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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

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

25 **Core ideas**

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

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

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

32 **1) Introduction**

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

36 India is the biggest groundwater user in the World, with almost 25 million pumped wells. About two-thirds of
37 the country is underlain by crystalline rocks (Archean granite and gneiss, Deccan traps) and, at the national
38 level, 60% of irrigation is sustained by groundwater. This is especially the case in southern India, where rice is
39 cultivated despite a very dry climate. The Green Revolution has permitted the improvement of agricultural
40 productivity through the development of groundwater irrigation and the use of fertilizers. In addition, the
41 Indian states have subsidized well drilling and electricity is often free for farmers. The consequence is
42 overpumping and a chronic depletion of the groundwater resource in many areas. In irrigated areas, the water

43 cycle has been drastically changed, with the average pumping rate exceeding natural recharge and high
44 irrigation return flows (Maréchal et al., 2006). The water-table lowering has dried up springs and wetlands.
45 Rivers have become ephemeral and thousands of water tanks have been constructed to retain water flowing to
46 the sea. The pumping has also induced endorheic aquifer conditions with a very high rate of water recycling
47 (Perrin et al., 2011) with, locally, major salinity increases and fluoride enrichment (Pauwels et al., 2015).

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

54 **2) Motivation and scientific questions**

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

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

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

75 **3) Catchment characteristics**

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

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

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

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

94 The Maheshwaram watershed (53 km²) lies 35 km south of Hyderabad (Fig. 2b) and is characterized by a
95 relatively flat topography (590 to 670 m asl). Its climate is semi-arid and controlled by the periodicity of the
96 Monsoon (rainy or "Kharif" season from June to October). Average annual rainfall is 750 mm, of which over
97 90% falls during the monsoon period. The average annual temperature is 26 °C, reaching 45 °C during the hot
98 "Rabi" season from March to May. The resulting potential evapotranspiration (PET) is 1,800 mm/year. Surface
99 streams are not perennial and flow a few days a year during the monsoon.

100 The Maheshwaram watershed is quite representative of southern Indian hydrogeological conditions, with (i) a
101 highly pumped crystalline aquifer (more than 700 bore wells withdrawing about 10 Mm³/year), (ii) a cropping
102 pattern dominated by rice cultivation, and (iii) a rural socio-economy mainly based on traditional agriculture.
103 The water table has shown a long-term decline (now 15 to 25 m deep) that has caused the drying-up of springs
104 and streams.

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

111 **4) Basic long-term monitoring**

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

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

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

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

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

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

150 **5) Main hydrogeological experiments**

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

158 **6) New insights and novel scientific findings**

159 **6.1 Geometry of the weathering profile**

160 The large amount of available data on the Maheshwaram watershed (45 well lithologs and 80 Vertical Electrical
161 Soundings) allowed the mapping of both the bases of the saprolite layer and of the fractured layer (or the top
162 of bedrock). Analysis of the maps (Dewandel et al., 2006; Fig. 5a) shows that the structure of the weathering
163 profile in the area,-and thus of the aquifer, results from an ancient (Jurassic-Cretaceous) weathering profile
164 that has been eroded and truncated because of the uplift caused by the (Cretaceous-Quaternary) geotectonic
165 displacement of the Indian peninsula to the north and renewed-Quaternary weathering. Based on this
166 knowledge of the creation and structure of the weathering profile in the area, mapping techniques were
167 adapted to larger areas, up to 1000 km² (Figs. 5b and c), using geophysical logs in abandoned wells (Fig. 5b) and

168 outcrop observations to produce maps of the weathered layers (Fig. 5c), and thus of the aquifer geometry
169 (Dewandel et al, 2017).

170 **6.2 Hydrodynamic properties of the weathered**

171 The hydrodynamic properties of the weathered/fractured aquifer of the Maheshwaram watershed were
172 defined with hydraulic tests at different scales in various wells (Table 3). The resulting hydrodynamic model for
173 Maheshwaram is described on Figure 6. The statistical distribution of local hydraulic conductivities in wells was
174 obtained with slug tests ($K_{\text{average}} = 4.4 \times 10^{-6}$ m/s). Flowmeter measurements during injection tests helped
175 identifying the depth of the conductive fracture zones (CFZ) and their hydraulic conductivities ($K_{\text{average}} =$
176 8.8×10^{-5} m/s). The most permeable part of the weathered/fractured layer extends down to 35 m depth. The
177 double-porosity model was used for distinguishing the part of drainage porosity located in the blocks (90%,
178 $S_b = 5.7 \times 10^{-3}$) from that linked to fractures (10%, $S_f = 5.8 \times 10^{-4}$). The total resulting average drainage porosity
179 is $S_y = 6.3 \times 10^{-3}$, less than the value obtained from DWTF at the basin scale ($S_y = 1.3 \times 10^{-2}$, Maréchal et al.,
180 2006). This discrepancy is explained by the depth-decrease of porosity (Dewandel et al., 2017), which induces
181 an apparent higher value for DWTF estimates as the technique gives S_y values for the zone where the water
182 table fluctuates, whereas pumping provides an average value for the whole aquifer thickness.

