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RESEARCH ARTICLE

Understanding the drying wells of Madhesh: looking through hydrogeologists' eyes

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ABSTRACT

Madhesh Province is experiencing increasing groundwater stress, manifested by seasonal declines in groundwater levels and well/pumping failures, particularly during the pre-monsoon period. These two areas were selected to illustrate a general hydrogeological principle: how quickly and visibly a well fails is governed largely by the aquifer's storage and pressure characteristics, not simply by the volume of water it contains. We argue that the apparently similar well failures reported across Madhesh often reflect groundwater-management problems and seasonal stress rather than permanent exhaustion of the regional aquifer system. This paper examines the problem from a field hydrogeologist's perspective by comparing two contrasting locations: Birgunj, an urban centre, and Mewa (Phatuwa Bijaypur) in Rautahat District, a rural agricultural area. The purpose is not to provide a statistically exhaustive province-wide assessment, but to illustrate how apparently similar well failures can arise from different hydrogeological conditions. The field evidence and hydrogeological interpretation indicate that the observed problem is more appropriately viewed as a groundwater-management and seasonal-stress problem than as evidence of permanent exhaustion of the regional aquifer system. Irregular and high-intensity rainfall, changes in land use and infiltration conditions, and increasing water requirements associated with population growth and intensified agriculture can increase groundwater stress. In Birgunj, concentrated abstraction from a low-storativity, confined and multilayered aquifer system produces rapid piezometric responses and seasonal pumping difficulties. In Mewa, the shallow phreatic aquifer has relatively high storage and responds more directly to local recharge, while observed domestic-well failures are often associated with well and pump limitations. The contrasting cases demonstrate the importance of considering aquifer-specific hydraulic characteristics when interpreting apparently drying wells and planning groundwater management.

Keywords: ***Groundwater stress, drying wells, groundwater management, Terai aquifer system, aquifer recharge***

INTRODUCTION

The Groundwater Paradox in Madhesh, Nepal

The Madhesh Province of Nepal relies heavily on groundwater for drinking, irrigation and industrial use. Field observations and reports from groundwater users indicate that many wells experience seasonal declines in water level or become operationally unusable during the late dry season.

This paper is a conceptual comparison, not a quantitative regional assessment. This paper examines the underlying hydrogeological causes through two contrasting field examples: the urban centre of Birgunj and the rural agricultural village of Phatuwa Bijaypur (Mewa) in Rautahat District. The objective is not to present a statistically exhaustive groundwater assessment of the entire province. Rather, the paper uses the two locations to demonstrate that a well becoming “dry” or ceasing to operate does not necessarily mean that the aquifer has been permanently depleted. The hydraulic response depends strongly on aquifer type, storage, transmissivity, recharge, well construction, pumping equipment and the spatial distribution of abstraction.

The Regional Hydrogeological Context: The Terai Aquifer System

The Madhesh Province forms part of the Terai, a 20–35 km-wide alluvial plain extending east–west along the Himalayan foothills, whose hydrogeology is strongly influenced by the piedmont–foredeep transition (JICA, 2005; BGS, 2015). Immediately south of the Siwalik Hills lies the Bhabhar zone, a 10–16 km-wide piedmont belt dominated by coarse talus and proximal fan deposits derived from torrential Siwalik streams (GSI, 1986). This zone slopes gently southward and merges into the finer alluvium of the foredeep to form the Terai proper. The boundary between the Bhabhar and Terai is typically marked by a spring line, which develops where highly permeable coarse Bhabhar sediments overlie or interfinger with finer foredeep deposits, forcing groundwater discharge at the surface (Lovelock & Murti, 1972; JICA, 2005; BGS, 2015). Progressing southward, the Terai deposits gradually transition into the overbank and channel sediments of the axial Sindhu–Ganga system, which ultimately form the Indo-Gangetic alluvial plain (Mukherjee, 2018).

Theoretical Framework: Storage and Hydraulic Diffusivity

A useful conceptual framework for interpreting different well responses is the relationship between aquifer storage and hydraulic diffusivity. Storativity (S) describes the volume of water released from storage per unit decline in hydraulic head in a confined aquifer, while specific yield (S_y) provides the corresponding storage response of a phreatic aquifer through gravity drainage. Hydraulic diffusivity is commonly expressed as $D = T/S$ for confined conditions, where T is transmissivity. Thus, a confined aquifer with very low S can transmit a pumping pressure disturbance rapidly, whereas a phreatic aquifer, with much larger effective storage associated with gravity drainage, generally shows a slower and more localized water-table response. The actual response depends on both transmissivity and storage, but the same amount of pumping can therefore produce very different visible well responses because of aquifer storage and pressure characteristics, rather than simply because one aquifer contains more water than the other.

