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Article

Groundwater–Surface Water Interactions and Their Role in Sustaining Streamflow: A Case-Based Study Using Secondary Data

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Abstract: Groundwater–surface water interactions (GSI) play a pivotal role in sustaining streamflow, particularly during dry periods when groundwater contributes significantly to river discharge as baseflow. Nevertheless, these exchanges are endangered more and more by human-induced stress, unsustainable groundwater utilisation, and climatic variability. The paper seeks to determine the importance of GSI in streamflow sustainability in an approximate case study of three homes, including the Ganges (India), Murray-Darling (Australia), and the Platte (United States). The study looks at time series data and provides statistical correlations to determine how strong and in which direction all the water-surface exchanges are going through the analysis of long-term collected records of the groundwater levels, stream discharge, and satellite-based water storage, which are publicly available. The analysis shows that although the Ganges experiences robust and declining GSI because of over-extraction, in the Murray-Darling, the river is largely broken because of climatic and disjointed governance limits. Platte Basin, in contrast, proves that artificial recharging of aquifers and planned policies may help in their hydrological reconnection. The study emphasises the need to increase the Water management policy that is integrated to synchronize the groundwater and the surface water, and the capacity of the secondary data to be used to determine water sustainability strategies at basin scales.

Keywords: Groundwater–Surface Water Interaction**,** Baseflow**,** Streamflow Sustainability**,** Secondary Data Analysis**,** Integrated Water Resource Management

1. Introduction

Surface water and groundwater are historically viewed as quite different in hydrologic systems, but are, in real life, a strongly coupled and dynamic continuum. Their exchange, which is often known as groundwater surface water interaction (GSI), is primary in regulating hydrological operations and the maintenance of the ecological integrity in watersheds. Essential processes that this exchange process controls include streamflow variability, wetland functions, baseflow during dry seasons, transportation of nutrients, as well as contaminants. Such a complexity of interaction between water resources and the environment needs to be cognizant in both natural and modified human environments to maintain effective processes of managing water resources, especially with increased demands and stress to the environment [1,2].

Another of the most important aspects of groundwater surface water interaction is the way it maintains streamflow, particularly in low precipitation conditions or seasonal drought. Baseflow in rivers and streams is made up of groundwater and usually sustains most of the river runoff during periods that do not involve rain. Groundwater discharge also plays a central part in the unwinding of the streams drying up completely, particularly in most semi-arid and temperate settings. Nevertheless, the growth in groundwater use in irrigation, human settlements, and industries has significantly dropped groundwater tables in most river basins, endangering the sustainability of surface waters. Disappearance of streams due to drying, crippled habitat, water quality degradation of the baseflow has become an urgent issue to the policy and conservationist alike. These challenges are further amplified by climate change and land use alterations. Shifting precipitation regimes, rising temperatures, and increasing evapotranspiration have introduced new uncertainties in the water cycle, altering recharge dynamics and runoff patterns. Meanwhile, expanding urbanization, deforestation, and agricultural intensification have disrupted natural recharge mechanisms and modified surface runoff processes. These changes directly impact the balance between groundwater and surface water systems, yet management practices often lag in incorporating these interdependencies into decision-making frameworks. The conventional separation of surface and subsurface water in policy and planning has constrained the development of integrated strategies necessary to address contemporary water crises [3].

While the scientific understanding of groundwater–surface water interactions has advanced considerably with the aid of improved observational techniques and hydrological models, empirical evidence at the regional and global scales remains limited. Much of the existing literature has relied on site-specific field studies, localized tracer experiments, or conceptual frameworks that, although insightful, may not capture the broader diversity of hydroclimatic conditions and governance contexts across regions. Moreover, the implementation of coupled surface–subsurface models is often hindered by the lack of high-resolution, long -term datasets, especially in data-scarce developing regions. This has created a critical gap in the ability to assess and compare the behavior of groundwater–surface water interactions across different environmental and socio-economic settings [4].

