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Consider the geology in hydrogeology

Charles W. Welby
Department of Marine, Earth, and Atmospheric Sciences
Box 8208, North Carolina State University,
Raleigh, North Carolina 27695, USA

ABSTRACT

The term "Hydrogeology" was coined to reflect that in its use one is considering all aspects of the occurrence of groundwater. In recent times, much emphasis has been placed upon development of theories of groundwater flow and the construction of models to explain how water moves through the geological materials of the earth's crust. First there were physical models, later analogue models, and most recently, with the advent of the computer, mathematical models. However, in each stage of model development the underlying problem has been how to represent properly the geological factors that control the occurrence, storage, and movement of groundwater. Thus it behoves us to improve our knowledge of the physical and chemical nature of the rocks, which contain the water, and to apply that knowledge to our exploration for, protection of, and exploitation of the groundwater resources available to us.

Aquifers are said to have three broad functions. The first is that of serving as a storage facility for the water infiltrating and moving to the saturated zone; the second is that of serving as a pipeline through which the water moves; and the third is that of affecting the chemical nature of the water. If we are to manage most efficiently the groundwater resources of the world, we must consider all three functions as we address the multitude of problems associated with groundwater management. In a broader context we must look at the hydrological cycle in general and must interpret from the geological record the broad outlines of the hydrological cycles of the geological past in order to understand the past and present volumes of groundwater available to us, both on a short-term and on a long-term basis. Climatology and palaeoclimatology give clues to the use of the storage facility; studies of the petrology and petrography of the rocks provide insight into the storage capacity of the aquifers and into the transportation capacity. Petrology and petrography combined with geochemistry indicate something about how groundwater may be chemically affected in its passage through the rocks, and whether or not manmade chemicals added to the water may be removed during transport. Modern stratigraphic and geophysical techniques can enhance our understanding of the geology upon which hydrogeology is based, and geology becomes an important aspect of the equation when consideration is being given to conjunctive use of surface and groundwater.

INTRODUCTION

In assessing the role of hydrogeology in human affairs, we find the need to address a number of related topics. This essay is designed to review some of these topics in view of the need to use hydrogeology for bettering the human condition in many parts of the world. Coined to describe in a general way the study of water and its occurrence in the crust of the earth, the geology of groundwater occurrence, the term over the years has developed a broader meaning. It has taken on some social implications, or at least become tied to social and political decisions. Its sister term, Geohydrology, has been less used, and many ideas about the movement of groundwater in the subsurface have been incorporated under the term hydrogeology.

Although there are few written records about the development of concepts of groundwater occurrence surviving from ancient times, studies of ancient civilisations show that the denizens of these civilisations had rudimentary understandings of where to find groundwater and how to develop it for their purposes. Early on there was the development of springs, infiltration galleries, and the art of well construction. True, some of the understanding was intimately tied to the mythologies and religious beliefs of the times, and by today's standards there were bizarre explanations. However, I have the innate feeling that the connection between climate, river flow, groundwater and conditions required for groundwater usage were intuitively understood those many eons ago. Groundwater related technology seems to have developed where there was a scarcity of water.

Certainly one of the critical points in the development of what today is known as Hydrogeology might be said to have started in the late 17th century when Perrault and Mariotte proved that river water could come exclusively from rainwater. Mariotte also demonstrated the connection between precipitation and groundwater by measuring the seepage in cellars in Paris and noted that spring flow varies with rainfall. When Henri D'Arcy expressed what is now known as Darcy's Law in 1856, modern understanding of hydrogeology began in earnest. In the ensuing years the predecessors of today's groundwater modellers developed the mathematical concepts upon which our understanding of the movement of groundwater and the extraction of groundwater depends. Early in its history the U.S. Geological Survey began providing important knowledge about the geology of groundwater, and in other countries research expanded our understanding of hydrogeology. At the time of the formation of the U.S. Geological Survey much of the United States was literally a developing country, its geology and groundwater resources largely unknown. The water resources, or lack thereof, of the arid and semi-arid west were important to the expansion of the United States westward, and groundwater played an important role. Today the population of the United States continues to grow; limits to development are everyday topics, and in many places, even in the humid east, groundwater availability, or lack of groundwater supplies, are critical factors to be considered. Yet, the water resources problems in the U. S. pale in comparison with other parts of the world, but I think that we can all learn from each other.