The Bhabhar zone is widely recognized as an important recharge area for the Terai aquifer system. Rainfall infiltration through coarse Bhabhar deposits, together with infiltration associated with streams crossing the Bhabhar and Terai, contributes to groundwater replenishment. The regional hydraulic gradient is generally southward, and groundwater ultimately contributes to the broader Ganga drainage system. Groundwater levels in both shallow phreatic and deeper confined systems exhibit seasonal variations, generally rising during and shortly after the monsoon and declining toward the pre-monsoon period. The timing and magnitude of these changes, however, differ between aquifer systems.

However, this system is under increasing stress.

- Changing Rainfall Patterns: In recent years, rainfall distribution has become more irregular, with intense short-duration rainfall events and longer dry intervals reported in the region (**Baidya et. all. (2008).** Such rainfall characteristics can increase runoff and reduce the opportunity for effective infiltration, particularly where infiltration capacity is exceeded. Changes in the seasonal rainfall calendar (Gautam, Dilip et. al. (2014). Recent Trends in the Onset and Withdrawal of Summer Monsoon over Nepal. ECOPERSIA. 1. 353-367) can also increase dependence on groundwater during critical periods. These processes are interpreted here as factors that may reduce effective recharge; their quantitative contribution requires further investigation.
- Land Use Change: The Bhabhar zone, historically associated with extensive forest cover including the "Char-Kose Jhadi" (Four-Kos Forest), has experienced encroachment, deforestation and urbanization. Such changes reduce natural infiltration areas and can increase surface runoff.
- Increased Abstraction: Population growth, changes in domestic water use and increased cropping intensity have increased groundwater demand and placed additional stress on the aquifer system.

Case Study 1: Birgunj - An Urban Challenge

The Hydrogeological Setting

Birgunj's groundwater system consists of two main aquifers:

- A shallow phreatic (unconfined) aquifer extending down to about 25 to 30 meters below ground level (bgl). This aquifer, composed of fine to medium sand, is often of poor quality in densely populated areas and is primarily used for non-potable purposes. However, in the northern part of the municipality, it is used for drinking, despite being iron-rich.
- A deeper, thick confined aquifer system lies below the phreatic zone. It is heterogeneous, anisotropic and multilayered, and consists predominantly of sand and gravel. It forms the principal source of drinking water for the city. For the purpose of groundwater-level interpretation, this deeper system is considered part of a laterally continuous alluvial groundwater continuum rather than as a collection of isolated buried-channel aquifers.

The Problem

In Birgunj town, the vast majority of drinking-water wells are drilled to approximately 70–95 meters and tap the same broad deeper aquifer horizon. Approximately 65% of households are reported to have their own tubewell. Well diameters vary, with smaller wells commonly fitted with hand pumps and/or centrifugal pumps and larger-diameter wells generally equipped with submersible pumps. The critical period is approximately the 2.5 months immediately preceding the main monsoon, referred to here as the peak groundwater-stress period. Changes in rainfall seasonality, winter rainfall, earlier cropping and changes in cropping patterns have altered the seasonal groundwater-demand pattern. During this period, the author has personally observed piezometric levels of approximately 4–5 m bgl under normal seasonal conditions declining to about 10–13 m bgl during the pre-monsoon period. A similar seasonal declining trend has also been observed in groundwater-level records maintained by government agencies, although these records are unpublished. Such a decline is sufficient to place the water level beyond the practical suction limit of many centrifugal pumps, causing operational failure. Larger wells equipped with submersible pumps may continue to operate, although with some reduction in discharge. This behaviour indicates a substantial decline in piezometric pressure but does not by itself indicate complete exhaustion of the aquifer.

Groundwater Continuum and Comparison of Wells: For interpretation of groundwater-level observations, the Birgunj area is considered part of a laterally continuous alluvial groundwater continuum within the southern Terai. The term "continuum" does not imply identical hydraulic heads at all locations. Rather, groundwater heads vary spatially within a hydraulically connected regional system according to the regional hydraulic gradient and local hydraulic conditions. The available hydrogeological information does not indicate a hydraulically isolated buried-channel aquifer controlling the wells considered. Most drinking-water wells penetrate approximately 70–90 m and tap the same broad deeper aquifer horizon. Measurements from several wells show a consistent regional pattern, with groundwater flow generally following the expected north-to-south hydraulic gradient. These observations support comparison of groundwater levels as measurements within the same regional hydraulic system.

