The living wisdom: using local well driller knowledge to construct digital groundwater data bases: Inferences from studies across the Indo-Gangetic Basin

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ABSTRACT

The low density of current groundwater instrumentation networks in developing countries, that are both cost and management intensive, is an impediment to informed management of groundwater. Counter to this, local knowledge of groundwater which is often perceptive has greater spatial coverage and can be obtained at a relatively lower cost. One efficient way to tap such local groundwater knowledge is through well drillers. In the Vaishali district of Bihar state in eastern India, a new methodological approach is used to identify and sensitize well drillers towards creating a local groundwater database. A localized lithology of a single village is created using both the experiential knowledge and current practice of these drillers. Though subjective and tangible sources of uncertainty enter into this process, the compiled knowledge is shown to be verifiable and cost-effective. There is a potential for upscaling this approach and create accurate regional groundwater databases at low cost.

1. Introduction

Knowledge is an important key to better management of any resource. A critical problem associated with management of groundwater, especially but not exclusively in developing countries, has been the limited established knowledge of the resource at local level. The existing monitoring networks established by scientific institutions and current management measures fail to bring out in sufficient detail, information of the local setting, thereby hampering adaptive, context-specific and appropriate water resources management . In fact, quite often such science-based information is also at counter with basic common sense-perception of local groundwater (see Section 1.1).

Different schools of thought about groundwater management debate over strategies to address the current problems. One school professes that it is the larger policies of energy, agriculture and trade that influence how groundwater is used and therefore one needs to focus on these policies. Another school professes that beyond these policies, local communities need to get together to assess, monitor and control the use and protection of groundwater in their own environment. In both these thoughts, however, know-how of what is exactly the current state of the resource and how it is affected by policy or local action needs to be known. Understanding of the way a system responds to stimuli is essential to proper guiding pro- and reactive measures. But, often, such knowledge of groundwater requires considerable investment on detailed studies and monitoring. Are there other ways in which local information on groundwater can be captured?

Taking the case of India, this paper explores and then argues that it is possible to capture such local information at a much lower cost by involving local key stakeholders who have much to gain or lose by what happens to groundwater. Where there is extensive use of groundwater, there is also a reasonable density of wells. And where there are wells, local professionals dealing with the business of drilling wells are present. These well drillers are usually located in the village itself or in small towns close to villages from where they set their base. Often, they belong to local communities such as fishermen, carpenters and masons for whom transitioning from their traditional occupations to well drilling is a natural process. Drillers are the root source of information for farmers on issues related to groundwater and between themselves they foster information-exchange across their area of operation. Our proposal here is that well drillers individually and together as a community possess critical knowledge about local lithology, groundwater flow and groundwater quality conditions and could create local databases on groundwater, with some external help. The questions we ask and intend to answer in this paper are:

i) do the well drillers really possess this knowledge,
ii) if so, how can we extract and collate this information into local information databases on groundwater
iii) can the knowledge be verified, i.e. by comparing this information database with science-based information that already exists through scientific institutions?
iv) how can this knowledge be made operational and used more widely,

von Hayek (1974) in his critical work on knowledge talks about the relevance of local and specific information in any complex science. The problem with many complex subjects is that global or conceptual pictures are easily made, but localized pictures are less available. However, it is this local knowledge that often adds substance and makes the concept useful. Unless this local knowledge is efficiently used, any global or theoretical knowledge remains irrelevant. Both traditional scientific knowledge and traditional local knowledge have their own benefits and disadvantages (Table 1). Ideally, one needs a fusion of both to achieve the best in terms of different factors, such as scale, tools used, spatial coverage, precision, repeatability, communication and purpose.

Table 1: Comparing science-based knowledge and local knowledge

Characteristic	Science	Local knowledge
Scale	Large scale, general, conceptual *Aquifers*	Smaller scale, specific, practical *Can describe nature of local flow*
Tool	Designed instruments, limited, focused, recorded *Rain gauge, Water level recorder, drill logs*	Many undefined instruments, unfocussed observation, mostly unrecorded *Different sensors, word of mouth, passing of information through generations*
Spatial coverage	Time and space sparse, interrupted time-series	Dense in space and time, long term observations

	Depends on monitoring network	*Every individual is an observer*
Precision	More precise, errors more objective and amendable *Results from repeated measurements*	Perceptive, individual, errors difficult to evaluate *Every individual has different perception, possible bias*
Repeatability	Repeatable measurements *Can use same monitoring equipment at different places*	Possibly poor repetition *Cannot expect similar perception and experiences for same observation*
Communication	Easy to translate and communicate *Somewhat standardized terms, such as porosity*	In local language and need to be interpreted Terms such as *Kankar*[1], *Pathar, Khara Nadi*
Purpose	Observations useful for scientific interpretation and modeling *Measurements such as hydraulic conductivity*	Observations of importance to daily life and water use *How fast does water fill into a well?*

1.1. Previous studies on local hydrologic knowledge

Man acquires intuitive knowledge that is essential for his occupation. A stock broker can feel the market going up and down with some degree of precision; a farmer can sense arrival of rainfall from the movement of clouds and wind; a lawyer can make out a criminal from a face. These perceptive ideas are built over time from experience and differ from one profession to another and from one professional to another depending on their experience, interest and ability of deduction and abstraction. If such professions continue over generations, especially within families and communities as traditional occupations, knowledge gained gets passed by word of mouth and becomes part of common sense. It is no wonder that different authors have documented rich cases of knowledge of local hydrology in communities closely associated with agriculture.

Rosin's study of a village in Rajasthan talks about groundwater irrigation and water management practices in this arid region based upon a rich knowledge of local water resources (Rosin, 1993). His study, spanning 25 years of observation, looks at how local water harvesting structures are built with knowledge of siltation, runoff, recharge to groundwater, salinization processes and groundwater flow. He documents the case of reasonably large diversion of water resource resulting in a rich discussion within the community and leading to a variety of alternative actions. In such discussion, Rosin observed that the community was able to envisage the consequences of future actions of water diversion much better than engineers and their speculations were vindicated by later results. He proposes that hundreds of years of groundwater use had naturally

[1] *Kankar: gravel; Pathar: stones; Khara: Saline; Nadi: River*

brought the community to a stage where they were able to conceptualize groundwater through external signals. For example, farmers would hold their ear to the ground during shallow drilling and visualize the direction of flow. Their know-how of local topography and flow was enough to indicate which were the areas of shallow groundwater table and surface water stagnation and therefore possible locations of salinization of water.