DISCUSSION

General observations

Today we must recognise that investigations related to hydrogeology encompass a variety of disciplines, yet the science as a whole concerns the geological framework within which water occurs in the subsurface and the various physical, chemical, and biological factors affecting the water. In a broad sense we can consider that the rocks containing the water, the aquifers, if you please, have three functions: (1) storage, (2) transport, and (3) chemical and biological modification of the water, or the water quality function. When water falls on the surface of the earth, it infiltrates and begins to move through the soil and rocks to some discharge point, and the earth materials serve as a pipeline. The transport or pipeline function allows us to visualise how water may move from an intake location (recharge) to a discharge location. Although we cannot measure directly the coefficient of friction involved in water movement through the rock mass, we can measure its effect. Thus aquifer tests provide us with the concepts of Transmissivity and Hydraulic Conductivity. An aquifer differs from a pipeline, however, in the fact that the water-bearing rocks may vary both vertically and longitudinally in their hydraulic conductivity and transmissivity. The water may reside in the intergranular openings of sediments and sedimentary rocks, in the fracture openings of the crystalline rocks, or in the intergranular openings and fractures of consolidated and cemented sedimentary rocks. Under the storage function we can view an aquifer as a tank holding a given volume of water, which we can extract, or divert. We most commonly think of the storage function when we estimate the quantity of water that may be available. Certainly there are plenty of examples in the world where we have literally mined an aquifer to the extent that there has been subsidence of the surface, and the water level in the aquifer has reached uneconomic pumping levels, or as a result of the overdraft less desirable water has entered the aquifer. We have also pumped dry fractures of crystalline rocks. Thus I would urge us in evaluating the use of groundwater to begin our thinking with the concept that an aquifer may have a limited volume. We must somehow describe that volume through our understanding of the geological relations.

The water quality function can control whether the groundwater is suitable for a particular use or whether changes wrought within the rocks have made the water not suitable for an intended use. The water quality function is especially important in all parts of the hydrological cycle, for chemicals and pathogens placed at or near the surface and picked up by infiltrating water may not be removed by the earth materials through which they move. The opposite is true, of course; the soil and rocks through which the water moves may allow the water quality to be changed for the better, either through chemical processes, biological processes, or a combination of them - the filter effect. One example of this function is the fact that rainwater falling on a limestone terrane becomes enriched in calcium carbonate as it passes through the limestones and becomes “hard water”. At the other extreme is the case where rainwater entering a sand aquifer may maintain essentially its initial quality and be very “soft”.

We come to see that geology is the key to hydrogeology. The rocks and their disposition in space provide the framework within which the water accumulates, through which it passes, and with which it reacts. The openings in the rocks provide the storage for the water; the connectivity of the openings in the rocks is the factor which permits the water to move from one place to another, and the possible chemical and biological reactions, or a combination thereof, control the water quality. In addition, the tectonic history of a place plays a role, as do the structural relationships of the rock bodies. Thus geological history must be considered, and the origin of a particular rock mass and its subsequent history influence whether water of suitable quality and quantity is available for exploitation.

At this point we should remind ourselves that groundwater does not necessarily occur in limitless quantities. Much of that which we are currently exploiting or have already exploited was accumulated millennia ago and can literally be mined without adequate replenishment. On the other hand, aquifers exist which are replenished with essentially an annual frequency, and overexploitation means water usage in excess of the annual recharge rate. Here one must consider carefully the water budget, and stream base flow can be used to estimate the recharge for shallow aquifers. So it is necessary to relate the geology of an area to the hydrological cycle and water budget and to develop an understanding of whether or not current and foreseeable climatic conditions will permit a continuing use of the water, or whether at sometime in the future we will have used the reserve in its entirety. In parts of the world the rocks are unsuitable for water accumulation, and we should recognise this fact. Overdraft and mining of aquifers has happened in some parts of the United States resulting in economic and political stress and physical changes to manmade structures. Thus it appears to me that one of the first orders of business in a hydrogeological study is to assess the potential groundwater reserves and recharge patterns and to develop techniques, which relate the groundwater resource to the population that it can sustain. The key here is the relation between the resource and its adequacy to sustain present and future populations. Knowledge of past and present climatic conditions is important to the understanding of the adequacy of the resource.

It is obvious, I believe, that water exploration techniques in an area of poorly fractured granitic rocks is quite different from that which should be used in a coastal plain environment, even if the precipitation in the two areas is similar. In each case we must make some judgement about the probability of recharge water reaching the openings in the rocks and about the percentage of the precipitation that might possibly be available for recharge. In other words, we have to look at the amount of water available for recharge and the nature of the "pail" into which the water might flow - a large opening or a very small opening and a large "pail" or a small "pail".