Recharge Estimation

The total population of Birgunj is 272,382. Assuming an average daily per capita consumption of 160 litres, the total domestic water requirement is estimated at 43.58 MLD (million litres per day). The major source of piped water supply is the Nepal Water Supply Corporation (NWSC), which operates 12 deep tube wells (DTWs). The combined discharge from these wells is reported to be approximately 9.4 MLD. According to the reported distribution-loss estimate of approximately 65%, the effective water delivered to consumers is about 6.1 MLD. This indicates a substantial shortfall. The remaining demand is therefore likely to be met substantially through private tubewells installed by households, institutions and industries. The detailed preliminary supply–demand calculation is presented in Table 1.

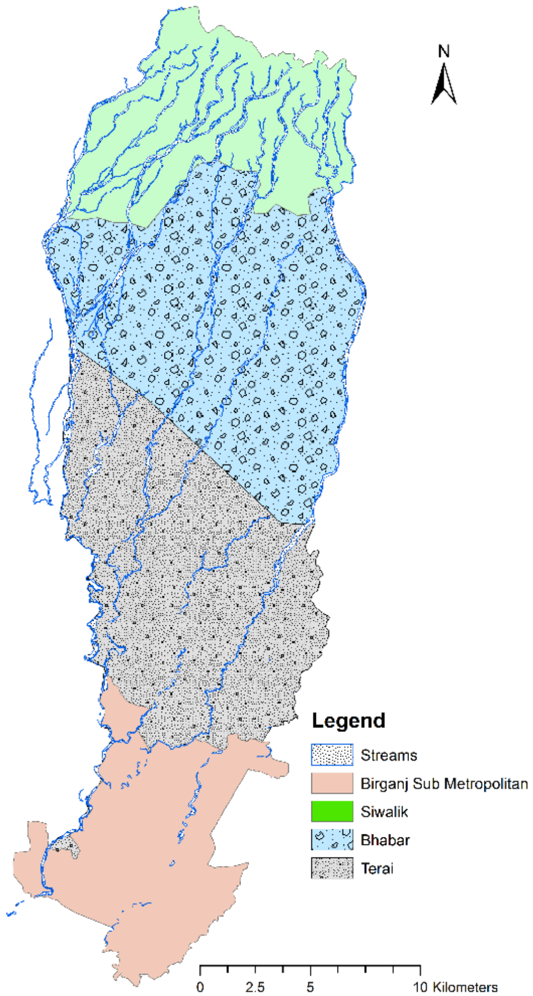
Table no 1: Groundwater extraction private tubewell

No of individual wells assuming 65% of HH	30624
Wells tapping phreatic aquifer (assuming 30% of total)	9187
no of well tapping confined aquifer	21437
Required discharge/well (l/day)	1224
Extraction from confined aquifer, MLD	35.64
Annual extraction from phreatic aquifer, MCM/annum	4.10
Annual extraction from confined aquifer, MCM/annum	13.01

The preliminary estimate of annual groundwater abstraction from the confined aquifer for domestic use only, excluding irrigation and industrial withdrawals, is approximately 13 MCM. The annual recharge estimate presented in Table 2, based on Duba's estimation, is approximately 75 MCM.

Table 2: Preliminary recharge calculation

Average Annual Rainfall (m)	Total Recharge (MCM)	
	Bhabar (33.6% of total rainfall)	
	Estimated Area (Km2)	Recharge
1.57	144.36	76.25



For the recharge calculation, only the area belonging to the Bhabhar zone is considered. This is a preliminary assessment and does not incorporate industrial and agricultural groundwater use within Birgunj Metropolitan City or areas to its north. The comparison between the preliminary annual recharge estimate and domestic abstraction suggests that annual replenishment may be sufficient in an average year to support the estimated domestic demand. This does not, however, preclude substantial seasonal piezometric decline because recharge is concentrated seasonally, groundwater continues to flow downgradient, and abstraction is concentrated during the dry season. The recharge estimate should therefore be further investigated. Infiltration may have changed in recent years because of uneven rainfall patterns and land-use change in the recharge zone. In addition, subsurface outflow during the dry season should be quantified in a detailed groundwater-budget study. The present calculation should consequently be interpreted as an indication of the scale of annual recharge rather than as proof that seasonal groundwater stress cannot occur.

