3D aquifer mapping employing airborne geophysics to meet India’s water future

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Abstract

With the growing dependence on groundwater, escalating demand, and increasing depletion of aquifers, the Government of India has accorded special emphasis to management of groundwater resources through precise aquifer mapping. We have carried out hydrogeophysical surveys, including airborne electromagnetic (AEM), in six hydrogeologically divergent areas comprising sedimentary basins, basalts, weathered and fractured granite gneisses and schists, desert, and costal alluvium with the objective to establish suitability of AEM for a countrywide aquifer mapping in India. Efficacy of the dual-moment AEM surveys in mapping the shallow and deep aquifers is evaluated in conjunction with geologic, geophysical, and borehole data. It is found that the AEM surveys provide reliable images of the subsurface resistivity distribution defining the 3D geometrical and electrical attributes of aquifers in different areas. The surveys helped identify the suitable zones for managed artificial recharge (MAR), subsurface structures controlling the groundwater conditions, regional continuity of principal aquifers, palaeoriver channels, variations in lithologic character of aquifers, and the quality of water in terms of salinity, etc. In this paper, we present the efficacy of the aquifer-mapping approach illustrated by an example from an alluvium-covered hard-rock terrain (Dausa, Rajasthan), where a weathered-fractured aquifer system with compartmentalization under alluvium cover is mapped. The integrated data set, comprising AEM, aeromagnetic, ground geophysical, and borehole measurements, was utilized to derive lithologic and hydrogeologic maps useful in developing an aquifer-based groundwater-management plan.

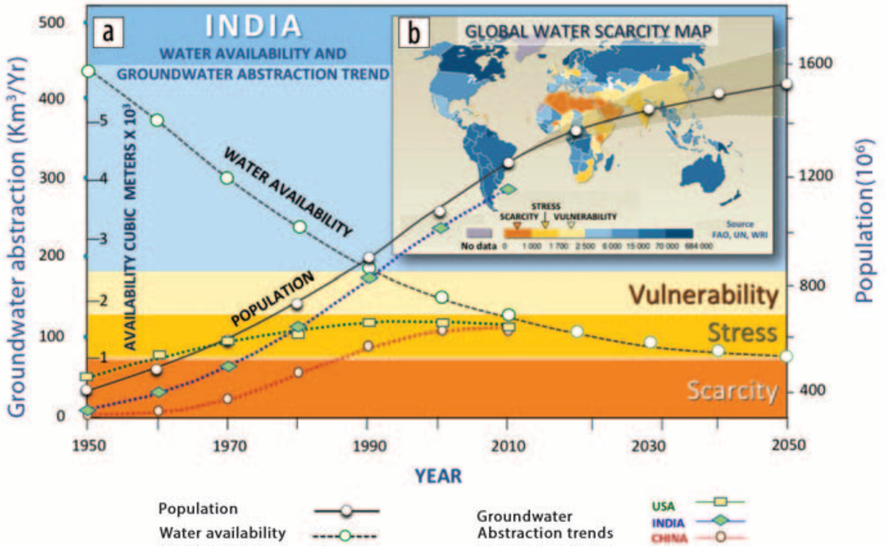

Figure 1. (a) Per capita water availability and vulnerability (TERI, 2006; Chandra, 2006) along with population trends for India (UN-DES, 2015) up to the year 2050. Abstraction trends for China, India, and the United States are also shown up to 2010. (b) Water scarcity worldwide (after Rekacewicz, 2008).

Introduction

Groundwater resources are under threat due to overexploitation and deteriorating quality in many parts of the world (Giordano, 2009). In general, rural and agricultural developments are mostly dependent on groundwater, whereas urban development needs surface as well as groundwater. Thus, it is observed that the groundwater level is declining at an alarming rate (Giordano, 2009). In India, about 65% of irrigation water and 85% of drinking water needs are served by groundwater resources (World Bank, 2010). Sustainability of water resources has been severely compromised by excessive use in agriculture, unrelenting population growth, and a number of environmental and anthropogenic factors. If the present trend continues unabated, India’s water scarcity will increase by many folds within a few decades. Therefore, water security is recognized as one of the major challenges to India’s economy and social development (Gorelick and Zheng, 2015).