The classic study on ‘Dying Wisdom’ (CSE, 2001) documents examples from across India on the traditional practices of water management. Their traditional water harvesting structures show sound understanding of local hydrological processes and intuitive knowledge of essential geology The Surangams of Kerala are tunnel-like structures constructed to collect groundwater and channel it out to collector wells. These ancient constructions reveal a sound understanding of groundwater dynamics and ability to use this knowledge for engineering activities. Examples of such structures have been found in various cultures in arid regions throughout the world under various local names, such as karez, qanat, foggara, and falaj. .

Shah in his study of a coastal village of Junagadh district of Gujarat describes how farmers built their own picture of local groundwater hydrology through observation of water level dynamics during pumping (Shah, 1993). These observations lead them to conceptualize their own understanding of the aquifer structure, be it in local language. This was in counter with the proposal of a groundwater hydrologist who based his conclusion upon a conventional hydro-geological survey of the area, proposing a leaky aquifer model. Later events confirmed the local perception of the aquifer structure that there is lateral outflow rather than vertical leakage.

Sengupta (1993) documents different cases of proper planning for local water resources development and the aggregate effect of many small water harvesting and extraction structures on a regional level. He suggests that there must have been some sort of regional level planning at basin level in the past and ancient cultures may have survived thanks to such integrated planning of water resources.

Shaw and Sutcliffe (2003) in their documentation of ancient small dams in the Betwa basin of central India links the size of these structures to the runoff from their catchment. This link leads to believe that the builders of these structures followed some variant of the rainfall-runoff curve during their design of these structures and that they were sound observations of local hydrology.

The publication by NIH Roorkee on hydrology in ancient India mentions verses from ancient poetry that exhibit knowledge of hydrology and groundwater (NIH 1999). Bio-indicators for groundwater exploration were in use and various thumb rules linked ground observations to the anticipated depth to the water table, eg. presence of certain plant species. Verses such as ‘The flow of water through earth is like blood flowing through veins’, shows mature understanding beyond mere poetic imagination.

Recent development efforts and research studies are showing appreciation of local knowledge in constructing hydro-geological information. There has been recent work on combining remote sensing with ethnographic studies to study local hydrology (Jiang, 2003). NGO-facilitated programs in Andhra Pradesh have organized efforts in participatory hydrologic monitoring by farmers to increase their awareness and local knowledge of groundwater and to better aid community-based groundwater management (Rama Mohan, 2007). A worldwide program, GLOBE, focusing on environmental data monitoring utilizes school children as a resource to record observations such a rainfall, water quality, humidity, etc., thereby reinforcing existing local knowledge. In Bangladesh, well drillers have been asked to locate local layers of arsenic enrichment in subsurface sediments and in locating sites for new wells and depth of water extraction for safe water supplies. (Jonsson and Lundell, 2004). The Honey Bee network operating from Ahmedabad, India, records and disseminates innovations in environmentally friendly agricultural practices made by local farmers by organizing annual walks through different regions (Honey Bee network). Another innovative program organized by the Arid Community Technologies (ACT) group in Kutch region, India, trains villagers as barefoot geologists to document local geological information in their language.

2. Methodology and Tools

This study was performed as part of a capacity building program called ‘Groundwater Governance in Asia: Theory and Practice’ in which water professionals from five different Asian countries participated in an intensive training and research program during 2006 and 2007. Part of the research work of this program was performed at four different field sites spread across the Indo-Gangetic basin. In each area, three villages were chosen for in-depth study. The topics studied were related to groundwater-based irrigation, institutions linked with groundwater management and the present study exploring local knowledge on groundwater via well drillers. The task was to identify 3 to 5 well drillers working in each area and interview them in a structured manner using pre-developed and tested questionnaires. Several parameters of importance to local groundwater conditions and utilization would be extracted in this interview. Furthermore, the drillers were requested to supply 5 to 10 lithologs from recent drilling operations. A pre-determined format for entering litholog information was designed. From our experience, drillers were more than keen to participate; the challenge, however, was to identify perceptive drillers who can relate with the study objectives and have a good experience of working in the area.

Appendices A and B show relevant portions of the interview schedule and the format used for recording lithologs. In some cases, drillers innovated their own procedure for storing and recording lithologs. The overall procedure followed was:

A. Obtain current piezometric maps in the study villages on a scale of 1:50,000
B. Obtain the temporal trend of groundwater table behavior in the past two decades in the different villages.
C. Obtain the lithology and structure of the local aquifer (up to a depth of 100 metres and 5 to 10 kms horizontally) using well logs provided by the drillers
D. Look at the rates of well failure, present and historic

E. Get a preliminary picture of the water quality
F. Collect any papers or studies performed on the local groundwater hydrology by nearby research institutions for comparison with the data obtained from A to E

In this paper, we focus on parts C and F above and elaborate our procedure to answer questions i) through iv) asked in Section 1. The following detailed methodology was used for achieving the objective of constructing the local aquifer structure using local well driller information in addition to being verified by scientific information.

1. Locating perceptive and experienced well drillers

It is important to locate well drillers who are able to summarize and synthesize knowledge from their work. In the course of their profession, they often visit the same or nearby plots over few years. Their personal level of curiosity, involvement and memory (and means of recording, if any) decide how able they are to e.g. reconstruct the drilling sequences and to align and interconnect them spatially. Not all drillers are able to demonstrate the same level of perceptiveness with respect to geology and groundwater hydrology. Therefore, an initial scanning is necessary in order to avoid spurious information.

