Air, Soil and Water Research

REVIEW

Groundwater Surveys in Developing Regions

Jeff Lewis and Birgitta Liljedahl

Swedish Defence Research Agency FOI-CBRN, Cementvägen 20, SE-901 82 Umeå, Sweden.
Corresponding author email: jeffrey.lewis@foi.se

Abstract: This paper discusses the interpretation of surface features that can assist in the evaluation of groundwater resources in semi-arid and arid developing regions. The lack of infrastructure in these areas places serious constraints on borehole drilling, which in turn limits the data which can be obtained directly from the subsurface. Under these conditions, surface indicators may be used to infer useful information about the subsurface, which includes shallow aquifers. This article summarizes those surface indicators which provide useful data in arid and semi-arid regions and provides a review of the literature to assist in their interpretation. Patterns of surface indicators covering a large area may be more effective and less costly for interpreting basic regional hydrogeological conditions than detailed data obtained from a limited number of boreholes. The hydrogeological information which can be obtained by using the methods discussed in this article include the regional flow patterns, an estimate of the depth to groundwater, aquifer geology and estimates of the regional recharge and discharge zones. This data may in turn provide support for subsequent well drilling campaigns, limited environmental assessments, and potable water assessments for humanitarian base camps in developing regions.

Keywords: hydrogeology, groundwater monitoring

Air, Soil and Water Research 2010:3 95–104

doi: 10.4137/ASWR.S6053

Introduction

There is a growing need for regional hydrogeological assessments in arid and semi-arid regions with little infrastructure and few technical resources. Only six of the fourteen Southern African Development Community (SADC) member states have national groundwater monitoring networks involving water level and some type of water quality measurements. In the majority of the remaining countries, groundwater monitoring is either ad hoc or is only carried out locally. In most cases, this monitoring is performed by private companies or water utilities and little or no data ever reaches the national groundwater authority.[1] This is significant because unplanned and poorly supervised well-installation projects have had unintended, serious consequences.[2]

Currently, groundwater-projects in developing regions are rarely supervised by trained groundwater professionals[3–6] and they by extension infrequently involve efforts to understand the regional hydrogeological context of an aquifer. In southern and eastern Africa, it has been stated that the quantification of groundwater resources is a major issue facing the integrated management of water resources and that data gathering and dissemination are key to the development of the groundwater resource.[7] While this article offers no solutions to the issues surrounding data dissemination, it outlines several cost effective and simple field methods that may contribute to data acquisition in such regions.

A modest investment in understanding the regional groundwater context substantially assists subsequent well drilling projects. Regional aquifer characterization can support the desk study of local well drilling campaigns by providing data on the expected aquifer characteristics. This allows better planning for the type and size of drill rig required (hard rock vs. consolidated deposits), and the approximate depth to the aquifer. It also permits the fabrication or purchase of appropriate well screens and packing materials based on the expected aquifer geology, which increases the probability successful well installation. All of this information ultimately minimizes the overall expense of well installation. The analysis of regional flow patterns can also suggest the age of the groundwater in a given region and therefore indicate its expected salinity, which directly impacts the potability. Furthermore, with climate change having the potential to dramatically change the water cycle in some regions, a better understanding of regional aquifer systems could support future modelling efforts to predict how and where potable water supplies may be found in the event of substantial shifts in precipitation.

Environmental assessments

In another context, organizations which operate in remote, semi-arid regions have begun to demand that environmental baseline studies and assessments be performed for infrastructure such as base camps, and regional hydrogeological studies are critical elements of such work. The United Nations Department of Peacekeeping Operations has recently produced a draft document which provides environmental guidelines for UN field missions.[8] This includes requirements for environmental background assessments and environmental impact assessments, both of which require an understanding of groundwater parameters. Acquiring this data in a cost-effective manner faces the same challenges as regional aquifer characterizations for the purposes of water supply—scarce expertise, expensive and limited drilling resources and very little local infrastructure.

Typical groundwater assessments require boring and installing an array of monitoring wells in order to observe both the geological stratigraphy of a region and the hydrogeological properties of the aquifer. This requires drill rigs and other dedicated equipment, including mud pumps, compressors, drill bits and strings, welding equipment, supply trucks, and hand tools. The failure of any one piece of equipment can bring a drill rig to a halt for extended periods of time. Similarly, specialized consumables are necessary to install wells, such as piping, well screens, sand packs, concrete and bentonite. The technical complexity of the equipment and the logistics involved with supplying the consumables means that work stoppages which may only take days to resolve in developed regions of the world often take much longer to resolve in developing regions. Furthermore, although heavy drill rigs have some off-road capability, they cannot access particularly rugged regions far from the nearest road. Therefore, in most cases the monitoring wells, piezometers and boreholes which hydrogeologists normally rely on for their data cannot be installed, or at least cannot be installed in a cost-effective fashion. It is therefore very challenging to perform a regional groundwater or aquifer assessment in remote locations which have little support infrastructure.