There have been a large number of research programs worldwide, as well as in India, on management of groundwater resources for the last few decades. However, as illustrated in Figure 1a, the United States and China have been able to control the abstraction trend (Rekacewicz, 2008; Van der Gun, 2012) whereas in India, it is growing, parallel to the population growth curve. Thus, there is an exigent need to devise and implement an efficient water-management plan to save India from becoming a water-scarce nation within a few decades. Figure 1b depicts the global water scarcity (Rekacewicz, 2008) highlighting the precarious condition of India.

The major cause of failure of groundwater resource management in India is not limited to uncontrolled population growth, but is also due to planning done without having an adequate knowledge of structural setup of aquifer systems and their hydrodynamic behavior, recharge and discharge rates, etc. Thus, it is imperative to acquire a comprehensive knowledge of the regional and local aquifer systems to evolve an effective groundwater-management strategy. Considering these factors, the Ministry of Water Resources, Government of India, launched a pilot project on aquifer mapping (AQUIM) in six different hydrogeologic terrains in India (Ahmed et al., 2016; www.aquiferindia.org) as shown in Figure 2.

An emerging approach increasingly used world over is to conduct regional-scale aquifer mapping employing airborne geophysical

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measurements and to integrate the results with the geologic and hydrogeophysical data to reliably characterize and model the aquifers. The AQUIM project was completed using a combination of airborne electromagnetic and magnetic surveys, electric resistivity imaging, borehole measurements, and structural analysis.

Methodology

The employed methodology consists of airborne electromagnetic (AEM) and airborne magnetic (AMAG) surveys combined with ground measurements employing vertical electrical soundings, electrical resistivity tomography, ground-based transient electromagnetics, borehole drilling, and geophysical logging. The AEM surveys were conducted using the SkyTEM system (Sørensen and Auken, 2004), which incorporates low and high moments for the transmitter. While the low moment provides critical information on near-surface features to assess the recharge potential, the measurements at high moment yield deeper information up to ~300 m in alluvial areas and ~200 m in hard rock areas. The survey also included measurement of magnetic field that was found to be particularly useful in areas where the occurrence of groundwater was structurally controlled. After applying various corrections, resistivity depth sections were obtained using laterally constrained inversion (LCI) (Auken and Christiansen, 2004) of various profiles and spatially constrained inversion (SCI) considering all the profiles in a particular region (Viezzoli et al., 2008). The SCI inversion provides a 3D volume of the resistivity in the survey area so that it is possible to create horizontal slices or vertical sections along any arbitrarily chosen profile/plane to correlate with available geologic, geophysical, or borehole information. Resistivity structures associated with interesting geologic features can also be examined.

The dual-moment system initially employs a small pulse (with magnetic moment of 3,500 amp m^2) to investigate the shallow regions, taking measurements in the time range of 10 µsec to 1.74 msec. Subsequently, a high-moment pulse (with magnetic moment of 1,65,000 amp m^2) energizes the deeper regions, recording transients in the range of 27 µsec to 9.0 msec. The dual-moment mode with partly overlapping time ranges ensures that the near-surface and deeper regions are mapped concurrently. The near-surface information is found to be particularly useful in delineating suitable zones for managed artificial recharge (MAR).

A major challenge was to translate the geophysical results into the hydrogeologic models to facilitate aquifer modeling. For this, the following approach was adopted:

1) The borehole geophysical logs and drilling logs were integrated to prepare borehole lithologs.
2) The borehole lithologs were used to calibrate the AEM-derived resistivity distribution, and litho boundaries were digitized along the individual flight lines.
3) These boundaries were contoured using kriging interpolation along the individual flight lines using a search radius of 50 m and across various flight lines with a search radius of 500 m, to construct the lithologic setup in 3D.
4) This lithology was constrained with the piezometric water level to construct major hydrogeologic units viz., desaturated aquifer (overexploited layer currently unsaturated and with potential for managed aquifer recharge), aquitard, aquiclude, principal aquifers, bedrock, etc.

Results and discussion: Example from alluvium-covered hard-rock terrain, Dausa, Rajasthan

An example from the AQRAJ, Rajasthan is presented in Figure 3. The area has undergone severe tectonic disturbances and consists of several faults and folds. The limited quantity of water in the top granular layer (desaturated alluvium aquifer) is more or less exhausted. The problem was to locate aquifers below the semiconfining layer and in the weathered fracture zones within the quartzite bedrock occurring at a depth range of 60–90 m. From the AEM resistivity image, hydrogeologic layer boundaries were interpreted at intervals of ~25 m along the flight line.