2. Extracting semi-statistical information and pattern-based sketch of the aquifer

Often, the first response of the well drillers is to convey an overly complex picture of their experience. However, upon specific inquiry and mutual understanding of the various concepts and terminology of hydro-geology their learnings can be extracted through a constructive dialogue. In case of aquifer lithology, these learnings are present in the form of frequencies of occurrences of different layers, and the spatial links between them in the form of a rough image. The first step is to be able to extract this image from the mind of the driller. The corresponding data extracted would be is in a semi-statistical, non-geo-referenced form.

3. Constructing a conceptual digital image of the aquifer using well driller information

Once the relevant semi-statistical data have been extracted and a conceptual sketch of the aquifer obtained, a digital image is produced and presented to the driller for verification. There may be a couple of iterations after which a final conceptual picture is derived. Very important here is to get the approximate scales correct, i.e. the vertical and horizontal dimensions. This conceptual image is localized and its extent depends on the work area of the driller being interviewed.

4. Verifying the conceptual aquifer picture using scientific data

To further test the accuracy of the image, a comparison with scientific-based information available at a broader scale is performed. These are reports published by government agencies and scientific research institutes. These reports and the data included can be used to check any obvious error in the localized picture and also confirm the scale in which it has been created.

5. Obtaining local well logs from current drillings by the well drillers

Another way to test the accuracy of the conceptual image is to carry out check drillings with the well drillers in the area. Here, it is important to be present in the field when the drilling season actually happens. In many parts of monsoon-dominated south Asia, the drilling season would be after the monsoon and generally before the second-crop season i.e. around December-January. But this season varies from place to place. For example, in areas where manual techniques are used for drilling i.e. in the eastern parts of south Asia, drillers avoid very cold days and wait for the winter to fade. In this process, it is necessary to identify the main layers of interest. Then, the driller needs to be trained to identify these layers during drilling and record the depths of these layers.

6. Geo-statistical analysis of the data

Once all these data are collected, they can be analyzed statistically and in a spatial form. Various techniques are present for such analysis and geostatistics offers tools to perform these analyses in a spatial form (Goovaerts, 1997).

7. Using the conceptual image as a training image and anchoring it to the local well logs

The conceptual image thus generated is known as a training image that contains the essential patterns of the local area. These essential patterns need to be extracted from this image and then fitted and adjusted along with the newly-derived well log data. The case study will describe an application of the SNESIM algorithm. This algorithm allows extracting patterns and statistics of the training image and anchoring them to actual log log data so as to construct a consistent picture of the aquifer (Strebelle, 2001). The algorithm maintains the geological conceptual picture and at the same time honors the collected well logs. The theory behind this technique is known as multiple-point geostatistics, which has been developed as an improvement over techniques that use only correlations considered incapable of capturing complex spatio-temporal patterns. Since the conceptual picture and the well logs are not enough to fully constrain the aquifer picture, the method provides not one but several of these aquifer pictures all of which are consistent with the training image as well as the well logs. These multiple pictures are equally likely depictions of the actual aquifer and together they provide a measure of the uncertainty of the mapping process.

8. Creating probability maps of lithology

The case study will illustrate how multiple equiprobable aquifer depictions, when used together, span the uncertainty of the process of generation of a localized aquifer model. A set of such equally likely depictions allows to deriving maps of the probability of occurrence of specific layers within the subsurface.

3. Description of sites

This study was conducted in four sites located across the Indo-Gangetic alluvial plains in India and Nepal. The areas were Hoshiarpur district (Punjab, India), Vaishali district (Bihar, India), Murshidabad (West Bengal, India), Jhapa district (Nepal). In each of these districts, three contiguous villages were selected for the study. In this paper, we will describe in details the study conducted in Vaishali (Figure 1).

The Vaishali district (area: 2036 km^2) lies north of the Gandak River, which flows into the Ganges River from the north. It is an area with extensive and deep alluvial aquifers composed of interspersed layers of clay, sand and gravel. There is a long history of settled civilization in this area. One of the study villages is said to be the ancient cultural centre of Buddhist society more than two millennia back. The topography is affected by the meandering rivers of the region with small depressions (called ‘Chaur’) formed by abandoned ox-bow lakes. These depressions dot the landscape and can be from 20-30 meters to several kilometers in diameter. The topographic variation and these depressions influence the soil type, vegetation and the groundwater table. In some depressions, monsoon-collected water remains almost perennial, whereas in others water is pumped out, mostly for agricultural use, within 4 to 5 months. The natural groundwater table can be down to 2-3 meters close to the centre of the depressions in the dry season and can have depths of 10-15 meters in more upland areas. The annual rainfall in the area is 1121 mm (CGWB 1993, NIH 2000).

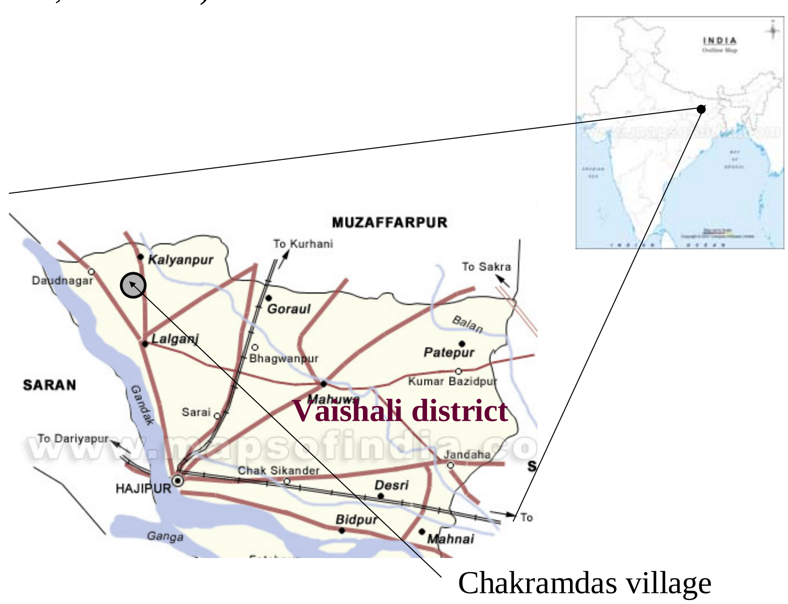

Figure 1. Location of Vaishali district, Bihar, eastern India

4. Application to the Vaishali example

Using the previous 8-step methodology, we develop the Vaishali example and illustrating different details of the process proposed.