The purpose of this paper is to provide a summary of both the field and desk methods available to perform regional-scale aquifer assessments in remote semi-arid locations with minimal logistical support and large areas to cover. These regions typically lack reliable roads, electricity, and background data such as prior drilling reports. They also often have security concerns. These issues hinder the deployment and maintenance of equipment like ground penetrating radar, cone penetration test equipment, borehole geophysical test equipment, survey-grade GPS or, as discussed above, drill rigs. Therefore, the interpretation of surface indicators may in some cases be a viable option for collecting hydrogeological information.

The data which can be collected using these methods is neither as accurate nor as reliable the data that can be obtained from more conventional groundwater assessments. In most cases, these techniques are only useful for shallow aquifers or for the uppermost of multiple aquifer systems. Despite this, they may still be cost effective depending on the application. The patterns which emerge from surface analysis may allow the formation of informed hypotheses concerning the recharge areas, discharge areas, the general groundwater flow patterns and the geology of the aquifer. These simple observations may contribute materially to the understanding of the hydrogeology of a region for which little or no data is available. Furthermore, these methods benefit directly from and document local inhabitants' knowledge of water resource conditions and availability.

Desk Study and Remote Imaging

Pre-existing data on aquifer properties and other hydrogeological data in developing regions is usually difficult to come by, in part due to the scarcity of trained hydrogeologists who work in these areas and in part because the governmental oversight of well drilling practices in developing areas is limited.[7] For example, although the Sudanese Ministry of Irrigation and Water Resources maintains a database of wells, the majority or the records do not provide coordinates, well construction details, or even the depth to water. No borehole logs are available, and therefore the geological stratigraphy at a well site cannot be determined.

For this reason, hydrogeological desk studies of developing regions are often dependent upon remote imaging techniques. Until very recently, satellite imaging has not been able to capture direct measurements of groundwater. Therefore, information relating to groundwater has been inferred from indirect observations of parameters such as elevation and vegetation. El Hadanai et al[9] used such image interpretation to substantially reduce the number of drillholes and thus drilling costs for groundwater development in Morocco.

Although aerial photography has been available for decades, the increasing quality and decreasing cost of satellite images have also made them attractive sources of information. Free visible-band satellite imaging is available on the internet in low to high resolution, while high resolution images are available commercially from various satellite platforms. The quality of the imaging is constantly improving, and costs can range from \$20 US per km^2 for Quickbird images to a few cents per km^2 for ASTER images to free online LANDSAT images. Sander[10] considers ASTER images to be the best choice for groundwater projects due to their spectral resolution, reasonable spatial resolution, the availability of digital elevation models, and their reasonable cost.

Lineament mapping or fracture tracing offers another yet approach to remote sensing for groundwater which is particularly suited for regions which have aquifers located in fractured crystalline rock. Given that substantial areas in Africa[11–13] are underlain by crystalline basement aquifers, this method may be of particular interest to those hydrogeologists who work in these regions. The fundamental idea behind this technique is that in areas where bedrock has a low primary porosity, productive groundwater are usually located at the intersections of fracture features. Remote imaging attempts to identify subsurface fractures by observing and mapping surficial linear features such as topographic, drainage, vegetation, or soil tonal anomalies. Often, images taken in various spectra can assist the user in identifying various surface anomalies. This technique was pioneered by Lattman and Parizek[14] and many projects have since used lineament mapping as the core of the groundwater exploration work, especially in complex terrain. A good summary of the methodology of remote lineament mapping with a relevance to the situation found in developing countries can be found in Kellgren[15] and Kellgren and Sander.[16]

Detailed, ground-proofed topographic maps at the 1:50 000 scale are unavailable in many developing regions. However, digital elevation models (DEM) from the Shuttle Radar Topography Mission (SRTM) are available for download free of charge on the internet and cover 80% of the planet. This DEM data has a vertical error on the order of 16 m and may be imported directly into GIS applications. In the absence of topographic maps, base maps printed from this DEM data can be useful for field work and may include reasonably accurate overlays of such major features as road networks, built up areas and surface water bodies. Of course, this only provides data concerning surface topography. Describing aquifers also requires digitized maps of the geologic strata, both in the horizontal plane and also vertical cross section.[17] Such data is extremely difficult to find in developing regions.

