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An observatory of groundwater in crystalline rock aquifers exposed to a changing environment - Hyderabad (India)

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Abstract

Multi-scale and long-term work is needed for tackling the scientific challenges found in areas vulnerable to climate change and anthropic pressure. This is the case in the semi-arid and drought-prone regions of southern India where freshwater is scarce, and agriculture near fast-growing cities is triggering high water demand. The Indo-French Center for Groundwater Research (IFCGR) was established in 1999 between the Indian National Geophysical Research Institute (CSIR-NGRI) and the French Geological Survey (BRGM), at the NGRI campus, Hyderabad. For almost 20 years, the IFCGR has studied the hydrodynamic properties and associated hydrological processes in crystalline aquifers. To that end, the Center set up two sites for observing groundwater in crystalline rock aquifers: (i) the Maheshwaram basin for the study of groundwater management at catchment scale and (ii) the Choutuppal experimental site for the detailed study of hydrogeological processes at local scale (between wells). Multi-scale approaches allow characterizing the hydrodynamic and transport properties of the shallow weathered part of such crystalline aquifers and the implications for groundwater management under overexploitation conditions. The objective is to provide

suitable definitions of aquifer properties for developing modelling and management tools applicable to such heterogeneous aquifers.

Core ideas

Long term observatories allow to study climate change and anthropogenic pressures on groundwater resource in India

Crystalline rock aquifers are heterogeneous and their management necessitates to solve several scientific questions

Multidisciplinary approach is necessary to tackle the issues related to groundwater management in India

1) Introduction

Crystalline rocks underlie a large part of the World. In arid tropical areas, groundwater stored in such hardrock aquifers, despite the low yields of wells, can supply small villages with drinking water and small farms with irrigation.

India is the biggest groundwater user in the World, with almost 25 million pumped wells. About two-thirds of the country is underlain by crystalline rocks (Archean granite and gneiss, Deccan traps) and, at the national level, 60% of irrigation is sustained by groundwater. This is especially the case in southern India, where rice is cultivated despite a very dry climate. The Green Revolution has permitted the improvement of agricultural productivity through the development of groundwater irrigation and the use of fertilizers. In addition, the Indian states have subsidized well drilling and electricity is often free for farmers. The consequence is overpumping and a chronic depletion of the groundwater resource in many areas. In irrigated areas, the water cycle has been drastically changed, with the average pumping rate exceeding natural recharge and high irrigation return flows (Maréchal et al., 2006). The water-table lowering has dried up springs and wetlands. Rivers have become ephemeral and thousands of water tanks have been constructed to retain water flowing to the sea. The pumping has also induced endorheic aquifer conditions with a very high rate of water recycling (Perrin et al., 2011) with, locally, major salinity increases and fluoride enrichment (Pauwels et al., 2015).

In this context of high stress on groundwater resources, there is a need for modelling and decision supporting tools that will improve the management of crystalline aquifers at suitable scales. However, the heterogeneity, and supposed high compartmentalization, of crystalline aquifers challenges the classical modelling tools. There is thus an urgent need for improving the understanding of hydrogeological processes in crystalline-rock aquifers, in order to adapt the existing methods, or to propose alternative solutions. To that purpose, an observatory of groundwater in crystalline-rock aquifers of southern India was created.

2) Motivation and scientific questions

The hydrogeology of crystalline-rock aquifers has been hotly debated for decades, especially the origin of permeability and porosity (St. Clair et al., 2015). The question of the heterogeneity of hydrodynamic parameters has been another issue (Gustafson and Krásný, 1994). Where hardrock is exposed to deep weathering, the international community since the nineties has converged to a hydrogeological model where aquifer properties are controlled by the weathering profile (Taylor and Howard, 1999; Wright, 1992). The commonly accepted conceptual model considers a shallow weathered and permeable layer composed of saprolite and fractured rock (Wyns et al., 2004). Particular attention should be paid to this “critical zone” (weathered/fractured part of the aquifer) above the fresh and low-permeable basement (Fig. 1) where horizontal groundwater flow and transfer processes mainly occur (box on Figure 1).

The hydrogeological characteristics of the fractured layer are then of primary importance. How heterogeneous is it? Is the fractured rock isotropic? Is the aquifer connected or highly compartmentalized at the basin scale? Can it be modelled with standard models? Is a discrete fracture network approach necessary? What is the impact of fracture distribution on recharge processes and transport properties?