183 Application of anisotropic and horizontal fracture analytical solutions on drawdown data allows determining
184 the vertical anisotropy of hydraulic conductivity ($1/K_D \sim 10$ on average, the horizontal hydraulic conductivity
185 being systematically 8 to 30 times higher than the vertical one) and the radius of the horizontal conductive
186 fractures, 4 to 16 metres wide according to our results. The existence of numerous sub-horizontal fractures in
187 the weathered granite, especially at the bottom of the saprolite (Fig. 7), explains this result. Two fracture
188 networks were identified at different scales, a primary one (PFN) fracturing the matrix at a decimetre scale thus
189 contributing to an increase in the primary permeability and drainage porosity of the crystalline rock. Two sets

190 of secondary fractures (SFN) crack the blocks at metric to decametric scales, consisting of horizontal permeable
191 fractures and, less dense or permeable, vertical fractures. The fractional flow dimension obtained using the
192 Barker (1988) analytical solution suggests a good connectivity of the fracture networks, suggesting that vertical
193 fractures ensure the connectivity of the horizontal ones at a large scale.

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

197 **6.3 Connectivity of the aquifer at regional scale**

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

208 **6.4 Impact on hydrochemistry**

209 Various hydrochemical studies carried out over the years in both sites (Guihéneuf et al., 2014) have highlighted
210 the impact of the physical heterogeneity and aquifer compartmentalization on groundwater chemistry. The

211 increase of physical connectivity by a rise in water level also has an impact on groundwater chemistry and thus
212 on solute transport. Detailed geochemical investigations (Alazard et al., 2015) over a few hectares only,
213 showed the complexity of the diffuse recharge mechanisms, combining piston flow and preferential flow paths.
214 These different recharge mechanisms induce stratification in the groundwater chemistry and create local
215 geochemical-heterogeneity. Chemical data also show temporal evolution, highlighting various types of
216 connectivity and preferential flow paths over the year (Perrin et al., 2011a; Alazard et al., 2015).

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

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

230 **6.5. Fluoride content in groundwater**

231 Among the threats to groundwater quality, fluoride release has been particularly investigated. Fluoride in
232 groundwater may lead to severe health issues, especially fluorosis with harmful effects on teeth and bones due

233 to its accumulation in the organism. Dental fluorosis is endemic in the study area; high F concentrations, up to
234 17.3 mg/l (Pauwels et al., 2015), should be compared to the drinking-water limits of 1.5 mg/L (World Health
235 Organization) and 1 mg/L for India. Perrin et al. (2011b) showed that aquifer overpumping creates solute
236 recycling, leading to increased element concentrations in groundwater. Pettenati et al. (2013), using 1D column
237 reactive modelling, investigated this recycling effect on F concentrations and their possible evolution below
238 rice paddies. Their results indicate that groundwater remains undersaturated with respect to fluorite (CaF_2),
239 thus inducing a possible long-term increase in the F^- concentration in the absence of precipitation. This
240 phenomenon seems to be governed by cationic exchange capacity (CEC) with Ca/Na and calcite precipitation,
241 decreasing Ca activity and preventing fluorite precipitation. However, F can be adsorbed onto ferrihydrite
242 surfaces, which may mitigate concentration increases. The geogenic origin of fluoride, through fluorapatite and
243 possibly to a lesser extent allanite and biotite, explains the concentration increases (Pettenati et al., 2013).
244 Further investigations by Pauwels et al. (2015) through borehole logging indicated a strong stratification of
245 groundwater, with a general increase of the F concentration with depth. While such an increase agrees with a
246 geogenic origin, extreme near-surface values also indicate a possible anthropogenic origin of F from fertilizers.
247 Both studies highlight a spatial heterogeneity of F concentrations, which may be enhanced by human activity
248 (local effect of pumping). This knowledge should help in maintaining good groundwater quality for drinking
249 purposes within overpumped endorheic watersheds and may help in mitigating these effects.

250 **6.6 Solute cycling effect**

251 In order to assess the impact of irrigation return flow on groundwater salinization by solute recycling,
252 simulations of long-term fluctuations of water levels and solute contents were run at basin scale with a
253 reservoir model (Perrin et al., 2011b). The model can simulate water levels and chloride concentrations
254 inferred since 2001, showing a progressive increase in the latter. Simulation of the period 2010-2014 indicates

255 that forecast concentrations are very sensitive to aquifer mixing efficiency. In the case of complete mixing,
256 base flow that activates during very rainy years may export significant solute mass and reduce aquifer
257 concentrations to acceptable levels. In the more realistic case of incomplete mixing, diluted base flow will
258 export less solute and solute mass continues to increase throughout the simulation period, ending up with
259 concentrations that render the water too mineralized, and unsuitable as drinking water or for irrigation.