1. Locating perceptive and experienced well drillers

We interviewed five well drillers for the Vaishali case study. Table 2 gives a description of these drillers, all of whom except Gopal Singh are currently practicing. All drillers are involved in drilling for domestic wells (known locally as *Chapakal*) as well as for irrigation wells. The mode of drilling is based on manual techniques using bamboo pipes as casings. We observed that well drilling is a significant livelihood option for some casts or communities such as the Malla in our study villages. In such communities, we find groups of 10-15 drillers staying together and operating over a wide area. Such communities have made a natural transition from their traditional occupation, in this case fishery, to drilling, which is considered a water-based occupation.

From our experience, the drillers were more than keen to participate. The important task was to identify perceptive drillers who could relate with our objectives and had a good experience of working in the area. We chose, through an initial and structured scoping of the drillers, Keshav Ram for further questioning about the aquifer structure. Both him and his father Gopal Singh had a wide and also localized understanding of the hydro-geological setting.

Table 2. Well drillers interviewed in the Vaishali case study

Name	Age	Village	Drilling since	No of wells drilled
Gopal Singh	70	Bedauli	1956	3500
Keshav Ram	45	Bedauli	1977	4500
Balini Sahini	45	Chakwezo	1985	1500
Rajesh Ram	42	Purkhali	1980	500
JayKishore Paswan	45	Vaishali	1985	2000

2. Extracting semi-statistical type information and pattern-based sketch of the aquifer

The biggest difficulty in extracting lithological information from a driller is that he is often not able to summarize his experience in a concrete form. The response is often that, “There is too much variation from farm to farm. At one farm, we get water at 10ft depth and at the next farm, there is no water till 50 ft.” Beyond this initial expression of uncertainty, further push can reveal a general understanding. But this needs to be brought out step-by-step. The process we followed was first identifying the general aquifer trends and then specifying these trends with specific depths and sediment characteristics. These were the progressive pieces of information that led to our pattern-based picture of the aquifer:

- The main types of layers are sand (Balu), concrete (clay, sand, and gravel mixture), clay (Mitti), and gravel (Pathar)
- Sand and clay can be both black and yellow
- Sand and clay are the dominating materials, with roughly 70% clay and 10-20% sand in the overall sequence of layers
- Within the first 100 ft:
    - Concrete is struck 1 to 6 times. It is 6 in to 2 ft thick and has a maximum of 5 ft thickness
    - Sand is first struck from 30ft-50ft , then at 80ft-100ft. Each Concrete layer is followed by sand, but not always
    - With depth, concrete and sand decrease and clay increases

From this initial information, we generated an initial image, which upon iteration turned into a pattern-based sketch of the aquifer that offered a regional picture of the area, at a scale corresponding to the area of operation of the drillers (approx.3-4 km). Figure 2 shows the non-directional 2-D vertical cross-section of the aquifer generated through this process.

(a) (b)

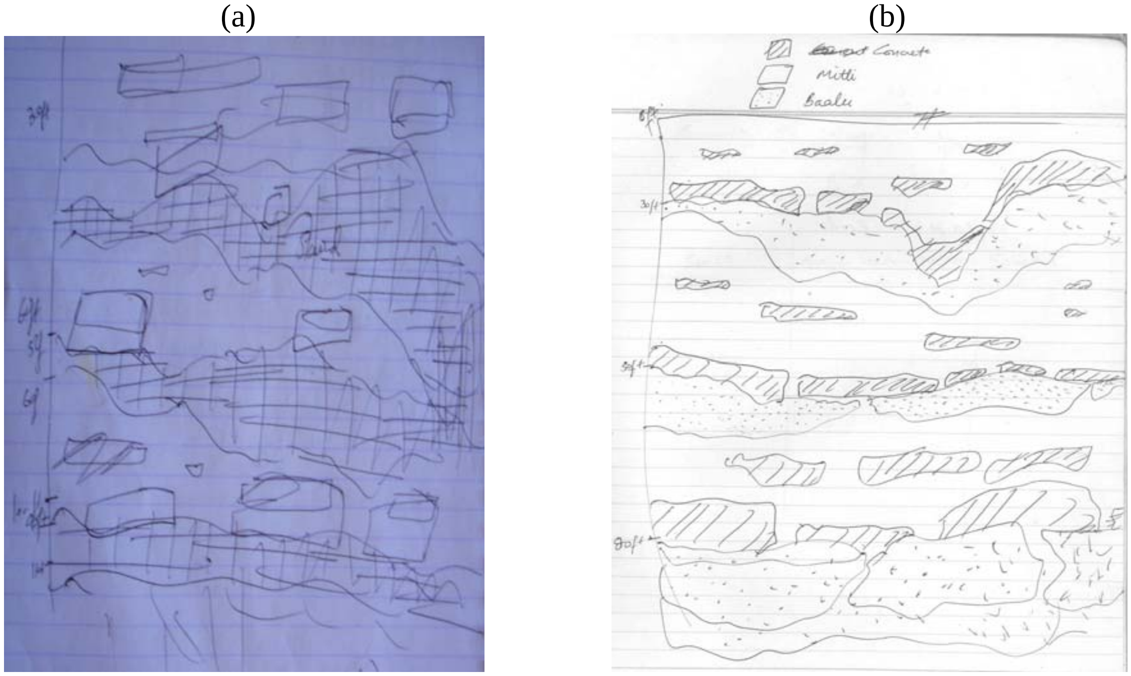

Figure 2. (a) Initial and (b) Final, iterated conceptual pattern-based sketch of the aquifer from well drillers' knowledge

3. Constructing a conceptual digital image of the aquifer using well driller information

The conceptual sketch is digitized as a 300 x 400 pixels image with three facies representing clay, concrete and sand (Figure 3). Each pixel corresponds to 10 m horizontally and 0.2 m vertical resolution. This image was presented to the well driller who verified its overall structure. Here, it is important to note the subjectivity involved in this process of training image generation which could lead to uncertainty in model generation. Here, we have chosen to retain only the essential characteristics and leaving out the specificities of the drawing above.