The Hyderabad observatory was created to improve our understanding of hydrogeological processes in crystalline-rock aquifers under global climate change, including transfer processes and hydrochemical cycles in order to improve the above conceptual model. Several techniques have been used in order to: (i) Characterize the hydrodynamic properties of the crystalline aquifer according to weathering profile structure; (ii) Improve the understanding of various hydrological components of the water cycle in irrigated areas at the watershed scale; (iii) Identify the impact of fracture orientation and distribution on recharge processes by monitoring infiltration basins; and (iv) Follow-up any cropping pattern changes and their influence on groundwater.

3) Catchment characteristics

The geology of the Hyderabad area is quite homogeneous and mainly composed of Archean granites with the remains of weathering profiles of varying ages. Several geophysical investigations helped in characterizing the geometry of the weathering profile (Kumar et al., 2007) and recent results describe a typical vertical profile (Fig. 1) constituted of layers with their own specific hydrogeological properties (Dewandel et al., 2006). These are from top to bottom:

- Saprolite, a clay-rich material, derived from prolonged *in-situ* weathering of bedrock, and up to a few tens of metres thick. Saprolite has a low permeability and high drainage porosity. Once saturated, saprolite contributes to the storage capacity of the aquifer.

- A fractured layer, generally characterized by several horizontal fractures in the first few metres (Maréchal et al., 2003) and a depth-decreasing density of fractures (Maréchal et al., 2004). This layer mainly ensures the transmissive function of the aquifer and is tapped by most wells drilled in crystalline-rock aquifers.
- The fresh basement has neither primary permeability, nor porosity. It is permeable only locally in fractures and faults.

Two experimental sites were investigated, Maheshwaram and Choutuppal, both underlain by Archean granite (Fig. 2a) near the City of Hyderabad in Telangana State. The work on the Maheshwaram watershed included crystalline-rock hydrogeology at the catchment scale as affected by the impact of high rural anthropic activity. On the Experimental Hydrogeological Park of Choutuppal, the main scientific questions were tackled at local bore-well scale to improve our understanding of local hydrodynamic and transport processes.

The Maheshwaram watershed (53 km^2) lies 35 km south of Hyderabad (Fig. 2b) and is characterized by a relatively flat topography (590 to 670 m asl). Its climate is semi-arid and controlled by the periodicity of the Monsoon (rainy or "Kharif" season from June to October). Average annual rainfall is 750 mm, of which over 90% falls during the monsoon period. The average annual temperature is 26 °C, reaching 45 °C during the hot "Rabi" season from March to May. The resulting potential evapotranspiration (PET) is 1,800 mm/year. Surface streams are not perennial and flow a few days a year during the monsoon.

The Maheshwaram watershed is quite representative of southern Indian hydrogeological conditions, with (i) a highly pumped crystalline aquifer (more than 700 bore wells withdrawing about 10 Mm^3/year), (ii) a cropping pattern dominated by rice cultivation, and (iii) a rural socio-economy mainly based on traditional agriculture. The water table has shown a long-term decline (now 15 to 25 m deep) that has caused the drying-up of springs and streams.

The Experimental Hydrogeological Park (EHP, 0.55 km²) is located near Choutuppal village in Telangana State (Fig. 2c), 60 km southeast of Hyderabad. Thirty boreholes were drilled to different depths and intersect the weathered profile down to fresh bedrock, which allowed experiments on fracture-scale processes (Table 3). At a regional scale, these granites are locally intruded by decametre-wide quartz veins or dolerite dykes that have been the topic of specific hydrogeological investigations (Dewandel et al. 2011; Perrin et al. 2011a). Such discontinuities are not present in the EHP.

4) Basic long-term monitoring

Dedicated to groundwater observation, the Hyderabad observatory has focused on the monitoring of water-table fluctuations in response to climate variability and forced pumping. The absence of surface streams due to the semi-arid conditions and the deep water table, disconnected from surface water, has prevented any stream-discharge monitoring. The duration and time steps of the measurements are described in Table 2.

In Telangana State, the electricity is supplied seven hours per day on average. The pumping strategy of farmers has been monitored by an indirect method for estimating the daily pumping duration in a well using automatic water-table measurements (Dewandel et al., 2008), as well as using water-temperature measurements at the outlet pipe (Massuel et al., 2009). During pumping, the outlet pipe has a steady temperature close to that of groundwater (Fig. 3), and the method consists in analysing the temperature changes and thus identifying the different stages of pumping.