Field Study

Field work verifies the data collected during the desk study and supplies information that cannot be obtained from other sources. The most useful surface features for hydrogeological analysis are outcrops of groundwater in the form of springs, seeps, and effluent surface water bodies. Vegetation indicators and surface soils may also provide some useable data. When attempting regional scale aquifer characterizations based on surface features, single indicators are usually of limited value. Collectively, though, they may offer relatively good information about shallow groundwater characteristics. The quality of the inferred information is usually directly proportional to the number of data points collected in the field.

The use of a GPS and good map reading skills are critical to the success of such a field study. Every surface observation and measurement must be mapped and accompanied by accurate coordinates and an elevation, along with the error associated with each. The subsequent processing and interpretation of the field data is dependent on knowing where and when the data was obtained. As the number of data points increases, the importance of accurate record keeping escalates.

Groundwater outcrops

While accessing groundwater is difficult without drilling equipment, it is not impossible. Natural outflows of the groundwater occur at springs, seeps, and direct discharges into effluent surface water bodies. These features provide some of the best data on groundwater conditions when installing monitoring wells is not feasible.

Springs

Springs are defined here as locations where water flows freely from a natural opening in the surface. Springs are of particular interest because they offer an opportunity to directly evaluate the chemical properties of the groundwater without the need to drill a borehole or install a well. They also offer insight into the elevation of the water table, the local flow conditions and the geology of the aquifer. Since these natural formations are extremely useful to local populations in arid and semi-arid regions, their whereabouts and history can usually be determined by talking to locals. Continuous flow even during periods of extended drought is a strong indication that the spring is directly linked with the aquifer.

The water issuing from springs is often highly mineralized, and thus objects near the spring which are periodically immersed such as partially submerged stones, and plants, may have a white efflorescence caused by the precipitation of sodium sulphate (alkali).[18] Yellow/brownish sediments and staining on rocks, plants and in trenches may indicate dissolved iron, and black deposits may indicate manganese.[19] Since both the brownish and black deposits are evidence of a sudden change in the redox potential of the water once they were exposed to the atmosphere, they are both good indicators that the water originates from an aquifer. In many cases, the spring issues from a circular or semicircular depression which is open on the downhill side and forms the headwater of an intermittent but well defined tributary to the main streams in the drainage basin.

The pattern and areal extent of springs can offer guidance about why the groundwater is ascending to the surface. Linear distributions of springs are indicative of geologic control of groundwater movement, either by means of structure (faults) or by stratified formations. On the other hand a random two dimensional spacing of the springs in the discharge area of a drainage basin suggests a normal distribution of groundwater flow independent of heterogeneities in the rock permeabilities.

Springs provide a clear indication of near-surface groundwater, so they can also be used to evaluate local groundwater indicators such as phreatophytes, seepages, salt precipitates, poor crop growth (due to alkali deposition), continuously wetted soil, and water logged soil. By observing these indicators around a spring, their reliability can be determined for situations where they occur alone.

Seepages

A seepage is an area where groundwater discharges without any noticeable flow. These areas are marshy and can be mistaken for other bodies of shallow surface water which are of meteoric origin. Seepages may be distinguished from other water bodies by analyzing the chemistry of the water and by observing salt or alkali deposits[20] or staining caused by changes in the redox potential to groundwater carrying metal ions. Halophyte (salt loving) vegetation will often be abundant at seepages while glycophytes (fresh water loving vegetation) will dominate marshes of meteoric water. Seepages are characterized by constant water levels even during periods of draught, whereas the water level in water bodies that are meteoric in origin will quickly lower—often indicated by wide strips without vegetation on the banks of the water body. Since seepages are often found in close association with springs, discrepancies or similarities in the elevation at which these features are found should give an indication of whether the seepage is of groundwater origin or not. Like springs, seepages occur mainly at the foot of the steep banks of local tributaries, at the foot of steep embankments in local hills, and on flat slopes.

Pre-existing wells

Wells which are already in place are can offer some information about the aquifer, although the results must be carefully scrutinized. Typically, the data obtained from pre existing wells in developing countries must be considered in the context of the other field parameters. Often, rural areas in semi arid or arid locations in the developing world will have one or more community wells which are either hand-dug or drilled. These wells are often in heavy use and may have considerable draw-downs. Therefore, measurement of static water levels should only be done after enough time has passed to allow full recovery of the well. This may not be a realistic possibility if the well is the only nearby source of potable water.