Hydrogeology has developed since the 1950s into a broad sub-discipline of geology. Examination of the publications relating to hydrogeology points to the interrelationships between water quantity and water quality and the utilisation of a wide range of techniques and methodologies to derive an understanding of the behaviour of water within the rocks of the earth's crust. In some studies isotopes play an important role in helping us to understand the origin and transport of water through the subsurface. We find ourselves having to couple the predictive aspects of the flow and transport equations with various equations expressing the nature of subsurface chemical reactions. Without detailed knowledge of the various geological factors affecting the parameters of the equations, we can only approximate the behaviour of the water movement and chemical reactions. In recent years we have come to recognise the importance of microbiological entities in the subsurface, beyond the simple question of microbial and viral contamination of groundwater resources.

In many parts of the world developing an adequate supply of potable water for growing populations is the major goal of hydrogeology. Thus the finding and management of groundwater is the primary and perhaps sole goal of the application of hydrogeology here. Protection of the groundwater source needs to become an important aspect of any management scheme. For instance, several years ago I had the opportunity to visit a small Masai village in East Africa. It had a shallow water well from which the villagers could obtain their water. However, there was no attempt to enforce any sanitary restrictions around the well. The animals of the village spent a good deal of time around the wellhead, and I cannot help but believe that there was faecal contamination of some sort in the groundwater. Perhaps in this semi-arid part of the world contamination was not a problem because of depth to water, but my experience suggests otherwise. In my own part of the world the leakage from lagoons used to store the waste from large "factory" farms of hogs poses the threat of nitrate and faecal contamination of the groundwater in the coastal plain sediments. My own research has demonstrated that application of municipal sewage sludge to croplands whose soils are derived from granite can eventually bring about nitrate build-up in groundwater where the water table is at depths of 30 to 50 ft (10 to 16 m). Almost innumerable studies from around the world document groundwater contamination derived from agricultural activities, especially application of artificial fertilisers, pesticides, and herbicides. Understanding of the local geology is important in evaluating the risk to aquifers of such contamination.

In the more industrially developed parts of the world we have ample evidence of not only agricultural contamination of groundwater supplies but also major impacts from industrial chemicals. In the U.S. we have come to recognise that we cannot clean up the subsurface to a pristine condition and have begun to use the concept of Risk Based Assessment in grading our cleanup goals. This approach calls for a detailed understanding of the geological framework within which the contaminated water occurs and the judicious application of hydrogeology, if you will. Stepping back for a moment to look at a bigger picture, we should realise that geology controls the destiny of the water after it enters the subsurface. That is to say, whatever is placed on the surface through which precipitation or irrigation water infiltrates or is in the materials below the soil affects the chemical nature of the water. The physical nature of the soil and rock controls the movement of the fluid, which is responding to the physical forces, largely gravitational.

Some specific observations

In this section it is my intent to present a broad summary of some ideas and observations about groundwater occurrence in selected general geological settings. There is no intent to be comprehensive in this review, but rather the intent is to provide a conceptual summary, a way of looking at some hydrogeological problems and situations. The framework to be used is that of the three functions, transport, storage, and chemical, of the rock masses within which groundwater may be found.

In any water supply problem the basic question is essentially, "How much water is available?" This question has two aspects: (1) the proportion of the precipitation that recharges the saturated zone and (2) our ability to extract the water from the "tank". The first aspect is dependent upon the water budget and the second upon the nature of the earth materials within which the water is found. In the case of the first aspect, the answer may be that present climatic conditions and geological relations do not permit any recharge, or the recharge may be intermittent and limited in volume. If there is no recharge or if we extract water from the "tank" at a rate greater than the recharge, whether it is continuous or intermittent, we mine the water resource much as we might mine some ore body. Thus in an evaluation of the long-term availability of groundwater we may try to determine the recharge to the aquifer through an estimation of stream base flow by hydrograph separation or by calculation of a water budget. Other methods have been studied. We also have to assure ourselves that the base flow really represents water that is discharged from the area where we are seeking groundwater. To do so requires an understanding of the basic geology of the rocks within which the water occurs, both petrographically and structurally.

Hydrogeology is important in the evaluation of geological hazards, such as landslides and in the construction of civilisation's infrastructures. Time and space permit only the recognition of this fact. Roads have been built along groundwater discharge points, resulting in the failure of the roads; dams have been proposed in alluvial valleys where streams recharge the groundwater. However, because of the nature of the papers offered for this symposium, I have concentrated my comments on water supply issues and problems.