The large number of abandoned, i.e. not pumped, boreholes (about 150) in the Maheshwaram watershed allowed the drawing of detailed piezometric maps of the aquifer (Zaidi et al., 2007; Fig. 4). Repetition of measurements twice a year before and after the monsoon period provided low- and high flow-condition maps.

A simple approach for calculating specific yield and natural groundwater recharge has been applied to these data (Maréchal et al., 2006). A technique of combining groundwater-budget data and water-table-fluctuation (WTF) data was developed for reducing the uncertainties inherent to each method. This combined technique is based on dividing the hydrological year into a rainy season and a dry season. By combining the groundwater budget during the dry season with the resulting water-table decline, a specific-yield value at the watershed scale is obtained. This value is then used for transforming the water-table rise during the rainy season into a corresponding rate of natural recharge using the WTF method. The proposed methodology was termed the "double water-table fluctuation technique" (DWTF) and is implemented within a Geographic Information System. The main advantages of this method are: (1) The groundwater budget, compared to the classic hydrologic budget, is unaffected by the large uncertainties on evapotranspiration estimates; (2) The WTF method enables estimation of a specific yield at a suitable (watershed) scale without considering the other aquifer hydrodynamic properties; (3) The ease and low cost of the DWTF technique. DWTF is particularly well-suited to this fractured environment, which needs an integrating approach and is characterized by a high density of abandoned bore wells that can serve for water-level measurements.

The DWTF technique has been included into a decision support tool (DST) for groundwater management, named DST-GW (Dewandel et al., 2010). This innovative DST-GW is constructed for using the combined groundwater-budget plus WTF method at a basin-wide scale. The tool can simulate water-table levels and drying-up in bore wells. It allows stakeholders to test various scenarios (e.g., changing the cropping pattern and associated groundwater withdrawal, or simulating managed aquifer recharge solutions and climate change) and observes the impact at the watershed scale. DST-GW is used as an interactive tool that is useful for provoking discussions between policy makers and groundwater users (farmers). It should help in arriving at sustainable solutions for reducing the water stress created by human activities.

More recently (Dewandel et al., 2012; 2017), the DWTF technique has been used to develop methodologies for regionalizing the hydrodynamic properties of a crystalline-rock aquifer at watershed scale (3-D map for specific yield and 2-D map for hydraulic conductivity).

5) Main hydrogeological experiments

Apart from long-term monitoring, several campaigns of hydrogeological experiments were carried out in the observatory. Table 2 summarizes the main experiments along with their objectives and published results. Thanks to the low cost of drilling (1000 USD for a 50 m deep borehole), many wells were drilled in the observatory. The objective was to study the weathering profile (saprolite and fracture-zone thickness), calibrate the geophysical methods, monitor the water-table fluctuations and carry out hydraulic tests. The studies were carried out at the watershed scale in the Maheshwaram basin, and at the local field-test scale at Choutuppal. In both sites, the impact of infiltration basins on groundwater resources has been studied as well.

6) New insights and novel scientific findings

6.1 Geometry of the weathering profile

The large amount of available data on the Maheshwaram watershed (45 well lithologs and 80 Vertical Electrical Soundings) allowed the mapping of both the bases of the saprolite layer and of the fractured layer (or the top of bedrock). Analysis of the maps (Dewandel et al., 2006; Fig. 5a) shows that the structure of the weathering profile in the area,-and thus of the aquifer, results from an ancient (Jurassic-Cretaceous) weathering profile that has been eroded and truncated because of the uplift caused by the (Cretaceous-Quaternary) geotectonic displacement of the Indian peninsula to the north and renewed-Quaternary weathering. Based on this knowledge of the creation and structure of the weathering profile in the area, mapping techniques were adapted to larger areas, up to 1000 km^2 (Figs. 5b and c), using geophysical logs in abandoned wells (Fig. 5b) and outcrop observations to produce maps of the weathered layers (Fig. 5c), and thus of the aquifer geometry (Dewandel et al, 2017).