Hand dug wells are typically limited to a depth of about 5 m,[21] and are characterized by large diameters to facilitate construction and to store water. They typically penetrate a meter or less into the aquifer due to the difficulty in digging underwater. These wells can be useful in observing the stratigraphy of the soil layers above the aquifer and the geology of the aquifer deposit itself. Modified slug and pumping tests have been proposed to determine the aquifer parameters from large diameter hand dug wells.[21,22] Chemical tests of water obtained from hand dug wells must take into consideration that the water has been exposed to the atmosphere.

The literature concerning drilled wells in Africa provides the strongest evidence that the regional field survey techniques proposed in this article could provide material benefits to developing regions. Danert et al[5] in discussing the cost effectiveness of boreholes in sub-Sahara Africa, point out that improvements in hydrogeological knowledge and enhanced experience in site survey can increase drilling success rates and reduce the disparity between anticipated and actual drilling depths. Sander[10] reports drilling success rates as low as 25% in Ghana, while Doyen[3] reports success rates of 51% in Kenya. An ANTEA report[23] indicates that two or three test wells are drilled per successful well in Mauritania. Doyen[3] goes on to report that success rates improved to 89% when geophysical techniques were used. It appears that many wells are still placed using the topographic method popularized by LeGrand.[24] This method relates well yield to topographic position. Well drillers use this concept in the field by locating wells in valleys and by avoiding hills and ridges. Unfortunately, Yin and Brook[25] have demonstrated that this approach to well placement has minimal success in regions with crystalline rock aquifers—which includes 40% of sub Sahara Africa.[5]

Drilled wells usually penetrate much further into an aquifer than hand dug wells, which makes drawdown a more significant issue to characterization or physical testing. Particularly if an electric pump is in use, a cone of depression will usually form around a production well, complicating measurement of the true static water level. This is a common problem and is not limited to developing regions. Furthermore, the borehole log of the well is usually unavailable or was never completed in the first place. The lack of a borehole log complicates the interpretation of physical or chemical data obtained from a drilled well. In particular, the placement of the screen in relation to the static water level will influence measurements. Typically, a screen is located in the bottom of a well. Variations in head through the depth of an aquifer will result in different static water levels depending on the depth at which the screen is placed. This means that even in the absence of any drawdown effects, the static water level in the well may not be representative of the water table.

Often, for purposes of maintaining hygiene a secure sanitary well cap is in place,[26] which makes direct access to the groundwater difficult or impossible without the disassembly of the cap or possibly the pumping mechanism. For practical purposes, this is usually not advisable as accidental damage to a well cap or pumping mechanism can have a serious impact on the population which relies on the well.[27] If the well head is capped, it will be impossible to perform any physical testing of the well such as pumping test or slug tests as these require monitoring of the drawdown, which requires measuring the static water level.[28]

Vegetation indicators

The value of plants as indicators of groundwater increases with increasing contrasts in moisture conditions between different parts of a drainage basin. In arid regions, large differences exist in the depths to the water table and consequently in the surface soil moisture content.[29] As a result, the boundaries of a single species may be well defined and be highly correlated to groundwater conditions. However, in developing regions which enjoy a more humid climate, the regional differences in the availability of groundwater for plants are so slight that these well defined boundaries disappear, making the superficial observation of vegetation patterns of little interpretive value.[18] One of the most useful features of vegetation is that it clearly indicates areas with anomalous moisture conditions on satellite imaging or aerial photographs.

In regions with agriculture, the phenomenon of "burnt crops" offers a good indication of near-surface, upwards flowing groundwater. This phenomenon is caused by high levels of sodium sulphate, which stunts the growth of grain crops. The affected crops are characterized by a conspicuous unhealthy yellow pattern in their growth. They are easily identified in areas of uniform crop growth by their sparse appearance, and they are particularly valuable in indicating areas of upwards moving groundwater when salt precipitates are hidden by rainwater.

Surface water analysis

There is a complex interaction between groundwater and surface water flows. Surface water has the advantage of being easily sampled, so surface water bodies that are hydraulically linked to the underlying aquifer may provide data about groundwater conditions. Surface water here refers to streams, lakes, wetlands and estuaries.

