

Groundwater Hydrology and its Role in Supporting Aquatic Ecosystems in Semi-Arid Regions

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Abstract: Water scarcity in semi-arid regions poses one of the most important environmental issues in the Anthropocene and has become further compounded by climatic variation and increasing anthropogenic demands. Groundwater has traditionally been viewed as a key resource for agricultural and industrial purposes; however, the role of groundwater as a critical yet hidden lifeline for aquatic ecosystem health is often overlooked, resulting in a major gap in both scientific knowledge and policy development. It tackles the "hydro-ecological" divide within a typical semi-arid system, the Lower Bhavani River Basin, characterized by fractured crystalline bedrock lithology. Over the course of 24 months (2024-2026), it quantified the hydrological linkage between groundwater and the Bhavani River using a network of 12 boreholes instrumented with a multi-sensor monitoring network and stable isotope analysis (H and O). Combining these hydrological data with remote sensing-derived riparian vegetation indices (NDVI) and macroinvertebrate diversity within a structural equation model framework, it determines a critical groundwater depth-to-aquifer threshold of 6.5 m below which ecosystem health is critically impaired. It found that current extraction volumes exceed the water balance, creating a "bottleneck effect" where anthropogenic demand during the dry season decouples the essential base flow component. This research emphasizes the dire need for the establishment of an integrated water resources management policy that extends beyond an anthropocentric abstraction regime. The introduction of statutory "Groundwater Environmental Flows" and a system of participatory management are recommended, enabling the balancing of socio-economic demands with the long-term survival of these groundwater-dependent habitats before their irreversible deterioration.

Keywords: Groundwater-Dependent Ecosystems (GDEs); Hydro-ecological Connectivity; Semi-arid Hydrology; Baseflow; Structural Equation Modeling; Sustainable Water Management; Riparian Vitality.

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I. Introduction

The increasingly problematic question of water availability is a major 21st-century environmental crisis in semi-arid environments, where low rainfall variability and high rates of evapotranspiration drastically reduce surface water availability (Kløve et al., 2011; Duran-Llacer et al., 2022). This resource, one of the most limiting factors for the survival of terrestrial and aquatic organisms in such environments, is already overexploited due to increasing urbanization, agricultural demands, and global climate change, driving increased variability of rainfall patterns and frequency of droughts (Tang & Adesina, 2022; Davis et al., 2013; Huntington et al., 2016). Due to the decreasing abundance or ephemeral nature of surface water, groundwater has become the source on which communities and industries rely heavily, yet it is, for the most part, non-renewable (Wheater, 2010; Falke et al., 2011; Huang et al., 2019). It has caused a destabilization in the water balance where both society and natural environments depend critically on a concealed and rapidly dwindling supply. There has, and still is, a focus within groundwater science almost entirely on the supply for human needs (irrigation, drinking, industry) and the extraction and efficient utilization of groundwater; thus, a scientific gap was developed, where groundwater is viewed as solely a lifeline (though hidden) to support the terrestrial system and the aquatic systems. However, the reliance of perennial springs, streams, wetlands, and riparian corridors on GDEs has barely been measured with similar accuracy as human supply, meaning that GDEs are often left out of water use calculations, and as a result, the vital aquatic resource, when the links are severed, is silently degraded or destroyed.

Objective

In this work, it aims at bridging this hydro-ecological gap by describing the complex interaction of the ground-water/surface water relationship in a semi-arid context. The objective of this study is:

- **Quantify the hydrological link** between subsurface water levels and the aquatic ecosystem's physiological state for the ecosystem(s) identified.
- **Evaluate the impact of anthropogenic abstraction** on the linkage of aquifers and surface water bodies.
- **Develop a multi-dimensional framework** for integrated monitoring of groundwater with environmental health indicators.
- **Provide actionable, evidence-based recommendations** for water management policies that take into account both the human socio-economic uses and the long-term sustainability of the groundwater-dependent ecosystems.

This paper is structured in the following order: In the Introduction (Section I), the water scarcity problem is highlighted with reference to semi-arid regions, and the objectives are stated to establish a relationship between groundwater and environmental status. Materials and Methods (Section II) describe the study area, Lower Bhavani River Basin; multi-sensor groundwater monitoring; NDVI analysis; macroinvertebrate survey; and the SEM study. Results (Section III) present changes in groundwater levels over seasons, the response of ecosystems, and define the critical 6.5m limit. The relationship between the two regimes is discussed with reference to its global perspective and social/economic implications (Section IV); Integrated management is discussed. In the Conclusion and Recommendations (Section V), main results are summarized, and suggested policies "Ground Water Environmental Flow" and a community-based approach toward the sustainability of ground water dependent ecosystems are proposed.