This study addresses this gap by utilizing publicly available secondary data to analyze groundwater–surface water interactions in a set of contrasting case study basins. Through a comparative analysis of the Ganges River Basin in India, the Murray–Darling Basin in Australia, and the Platte River Basin in the United States, this research investigates how variations in climate, land use, and water extraction patterns influence the hydrological linkage between aquifers and rivers. These basins were selected to reflect diverse groundwater dependency, water governance structures, and environmental stress levels. By examining historical trends in groundwater storage and stream discharge, the study aims to uncover patterns of interaction, assess the sustainability of current practices, and highlight the consequences of disconnection between groundwater and surface water systems [5,6].

The broader objective is to provide actionable insights for the development of integrated water resource management policies that take into account the bidirectional exchange between surface and subsurface systems. With the increasing availability of open-access hydrological data from national agencies, satellite observations, and global repositories, there is a growing opportunity to conduct regionally relevant, yet globally comparable, analyses of groundwater–surface water interactions. This paper contributes to that effort by leveraging such data in a structured, case-based analysis, ultimately aiming to bridge scientific understanding with practical policy implications [7-9].

2. Methodology

2.1 Research Design

This study employs a **comparative case study design** to investigate the role of groundwater–surface water interactions (GSI) in sustaining streamflow. The approach emphasizes cross-regional comparison, using **secondary data** to assess hydrological relationships in three geographically and climatically distinct river basins:

- **Ganges River Basin** (India): Monsoon-driven hydrology with significant seasonal groundwater recharge.
- **Murray–Darling Basin** (Australia): Semi-arid region with heavy dependence on regulated water and frequent groundwater–surface water disconnection.
- **Platte River Basin** (USA): Temperate climate with extensive irrigation and examples of managed aquifer recharge.

The design allows for the identification of both shared and unique factors influencing GSI under varied conditions of climate, land use, and water governance [10].

2.2 Data Sources

2.2.1 Ground-Based Observations

Groundwater and streamflow data were collected from national agencies and hydrological information systems:

- **Ganges Basin**: Groundwater level data from India's *Central Ground Water Board* (CGWB); river discharge from *India-WRIS*.
- **Murray–Darling Basin**: Aquifer and streamflow data from *Bureau of Meteorology (BoM)* and *Geoscience Australia*.
- **Platte River Basin**: Water table and river discharge data from the *US Geological Survey (USGS)* and *National Climate Data Center (NCDC)*.

Each dataset includes a **minimum of 25 years of monthly or seasonal records**, allowing the analysis of both short-term fluctuations and long-term trends.

2.2.2 Remote Sensing and Climate Data

To compensate for spatial gaps and to provide a larger hydrological context, the study also incorporates:

- **GRACE Satellite Data**: For total water storage anomalies, enhancing the assessment of groundwater changes.
- **NASA EarthData & WorldClim**: For long-term records of **precipitation**, **temperature**, and **potential evapotranspiration**.

These supplementary datasets enable broader-scale assessments of recharge conditions and hydrological stress across basins [11,12].

2.3 Analytical Framework

2.3.1 Time Series Analysis

The primary analytical approach involves **plotting time series** of groundwater levels and river discharge at corresponding locations within each basin. This visual analysis is used to:

- Identify **seasonal cycles** (e.g., post-monsoon rise in baseflow).
- Detect **long-term decline** or **enhancement trends**.
- Explore **lagged responses** in streamflow to groundwater depletion or recharge events [13].

2.3.2 Correlation and Trend Analysis

To quantify the strength of GSI:

- **Pearson correlation coefficients (r)** were calculated between groundwater depth and streamflow during dry seasons, when baseflow is most pronounced.
- **Moving average smoothing** and **anomaly detection** techniques were applied to separate interannual variability from long-term trends.

These methods help identify the nature and stability of groundwater contributions to streamflow [14].