6.2 Hydrodynamic properties of the weathered

The hydrodynamic properties of the weathered/fractured aquifer of the Maheshwaram watershed were defined with hydraulic tests at different scales in various wells (Table 3). The resulting hydrodynamic model for Maheshwaram is described on Figure 6. The statistical distribution of local hydraulic conductivities in wells was obtained with slug tests ($K_{average}$ = 4.4 x 10^{-6} m/s). Flowmeter measurements during injection tests helped identifying the depth of the conductive fracture zones (CFZ) and their hydraulic conductivities ($K_{average}$ = 8.8 x 10^{-5} m/s). The most permeable part of the weathered/fractured layer extends down to 35 m depth. The double-porosity model was used for distinguishing the part of drainage porosity located in the blocks (90%, Sb = 5.7 x 10^{-3}) from that linked to fractures (10%, Sf = 5.8 x 10^{-4}). The total resulting average drainage porosity is Sy = 6.3 x 10^{-3}, less than the value obtained from DWTF at the basin scale (Sy = 1.3 x 10^{-2}, Maréchal et al., 2006). This discrepancy is explained by the depth-decrease of porosity (Dewandel et al., 2017), which induces an apparent higher value for DWTF estimates as the technique gives Sy values for the zone where the water table fluctuates, whereas pumping provides an average value for the whole aquifer thickness.

Application of anisotropic and horizontal fracture analytical solutions on drawdown data allows determining the vertical anisotropy of hydraulic conductivity ($1/K_D$ ~10 on average, the horizontal hydraulic conductivity being systematically 8 to 30 times higher than the vertical one) and the radius of the horizontal conductive fractures, 4 to 16 metres wide according to our results. The existence of numerous sub-horizontal fractures in the weathered granite, especially at the bottom of the saprolite (Fig. 7), explains this result. Two fracture networks were identified at different scales, a primary one (PFN) fracturing the matrix at a decimetre scale thus contributing to an increase in the primary permeability and drainage porosity of the crystalline rock. Two sets of secondary fractures (SFN) crack the blocks at metric to decametric scales, consisting of horizontal permeable fractures and, less dense or permeable, vertical fractures. The fractional flow dimension obtained using the Barker (1988) analytical solution suggests a good connectivity of the fracture networks, suggesting that vertical fractures ensure the connectivity of the horizontal ones at a large scale.

Injection tests and pumping tests using packers have shown that the conductive fracture zone at the interface between the saprolite bottom and the top of the fractured layer is the most permeable part of the aquifer (Boisson et al., 2015a). This plays a role in the connectivity of the aquifer, as discussed hereafter.

6.3 Connectivity of the aquifer at regional scale

By focusing on fracture-network connectivity, Guiheneuf et al. (2014) highlighted the compartmentalization of aquifers during low water-level conditions (Fig. 8). During high flow periods, however, the permeable zone formed by the saprolite bottom and the upper part of the fractured layer is horizontally well connected. At basin scale, groundwater will flow mainly through this permeable zone after the monsoon. The authors showed that the hydraulic connectivity of the fractured layer strongly decreases with depth. The small lateral extension of the deeper conductive fractures induces a lateral compartmentalization of the aquifer when the water table is low before the monsoon. Depending on water-table fluctuations, the aquifer moves from a regional flow scheme to independent local flow (Guiheneuf et al. 2014). This result is important not only for groundwater management in hardrock aquifers, but also for the way such aquifers can be modelled by deterministic approaches.

6.4 Impact on hydrochemistry

Various hydrochemical studies carried out over the years in both sites (Guihéneuf et al., 2014) have highlighted the impact of the physical heterogeneity and aquifer compartmentalization on groundwater chemistry. The increase of physical connectivity by a rise in water level also has an impact on groundwater chemistry and thus on solute transport. Detailed geochemical investigations (Alazard et al., 2015) over a few hectares only, showed the complexity of the diffuse recharge mechanisms, combining piston flow and preferential flow paths. These different recharge mechanisms induce stratification in the groundwater chemistry and create local geochemical-heterogeneity. Chemical data also show temporal evolution, highlighting various types of connectivity and preferential flow paths over the year (Perrin et al., 2011a; Alazard et al., 2015).

These studies highlight a vast range of flow and contaminant transport velocities, from rapid horizontal transport in the fractured zone (Guihéneuf et al., 2017) to slow vertical infiltration (Alazard et al., 2015) with seasonal variations in the flow paths (Perrin et al., 2011a); they also highlight the questions of the representativeness of point sampling and of the generalization of geochemical measurements. This chemical compartmentalization may have significant impact on contaminant transport and pollution management, as well as affecting the Managed Aquifer Recharge (MAR) structures currently developed throughout the country.

Regular hydrochemical sampling campaigns carried out since 2011 under different hydrodynamic conditions have shown the existence of hydrochemical compartments of hectometric size (Fig. 9) and of lateral exchange limited to high-water-table conditions. Such compartmentalization implies semi-confined aquifer settings at the local scale, with limited vertical connectivity in the fractured zone, dominant horizontal flow and transport, and the transmission of recharge water with a marked lateral component. Within a compartment, spatial variations in groundwater chemistry are attributed to different residence times; for instance, higher potassium content is caused by longer water-rock interaction in low transmissivity zones.

