Supplementary Material

Event-Based Analysis of Recharge Dynamics in a Heterogeneous Hard-Rock Catchment using Hydrogeophysical Techniques

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S1. Study Area

The Sanwara catchment lies in the northeastern part of Rajasthan's Baran district, near the Madhya Pradesh border. The region consists of red gravelly loam soils and exposes the Govindgarh Sandstone (Upper Rewa Sandstone). The catchment lies within the Chambal basin and exhibits gently undulating topography with a dendritic drainage pattern. The catchment drains into the Palku River, a tributary of the Kuno River.

The Upper Rewa Sandstone appears buff to red in color, quartzitic, hard, and compact, with negligible primary porosity. Groundwater occurs within secondary porosity zones formed by weathering, joints, fractures, and bedding planes. These features control groundwater occurrence and movement.

Groundwater levels typically vary between 10 and 30 m below ground level and fluctuate seasonally depending on recharge (CGWB, 2019, 2013). Groundwater occurs under unconfined to semi-confined conditions. Exploratory drilling confirms water-bearing zones at depths exceeding 100 m. Tube wells show highly variable yields, ranging from negligible discharge to about 2000 liters per minute depending on fracture connectivity.

In adjacent regions such as Shivpuri, similar Vindhyan lithology shows that fracture networks and shallow weathered zones sustain aquifer systems. Well yields typically range from 60 to 120 liters per minute with variable drawdown responses, reflecting limited permeability and discontinuous aquifer conditions (CGWB, 2013).

S2. DC Resistivity and Induced Polarization Principles

The DC resistivity method injects a low-frequency current into the ground through current electrodes and measures the resulting potential difference using potential electrodes (Seidel and Lange, 2007). The induced polarization (IP) method measures the ability of subsurface materials to store electrical charge (Slater and Lesmes, 2002).

The apparent resistivity is calculated as:

$$\rho_a = K\frac{\Delta V}{I} \tag{1}$$

The apparent chargeability is expressed as:

$$M_a = \frac{1}{V_0(t_2 - t_1)}\int_{t_1}^{t_2} V(t)\, dt \tag{2}$$

where K is the geometric factor, ΔV is the measured voltage, I is the injected current, V_0 is the primary voltage, and $V(t)$ is the decaying voltage.

S3. Induced Polarization Method

IP surveys use a four-electrode configuration similar to resistivity methods. The method operates in two modes: time-domain, where voltage decay occurs after current shut-off, and frequency-domain, where phase shifts between current and voltage are measured. The decay curve reflects polarization at grain-fluid interfaces (Binley and Kemna, 2005).

The apparent chargeability can also be expressed as:

$$m_a = \frac{V_s}{V_p} \tag{3}$$

Since V_s is difficult to measure directly, the time-integrated form is used:

$$m_a = \frac{1}{V_p(t_2 - t_1)} \int_{t_1}^{t_2} V(t)\, dt \tag{4}$$

Chargeability is expressed in mV/V (Seigel, 1959).

S4. Electrical Resistivity Tomography and Array Configuration

Electrical Resistivity Tomography (ERT) produces two-dimensional subsurface resistivity images by measuring multiple combinations of current and potential electrodes. The method resolves both lateral and vertical heterogeneities.

The Wenner–Schlumberger array combines features of Wenner and Schlumberger arrays. The electrode configuration consists of C_1, P_1, P_2, and C_2 with equal spacing a. The separation between current and potential dipoles is na.

The geometric factor is:

$$K = \pi a \left(\frac{n(n+1)(n+2)}{2} \right) \tag{5}$$

S5. Field Measurements

We conducted 12 DCIP profiles in the Vindhyan sandstone region using the IRIS Syscal Pro Switch 72 system. Multielectrode cables with 10 m spacing.

We used the Wenner–Schlumberger array due to its high signal-to-noise ratio and depth resolution. Acquisition parameters included 0.5 s current cycles, IP windows of 40, 80, and 160 ms, a delay of 40 ms, $V_P = 20$ mV, and $V_{AB} = 800$ V. We used stacking values between 4 and 8.

S6. Data Processing and Inversion

We filtered raw data in Prosys II by removing points with standard deviation greater than 10%. We performed further filtering and inversion using `Res2DInv` (Loke and Barker, 1996). The inversion uses a smoothness-constrained damped least squares approach:

$$(J^T J + \lambda I)\Delta q_k = J^T g - \lambda F q_{k-1} \tag{6}$$

where J is the Jacobian matrix, λ is the damping factor, and F represents spatial roughness constraints.

S7. Slug Test Methodology

We conducted slug tests by introducing an instantaneous change in water level and monitoring the recovery response. We used the Bouwer–Rice method to estimate hydraulic conductivity (Bouwer and Rice, 1976):

$$\ln(H_0) - \ln(H) = \frac{2K_r L t}{r_{ce}^2 \ln\left(\frac{R_e}{r_{we}}\right)} \tag{7}$$

$$r_{ce} = \sqrt{(1 - n_e) r_c^2 + n_e r_w^2} \tag{8}$$

$$r_{we} = r_w \sqrt{\frac{K_z}{K_r}} \tag{9}$$

where H is water level displacement at time t, H_0 is initial displacement, K_r and K_z are hydraulic conductivities, and other terms represent well geometry.

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