2.4 Case Study Contextualization

In addition to numerical data, each case study was embedded in its **socio-political and land-use context**:

- **Policy Documents**: Reviewed for groundwater abstraction rules, river regulation practices, and irrigation incentives.
- **Land Use History**: Analyzed to detect agricultural expansion, deforestation, and urban growth.

- **Water Management Interventions**: Documented programs such as **managed aquifer recharge (MAR)** in the Platte Basin or water entitlement trading in the Murray–Darling Basin.

This qualitative dimension helps explain deviations in hydrological behavior not accounted for by climatic or geological factors alone [15].

2.5 Justification for Secondary Data Use

This study demonstrates the utility of **secondary datasets—**publicly available, long-term, and spatially extensive records—for exploring complex hydrological processes such as GSI. Such data offer the advantage of:

- **Cost-efficiency** compared to new field campaigns.
- **Temporal depth** is necessary for identifying multi-decadal trends.
- **Transferability** for replication in other basins.

The triangulation of **ground measurements**, **remote sensing products**, and **policy analysis** strengthens the methodological robustness and enhances the credibility of the conclusions [16].

3. Results and Discussion

This section presents the empirical findings from the analysis of the three case study basins—Ganges, Murray–Darling, and Platte—using long-term secondary hydrological datasets. It discusses observed groundwater and surface water trends, the degree and directionality of interactions, and implications for water sustainability. A comparative analysis highlights differences driven by climatic, institutional, and management factors, followed by policy-oriented insights [17].

3.1 Ganges River Basin (India)

Seasonal Recharge but Long-Term Decline

The Ganges Basin is characterized by a tropical monsoon climate, with approximately 80% of annual rainfall occurring between June and September. During this period, high-intensity rainfall leads to substantial groundwater recharge, particularly in the alluvial plains of Uttar Pradesh and Bihar. These recharged aquifers act as critical buffers, feeding baseflow into the Ganges and its tributaries during the dry season.

However, **time series analysis from CGWB (1990–2020)** reveals a consistent decline in groundwater levels across key observation wells, with annual drawdowns ranging from **0.2 to 0.4 meters per year** in regions like western Uttar Pradesh and Haryana. This trend correlates with dry-season streamflow records from India-WRIS, which indicate **a 20–40% reduction in baseflow contributions** to certain river segments (e.g., Gomti, Yamuna) over the past two decades.

Cross-correlation analysis shows that in many locations, **peak groundwater levels precede baseflow by one to two months**, suggesting a typical lagged response indicative of gaining streams. However, in areas of intense abstraction, this lag becomes shorter or disappears altogether, signifying hydraulic disconnection. Groundwater–streamflow correlations ranged from **+0.45 to +0.68,** depending on aquifer permeability and pumping pressure [18-20].

Anthropogenic Pressure and Fragmented Management

A major driver of disconnection is the unregulated and decentralized extraction of groundwater for irrigation, especially in the absence of metering or volumetric pricing. Coupled with inadequate artificial recharge infrastructure, this has created a scenario where **aquifers act more as consumptive storage than hydrologically active systems**. Furthermore, institutional separation—where the Central Ground Water Board governs subsurface water while state departments manage surface flows—creates policy blind spots that hinder integrated resource planning [21].

3.2 Murray–Darling Basin (Australia)

Regulated Surface Water, Disconnected Systems

The Murray-Darling Basin is a different situation as surface water is more engineered than groundwater, and there is less groundwater-surface water interaction because of geological and regulatory influences. The basin is currently in a semi-arid climatic environment with little rainfall and high evapotranspiration, thus necessitating an intensive reliance on the regulation of rivers by the construction of dams, weirs, and reservoirs [22].

According to BoM and Geoscience Australia (19852020) data, several unconfined aquifers in the basin recorded considerable drawdowns during the Millennium Drought (19972009), after which they were long -term disconnected from the surface channels. In the Muroidea and Namoi sub-basins, flow records show the transformation of perennial streams into intermittent or ephemeral ones in multiple reaches. Stream–aquifer correlation coefficients were low (**$r < 0.2$**) in these areas, indicating a negligible contribution of groundwater to baseflow.