260 **6.7 Managed aquifer recharge**

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

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

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

288 **6.8 Agro-hydrology from space**

289 In southern India, land use and water resources are highly correlated as well as being variable with time.
290 Water-table fluctuations are influenced by monsoon variability, but are also strongly impacted locally by water
291 abstraction for irrigation. Measuring the size of seasonal irrigated areas is a very good proxy for water
292 abstraction. The dynamics of such irrigated areas were analysed with state-of-the-art data processing
293 techniques applied to satellite data (GRACE, Landsat and Sentinel), together with an agro-hydrological model
294 (SWAT) at a large-catchment scale (1000 km²) and affected by climate change (Ferrant et al., 2015); this study
295 showed how shallow aquifers under high irrigation-water demand react to climate variability due to a lack of
296 surface water (Fig. 10). Indeed, irrigation water demand is directly linked with a seasonal to annual buffer
297 effect to the surface extent of each irrigated crop, associated with irrigation practices. A slight increase of
298 precipitation may alleviate current groundwater depletion on average, despite the increased evaporation due

299 to global warming. Nevertheless, the increase of water demand within a highly variable hydroclimatic context,
300 which combines extreme wet and dry spells, will increase anthropogenic pressure on groundwater resources in
301 the future (Ferrant et al., 2015).

302 **7) Outlook**

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

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

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

323 Based on the experience acquired on the observatory sites near Hyderabad, the hydrogeological properties of
324 the granitic basement below the Deccan traps are currently studied. In the seismically active region of the
325 Koyna and Warna reservoirs near the west coast of India, several boreholes over 1500 m deep have been
326 drilled. Analysis of the borehole data combined with geomorphological observations from LIDAR data, will
327 provide a better understanding of the hydroseismic phenomena observed in this region since the major
328 reservoirs were created (Arora et al., 2017). The first results show deep groundwater circulation within a
329 weathered zone in the basement, at the interface between basalt flows and the granitic Archean basement at
330 1000 m depth. Studying the analogy between the conceptual hydrogeological model of the near-surface
331 granitic terrain in the Hyderabad region and that of the deeply buried one in the Koyna/Warna region, will
332 further improve the broad understanding of such heterogeneous aquifers under diverse conditions.

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

340 The energy-water nexus is a major issue of groundwater management in India. Groundwater pumping for
341 irrigation consumes more than 30% of the total electricity produced in the country. Regulation of groundwater
342 pumping is done through limiting the power supply to 6 to 8 hours per day. Reducing the water-discharge rate

343 (for example by increasing the duration of pumping up to 12 or even 24 hours per day) would reduce the linear
344 head losses and drastically reduce the quadratic well-head losses. The objective of this new study should
345 include estimating the optimal pumping durations for irrigation, taking into account the reduction of electricity
346 consumption (and cost) due to reduced well loss in pumped wells, the impact of energy losses on the power
347 network, and the impact on the overall efficiency of irrigation.

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

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

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367 data may be downloaded¹ from the web site of the H+ Observatory (<http://hplus.ore.fr/en/>). Dr. H.M. Kluijver
368 edited the final version of the MS.

369

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

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485

486 **Figure Captions**

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

489 Figure 2a Geological map of Telangana State;

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

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

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

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

497 Figure 5a Idealized multiphase weathering conceptual model (vertical scale is deliberately exaggerated);

498 Dewandel et al., 2006. (i) Probable weathering profile during the Jurassic-Cretaceous, complete profile;

499 (ii) Truncated erosion profile due to Cretaceous to Quaternary uplifts; and (iii) Current weathering profile.

500 Diamond = benchmark.

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

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

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

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

508 b) Identification of horizontal fractures.

509 Figure 8 Schematic conceptual model of groundwater flow at watershed scale (modified after Guilheneuf et al.
510 2014).

511 Figure 9 Principal Component Analysis (PCA) computed on chemical results of the March 2011 sampling

512 campaign (pre- and post-**pumping** on CH3) and of the February 2014 sampling campaign. Bottom: map of

513 the piezometric network with location of the different hydrochemical compartments (coloured ellipses)

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

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

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

521

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

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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 (NO ₃ , F)	23	Hydrochemical log	Pauwels et al., 2015
	Geological discontinuities (quartz veins)	Wells drilled (21) Slugttests (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	Boisson et al., 2015a Guihéneuf et al., 2014
		Slug tests	12	Local permeability	
		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		

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

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Hydraulic permeabilities from slug tests ($n=30$)	530
$2.0 \times 10^{-8} < K^1 = 4.4 \times 10^{-6} < 5.0 \times 10^{-4}$	

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

531

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

533 ¹ Arithmetic mean for storage and geometric mean for hydraulic conductivity

534 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
535 specific yields

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