Figure 3a shows a geologic map of the area (Sinha, 2008), where faulted blocks are dislocated to a maximum separation of 8 km. Such large-scale subsurface structures are expected to continue even beneath the alluvium cover. The folding pattern in the geologic map, exposed on the northern and western boundaries, is clearly reflected in the adjacent magnetic map (Figure 3b). Figure 3c shows AEM measured mean resistivity map of 40–50 m depth below ground. High resistivity on the order of 10^3 Ωm reveals occurrences of bedrock. In general, bedrock is dipping toward the east and south.

Figure 4a depicts the geologic cross section along line A–B marked on the geologic map (Figure 3a) located outside of the study area in the north. We have prepared a geophysical cross section along a parallel line CD in the study area to see the impact of exposed structural disturbances. The resistivity distribution along profile CD can be broadly divided into two major categories: (1) a low-resistivity (≤30 Ωm) zone composed of alluvium; and (2) a high-resistivity

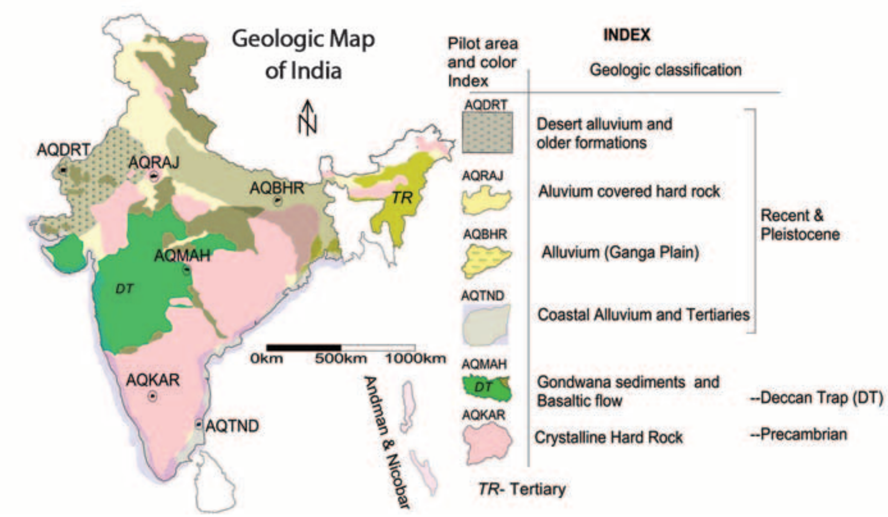

Figure 2. Six pilot areas as representative of major geologic terrains in India studied under the pilot project. The geologic settings of different areas are shown to the right in the figure.

(>30 Ωm) zone composed of quartzite and gneiss bedrock underneath (Figure 4b). Resistivity below the line of depth of investigation (DOI) has been masked due to insignificant sensitivity. The bottom surface of the resistivity can be seen with sharp depressions at places, which are found to coincide with the tectonic disturbances. Hence, these sharp depressions of low resistivity are nothing but fracture zones. The borehole lithologs from Noorpur and Kothin villages are superimposed over the resistivity section. It is found that they correlate well with the resistivity distributions.

The major deep fracture zones in the bedrock are controlled by tectonic features such as folds and faults. The area has been suffering from groundwater overexploitation for the past several decades, which has resulted in the drying up of granular Proterozoic sediments (desaturated aquifer) that lie below the soil. The present water table almost coincides with the top surface of the weathered-fractured bedrock (aquifer). The AEM results identified the deeper aquifer, as well as the potential aquifer zones in the fractured bedrock (Figure 4c). The bedrock topography and water-table distribution show a compartmentalized aquifer system. The deep tectonic features qualify to be potential sites for groundwater resources. The tectonic features have significant impact down to a depth of about 200 m, extending under the alluvium cover. This knowledge can be used to locate suitable sites for creating artificial recharge structures to enhance groundwater reserves. The fractured pathways are, in general, highly permeable in nature and hence provide higher recharge rate. Thus, the tectonic pathways will act as feeders to the associated fracture network and weathered horizon for managed aquifer recharge.