The groundwater-surface water relationship can be either effluent or influent. If a region is effluent, groundwater drains into surface water features. If a region is influent, the opposite is true. The status of a river can change spatially or temporally. A stream can be influent as it crosses a region of recharge, losing water to the aquifer. It may then become effluent as it enters a discharge area. Furthermore, a stream which is influent during the dry season can become effluent during periods of flooding when the water in stream rises above the water table and begins to infiltrate its banks. In areas of low precipitation, the water table is usually well below the base of the stream channel and as a result, channel seepage is often the largest source of recharge[30] Simple seepage meters allow rapid field measurement of this property and provide evidence of whether a surface body is influent or effluent.[31]

Perennial streams flowing continuously throughout the year are primarily effluent. Intermittent streams are influent or effluent depending on the season and only receive groundwater at certain times of the year. Ephemeral streams only appear after significant precipitation events and are exclusively influent when they are flowing.[32] When a stream channel on a flat alluvial plain has a water surface at approximately the same elevation as the water table, there are likely to be gaining (effluent), losing (influent) and flow-through stretches. Flow-through will occur when the groundwater head is higher than the surface water on one side of the stream and lower on the other, and this occurs most often when a stream cuts perpendicularly across a fluvial plain.[33]

The dynamics of the stream flow can also provide information about the groundwater flux. Groundwater flows tends to run parallel to wide, shallow, slow moving streams and rivers. If the river is effluent, the river penetrates less than 20% into the aquifer. On the other hand, groundwater flow is perpendicular to stream flow in steep, rapidly flowing rivers, depending on whether it is influent or effluent.[34]

Physicochemical analyses

The chemical parameters a water sample can provide a strong indication of whether it is meteoric (recently fallen as precipitation) or groundwater. This is critical in determining whether a surface water body has a link with the groundwater regime. The typical pattern is for fresh, unaltered meteoric water with little salt and dissolved components to be found in recharge areas with progressive increases in salinity down the flow system. Patterns of physicochemical analyses can therefore provide information about groundwater flow and recharge. Since most field studies performed in developing nations do not have access to laboratories, the chemical properties of groundwater as they relate to the hydrogeology of an areas will be limited to those parameters which can be easily determined in-situ using simple field equipment. Commercially available field instruments are capable of detecting pH, conductivity, redox potential, nitrates, ammonium, chloride, temperature, dissolved oxygen, total dissolved solids, salinity, and specific conductance. Simple colorimetric and paper strip tests can be performed for metals, nitrates, nitrites, ammonia, and phosphates. Nitrates and nitrite testing of groundwater can be particularly important in the third world as they are chemical indicators of faecal pollution.[19]

The techniques of field analysis of water in the third world have been discussed in detail by Hutton[35] and the remainder of this section will focus on their interpretation in the context of groundwater.

Pure water has a low electrical conductance of around 0.1 μS (microsiemens). Ionic species dissolved in the water will increase the conductivity, but conductance measurements cannot be used to estimate ionic concentrations since natural water contain a variety of dissolved species in various amounts. However, electrical conductivity tests are easily performed in the field[13] and can be converted into readings of TDS (Total Dissolved Salts). TDS represents the chemical composition of the aquifer solids. Most of the salt in groundwater comes from input loading, which includes aerosol salts, salt dissolved in the water recharging the system, and salt contributed from mineral dissolution within the groundwater flow system. Although the relationship between TDS and residence time is complex, the salinity of groundwater generally increases in the direction of groundwater flow and with increasing residence time in an aquifer.[18,36–38] Therefore, temporal and spatial comparisons of TDS values in a study area can provide insight as to whether a given sample is meteoric in origin, or was obtained from a local or regional aquifer. Spatial changes to TDS can also suggest the direction of groundwater flow. The evolution of groundwater generally progresses from precipitation with a TDS of nearly zero to seawater with a TDS of 35 000 mg/L, although some deep brine aquifers can have salinities as high as 300 000 mg/L.[39] An increase in pH or temperature will lead to an increase in salinity by facilitating dissolution and thus lead to an increase in the TDS. Likewise, a decrease in pH will lead to precipitation and a decrease in TDS. Therefore, these measurements must be taken together in order for any meaningful trends to be observed.

The pH of water is easily measured in the field and must be measured in-situ to achieve accuracy. When groundwater is exposed to the atmosphere, dissolved CO_2 escapes and the pH rises. Therefore, when enough water samples have been obtained for patterns to emerge, pH can provide circumstantial information as to whether a given water sample originated from meteoric or ground water.

The oxidation reduction potential (Eh) may also be referred to as the oxidation reduction potential (ORP) or redox potential. It is another valuable parameter that is easily and rapidly measured in the field. In general, redox conditions will become progressively more reducing as water travels into deeper formations and is out of contact with the atmosphere for longer periods of time. Furthermore, sand and gravel aquifers will tend to have higher levels of dissolved oxygen than silty or clayey materials and therefore a higher Eh. Highly oxidizing conditions produce a potential of around +800 mV while highly reducing conditions are found at a potential of about −400 mV. An Eh value below +200 mV is an indicator of reducing conditions. However, it has been reported that oxidizing conditions have been found in aquifers down to 1000 m depth.[40] Furthermore, high levels of natural organic components such as humic or fulvic acids or organic substances of human origin such as pesticides or fertilizers[41] will increase microbiological activity which will in turn cause a rapid depletion in the available oxygen, leading to reducing conditions. Unfortunately, no simple field test is available for either total organic carbon or dissolved organic carbon and the investigator must understand that unexpected redox results could be due to these parameters.