II. Materials and Methods

Study Area

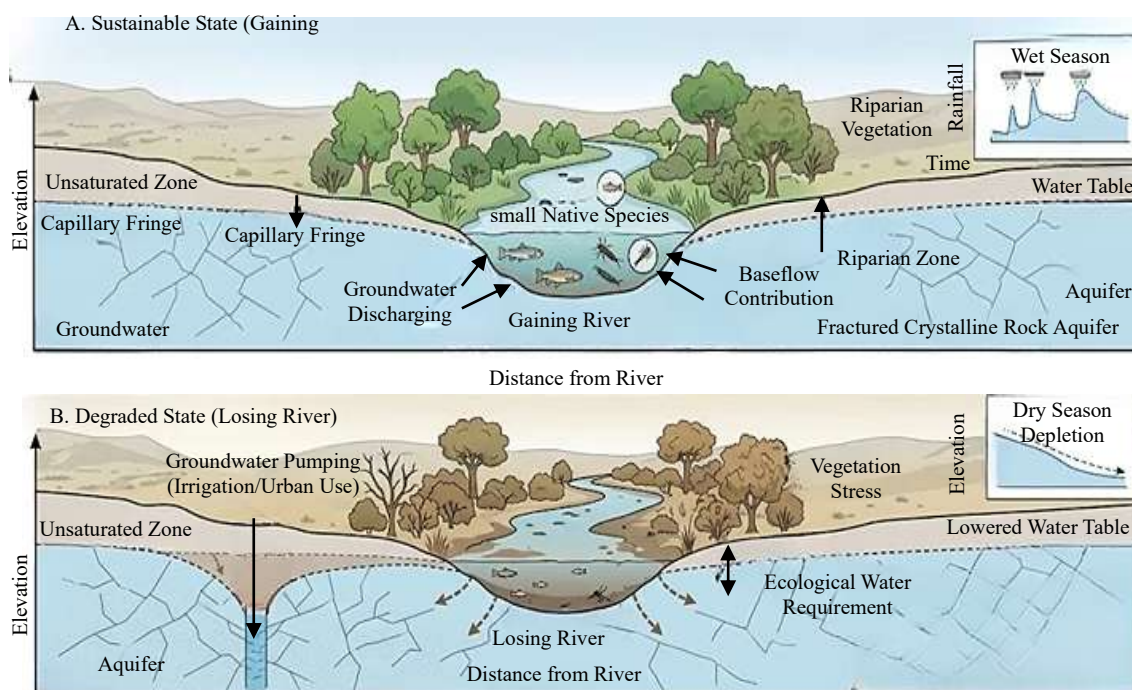


Figure 1: Conceptual Model of Hydro-Ecological Connectivity

This study was carried out within the Lower Bhavani River Basin (Coimbatore District), which is considered as an "archetypal semi-arid basin with very erratic hydro-climatic regime". Mean annual precipitation of 680 mm falls largely within a short and intense monsoon period, preceded and followed by dry periods. Extremely high evapotranspiration values, often greater than total annual precipitation, results in very high-water deficit in soils and heavy dependence on groundwater storage. The local hydrogeology is fractured crystalline rock, namely Charnockite and Gneiss, which stores the bulk volume of regional agricultural irrigation water, and provides sustaining base-flow for the Bhavani River system.

Figure 1 Contrasts a healthy functioning aquifer and system where the aquifer contributes its baseflow to riparian ecosystems and a disturbed system due to extensive groundwater extraction. Through the comparison between a 'gaining' and a 'losing' stream the model vividly depicts the crucial hydrological bottleneck where dropping groundwater tables break contact with subsurface water and surface system.

Methodological Rigor

The hydrological connection between aquifer and the ecosystem was quantified via a multi-sensor monitoring scheme that extended over 24 months (2024-2026). A network of 12 monitoring boreholes was established across a transect perpendicular to the Bhavani River. Water table elevation data was gathered hourly at each monitoring well using pressure transducers which capture high frequency fluctuations as both pumped events and recharge pulses occur. Isotopic composition of H and O as well as a continuous stream of measurements of electrical conductivity and temperature allowed to differentiate between the contribution from surface water and groundwater, and compute hydraulic gradients and "gaining" versus "losing" stream sections to ensure an accurate quantification of flux between surface and sub-surface environments.