6.5. Fluoride content in groundwater

Among the threats to groundwater quality, fluoride release has been particularly investigated. Fluoride in groundwater may lead to severe health issues, especially fluorosis with harmful effects on teeth and bones due to its accumulation in the organism. Dental fluorosis is endemic in the study area; high F concentrations, up to 17.3 mg/l (Pauwels et al., 2015), should be compared to the drinking-water limits of 1.5 mg/L (World Health Organization) and 1 mg/L for India. Perrin et al. (2011b) showed that aquifer overpumping creates solute recycling, leading to increased element concentrations in groundwater. Pettenati et al. (2013), using 1D column reactive modelling, investigated this recycling effect on F concentrations and their possible evolution below rice paddies. Their results indicate that groundwater remains undersaturated with respect to fluorite (CaF_2), thus inducing a possible long-term increase in the F^- concentration in the absence of precipitation. This phenomenon seems to be governed by cationic exchange capacity (CEC) with Ca/Na and calcite precipitation, decreasing Ca activity and preventing fluorite precipitation. However, F can be adsorbed onto ferrihydrite surfaces, which may mitigate concentration increases. The geogenic origin of fluoride, through fluorapatite and possibly to a lesser extent allanite and biotite, explains the concentration increases (Pettenati et al., 2013). Further investigations by Pauwels et al. (2015) through borehole logging indicated a strong stratification of groundwater, with a general increase of the F concentration with depth. While such an increase agrees with a geogenic origin, extreme near-surface values also indicate a possible anthropogenic origin of F from fertilizers. Both studies highlight a spatial heterogeneity of F concentrations, which may be enhanced by human activity (local effect of pumping). This knowledge should help in maintaining good groundwater quality for drinking purposes within overpumped endorheic watersheds and may help in mitigating these effects.

6.6 Solute cycling effect

In order to assess the impact of irrigation return flow on groundwater salinization by solute recycling, simulations of long-term fluctuations of water levels and solute contents were run at basin scale with a reservoir model (Perrin et al., 2011b). The model can simulate water levels and chloride concentrations inferred since 2001, showing a progressive increase in the latter. Simulation of the period 2010-2014 indicates that forecast concentrations are very sensitive to aquifer mixing efficiency. In the case of complete mixing, base flow that activates during very rainy years may export significant solute mass and reduce aquifer concentrations to acceptable levels. In the more realistic case of incomplete mixing, diluted base flow will export less solute and solute mass continues to increase throughout the simulation period, ending up with concentrations that render the water too mineralized, and unsuitable as drinking water or for irrigation.

6.7 Managed aquifer recharge

Rainwater harvesting tanks (ponds) have been widely used in southern India for over 2000 years and are promoted by local government for their presumed “crucial impact” on groundwater recharge. We assessed the impact of such Managed Aquifer Recharge structures (MARs) on the groundwater system through different approaches on the study sites. By combining a surface-water-budget approach with a groundwater-budget model (Boisson et al., 2014), it was found that the part of stored water in the aquifer deriving from MARs is low, with a total annual percolation efficiency close to 49%. Another study has confirmed this result, finding a maximum of percolation of less than 60% in another site (Massuel et al., 2014). Boisson et al. (2015b) highlighted such delayed aquifer recharge caused by slow vertical water flow through the unsaturated zone. This underlines the limited benefits of this slight water-level increase by the MAR system during years of medium or low monsoon rainfall. The interaction between MAR and aquifers was further assessed via a hydrochemical approach: Alazard et al. (2015) showed how geochemical recharge is affected by poor vertical mixing and stratification of the groundwater. The horizontal compartmentalization was also identified through groundwater chemistry, highlighting the crucial role played by the upper layer of the weathering profile, particularly the top of the fractured layer, in the chemical evolution over time. This aspect was also explored by Pettenati et al. (2014), who showed that tank infiltration can have a positive effect on decreasing geogenic fluoride concentrations in an aquifer during the monsoon period, thanks to dilution compensating evaporation.

For the dry period, however, their study illustrated an increase in fluoride content due to both concentration by higher evaporation and F-release induced by the weathering of fluoride-bearing minerals on the flowpath of tank water infiltration. This work thus had a two-fold impact: Not only does it provide further data to the scientific community that until now lacked detailed data on percolation tanks/ponds in crystalline aquifers, but its results can also be incorporated in future MAR plans for improving the management (pumping *versus* gravity-fed irrigation) and maintenance (desilting) of such tanks.