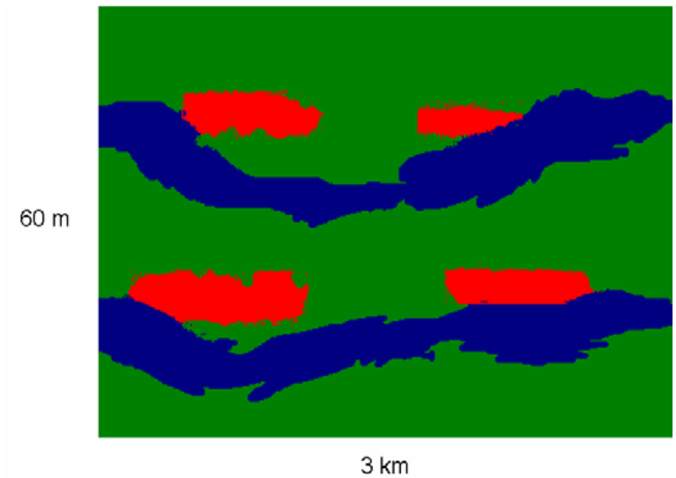

Figure 3. Digital image of the aquifer, created from well driller information (blue: sand; red: concrete and green: clay)

4. Verifying the conceptual aquifer picture using scientific data

We verify the conceptual image with other information obtained from surveys by government agencies in the study area. A survey of the Vaishali district itself produced a fence diagram shown in Figure 4, which is at a much larger scale (CGWB, 1993). Verification against such large scale information is not possible. However, this government survey depicts a similar pattern of multiple aquifers interspersed by clay.

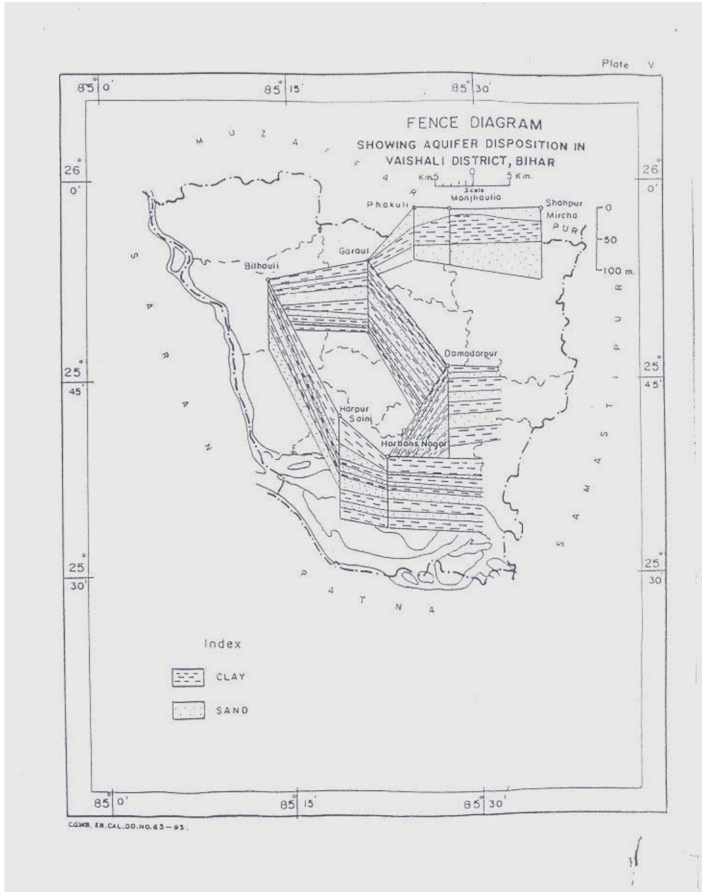

Figure 4. Fence diagram of lithology for Vaishali district (CGWB, 1993)

We therefore use another science-based survey for our purpose, conducted in the Gandak canal irrigation command area (NIH, 2000). This report produced seven logs, whose locations however are not exactly provided. Also, the distinction of the lithologs is only as sand and clay. Nevertheless, we compare this data with our conceptual picture, now replacing concrete with clay for purpose of comparison.

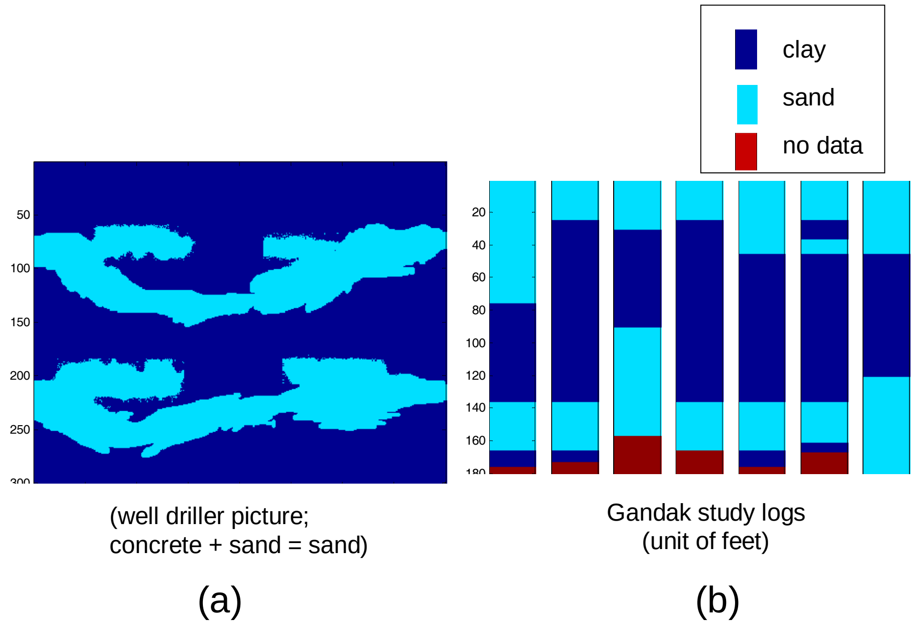

Figure 5. Comparison of conceptual image (a) with logs provided in the Gandak report (b) (NIH, 2000)

This comparison shows that a similar conceptual idea is given by these logs also and justification of the scale of our image is now possible. Note that with our image produced using the well driller's experience, we add more detail in the form of the `concrete' layer to that given by the Gandak report.