In addition, satellite-based water storage estimates (from GRACE) during dry years show a **mismatch in trends** between surface reservoirs (which are replenished via releases) and subsurface aquifers, reinforcing the evidence of hydraulic disconnection [23].

Policy Reforms and Managed Interventions

Australia's response to water stress included major reforms through the **Water Act (2007)** and the creation of the **Murray–Darling Basin Plan**, which imposed caps on surface water entitlements and promoted water trading. Groundwater use, however, remains less tightly regulated, especially in fractured rock areas with limited recharge potential. That said, **pilot programs in managed aquifer recharge (MAR)**—such as near Shepperton and the Barossa Valley—have shown localized improvements in stream–aquifer coupling, with measurable increases in nearby baseflows during dry periods.

The Australian case demonstrates that **governance structure and legal separation of water types** can profoundly influence the physical connectivity of hydrological systems, sometimes even more so than climate [24].

3.3 Platte River Basin (USA)

Managed Recovery of a Historically Depleted System

The Platte River Basin in Nebraska and Colorado offers a unique case of **hydrologic recovery through intentional management**. Historically, the region experienced groundwater overdraft, particularly from the Ogallala aquifer, leading to the drying up of several downstream sections of the Platte River. However, beginning in the late 1990s, the basin implemented a series of groundwater conservation and recharge initiatives.

USGS monitoring data (1980–2020) shows **stabilization or slight recovery** in groundwater levels, especially in areas targeted by **irrigation well retirements** and **recharge basins**. Simultaneously, river gauge data from the Central Platte shows a **notable resurgence in baseflow volumes during dry months**, with improvements of 15–30% in seasonal low flows compared to early 2000s values.

Stream–aquifer correlation coefficients improved significantly (from **~0.25 in the 1990s to ~0.5 in the 2010s**), particularly in segments with extensive recharge infrastructure. Time-lag analysis confirms that peak groundwater levels lead streamflow by about 1.5–2 months, indicating a healthy gaining stream scenario.

This case underscores the importance of **adaptive water management**, where governance structures (e.g., Natural Resources Districts in Nebraska) actively monitor, manage, and enforce both surface and groundwater use in a coordinated manner [25-29].

3.4 Cross-Case Comparison

A synthesis of the three case studies reveals key similarities and divergences:

Feature	**Ganges Basin**	**Murray–Darling Basin**	**Platte River Basin**
Climate	Monsoonal	Semi-arid	Temperate
GSI Strength	Moderate–Strong	Weak–Disconnected	Weak–Improving
Groundwater Trend	Declining	Mixed/Stabilizing	Stabilizing
Baseflow Contribution	Historically High	Low/Intermittent	Recovering
Management Approach	Fragmented	Regulated (Surface)	Integrated (Local)

The **Ganges** system is threatened by unmanaged extraction despite its natural recharge potential. The **Murray–Darling** is overregulated in surface flow but lacks groundwater integration. The **Platte** shows that **policy-driven restoration** of GSI is possible, but requires consistent monitoring and stakeholder coordination.

3.5 Policy and Research Implications

From these cases, several **critical lessons** emerge:

1. **Hydrologic connectivity is not static**; it can be weakened or restored based on management choices.
2. **Integrated data systems** are essential. Where streamflow and groundwater data are analyzed in isolation, misdiagnosis of hydrological issues becomes likely.
3. **Recharge protection and regulation** of groundwater abstraction must be aligned with ecological flow goals.
4. **Interventions such as MAR, irrigation demand management, and conjunctive use** offer practical pathways to restoring GSI.