Case Study 2: Phatuwa Bijaypur (Mewa) - A Rural Perspective

The Hydrogeological Setting

In the agricultural village of Mewa, most wells for drinking and irrigation tap the shallow phreatic aquifer, which consists mainly of coarse sand with some gravel down to approximately 20–25 m. Drinking-water wells are typically 20–25 m deep, while irrigation wells are generally shallower, between 7 and 20 m. Seasonal variation of the water table is approximately 2–8 m.

The Observation

Despite a high density of wells (>50 wells per 100 hectares) and intensive agriculture with approximately 270–300% cropping intensity, the phreatic aquifer remains comparatively resilient. Even during the driest months, irrigation wells of approximately 100 mm diameter generally continue to operate without substantial decline in discharge. Domestic drinking-water wells using 32 mm HDPE pipes sometimes experience operational difficulties. These difficulties are commonly associated with clogging of locally made screens. Their perforations can leave thin fibrous protrusions that are susceptible to blockage. When the water table declines seasonally, a partially clogged screen can increase the pumping effort and cause operational failure. The observation that hand pumps on some of the same wells continue to function supports the interpretation that the problem is associated with well efficiency and pumping mechanics rather than complete loss of aquifer yield.

Recharge Estimation

The phreatic aquifer in this region is primarily recharged by direct rainfall and irrigation return flow. A key characteristic is its anisotropy: the horizontal hydraulic conductivity (Kx) is typically greater than the vertical hydraulic conductivity (Kz). This contrasts with the adjacent Bhabar zone, where vertical conductivity dominates.

As the wetting front moves downward, flow paths are affected by the conductivity contrast and may preferentially spread along more permeable layers. Because the Terai plain slopes southward, the regional subsurface flow direction is also generally southward. Consequently, the effective recharge contribution to a particular shallow aquifer may extend beyond the surface area immediately overlying the point of observation. The magnitude and spatial extent of this contribution require site-specific investigation.

Analysis of the Causes: Aquifer Physics and Human Impact

The contrasting situations in Birgunj and Mewa are explained primarily by the fundamental differences between confined and phreatic aquifers, together with differences in recharge, abstraction intensity, well construction and pumping conditions.

Why are wells failing in Birgunj?

The principal problem in Birgunj is the concentration of withdrawals from the same broad deeper horizon within a multilayered confined aquifer system.

- Low Storativity & High Diffusivity: Confined aquifers generally have low storativity, commonly on the order of 10^{-3} to 10^{-5}. Because water is released predominantly through compression of the aquifer and water, a relatively small withdrawal can produce a substantial pressure response. Hydraulic diffusivity is defined as D = T/S. Because hydraulic diffusivity is given by D = T/S, the several-orders-of-magnitude difference in storage between confined and phreatic conditions can produce a correspondingly large difference in diffusivity when transmissivity is of comparable order; the actual diffusivity depends on both T and S.
- Well Interference: The high density of wells and simultaneous pumping can produce overlapping cones of depression in the vicinity of the pumping wells. The magnitude and spatial extent of the interference depend on transmissivity, storativity, pumping rate and duration. The fine-grained and multilayered nature of the Birgunj alluvial sequence should not be interpreted as producing an unlimited regional cone of depression; rather, the concern is substantial local and inter-well interference where wells tap the same productive horizon.
- Recharge and Recovery: The deeper confined system receives recharge through the regional alluvial system, including the Bhabhar recharge zone. If effective recharge is reduced, seasonal recovery can be weakened. Recharge and groundwater flow must therefore be considered together when interpreting the seasonal piezometric decline.

Why is the aquifer in Mewa resilient?

The shallow phreatic aquifer in Mewa is relatively resilient because of its larger specific-yield/storage response and its direct connection to local recharge.

- High Storativity & Lower Diffusivity: Phreatic aquifers commonly have much higher specific yield than confined storage coefficients. A comparatively large volume of water can therefore be removed through gravity drainage before producing the same magnitude of water-table decline that would occur as a pressure response in a confined aquifer. The corresponding hydraulic diffusivity is generally lower, although its actual value depends on both transmissivity and storage.

- Rapid Local Response: The observed rise of water levels following rainfall events indicates a rapid response to local recharge. This supports continued seasonal use where abstraction remains within the capacity of seasonal replenishment.

CONCLUSION

The field observations and measurements from Birgunj and Mewa indicate that an apparently drying or non-functional well should not automatically be interpreted as evidence of absolute aquifer depletion. The two locations demonstrate contrasting responses arising from different aquifer conditions, recharge characteristics, abstraction patterns and well/pumping configurations.