5. Obtaining local well logs from current drillings by the well drillers

The next step is obtaining local logs of wells being drilled as part of the field activity in December 2006 - January 2007. Our surveyed drillers were requested to record the different lithologies encountered, their depths and the location of drilling. After an initial training, the drillers were able to carry out this activity by themselves and, in all, nine such logs were recorded in and around the village of Chakramdas in Vaishali district, covering an area of approx. 8 km^2 (Figure 6).

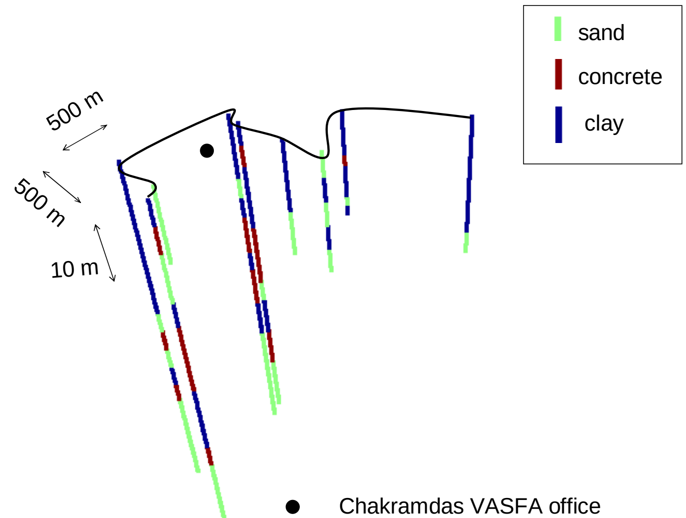

Figure 6. Collected well logs in and around Chakramdas village

We connect these logs to construct a single fence diagram, as shown in Figure 7. The key assumption is that the horizontal continuity is isotropic i.e. does not show any preferred direction of continuity. This assumption however, might not be true. We make this assumption in order to demonstrate the simpler 2D analysis. There is no difference in methodology when making a 3D analysis, except that the training image (see below) would have to be made in 3D.

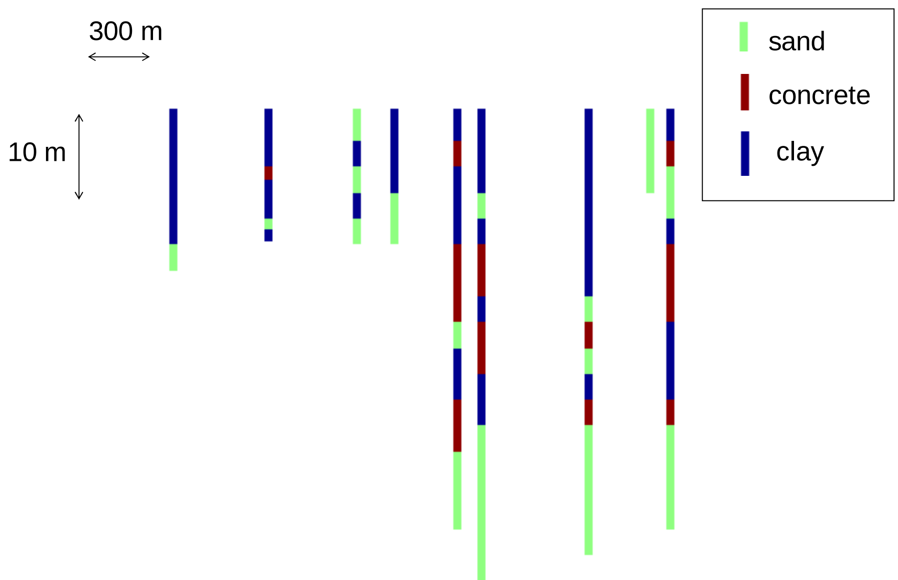

Figure 7: 2-D planar representation of the well logs in Chakramdas village

6. Geo-statistical analysis of the data

There is a proportion of 45% for clay, 35% for sand and 20% for concrete. The spatial correlation between clay, sand and concrete layers can be shown by using variograms in different directions.

Figure 8 shows that the sand layers are connected much better horizontally than vertically. The concrete layers show a similar lesser degree of horizontal anisotropy. The cross-correlation between sand and concrete is also greater in the horizontal direction than the vertical direction.