Exposing water samples to the atmosphere will produce immediate changes to Eh and thus measurements must be taken in-situ whenever possible. Furthermore, Eh and pH are often linked, with an increase in pH generally producing a decrease in the Eh. Highly reducing conditions will often produce a characteristic rotten egg smell.[42]

Toth[18] observed that bicarbonate is the dominant anion in areas of recharge while chloride and sulphate will increase in concentration as the water moves towards the discharge areas. Furthermore, the ratio of Ca^{2+} to Mg^{2+} will generally decrease as the water moves towards discharge areas because of the higher solubility of magnesium compounds than that of calcium compounds. The physical properties of the water, including colour, odor, and turbidity will not offer much information unless a striking anomaly exists.

If a water source is destined for human consumption, it is of course of critical importance to have the water regularly analysed by a lab according to either the water quality guidelines of the country or the recommendations of the World Health Organisation's guidelines for drinking water quality.

Surface soils

Observations of surface soil deposits can sometimes provide information about the subsurface. In particular, soil conditions in proximity to natural groundwater outcrops such as springs or seepages can suggest the geology of the aquifer. Minor excavation can reveal the depth of the different soil horizons and therefore provide a picture of how similar the surface geology is to the weathered zone beneath it. Regions with thick soil horizons such as fertile agricultural regions will provide less useful data about the subsurface that those areas that have thinner surficial deposits. Distinct changes in soil texture, in particular between permeable sands or gravels and impermeable clays should be noted. Similarly, outcroppings of bedrock should be observed. A linear pattern of bedrock outcroppings can suggest a groundwater divide if the aquifer is primarily located in the overburden. The fracture patterns in visible bedrock can be indicative of the subsurface fracture patterns as well.

Open pit mines, road cuts, major excavations sharply defined valleys and as mentioned above hand dug wells can all offer insight into the geological stratigraphy of a region.

Data Consolidation

A single surface observation is unlikely to provide substantial information about the subsurface. For the purposes of regional groundwater assessments, the value of surface indicators lies in collecting large quantities of data in order to observe patterns. For this reason, effective data consolidation is necessary. In the field, this will often be performed on topographic maps or whatever physical cartographic resource is available. By doing this, daily work may be planned by identifying areas where conflicting indicators require further data collection, or by identifying regions where too few observations have been made.

However, due to the quantity of information, proper interpretation of the field data usually requires the use of a geographic information system (GIS). Comparisons of multiple datasets can then reveal relationships between various surface indicators that may suggest subsurface properties. For example, an area may have a high density of glycophytes, show an unusually deep static water surface at a nearby village well and be traversed by a primarily influent river. Individually, each of these surface indicators is of limited value. Collectively they provide substantial evidence that the area lies on a recharge zone. Similarly, a linear pattern of springs and seepages surrounded by halophytes and phreatophytes in a low lying region beside a major water body would strongly suggest that the area is a discharge fault zone for an intermediate or regional flow system. Areal variations of various physicochemical parameters will suggest the age of the water being measured and by extension the flow patterns. When this data is cross referenced with digital elevation models, the flow hypotheses can be refined.

In areas with particularly complex geologies, care must be taken to avoid over-analysis of the field data.

Surface features cannot always provide useful data about the subsurface, and the researcher must develop a feel for the quality of the data and the uncertainties implicit in their analysis. Unfortunately, there is no formula or method to accomplish this. It is largely a question of the researcher's experience.

Cost

Not all methods discussed in this article are appropriate for all developing regions, and many other methods have been successfully used including various geophysical techniques. The use of multiple methods will generally increase the amount of data, which for the purposes of analysis is a good thing. However, the cost-benefit ratio must always be considered—both monetarily and with respect to manpower.

Projects in developing regions often have limited budgets, and deploying expensive equipment may or may not be worthwhile. A trained hydrogeologist making only surface observations can be expected to map up to 8 km^2 per day.[18] A team of two hydrogeologists working for 30 days can therefore be expected to cover approximately 480 km^2. Assuming consultant fees of $500 US per day per person, the cost of this field work will total $30 000 US plus expenses. According to Carter et al[4] a hard rock borehole in many African countries may cost up to $10 000 US. Therefore, approximately three boreholes could be completed for the same amount of money as would be spent on the surface assessment of 480 km^2. The general picture of groundwater movement and distribution over an area 480 km^2 cannot possibly be captured by three boreholes. No matter how detailed and accurate the data obtained from those boreholes may be, the field survey will provide more meaningful information on the regional groundwater situation.

