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GUEST EDITORIAL

Recognizing spatial heterogeneity in aquifer distributions: lessons for sustainable groundwater management

India, the largest user of groundwater for agriculture in the world, has seen a revolutionary shift from large-scale surface water management to widespread groundwater abstraction in the last 40 years, particularly in the northwestern states of Punjab, Haryana and Rajasthan. These are some of the foremost agricultural regions of India, with irrigation predominantly provided by groundwater extraction. As a result, the region has become one of the largest hotspots of groundwater depletion in the world. A mean rate of groundwater decline of ~4 cm/yr and regional depletion rate of ~20 Gt/yr have been suggested from 10 years of Gravity Recovery and Climate Experiment (GRACE) measurements[1–3]. This unsustainable use of groundwater is further complicated by (i) increasing demands from a burgeoning population and industrialization, and (ii) potential but poorly-understood effects of climate-driven changes in the water cycle.

Groundwater in northwestern India is thought to be largely hosted within buried, sandy former river channels, which extend from the Himalayas toward the southwest and are separated by fine-grained mud. Only a few channels are visible at the surface; most are buried and their existence must be inferred. Systematic data on the subsurface stratigraphy of this region are rather fragmentary, making both assessment of the aquifer system as well as groundwater management, challanging. Before a sustainable management strategy can be formulated, there are several questions that need to be answered: (a) What is the spatial distribution of groundwater depletion? (b) What are the sources and residence times of the groundwater in different parts of the system? (c) How are aquifer bodies distributed in the subsurface and what controls this distribution? (d) How connected are the aquifers and how has connectivity changed in recent geological time?

The findings of a collaborative project funded by the Ministry of Earth Sciences, New Delhi and NERC, UK suggest that the greatest decline in groundwater levels during the last four decades has occurred within the Ghaggar River basin along the Punjab–Haryana border, with broader areas of loss across central Punjab and Haryana. Many areas show near-stable or gradually declining groundwater levels between 1974 and 1998, but increasing rates of decline beginning in 1998–2000. District-wide estimates of rainfall, abstraction and tubewell densities and their changes over the time period do not match these patterns and so cannot by themselves explain the observed decline. Thus, there is a need to first understand the geology and geometry of the aquifer system defined by the buried channels before we can estimate the way it will respond to a complex set of present and future stresses. This means that we must be able to describe the locations, sizes and characteristics of the channel aquifer bodies as well as their age and three-dimensional pattern.

An efficient way to do this is to combine stratigraphic investigations aimed at documenting how aquifer-body geometry and properties vary across the region, with geomorphic investigations of the river systems that have deposited those aquifer bodies. This powerful combination of surface and subsurface data gives us a conceptual or predictive model for aquifer body dimensions and how they vary across the region. We find that the aquifer system in northwestern India consists of large sedimentary fans deposited by the Sutlej and Yamuna rivers. These are separated by an inter-fan area that has not received sediment from the Sutlej or Yamuna rivers, but has been built up instead, by sediments transported from smaller rivers fed from the foothills, such as the Ghaggar. Deposition of these fans has built up major aquifer systems and thus sets the thickness, stacking pattern and connectivity of individual aquifer bodies. These individual bodies are limited in both thickness and width and not laterally extensive. The number, dimensions and connectivity of the aquifer bodies in turn help determine the magnitude of groundwater decline. The spatial heterogeneity in the system that is imposed by the geomorphic and depositional setting of the fans must therefore be considered in any aquifer management scheme. This understanding can also lead to the development of probabilistic maps of likely paleochannel positions, using existing aquifer thickness data and simple geomorphic rules that govern channel geometry and fan construction.

Based on recent studies and ongoing investigations, a series of policy recommendations can be proposed for sustainable groundwater management in the Indian context.

Replace state boundaries with aquifer boundaries

- Aquifer management schemes should encompass coherent groundwater catchments, i.e. areas with similar aquifer characteristics, and whose past and future behaviour is likely to be similar – and include all relevant states.
- Adopt a geomorphic framework to guide interpretation of alluvial aquifer characteristics, water-level changes and proposed management strategies.
- Use geomorphic mapping to define focus areas based on different units (e.g., fans, interfan areas, cratonic areas, etc.) with different depositional histories and aquifer body characteristics.
- Use this framework to organize and relate other datasets (e.g. water levels, shallow geophysics, isotopic studies, hydrogeological modelling).

Integrate all available groundwater data from the Central Groundwater Board (CGWB) and State Groundwater Boards into an integrated database for water-level characterization

Individual organizations are unlikely to hold all of the data needed to characterize such spatially complex and heterogeneous aquifer systems. It is therefore important to integrate all available data from a given region and then standardize in terms of representation according to global practices.

Update the ways in which subsurface aquifer data are combined and analysed

- Use statistical analysis of CGWB aquifer thickness logs to assess thickness and stacking patterns of shallow aquifer bodies.
- Abandon correlation of aquifer sandbodies over large distances (>10 km) as 'tramlines' to characterize alluvial aquifer geometry. Fence diagrams of aquifer geometry should reflect uncertainty in correlation.
- Explore the application of probabilistic stratigraphic maps as an alternative to deterministic aquifer maps with hard (but highly uncertain) boundaries.
- Properly account for lateral heterogeneity and the dimensions of aquifer bodies in modelling of the groundwater system.

Registration of all tube well locations

This is an important step towards legalization of groundwater usage. More importantly, the estimation of tube well densities and abstraction rates is rather uncertain without this information.

Update training for subsurface aquifer analysis and characterization

Incorporate aquifer-body mapping and characterization into a more integrated understanding of groundwater dynamics. This should include:

- Geomorphic mapping of alluvial aquifer systems, using DEMs and satellite imagery in a GIS.
- Integration, cleaning, interpolation, visualization and analysis of water-level data.
- Basic fluvial fan sedimentology and stratigraphy, and links between process and form in alluvial systems.
- Statistical analysis of aquifer or bed thickness data, including cumulative distribution functions, fitting and simple probabilistic estimation, compensational analysis and simple predictive modelling.

The rapid drawdown of the northwestern Indian aquifer system indicates that management of alluvial aquifers in India now needs a serious rethink. There have been major advances over the last decade in our understanding of how fan stratigraphy and thus the basic framework of these major aquifer systems is constructed, but these advances have not yet been used to refine groundwater assessment and management strategies. The combination of geomorphic and stratigraphic mapping, made possible by the wealth of data held by CGWB and State Groundwater Boards as well as the advent of new technologies of terrain mapping, is a promising but unexplored approach.

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