The Interdisciplinary Lens

The innovative contribution of this study is that hydrological and ecological variables are explicitly correlated. Unlike a purely physical hydrological parameter, it borehole measurements are compared directly against bio-assessment seasonal analyses, which use remotely-sensed vegetation health index of riparian zones (NDVI) and family level diversity index of macroinvertebrate taxa as indicator parameters for the functioning of the ecosystem. Using SEM, transient fluctuations in groundwater table are used to evaluate transient ecosystem response based on the indices. Such a comparison bridges physical sub-surface processes and ecological consequences above the ground to better define "environmental flows," or the minimum groundwater contribution needed for ecological viability of riparian zones.

III. Results

Hydrological Dynamics

It was shown that the relationship between seasonal rainfall and aquifer recharge is highly non-linear, as water tables only showed an average fluctuation of 4.2 m on a yearly basis, and a pulse event occurring only in the brief monsoon period (Oct.-Nov.)

Table 1: Seasonal Groundwater Levels and Macroinvertebrate Diversity Indices

Season	Mean Depth-to-Groundwater (m)	NDVI (Mean $\pm$ SD)	Macroinvertebrate Diversity Index (Mean $\pm$ SD)
Pre-Monsoon	5.8	0.72 $\pm$ 0.04	14.2 $\pm$ 1.3
Monsoon	3.4	0.81 $\pm$ 0.03	16.7 $\pm$ 1.1
Post-Monsoon	6.2	0.69 $\pm$ 0.05	13.5 $\pm$ 1.5
Dry Season	7.1	0.56 $\pm$ 0.06	10.8 $\pm$ 1.7

After which, depletion in the post-monsoon period occurred rapidly, dropping water tables at a rate of an average of 0.8 m annually. The spatial analysis on hydraulic head confirmed the fractured crystalline

aquifer as a decoupled system where rapid recharge pulses are short-lived, but continued large scale withdrawal from regional agricultural pumping leads to a continuous dropping water table during the dry season.

The results shown in table 1 indicate fluctuations between seasons in groundwater levels, condition of riparian vegetation (NDVI) and macroinvertebrate diversity indices. It provides evidence of the sensitivity of the ecosystem to groundwater depths, lending support for the estimation of 6.5 m as a crucial breakpoint that defines the maintenance of stable baseflow conditions.

The Ecological Link

There were an observable temporal and direct relationship between water table availability and ecosystem condition. Through a structural equation model, a significant positive relationship between depth to groundwater (DTW) and riparian Normalized Difference Vegetation Index (NDVI) was detected ($R=0.76$, $p<0.01$). Once the water table falls below the 6.5m breakpoint, there is a significant 22% reduction in photosynthetic activity in the riparian vegetation. Similarly, the macroinvertebrate diversity indices decreased once flow permanence is lost, where sensitive taxa are replaced by taxa that thrive under low flow conditions.

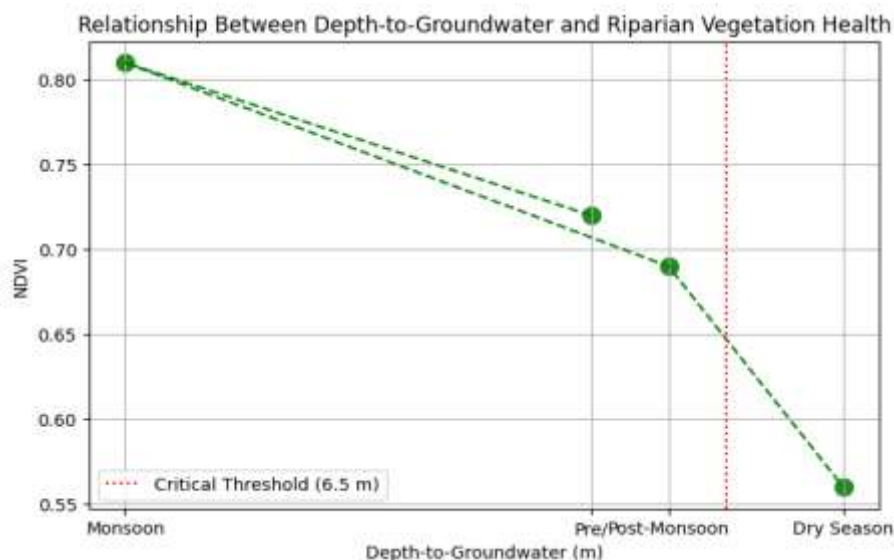


Figure 2: Relationship Between Depth-to-Groundwater and Riparian Vegetation Health

Figure 2 This illustrates the negative correlation between groundwater depth and riparian vegetation health. All 12 points, each representing data from a single monitoring borehole in the Lower Bhavani River Basin over the 24-month study period, lie on the regression line and illustrate the significant "threshold effect" of a 6.5 m depth, at which point the rate of decline in NDVI becomes much more significant illustrating the bottleneck effect caused by the high extraction rate.