The DOI is normally observed deeper in resistive areas than in conductive areas. However, in the present case of alluvium-covered hard rock, the alluvium is conductive and the underlying hard rock is resistive. The underlying hard rock can be broadly divided into two layers: upper weathered-fractured and underlying compact bedrock. While the weathered-fractured hard rock acts as a conductive target, the compact bedrock acts as resistive to AEM measurements. In this situation, the upper alluvium and middle weathered–fractured bedrock are expected to respond significantly to AEM investigations in contrast to the bedrock. However the compact bedrock, devoid of fractures, may not respond significantly to AEM. Since the AEM measurement is less sensitive to resistive units, the horizon of compact bedrock limits the line of DOI derived from the recalculated sensitivity (Jacobian) matrix of the final model (Christiansen and Auken, 2012). In such situations, the DOI line can be considered to coincide with the top of underlying compact bedrock.

In granite hard rock, fractures filled with water undergo weathering and alteration. The most susceptible mineral in this respect is biotite (Eggler et al., 1969; Tieh et al., 1980). Once in contact with water, it weathers, alters, and swells leading to a local increase in volume that favors further development of cracks and fissures in the host rock (Dewandel et al., 2006). Thus, fractures filled with water and additional weathering, in association with developed cracks and fissures, combine to widen the effective fracture dimension. The overall altered fracture zone increases the electrical conductivity relative to that of the fresh and compact rock. Therefore, the deepwater-filled fractures have a larger effective conducting dimension that enhances the EM sensitivity to deeper levels and hence greater DOI.

The mapped aquifer has shown the impact of tectonic features on groundwater resources. Deep fractured zones associated with the fault and fold planes create suitable horizons for groundwater

