supported pilots under the KISAN II and Renewable Energy for Rural Livelihoods (RERL) projects demonstrated dual-use solar systems powering both irrigation and local micro-enterprises such as rice mills and water filtration units (AEPC, 2024; World Bank, 2023). Similarly, ICIMOD (2022) documented community-level solar mini-grids in the eastern Terai that operate irrigation pumps during the day and supply power for homes and schools in off-peak hours.

Discussion

The findings reveal that solar irrigation in Madhesh Province is primarily driven as an energy solution, while the critical groundwater resource remains unmanaged, reflecting a one-dimensional approach that overlooks the hydrogeological limitations of the Terai aquifers. This underlines the necessity of adopting a combined water–energy nexus framework, where solar energy for pumping is balanced by water recharge and conservation mechanisms (Mishra & Mishra, 2024). Integrating the Chure–Bhabar restoration program into provincial irrigation and energy planning is critical, as this zone controls groundwater recharge. Despite ongoing government and NGO restoration efforts over the past decade, the programs have been insufficiently effective, evident in this year's severe drought in Madhesh Province. Without proper restoration of infiltration zones and regulation of groundwater abstraction, gains in energy efficiency will not translate into water sustainability (Mishra et al., 2018; Mishra et., 2024).

The recent drought emergency declaration in Madhesh Province highlights the urgent need for integrated management approaches that address both groundwater depletion and solar irrigation expansion. Reports emphasize that unchecked groundwater extraction diminishes recharge capacity and puts agricultural productivity and food security at risk (Mishra et al., 2024; ICIMOD, 2025). A stakeholder-driven governance framework in Barahathawa Municipality underscores the fragmented technical capacity, institutional gaps, and unmonitored extraction that threaten water sustainability (KC, 2025). Consequently, sustainable water and energy security in Madhesh demands coordinated interventions combining solar irrigation with groundwater recharge initiatives, restoration of the Chure–Bhabar recharge zones, and broader applications of solar energy for household and community use (Mishra & Regmi, 2017; Mishra et al., 2021).

Solar irrigation represents progress toward renewable energy and agricultural modernization. However, sustainability cannot be achieved through clean energy alone. The long-term security of Madhesh's water resources depends on monitoring groundwater levels, regulating tubewell expansion, restoring the Chure–Bhabar recharge zone, and integrating solar systems with recharge ponds and diversified uses.

An integrated solar–water management approach can transform solar irrigation from a short-term adaptation tool into a sustainable solution that ensures both energy access and groundwater resilience.

Recommendations

- o **Integrate Solar Irrigation with Recharge systems:** Make recharge ponds or percolation pits mandatory for all new solar irrigation installations.
- o **Implement Groundwater Monitoring and Licensing:** Introduce a provincial well registration and monitoring system managed by local water user committees.
- 3. **Link Solar Policies with Water Sustainability:** AEPC and DWRI should coordinate to measure groundwater outcomes, not only energy capacity.
- o. **Restore Chure–Bhabar Ecosystems:** Prioritize reforestation, control of sand mining, and watershed protection to improve natural recharge.
- o **Promote Multi-purpose Solar Use:** Extend solar systems to power streetlights, rural electrification, and small enterprises for wider socio-economic benefits.
- o **Develop an Integrated Water–Energy–Food Policy Framework:** Align provincial programs to balance energy expansion with sustainable water management.

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