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Editor's message: The *sunk cost fallacy* of deep drilling

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The observed facts

At the beginning of 2008, I visited a watershed located in Karkinatam village in the state of Karnataka, South India. There, crops are intensively irrigated using groundwater. The water table has been depleted from 5 m-depth to 50 m-depth in a large part of the area. Now, 42 % of a total of 158 water wells in the watershed are dry. Speaking with the farmers, I have been amazed to learn that they were drilling down to 500 m to tap water. This case is, of course, not isolated.

Large regions, for example in South America, Africa and South Asia, are constituted by crystalline rocks. The same regions face water scarcity under arid to semi-arid conditions. Therefore, fractured crystalline aquifers constitute groundwater reserves that are exploited in many parts of the world. In India, groundwater pumped from hard rocks represents the main resource for irrigation and has been sustaining the Green Revolution (Swaminathan 2007) for several decades. The mining of groundwater resources leads to lowering of the water table. As a reaction, the farmers are ready to pay more for deeper boreholes which, most of the times, are found to be dry. This trend is not restricted to rural areas, as private well development in the cities faces the same trend.

A detailed study of groundwater extraction in the world shows that the examples of deepening of wells up to hundreds of meters for water exploration in hard rocks are not limited to India but are also found in large numbers in other regions of the world (USA, Africa, etc).

The scientific knowledge

The concept that groundwater flows in crystalline rocks dominantly occur in a shallow higher-permeability zone (''active'' zone) that overlies a deeper lower-permeability zone hosting little flow (''inactive'' zone), is now accepted. This has been documented in mountainous regions (Mayo et al. 2003) and in flat bedrock areas (Davis and Turk 1964; Dewandel et al. 2006; Maréchal et al. 2004). Some flows occur in the inactive zone and can be significant on a geologic timescale but can hardly sustain intensive pumping at a daily timescale.

The pioneering work of Davis and Turk (1964) on crystalline rocks of eastern United States was one of the first to describe a decrease of hard-rock permeability with depth. In Scotland (UK), a trend in decreasing mean permeability with depth in bedrock has also been observed on the basis of data from the Altnabreac granite (Holmes 1981). In Victoria Province of Zimbabwe, below a 15-20 m thick regolith, the fractures of the top 20 m–thick zone of fractured rock are found to be crucial for the provision of an adequate yield (Houston and Lewis 1988). This has been confirmed by Chilton and Foster (1995). Higher permeability at shallower depths is generally attributed to a greater degree of weathering and/or smaller overburden loads allowing more fractures to remain open. The thickness of the active layer is dependent on local geological settings. In gneiss of South India, the interpretation of multiple pumping tests identifies an active part of the aquifer of about 25-35 m thickness (Maréchal et al. 2009). In crystalline bedrock of New Hampshire (USA), the well yield increases to approximately 130 m depth (Drew et al. 2001). In South Korea, the specific capacity of the wells is at a maximum above 80-m depth (Cho et al. 2003). In a granitic area of South India, it is observed that the cumulative air lift flow rate increases drastically in the weathered-fractured layer between 20 and 30 m deep; below 30 m, the flow rate is constant and does not increase with depth. In practice, drilling deeper than the bottom of the weathered-fractured layer does not increase the probability of improving the well yield (Maréchal et al. 2004).

The initial conceptual model of hard-rock hydrogeology, with the most productive zones located at the base of the regolith and the top of the fractured-weathered bedrock (Foster 1984), has been confirmed in various countries (Acworth 1987; Barker et al. 1992; Dewandel et al. 2006; Wright 1992). The data confirm that the weathered-fractured layer is the most productive part of the hard-rock aquifer compared to the deeper fresh bedrock (Taylor and Howard 2000).

As a general rule, fractures near the bedrock surface are most numerous and have the largest openings, so that the yield of most wells is not increased by drilling to depths greater than the bottom of this active zone. Exceptions to this occur where water-bearing faults or fractured zones, due to tectonic activity, are present at depths as great as 200 to 300 m. Nevertheless, statistically, it is clear that beyond the active zone, the probability of increasing the yield of a given well in hard rocks is very low.

Stop the *sunk cost fallacy*

One can observe a gap between hydrogeological practice and science. The most probable reason to explain this gap is called, in psychological sciences, the *escalation of commitment*. This phenomenon is where people justify increased investment in a decision, based on the cumulative prior investment, despite new evidence suggesting that the decision was probably wrong (Staw 1976). In economics and business management, it is well known as the *sunk cost fallacy*: increasing the resources available to an unsuccessful venture in the hope of recovering past losses. More generally, the sunk cost effect is manifested in a greater tendency to continue an endeavor once an investment in money, effort, or time has been made (Arkes and Blumer 1985). In water exploration, the escalation of commitment consists of drilling a borehole deeper in the hope of recovering the money wasted to drill the first dry meters. Once started, it is difficult to decide to stop drilling if the well is dry because the driller thinks that expected water-bearing structure could be a few meters away. This is similar to the compulsive gambler who needs, after losing, to gamble again to recover his losses. Of course, it can sometimes happen that a dry well becomes productive after deepening but, as suggested by the limited thickness of the active zone, it becomes a matter of luck.

This escalation of commitment for drilling deeper and deeper may be encouraged by drilling companies as the potential money gains are increased. In India, the cost of dry deep wells becomes unaffordable for most of the farmers. The rate of farmer suicides has reached high levels as they cannot reimburse loans undertaken for increased expenses, among which are well drilling costs (Sainath 2004). As water engineers and water experts, our duty is to contribute to end this unreasonable trend of well-deepening in hard rocks. This could be done by planning drilling better, and includes the *a priori* definition of a maximum drilling depth according to local hydrogeological knowledge and statistical information on the local relationship between yield and depth (Wright 1992). After reaching that depth, instead of drilling deeper, the borehole should be closed.

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