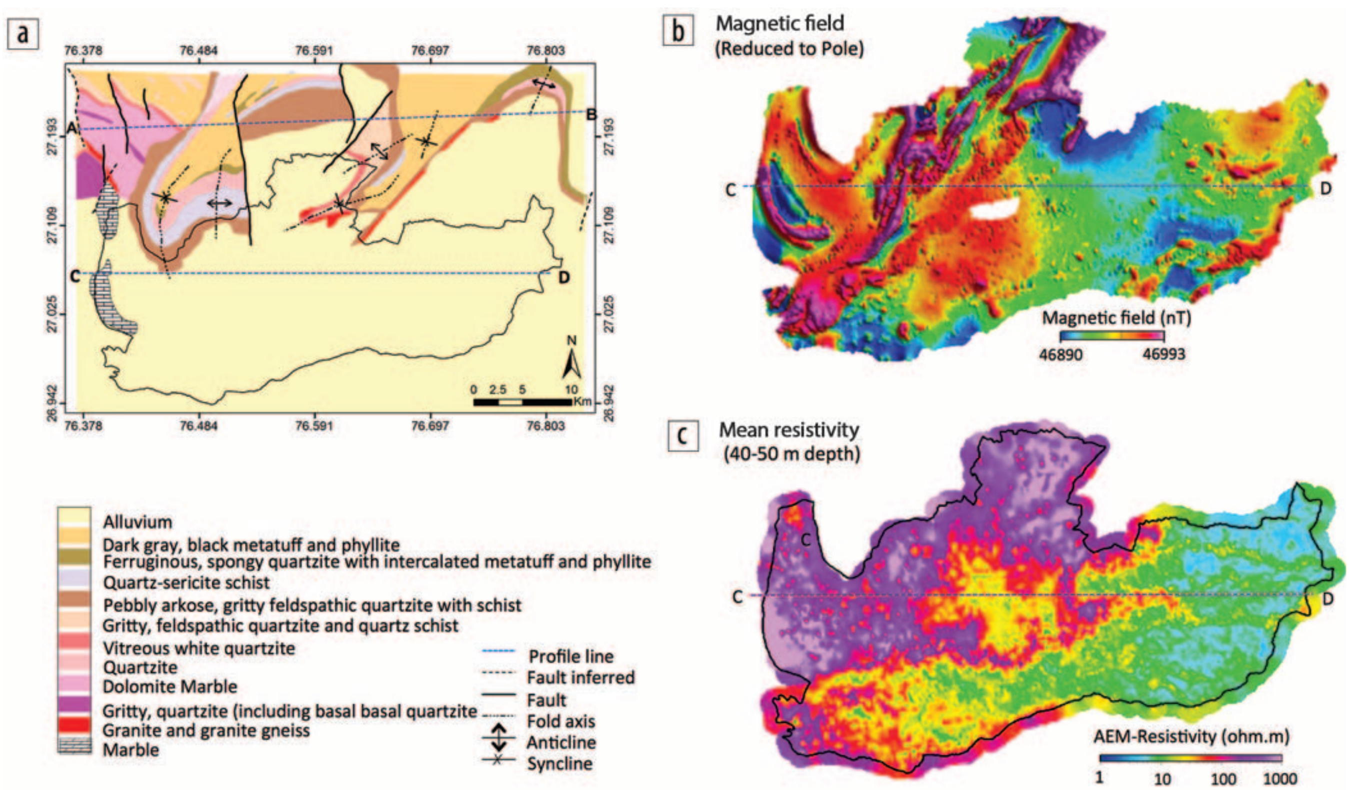

Figure 3. Maps showing: (a) geology of AQRAJ area (after Sinha P. K., 2008, GSI) with AB and CD profile lines; (b) magnetic field intensity map (reduced to pole) in nT; and (c) mean resistivity map at 40–50 m depth below ground.

occurrences. These tectonic features create compartmentalization in the deep aquifer system affecting the aquifer dynamics significantly, particularly in the case of overexploitation and deeper water levels. However, fracture-driven aquifer systems are, in general, highly permeable and hence provide locations for high-yielding wells. The fractures associated with such tectonic features, in general, are relatively larger in dimension and hence can connect many aquifer systems at the regional scale. Once artificial recharge structures are constructed over such features, the managed aquifer recharge can be very effective; the large tectonic features and associated groundwater recharge act as feeders to the associated fracture network, thereby enhancing the groundwater resources.

General results

Integration of the electrical images derived from the AEM surveys with the ground investigations and borehole information was utilized to derive lithologic and hydrogeologic maps useful in developing an aquifer-based groundwater-management plan. Six pilot areas (Figure 2) representing much larger geohydrologic regimes include the desert region in northwest India (AQDRT, 755 km^2); Gangetic alluvium in Bihar (AQBHR, 572 km^2); hard rock areas in Karnataka (AQKAR, 378 km^2) and alluvial-covered hard rock in Rajasthan (AQRAJ, 642 km^2); the Deccan Traps (basalts) covered area in Maharashtra (AQMAH, 400 km^2); and a saline water intruded coastal sedimentary basin in Tamilnadu (AQTND, 517 km^2). The results were used to delineate the 3D geometry of aquifers along with prominent structural controls and to understand the prevailing hydrogeologic conditions.

Analysis of the AEM data in the pilot areas demonstrated the efficacy of the employed approach in mapping the 3D configuration of aquifers in diverse hydrogeologic settings (Ahmed, 2014). Some major findings of the AQUIM program include:

1) demarcation of low-salinity aquifer zones below highly saline top aquifers in the Thar Desert
2) mapping of several basaltic flows and aquifers within the Deccan Traps in Maharashtra
3) delineation of paleochannels in the Ramgarh Desert; Dausa, Rajasthan; Gangetic plains, Bihar; and Cuddalore coastal region, Tamil Nadu
4) identification of a two-layered aquifer system in the arsenic-affected Patna region; vital information on the disposition