When we develop an aquifer, perhaps we need to ask questions beyond that of "How much water?" Detailed studies often need to be made to determine an aquifer's hydrogeological properties and their distribution. Are there discontinuities that affect the water flow, and how do they affect possible modelling attempts? Can we use Darcy's Law or are other approaches to groundwater flow better? How do changing land use patterns affect the aquifer through withdrawal of water or the covering of recharge areas? Will there be changes in water quality with time because of the water withdrawal or land use changes or because of geochemical factors associated with the water withdrawal?

Crystalline rocks

If one investigates the literature related to the occurrence and use of groundwater found in crystalline rocks, one can come away with a general model. It appears that the bulk of the groundwater is stored in the weathered material overlying the crystalline rocks, the saprolite, unconsolidated sediments, or in some cases glacial deposits. Conceptually, these are the reservoir or tank for the bulk of the water. The fractures in the crystalline rocks can be likened to a series of pipes draining the tank. Understanding the results of a drawdown and recovery test may require viewing the recharge to the well bore as if the fractures were an orifice discharging from a tank.

It is possible to locate fractures intersected by a well bore drilled into crystalline rock through use of fluid conductivity logging. In this technique deionised water is pumped into the well bore, replacing the native water. The deionised water is withdrawn from the well slowly, and at the same time a conductivity log is run in the well. The incoming native water exhibits greater conductivity as it enters the well bore from the fracture or fractures, and the log shows this conductivity change opposite the fracture or fractures. From my perspective this technique under the right circumstances can be cost-effective and technologically rather simple to use. The key to finding groundwater in crystalline rocks is locating fractures. It appears that the geological history of the crystalline rocks and the structural history control the placement of the fractures and their extent and intersection. Furthermore, although thickness of the weathered material above the crystalline rocks may provide some clue to the possibility of discovering adequate amounts of water in the crystalline rocks, the topography may also play a significant role. One has to consider whether the surface upon which the precipitation falls is a water-spreading or a water-concentrating surface and the position of the surface with respect to possible routes through the weathered zone overlying the crystalline rocks. Also evidence exists that recharge to the fractures takes place through macro pores such as root channels, relict fractures, and quartz veins left behind as the rock mass weathered. The final success of a given borehole depends upon the nature of the "plumbing" in the crystalline rocks, our ability to decipher it, and upon the hydraulic gradient within the fractures of the rock mass. On occasion, a well drilled into crystalline rocks may show evidence that it has encountered confined conditions, but as a whole groundwater in crystalline rocks occurs under phreatic conditions. The complexities of the relationships associated with the occurrence of groundwater in crystalline rocks make mathematically modelling of the relationships difficult, and at best only generalised ones that may have some slight similarity to a given geological situation seem possible. Basically, there is not enough data available to construct a model that is truly representative of a given situation.

Because the weathered zone over the crystalline rocks may be thin, there has to be some concern about contamination of the water in the bedrock from human activities. Even when the regolith is as much as 30 or 40 metres thick, there may be impacts from surface activities on the groundwater found in the fractures. Agricultural activities and waste disposal are of particular concern. Another concern is the fact that the fractures from which the water may be produced may be of limited extent and that during drought periods the overlying saprolite, the "tank," may actually be drained dry and the fissures also. In a broad sense, it is possible to look at groundwater occurrence in crystalline rocks as a situation in which there are compartments into which recharge takes place and from which there may or may not be natural discharge.

Porous media

To summarise fully and in a meaningful way the many issues and problems associated with the hydrogeology of porous media aquifers in the allotted space and time is obviously impossible. We all are familiar with the general concepts that relate to the occurrence and movement of water through the sediments and sedimentary rocks of the earth's crust. We also are familiar with the general principles by which these rocks are evaluated for their storage capacity and their ability to transmit water from one place to another. However, it might be useful at this point to discuss briefly some concepts related to evaluation of clastic sedimentary sequences and their ability to store water and to transmit it to some discharge point, whether a natural discharge point or to a well or a series of wells.

Stratigraphy and stratigraphic information have been the basis of defining aquifers for a considerable period of time. That is, we have recognised that there are permeable, semi-permeable, and impermeable beds, which control the movement of groundwater. Sometimes the sequence of beds is such that groundwater crosses formational boundaries, and we lump several formations and describe them as a named aquifer. However, it is becoming evident that such a procedure may not be appropriate in many cases. In dealing with the occurrence of groundwater in coastal plain settings it may be to our advantage to consider the regional stratigraphy in terms of sequence stratigraphy wherein the understanding of the distribution of the water-bearing properties of the rocks are related to the geological history of the sequence. This approach defines a body of sediments and sedimentary rocks in terms of unconformities and the transgression and regression of the ancient seas across an area.