For that purpose, the monitoring of water tanks by remote sensing has been validated for the Maheshwaram MAR site, where automated processing of satellite images provides accurate estimates of water volume changes before and after the monsoon. The launch of the Sentinel-1 and -2 satellites in 2015 has opened promising perspectives for the evaluation of water balance at the regional level for hundreds of water tanks, whose efficiency for recharge is still debated.

6.8 Agro-hydrology from space

In southern India, land use and water resources are highly correlated as well as being variable with time. Water-table fluctuations are influenced by monsoon variability, but are also strongly impacted locally by water abstraction for irrigation. Measuring the size of seasonal irrigated areas is a very good proxy for water abstraction. The dynamics of such irrigated areas were analysed with state-of-the-art data processing techniques applied to satellite data (GRACE, Landsat and Sentinel), together with an agro-hydrological model (SWAT) at a large-catchment scale (1000 km^2) and affected by climate change (Ferrant et al., 2015); this study showed how shallow aquifers under high irrigation-water demand react to climate variability due to a lack of surface water (Fig. 10). Indeed, irrigation water demand is directly linked with a seasonal to annual buffer effect to the surface extent of each irrigated crop, associated with irrigation practices. A slight increase of precipitation may alleviate current groundwater depletion on average, despite the increased evaporation due to global warming. Nevertheless, the increase of water demand within a highly variable hydroclimatic context, which combines extreme wet and dry spells, will increase anthropogenic pressure on groundwater resources in the future (Ferrant et al., 2015).

7) Outlook

Future research at the Indo-French Center for Groundwater Research (IFCGR) should focus on using our expertise in crystalline-rock aquifers in semi-arid areas for improving the integrated conceptual model of these complex systems at larger scales. The knowledge acquired at local and catchment scales will be combined with the latest remote-sensing techniques (Sentinel 1 and 2 images at 10 m and 20 m resolution, and GRACE for example (Ferrant et al., 2017)). The objective will be to simulate the space/time fluctuations in surface and groundwater resources, using an agro-hydrological model of the SWAT type. The surface-water and groundwater balance will be determined—integrating recharge, basin evaporation *versus* infiltration flux, horizontal groundwater circulation, irrigation-return flow and groundwater abstraction—with the input of climatic variables (rainfall, potential evapotranspiration) and the extent of irrigated crop areas (Fig. 11). Combined with the techniques developed for regionalizing aquifer parameters (Dewandel et al., 2017), this integrated approach should provide, among others, reliable information on how recharge varies at the watershed or even regional scale. This method will also identify the governing processes, and then, for practical purposes, should lead to new decision support tools for making predictions on a larger scale.

Recently, using seismic velocity and electrical resistivity surveys, St. Clair et al. (2015) have shown that disturbances to regional tectonic stress fields induced by local topography can explain changes in the distribution of bedrock fractures. The base of the fractured zone roughly follows surface topography, where the ratio of horizontal compressive tectonic stress to near-surface gravitational stress is relatively large, and it becomes parallel to the surface topography where the ratio is relatively small. We plan to use the recent Time

Domain ElectroMagnetic (TDEM) airborne survey flown over the same Archean granite, in order to compare it with the stress-field conditions and to validate the results for tropical conditions.

Based on the experience acquired on the observatory sites near Hyderabad, the hydrogeological properties of the granitic basement below the Deccan traps are currently studied. In the seismically active region of the Koyna and Warna reservoirs near the west coast of India, several boreholes over 1500 m deep have been drilled. Analysis of the borehole data combined with geomorphological observations from LIDAR data, will provide a better understanding of the hydroseismic phenomena observed in this region since the major reservoirs were created (Arora et al., 2017). The first results show deep groundwater circulation within a weathered zone in the basement, at the interface between basalt flows and the granitic Archean basement at 1000 m depth. Studying the analogy between the conceptual hydrogeological model of the near-surface granitic terrain in the Hyderabad region and that of the deeply buried one in the Koyna/Warna region, will further improve the broad understanding of such heterogeneous aquifers under diverse conditions.