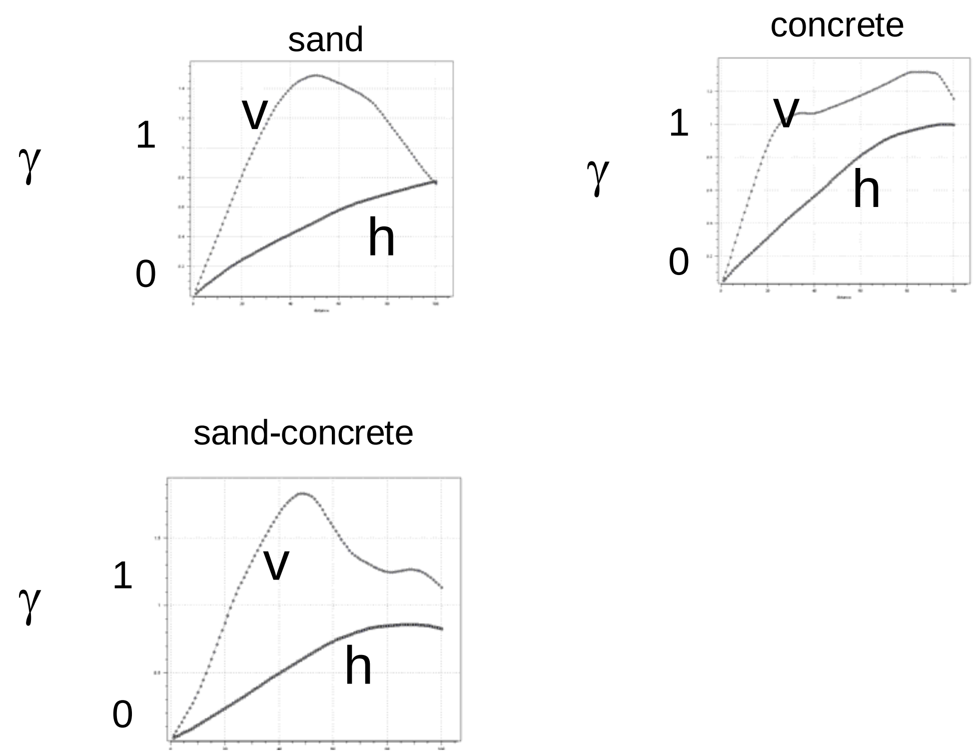

Figure 8. Variograms and cross-variograms extracted from drilling logs of Chakramdas village (h: horizontal, v: vertical)

7. Using the conceptual image as a training image and anchoring it to the local well logs

Geological structures are often too complex to be described merely by statistics such as histograms and variograms or covariances. A digital representation such as Figure 3 is a provides a richer and more useful representation of the geology since it incorporates higher statistics beyond the histogram and correlations. Figure 3 can be said to be one, out of many possible outcomes or representations of the aquifer structure. Applying the statistical anchoring procedure involving the SNESIM algorithm and Figure 3 as the training image, several equally likely images are produced. Figure 10 shows two such aquifer depictions. Note the similar locations of the second sand layer in both these depictions since the well log data strongly affirms that, but note the different placement of the other sand and concrete formations within the clay background.

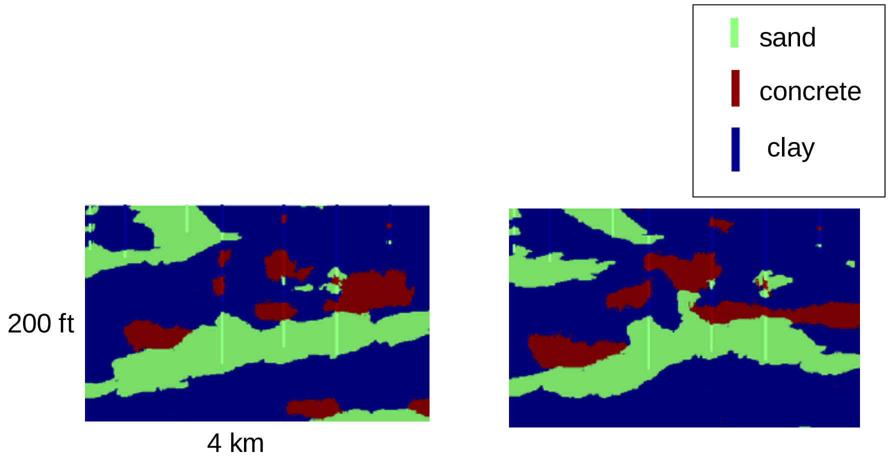

Figure 9. Two equally likely depictions of the aquifer, anchoring the collected well logs to the training image

8. Creating probability maps of lithology

In order to use these simulations to obtain a measure of the uncertainty, it is necessary to generate many different simulations and look at the frequency of the occurrence of the various layers. Here, we generate 15 such equally likely aquifer depictions and at each location compute the probability of occurrence of sand and concrete (Figure 10). Probabilities of other facies (clay and gravel) were likewise computed.

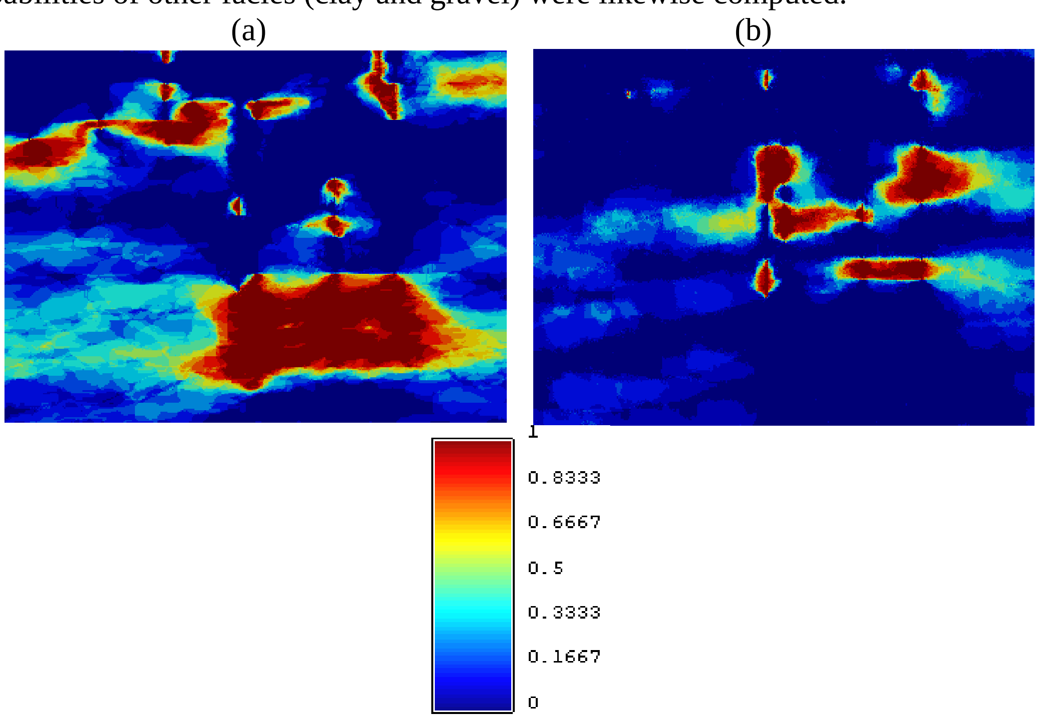

Figure 10. Probability of occurrence of sand (a) and concrete (b) based on averaging of 15 equally likely depictions

We can make out two distinct layers of sand in this aquifer (from Figure 10 (a)) out of which the second layer is much more probable. Also, we see some layers of concrete (from (b)) are highly likely and they are located right above the second sand layer of the aquifer depicted by the large red path in the bottom of Figure 10 (a).