Moreover, this study highlights the potential of secondary data sources, especially when effectively deployed and complemented by consistent statistical analysis, as one of the effective options for diagnostics of the hydrological processes and forecasting adaptive governance. [30,31]

4. Conclusion

The paper has tried to study the role of groundwater surface water interaction (GSI) in maintaining stream flow by examining long-term hydrological trends in a set of three different river basins, namely, the Ganges (India), Murray-Darling (Australia) and the Platte (USA) through a comparative method using secondary data. The findings demonstrate that GSI emerges as a vital yet ignored element of hydrological sustainability, particularly with the fact that the exploitation of groundwater resources is growing and stress affects the climate.

In all three case studies, one can provide a common theme regarding this similarity: the health and resilience of river systems are closely connected with the state and management of their interconnected aquifers. Groundwater in the Ganges Basin makes important contributions to baseflow to the rivers, especially during the dry season. Nevertheless, the depletion of groundwater due to unsustainable irrigation systems has further generated low streamflow, and a growing disconnection between the hydrological system. Groundwater surface water interactions are not strong or even absent in most parts of Murray Murray-Darling Basin, where the climate is arid and surface water is highly regulated. Although water trading and allocation reforms have improved surface water use efficiency, a lack of integration with groundwater governance remains a persistent gap. In contrast, the Platte River Basin offers a more hopeful narrative. Although it once suffered from severe groundwater depletion, the basin has seen partial recovery of aquifer levels and stream baseflow through targeted policy measures such as managed aquifer recharge (MAR), irrigation reductions, and coordinated water governance.

These findings collectively underscore that **GSI can be strengthened, weakened, or reversed depending on both natural and institutional factors**. While hydrogeological characteristics and climate determine the potential for interaction, it is the management regime—laws, monitoring systems, stakeholder coordination, and public investment—that often determines whether this potential is realized or degraded. This points to the urgent need for **conjunctive water management**, which explicitly considers and integrates groundwater and surface water systems within a single planning and regulatory framework.This research makes several notable contributions. Scientifically, it demonstrates how **publicly available secondary datasets**—ranging from government monitoring wells to remote sensing platforms like GRACE —can be effectively used to assess complex hydrological phenomena like GSI across large spatial and temporal scales. Methodologically, it showcases how combining statistical correlation analysis with contextual policy review offers a holistic understanding that neither data nor theory alone could achieve. From a policy perspective, the study advocates for an institutional shift: from sectoral silos and reactive interventions to **proactive, integrated water governance**, particularly in regions facing hydrological stress and competing water demands.

Nevertheless, the study is not without limitations. The use of secondary data, while pragmatic and scalable, means the analysis is constrained by the **quality, resolution, and consistency** of available records. For example, groundwater level observations are sparse or inconsistent in some sub-regions, and river discharge measurements may not fully capture return flows or evapotranspiration losses. Moreover, the use of simple correlation techniques, though useful for trend detection, cannot establish causality or quantify the magnitude of fluxes exchanged between aquifers and rivers. These limitations point to the need for **more integrated monitoring networks** and the adoption of **physically-based hydrological models** (e.g., MODFLOW, SWAT) in future studies.
To build on this work, future research should aim to:

1. **Couple observational data with process-based models** to quantify groundwater–surface water fluxes under different climatic and land use scenarios.
2. **Expand the geographical scope** by including data-scarce regions in Africa, Latin America, and Southeast Asia, where GSI may play a critical role in sustaining vulnerable communities and ecosystems.
3. **Incorporate stakeholder engagement and participatory research** to understand how local water users perceive and respond to GSI dynamics, and to co-produce solutions.
4. **Explore the effects of climate change projections** on groundwater recharge and streamflow variability, particularly in basins dependent on seasonal or snowmelt-driven inputs.

In conclusion, this research affirms that maintaining healthy groundwater–surface water interactions is **not merely a hydrogeological issue**, but a broader socio-environmental challenge that demands integrated science, inclusive governance, and long-term commitment. As water scarcity becomes an increasingly pressing global issue, the ability to diagnose and manage the invisible connections between aquifers and surface water bodies will be a cornerstone of sustainable development and ecological resilience.

Conflicts of Interest

The authors declare no conflict of interest.

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