Conclusions

There is a growing need to efficiently and cost effectively map regional groundwater resources in developing nations. The techniques described in this article are most useful in areas where information about the groundwater is scarce or nonexistent and deploying heavy equipment is financially or logistically unfeasible. In order to effectively interpret surface data, it is necessary to gather a substantial number of data points to allow an evaluation of patterns. The quality of the analysis increases with the number of data points collected. While this analysis will not be sufficient to construct detailed numerical models, it can provide useful data for local well drilling projects or limited environmental studies. Many of the surface features which are indicative of near-surface groundwater are easiest to identify in arid and semi-arid regions, meaning these methods are particularly well suited to the developing regions where they are most needed.

Acknowledgments

Thanks to Fernando Gryzbowski, environmental officer of the United Nations Missions in Sudan (UNMIS) for first suggesting the need for this article. We are also grateful to Dr. Jan Sjöström for his advice which substantially improved the manuscript. The authors would also like to acknowledge the work of the many dedicated individuals who conduct groundwater related work in developing regions around the world. We hope this article will support their efforts.

Disclosure

This manuscript has been read and approved by all authors. This paper is unique and is not under consideration by any other publication and has not been published elsewhere. The authors and peer reviewers of this paper report no conflicts of interest. The authors confirm that they have permission to reproduce any copyrighted material.

References

1. SADC Compilation of the hydrogeological atlas for the SADC region. Draft Final Version Bee Pee (Pty) Ltd and SRK Consulting (Pty) Ltd, Lesotho, 2002. pp. 54.
2. UNEP. From Conflict to Peacebuilding. The Role of Natural Resources and the Environment. United Nations Environment Programme, Nairobi, Kenya 2009.
3. Doyen J. A Comparative Study on Water Well Drilling Costs in Kenya. Unpublished Report. Research commissioned by UNDP- Water and Sanitation Programme of the World Bank; 2003.
4. Carter D, Belete E, Berha E, Defere E, Horecha D, Negussie Y. Reducing the costs of borehole drilling in Africa: insights from Ethiopia. *Waterlines*. 2006:25.
5. Danert K, Carter RC, Adekile D, MacDonald A. Cost-Effective Boreholes in Africa. 33rd WEDC International Conference, Accra, Ghana; 2008.
6. Macdonald AM, Davies J, Calow RC. African hydrogeology and rural water supply. In: Adelana SMA, MacDonald AM, editors, *Applied Groundwater Studies in Africa. IAH Selected Papers in Hydrogeology*, Volume 13, CRC Press; 2008:127–48.
7. Robins NS, Davies J, Farr JL, Calow RC. The changing role of hydrogeology in semi-arid southern and eastern Africa. *Hydrogeology Journal*. 2006;14: 1483–1492. DOI 10.1007/s10040-06-0056-x.
8. UNDPKO Environmental guidelines for UN Field Missions. Director, Logistics Support Division; 2009.
9. El Hadanai D, Limam N, El Meslouhi R. Remote sensing applications to groundwater resources. Int. Symp on the Operationalization of Remote Sensing Earth Science Applications, Enschede, The Netherlands; 1993:93–103.