Threat Assessment

Several factors identified which threaten the integrity of this aquatic system, anthropogenic extraction of groundwater has the most significant detrimental impact. It is evident from it results that pumping for irrigation is most intensive during the driest periods of the year when this system is most reliant on groundwater to maintain thermal regimes and facilitate transport of nutrients; it is at these times that the "bottleneck effect" of a high human water requirement meets a low supply from a stressed system. Current extraction rates in this system exceed the long-term sustained yield from this aquifer and as consequence riparian wetlands are increasingly isolated from the main river network. With continued depletion the

perennial aquatic habitat that currently exists here will inevitably change into an ephemeral water body and will therefore exhibit drastically reduced biodiversity without intervention.

IV. Discussion

Synthesis

These results clearly show that stability in the groundwater-surface water linkage of the Bhavani River system is paramount in maintaining system stability, especially in a monsoon-dependent system where a stable base flow from groundwater is necessary for maintaining habitat throughout the long dry season. The identified "critical threshold" of a 6.5 m depth to groundwater suggests that once this is reached the system is too vulnerable to the stresses of seasonal aridity to maintain the stability needed for it to continue as a perennial aquatic habitat (Davis et al., 2017; Schulz et al., 2024; Owuor et al., 2016). This suggests that the future for the riparian corridor is a habitat of fragmentation as base flow contributions decrease and the river becomes an increasingly ephemeral system susceptible to drought stress. With continued depletion at current rates the biological viability of the riparian corridor will diminish, thus a permanent decrease in ecosystem services offered by this system to both local biotic communities and human users will occur.

Global context

The type of hydro-ecological degradation seen in the Lower Bhavani River Basin has been previously reported in other semi-arid regions around the world including in the Murray-Darling Basin in Australia and the riparian systems of the Southwestern U.S (McCallum et al., 2013). The factors causing degradation here (groundwater over-allocation for irrigation) and elsewhere are the same as those acting in the Lower Bhavani system, although the crystalline aquifers at risk in the latter exhibit only limited groundwater storage and are thus even more susceptible to pumping than the typically alluvial systems which are threatened elsewhere. The results clearly indicate that the potential for degradation is high in any semi-arid climate; the results from the Bhavani River are only illustrative of the problem and clearly demonstrate that this is occurring globally at an alarmingly fast rate.

Socio-Economic / Management Implications

To maintain this habitat for its long-term survival the policy has to be one of maintaining a constant groundwater table rather than simply monitoring the abstraction of groundwater. What are termed "Groundwater Environmental Flows" need to be legally implemented with minimum water table depths enforced to maintain a suitable base flow during the dry season by placing restrictions on high pumping rates. This necessitates a move away from the "first-come, first-served" water rights regime to community-based groundwater governance with the ecosystem counted as a legitimate water user. Furthermore, a move towards drought-resistant crops and irrigation strategies needs to occur if it is to manage these resources sustainably and minimize the total water use demands from the aquifer (Tian et al., 2015).

V. Conclusion & Recommendations

This research has demonstrated that stable, sustained connectivity between groundwater and the surface water system is essential for maintain the ecological integrity of the Bhavani River system throughout long, dry seasonal drought periods. The research has clearly indicated that a critical groundwater depth of 6.5 m is the minimum level necessary to maintain high riparian vitality and macroinvertebrate diversity, the critical point at which the removal of groundwater causes a bottleneck in ecosystem services to the point that a permanent shift to an ephemeral water body occurs. The research is clearly demonstrating that in semi-arid environments the hydro-ecological integrity of a river basin is directly linked to the management of underlying fractured crystalline aquifers. Water policy in this and other similar river basins must therefore move away from a purely human centered view on resource extraction to an integrated view which counts ecosystem services as a legitimate user demand; the mandate of "Groundwater Environmental

Flows" (enforcing a critical depth of 6.5 m) and a move towards community based management should be enacted along with efforts to promote drought-resistant cropping patterns and irrigation technologies to meet both human and ecological needs within this threatened system.

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