On the Choutuppal site, a new infiltration basin was constructed very close to our borehole network. Water from the Musi River downstream of Hyderabad is diverted into this basin by a long canal. This water is highly polluted by domestic waste and concentrated organic matter. We plan to study the processes of attenuating this pollution in soil and the vadose zone, by monitoring groundwater quality in the boreholes and charting the displacement of the pollution plume. This will be done through analysis of major ions and metallic-ion traces, of microbiology (Escherichia coli, global bacterial population), of organic matter (composition, evolution, type of molecules and size, degradation) and of isotopes (boron).

The energy-water nexus is a major issue of groundwater management in India. Groundwater pumping for irrigation consumes more than 30% of the total electricity produced in the country. Regulation of groundwater pumping is done through limiting the power supply to 6 to 8 hours per day. Reducing the water-discharge rate (for example by increasing the duration of pumping up to 12 or even 24 hours per day) would reduce the linear head losses and drastically reduce the quadratic well-head losses. The objective of this new study should include estimating the optimal pumping durations for irrigation, taking into account the reduction of electricity consumption (and cost) due to reduced well loss in pumped wells, the impact of energy losses on the power network, and the impact on the overall efficiency of irrigation.

All these points show the value of a hydrogeological observatory for long-term multi-disciplinary research on representative sites, particularly through obtaining a detailed understanding of how natural and anthropogenic changes affect groundwater processes in such complex aquifers. A very recent and independent bibliometric study (Shilpa and Bhattacharya, 2017) has shown how the Indo-French Center for Groundwater Research and its associated observatory sites has shown the intrinsic worth of Indo-French cooperation in the water sciences.

Crystalline rocks exposed to tropical semi-arid conditions, or more generally to weathering processes, are found throughout the World, especially in Africa where groundwater usage is still moderately developed. The specificity of the hydrogeological model resulting from our investigations in India thus should be validated elsewhere, and in different hardrock geological environments, such as schist and other metamorphic rocks. Particular attention should be paid to the shallow critical zone in saprolite and the weathered-fractured layer of underlying hardrock. Here, the dominant role of horizontal fractures—inducing a vertical anisotropy in hydraulic conductivity as well as a variable connectivity according to water-level conditions—should be explored in detail as its structure may strongly compartment underground flow, implying complex mass-transport conditions at a regional scale. The role played by this interface on recharge processes is another pending scientific question. New results and understanding obtained on crystalline aquifers in India should further help in avoiding the degradation in quality and quantity caused by overpumping groundwater.

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[1] The database is protected by user accounts. New users should create an account and a password shall be sent.

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Figure Captions

Figure 1 Conceptual hydrogeological model of crystalline rock aquifers (after Maréchal et al. 2004).The box identifies the saturated weathered and fractured part of the aquifer.

Figure 2a Geological map of Telangana State;

b) Maheshwaram watershed with location of pumping wells for irrigation (July 2002);

c) EHP (0.55 km²) site near Choutuppal village, with two clusters of monitored borewells: 30 wells dedicated to hydrodynamic experiments at local scale and 4 wells focusing on the impact assessment of the nearby artificial recharge tank.

Figure 3 Temperature time series: identification of groundwater temperature plateau. The pumping duration is overlain in grey (after Massuel et al., 2009).

Figure 4 Piezometric map of the Maheshwaram watershed (2002).

Figure 5a Idealized multiphase weathering conceptual model (vertical scale is deliberately exaggerated); Dewandel et al., 2006. (i) Probable weathering profile during the Jurassic-Cretaceous, complete profile; (ii) Truncated erosion profile due to Cretaceous to Quaternary uplifts; and (iii) Current weathering profile. Diamond = benchmark.

b) Example of electrical resistivity well logging (apparent resistivity); Kudaliar watershed.

c) Mapping of the weathered layers in the Kudaliar watershed (983 km²) after Dewandel et al., 2017; the insert shows the variogram used for data interpolation.

Figure 6 Hydrodynamic properties of the fractured layer in the crystalline aquifer (modified from Maréchal et al., 2004). PFN: primary fracture network – SFN: secondary fracture network – CFZ: conductive fracture zone.

Figure 7a Picture of a dugwell in the Maheshwaram basin.

b) Identification of horizontal fractures.

Figure 8 Schematic conceptual model of groundwater flow at watershed scale (modified after Guilheneuf et al. 2014).