In this entire process of constructing the local aquifer picture using well driller knowledge, there are multiple levels of uncertainty:

- Subjective conceptual picture: From the point of constructing the rough picture from the well driller, to verifying it from scientific information, there is subjectivity involved. Another training image constructed in this manner would give a different picture of the aquifer. This is the first level of uncertainty encountered in the process.
- Recording and interpretation of logs: The logs have been recorded by the drillers themselves. The length of the drilling rod decides the vertical resolution of measurement. The accuracy of the horizontal positioning is also subject to errors.
- Algorithm used for constructing aquifer model: There are assumptions involved in the methodology and algorithm used. Specific assumptions on pattern recognition from the training image, if changed can give rise again to a different aquifer picture. This is, however, a lesser second level of uncertainty.
- Data sparseness: Finally, the more well log data collected, the more accurate is the picture of the aquifer. Given the subjective conceptual picture and given an algorithm such as SNESIM for constructing the aquifer, the uncertainty arising from data sparseness can be measured as the probability of occurrence of say, sand or concrete at any particular location. Note that this measure of uncertainty is subject to uncertainty of the two previous steps above and therefore cannot be considered absolute. It is at best indicative.

5. Discussion and conclusion

From our study, it has been possible to answer all four questions that we initially posed. First, well drillers do possess a good amount of information on local groundwater hydro-geology. It is very important for this purpose to select the right kind of driller(s) who are experienced, collaborative, knowledgeable and systematic in their approach. Not only do they possess knowledge of lithology and water bearing layers, but their perception of groundwater quality in very localized settings was also observed, though not described in this paper.

Second, we also answered the question on how to extract lithological and other information that drillers possess and translate it into a local digital database of groundwater lithology, using the case of Chakramdas village of Vaishali district in Bihar state of eastern India as an example.

Third, we were able to compare and combine this information with science-based knowledge and thereby verify the correctness of the local knowledge and improve the overall picture of the local aquifer setting. Furthermore, using advanced geo-statistical software, it was possible to create multiple equally likely aquifer maps and thereby give a measure of uncertainty to the process and the probability of occurrence of specific lithological layers.

The cost of using existing information from local well drillers and supplementing with new drilling logs performed by these drillers after short training is more cost-effective than using traditional exploratory drilling for the purpose of applying the described methodology of local groundwater database generation (Figure 12). Below, we also include the cost of processing the logs in the laboratory, which in fact comes to around 90% of the total cost. The actual cost per log can be estimated to be around Rs 100-150. If one imagines expanding this methodology to say a district for a period of 1 year, then with 25 well drillers, each supplying say, 20 logs, there can be a database of 500 logs which will cost Rs. 75,000 (around USD 1900 at December 2007 rates) for data collection. This is approximately equivalent to only 10 traditional drill logs.

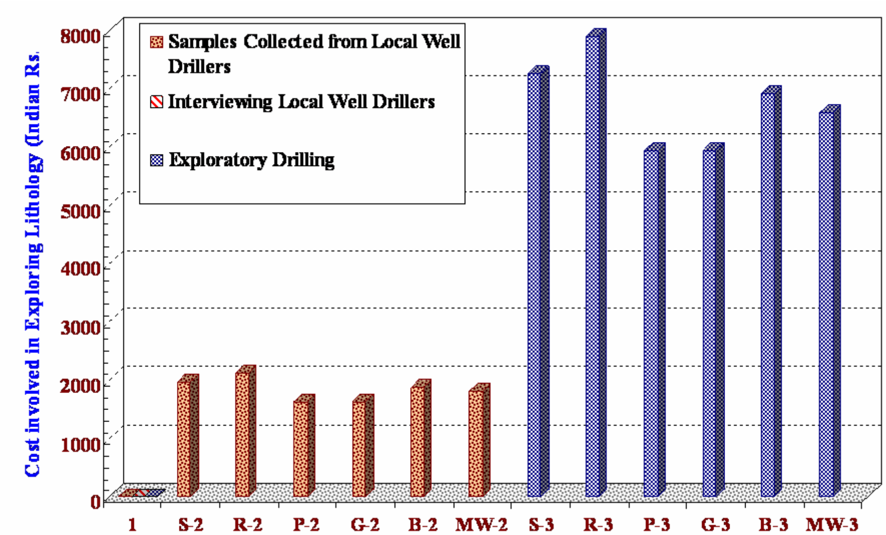

Figure 11. Comparative costs of obtaining lithology information using well driller experience, current drilling by drillers, and traditional exploratory drilling

In order to use this approach more widely, and thereby answering the last question posed, techniques like the one presented in this paper should be more broadly disseminated and adapted. In this process, diverse skills and methodologies may have to be developed and combined, from interviewing and interacting with local well drillers in remote villages to applying advanced software-based technologies.

Looking in general at the subject of local hydrological knowledge generation, there is potential for many more such local resource persons and institutions than just well drillers. Local schools have been used previously as environmental monitoring stations (GLOBE) and they also provide another low-cost means of creating such databases. The concept of village information centers in Tamil Nadu is also a means of actualizing these ideas (MSSRF). The use of information technology in mass knowledge transfer has also been attempted by different initiatives (AAQUA, VASAT).

As a last note, it is important with all these means of alternative knowledge generation to keep in mind that there is always some tradeoffs. As Table 1 shows, there are positive and negatives to proceed in the direction of locally based knowledge generation. As long as this perspective is maintained and appropriate corrections as suggested in this paper are made, locally based knowledge generation promises to be a favorable direction to take for a host of environmental data generation activities in many developing countries.

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