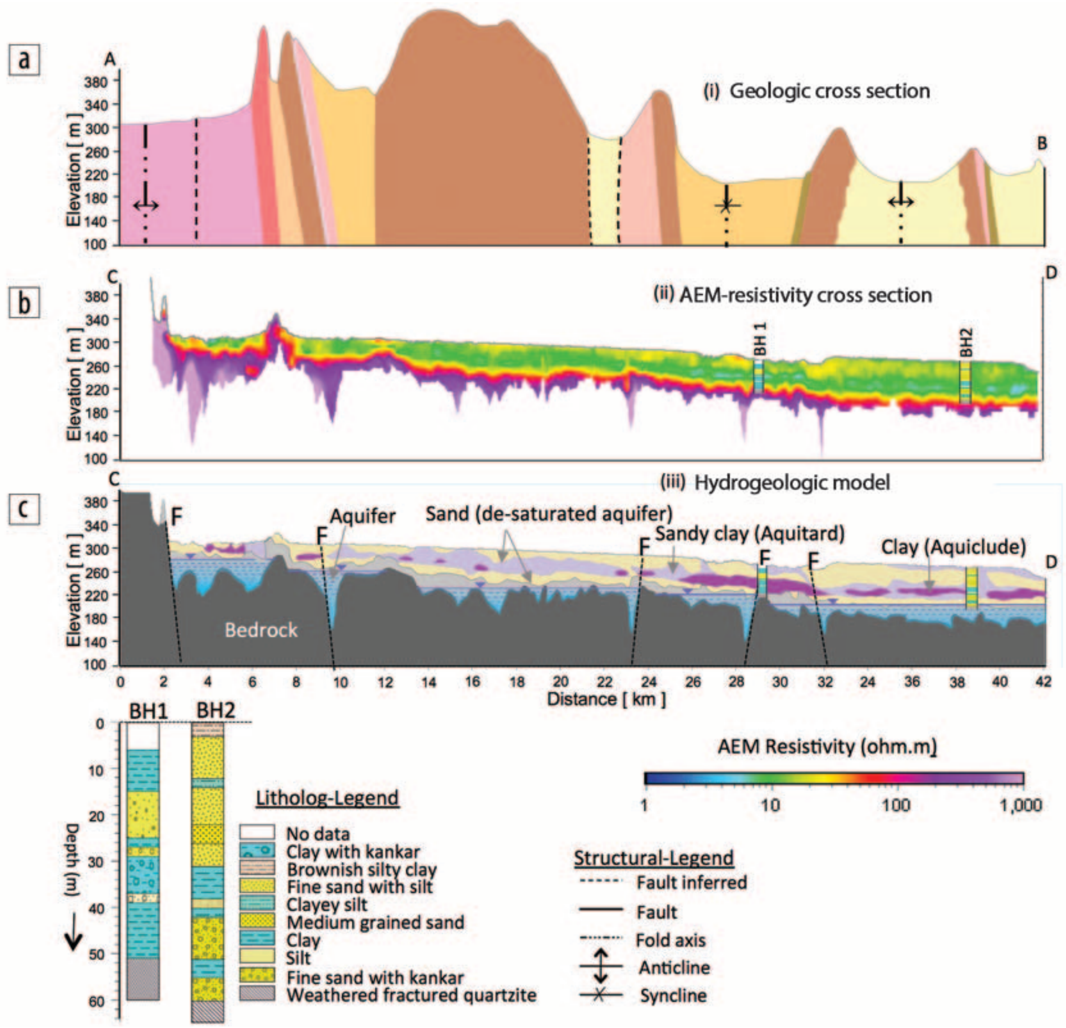

Figure 4. (a) Geologic depth cross section prepared by Sinha (2008, GSI). (b) Resistivity-depth image obtained from the AEM data. Borehole lithologs from Noorpur and Kothin villages showing distribution of sand, weathered-fractured hard rock, and bedrock are superimposed. (c) Geophysical results translated into a hydrogeologic model with the water table measured in wells, and inferred major tectonic features.

and merging of the mapped aquifers is found to be crucial in designing an arsenic-free aquifer-management plan

5) mapping of potential fractured aquifer zones controlled by tectonic features in the hard rocks in Tumkur, Karnataka, and Dausa, Rajasthan
6) demarcation of suitable zones for artificial recharge utilizing early time information from the AEM data

The AEM survey was found to be a cost-effective, fast approach to delineate the aquifers over a large area. The six selected regions represent more than 90% of the hydrogeologic settings in India. The pilot surveys helped in developing protocols in terms of optimal parameters for the AEM surveys in different hydrogeologic terrains. Also, the efficacy and optimal combination of various ground geophysical methods for different hydrogeologic settings were established. The experience thus gained can now be upscaled to the nationwide aquifer mapping.

Conclusion

The management of underground aquifers is practical and guaranteed only with complete knowledge of the system. The integrated study consisting of heliborne, surface, and borehole geophysical investigations helped establish the efficacy of the employed methodology for upscaling to the regional scale. The dual-moment AEM surveys efficiently delineated the 2D/3D configuration of aquifers in the six pilot areas, and the results correlated well with the available geologic, hydrogeologic, and borehole information. TLE

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