Figure 9 Principal Component Analysis (PCA) computed on chemical results of the March 2011 sampling campaign (pre- and post-**pumping** on CH3) and of the February 2014 sampling campaign. Bottom: map of the piezometric network with location o**f** the different hydrochemical compartments (coloured ellipses)

Figure 10a Monthly water-table fluctuations simulated using SWAT-IMD (black line) at large (1000 km²) basin scale and the observed water table in a reference well (grey line). The spatial distribution of observed water-table depths is represented by boxplots.

b) Monthly water storage simulated using SWAT-IMD (black line) and monthly GRACE water equivalent thickness anomaly (grey line) for the grid containing the studied watershed (90,000 km²). The grey area provides the confidence interval of GRACE measurements (Ferrant et al., 2015).

Figure 11 Multi-scale combined approach of water balance using remote sensing data

Tables

Observatory	Data type	Period	Time step
Maheshwaram	Meteorological data (1)	2000-Now	Hourly
	Groundwater level (2 wells)	2000-Now	15 min to Hourly
	Groundwater level (100-200 wells)	2002-Now	Semester
	Pumping strategy (-)	Variable	Minutes
Choutuppal	Meteorological station (1)	2009-Now	Hourly
	Groundwater level (10 wells)	2009-Now	15 min to Hourly

Table 1: Long-term observations in the Hyderabad observatory

Wshd*	Study stage	Experiment	Nr	Objective	Reference
Maheshwaram	Aquifer regional study	Well drilling	45	Geological log	Dewandel et al., 2006 Kumar et al., 2007
		Vertical Electronic Soundings	80	Weathering profile structure	
		Slug tests	30	Local permeability	Maréchal et al., 2004
		Injection tests	28	Permeability	
		Flowmeter tests	28	Number of Conductive Fracture Zone	Maréchal et al., 2004a Dewandel et al., 2006
		Pumping tests	6	Permeability, double porosity, anisotropy	Maréchal et al., 2004a Maréchal et al., 2004b
		Hydrochemical analysis campaigns, isotopes of the water molecule			Perrin et al., 2011b Negrel et al., 2011
		Hydrochemical borehole logs (NO3, F)	23	Hydrochemical log	Pauwels et al., 2015
	Geological discontinuities (quartz veins)	Wells drilled (21) Slugtests (21) Pumping tests (5) Electrical Resistivity Tomography (6)		Weathering profile structure, hydrodynamic properties	Chandra et al., 2010, Dewandel et al., 2011
	Vadose zone study	Infiltration tests	60	Soil saturated permeability	Condappa de et al., 2008
		Soil volumetric masses measurements	43	Soil porosity	
		Neutron probe measurement	30	Soil moisture profiles	
	Managed Aquifer Recharge study	Infiltration-basin water level	1	Infiltration basin water balance	Boisson et al., 2014, 2015b
		Well drilling	8	Geological log, water level monitoring	
		Hydrochemical analysis campaigns		Artificial recharge	Alazard et al., 2015
Choutuppal	Aquifer local study	Well drilling	30	Weathering profile thickness	
		Slug tests	12	Local permeability	Boisson et al., 2015a Guihéneuf et al., 2014
		Falling-head borehole / Permeameter	4	Saturated permeability	
		Packer tests	6	Vertical connectivity	
		Pumping tests	2		
		Convergent tracer tests	3	Dispersivity, effective porosity	Guihéneuf et al., 2017
		Push-Pull tracer tests	8	Dispersivity	
	MAR study	Infiltration-basin water level	1	Infiltration basin water balance	Under work
		Well drilling	4	Geological log, water level monitoring	

Table 2: main experiments carried out on the Hyderabad observatory since 1999 (: watershed)*

Hydraulic permeabilities from slug tests (*n*=30)
$2.0 \times 10^{-8} < K^{1} = 4.4 \times 10^{-6} < 5.0 \times 10^{-4}$

Average parameters calculated by adjustment on double-porosity model (*n*=10)					
T_f m^2/s	K_f m/s	S_f[2]	K_b m/s	S_b[2]	S_y[2]
3.5×10^{-4}	2.1×10^{-5}	5.8×10^{-4}	5.1×10^{-8}	5.7×10^{-3}	6.3×10^{-3}

Average parameters calculated by adjustment on anisotropic model (*n*=6)			
K_r m/s	K_z m/s	K_D $(=K_z/K_r)$	$1/K_D$
1.1×10^{-5}	1.3×10^{-6}	0.1	8.7

Table 3: Values of hydrodynamic properties calculated using the double-porosity and anisotropic models

[1] Arithmetic mean for storage and geometric mean for hydraulic conductivity

[2] S_b, S_f, and S_y : blocks, fractures and total storage coefficients ($S_y = S_b + S_f$), corresponding, in unconfined aquifer, to specific yields