- In Birgunj, concentrated abstraction from the same broad horizon of a multilayered confined aquifer produces significant seasonal piezometric decline and local well interference. The resulting centrifugal-pump failures can occur even while deeper submersible-pump wells continue to yield water. The issue is therefore strongly related to the hydraulic response of the aquifer and the manner in which abstraction is distributed.
- In Mewa, the shallow phreatic aquifer receives direct local recharge and has a much larger storage response than a confined aquifer. The observed domestic-well failures are frequently associated with screen clogging and pump limitations rather than complete loss of aquifer yield.

The comparison highlights the need to move beyond the simple interpretation that a "dry well" means a "dry aquifer". Groundwater management should consider the hydraulic characteristics of the aquifer, the depth and screened interval of wells, the distribution and timing of abstraction, recharge conditions and pumping equipment.

SOLUTIONS AND RECOMMENDATIONS

Addressing groundwater stress in the Terai requires a combination of recharge enhancement, demand management, aquifer-specific well planning and long-term monitoring.

1. Implement Managed Aquifer Recharge (MAR): Recharge enhancement should be considered in suitable parts of the Bhabhar and adjoining recharge zones where surface water is available and infiltration conditions are favourable. Bharat Taal, an artificial lake along the left bank of the Bagmati River approximately 2 km south of Karmaiya on the East–West Highway, lies within the Bhabhar zone. Field observations of groundwater-level response in shallow and dug wells south of the lake suggest substantial infiltration and rapid subsurface movement through the coarse Bhabhar deposits. This example illustrates the potential of surface-water infiltration but should not be treated as a quantitative recharge estimate for Birgunj. A systematic programme of percolation ponds and other recharge structures may be considered in appropriate parts of the northern Bhabhar zone. Such measures should be designed on the basis of site-specific infiltration capacity, sediment characteristics, water quality and availability of surface water.
2. Develop Aquifer-Specific Management Plans: A one-size-fits-all approach to groundwater abstraction is inappropriate for a multilayered alluvial system. Management should be based on the hydraulic characteristics of the aquifer being tapped. In urban areas such as Birgunj, measures may include appropriate well spacing, monitoring of pumping levels, regulation of abstraction where necessary, and improved well construction.

   Rather than continuing uncontrolled proliferation of small-diameter private wells, a more manageable approach could be to develop fewer, strategically located, large-diameter production wells. In Birgunj, deeper wells in the range of approximately 250–300 m, potentially capable of yields exceeding 100 L/s where sufficiently productive horizons are encountered, may be considered where hydrogeological investigations demonstrate suitable deeper horizons. These values are illustrative hydraulic design concepts, not guaranteed well depths or yields. Longer effective screen intervals can distribute inflow over a greater aquifer thickness and may reduce drawdown for a given discharge, consistent with the hydraulic principle represented by Logan's approximation. The actual depth, screen placement, discharge and spacing must be established from lithological information, aquifer testing and pumping-test analysis.

The Terai aquifer system is multilayered. Appropriately designed screens in deeper productive horizons need not produce an immediate equivalent response in shallow aquifers; the degree of hydraulic interaction depends on the intervening layers, vertical hydraulic conductivity, screen placement, pumping rate and duration. Centralized production wells should therefore be designed to take advantage of vertical aquifer architecture while protecting shallow groundwater resources.

3. Promote Water-Efficient Technologies: Efficient pumps and appropriate well designs should be promoted to reduce operational failures caused by screen clogging, inadequate pump selection and excessive drawdown. In agriculture, water-saving irrigation technologies and improved irrigation scheduling can reduce groundwater demand.
4. Invest in Hydrogeological Research and Monitoring: A robust long-term monitoring network for groundwater levels and quality is essential for adaptive management. Further investigation is required to map the multilayered aquifer system, quantify recharge and discharge, evaluate vertical hydraulic connectivity, determine sustainable well spacing and abstraction rates, and assess the effects of rainfall and land-use change. The proposed management measures should therefore be regarded as hydrogeologically informed options requiring site-specific verification rather than as fixed prescriptions.

AUTHOR CONTRIBUTIONS

Both authors contributed substantially to this study. Author 1 conceived and designed the study, conducted the field investigation and data analysis, and prepared the first draft of the manuscript. Author 2 contributed to the interpretation of the results, discussion, manuscript revision, and overall improvement of the paper. Both authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request and can be obtained directly through email communication.

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