10. Sander P. Lineaments in groundwater exploration: a review of applications and limitations. *Hydrogeology Journal*. 2007;15:71–4. DOI 10.1007/s10040-006-0138-9.
11. Wright EP. The hydrogeology of crystalline basement aquifers Africa. The Geological Society of London; 1992:1–27.
12. Clark L. Groundwater abstraction from basement complex areas of Africa. *Quarterly Journal of Engineering Geology and Hydrogeology*. 1985;18:25–34.
13. Bromwich B, Abuelgasim A, Abduljabbar A, et al. Darfur: relief in a vulnerable environment. Tearfund; 2007.
14. Lattman LH, Parizek RR. Relationship between fracture traces and the occurance of groudnwater in carbonate rocks. *Journal of Hydrology*. 1964;2:73–91.
15. Kellgren N. Applicability of remote sensing techniques to groundwater exploration in semi-arid Hard Rock Terrain—a systematic approach. Ph.D., Chalmers University of Technology, Sweden; 2002.
16. Kellgren N, Sander P. Remote sensing data for effective borehole sitsing: applications in a digital decision support system for the Community Water Supply and Sanitation Programme. Chalmers University of Technology; 1997.
17. Maidment DR. GIS and Hydrologic Modelling. In: Goodchild MF, Parks BO, Steyaert LT, editors. Environmental Modelling with GIS. Oxford University Press, New York, NY; 1993.
18. Toth J. Mapping and interpretation of field phenomena for groundwater reconnaissance in a prairie environment, Alberta, Canada. *International Association of Hydrological Sciences*. 1966;11:1–49.
19. Hutton L. Field testing of groundwater quality with particular reference to pollution from unsewered sanitation; Hydrogeology in the Service of Man, Mémoires of the 18th Congress of the International Association of Hydrogeologists, Cambridge; 1985.
20. Winter TC. Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal*. 1999;7:28–45.
21. Mace RE. Estimation of hydraulic conductivity in large-diameter, hand-dug wells using slug-test methods. *Journal of Hydrology*. 1999;219:34–45.
22. Herbert R, Kitchinga R. Determination of aquifer parameters from large diameter dug well pumping tests. *Ground Water*. 1981:19.
23. Antea. Étude sur l'optimisation du coût des forages en Afrique de l'ouest—rapport de synthèse. Banque Mondiale Programme pour l'eau et l'assainissement—Afrique; 2007.
24. LeGrand HE. Ground water of the Piedmont and Blue Ridge Provinces of southeastern States. *United States Geologic Survey*; 1967.
25. Yin ZY, Brook GA. The topographic approach to locating high-yield wells in crystalline rocks—does it work. *Ground Water*. 1992;30:96–102.
26. Gehrels J. Lifewater drilling and well construction reference manual Lifewater Canada, 2004:176.
27. Barrell R, Rowland MG. The relationship between rainfall and water well pollution in a West African (Gambian) village. *Journal of Hygiene*. 1979;83:143–50.
28. Renard P. The future of hydraulic tests. *Hydrogeology Journal*. 2005;13:259–262. DOI 10.1007/s10040-004-0406-5.
29. Pan S, Wang Z, Su Q, Sun T, Zhang Y. Groundwater level monitoring model using multi-temporal images in arid region of northwest China. International archives of the photogrammetry, remote sensing and spatial information sciences; 2008:37.
30. Stephens D. Vadose Zone Hydrology CRC Press—Lewis publishers, Boca Raton, Florida. 1996.
31. Brodie RS, Baskaran S, Ransley T, Spring J. Seepage meter: progressing a simple method of directly measuring water flow between surface water and groundwater systems. *Australian Journal of Earth Sciences*. 2009;56:3–11. DOI 10.1080/08120090802541879.
32. Gordon N, McMahon T, Finlayson B. Stream hydrology: an introduction for ecologists John Wiley and Sons, Chichester; 1992.
33. Woessner WW. Stream and fluvial plain ground water interactions: rescaling hydrogeologic thought. *Ground Water*. 2000;38:423–9.
34. Larkin RG, Sharp JM. On the relationship between river-basin geomorphology, aquifer hydraulics and groundwater flow direction in alluvial aquifers. *Geological Society of America Bulletin*. 1992;104:1608–20.
35. Hutton L. Field testing of water in developing countries Water Research Centre for Water and Waste Engineering for Developing Countries Group, Loughborough; 1983.
36. Salama RB, Otto CJ, Fitzpatrick RW. Contributions of groundwater conditions to soil and water salinization. *Hydrogeology Journal*. 1999;7:46–64.
37. Sharaf MAM. Review of the hydrogeological and hydrochemical aspects of groundwater in the Umm-Er-Radhuma aquifer system, Arabian Peninsula. *Journal of African Earth Sciences*. 2001;33(2):349–62.
38. Howari FM, Yousef AR, Rafie S. Hydrochemical analyses and evaluation of groundwater resources of North Jordan. *Water Resources*. 2005;32(5):555–64.
39. Kreitler C. Hydrogeology of sedimentary basins as it relates to deep well injection of chemical wastes. Proceedings of the international symposium on subsurface injection of liquid wastes National water well association, Dublin, OH; 1986.
40. Winograd I, Robertson F. Deep oxygenated ground water: anomaly or common occurance? *Science*. 1982;216:1227–30.
41. Visco G, Campanella L, Nobili V. Organic carbons and TOC in waters: an overview of the international norm for its measurements. *Microchemical Journal*. 2005;79:185–91. DOI 10.1016/j.microc.2004.10.018.
42. Bartlett RJ, James BR. System for categorizing soil redox status by chemical field testing. *Geoderma*. 1995;68:211–8.