The concept has proven itself extremely useful in the exploration for petroleum where the physical stratigraphy can be combined with geophysical exploration data to pinpoint favourable locations for petroleum deposits. Except in the most rare of cases hydrogeologists do not have at their disposal the sophisticated data-collecting ability available to petroleum exploration. However, we can use the concepts of sequence stratigraphy to understand better the occurrence of groundwater, and the ideas can be applied to local problems. For instance, an understanding of the internal sedimentary structures and fining upward or downward sequences can provide insight into how water may move through a porous media. Also the use of sequence stratigraphy may in some instances provide us with insight into where the more favourable and less favourable places are for siting a water supply well. It is possible that such an understanding may provide the opportunity to explain chemical inconsistencies found between different wells tapping the same aquifer or may be used in conjunction with geochemical data to differentiate regional flow patterns within a sedimentary sequence.

If one examines alluvial fans, one finds that there are patterns of sediment distribution within the fan reflecting the developmental history of the fan. Careful consideration must be given to controls on base level and to the nature of the controls, especially tectonic, on sediment supply. The more permeable sequences may allow water to move more rapidly to the basin, or to a well, than the less permeable; the three-dimensional distribution of hydraulic conductivity related to the pattern of fan development may cause the water to move in unexpected patterns.

Water quality

Next I turn to the water quality function of water-bearing earth materials. Again, we are all more or less familiar with salinisation problems associated with irrigation of crops in arid and semi-arid climates. The transport function of water-bearing materials can become important here, for it is possible for irrigation water to be applied at one place, to seep into the shallow saturated zone and to then be withdrawn farther down gradient to be used again. Eventually the water may move as a base flow contribution to a river, despoiling the water quality of the surface stream for additional irrigation or for human consumption. Even in areas of low pesticide, herbicide, and chemical fertiliser use the application of fertiliser in the form of manure or human sewage sludge can lead to the build-up of nitrate in both groundwater and surface water. Base flow discharge from the saturated zone can carry the nitrate to the streams. We can use hydrogeological principles and knowledge of the geology to help alleviate, or better yet, avoid some of the problems. The question, however, is whether there exists the economic and cultural willingness to carry out an appropriate programme.

There are places in the world where some natural chemical attribute of a potential aquifer makes the water unsuitable for human consumption. In one case, in the Champlain Valley of Vermont, U.S.A., the groundwater recovered from Lower and Middle Ordovician limestones and dolostones overlying a thrust fault while "hard" is generally usable. However, water recovered from fractures in the carbonaceous limestones and pyritiferous shales lying beneath the thrust fault is enriched in hydrogen sulphide because of oxidation of pyrite found in the shales. Thus the geology of the region determines whether or not water of suitable quality is available for human and livestock consumption and guides the exploration for groundwater.

In the San Joaquin Valley of California selenium occurs naturally in the alkaline soils. Through irrigation practices selenium has been leached out of the soils into the drainage ditches and surface streams. These in turn drain into a large lake, part of the Kesterson National Wildlife Refuge. One wonders whether or not some oxidation source, such as nitrate might not be responsible for developing the mobility of the selenium. It was discovered in 1983 that the selenium had deleterious effects on the wildfowl using the lake, and what had been designed as a major wildfowl refuge became limited in its use as wildfowl offspring were badly deformed, and the wildfowl populations decreased sharply.

SUMMARY

In the immediate discussion I have suggested that in some cases it might be useful to set our exploration for groundwater and management of the resource in a broader geological context. It is obvious that a water supply well needs to be somewhere near the point of use of the water. However, setting the location in a broader geological context and allowing us to understand possible restrictions on the use of the water potentially empowers us to manage a limited supply with increased physical and economic efficiency.

APROPOS THE INTERNATIONAL SYMPOSIUM

In reviewing the titles of papers on hydrogeology proposed for presentation at this International Symposium, I became intrigued by one dealing with the arsenic pollution of the groundwater in Bangladesh and a paper describing arsenic in groundwater in West Bengal. Search of the World Wide Web provided me with some background information on the Bangladesh situation and a preliminary understanding that the arsenic in Bangladesh is derived from the alluvial materials from which the groundwater is withdrawn. It will be interesting to learn about the source of the arsenic in both Bangladesh and West Bengal, and whether or not it is endemic to the sediments like the selenium in the San Joaquin Valley of California is endemic to the alluvial materials there, or whether the source of the arsenic is the result of some past human activity. Speculatively speaking, one cannot help but wonder if perhaps nitrate from agricultural applications or sewage might not provide a source of oxygen under the proper oxidation/reduction scenario for oxidation of the arsenic into a soluble form. At the same time the nitrate would be denitrified. Another groundwater contamination paper describes a case of nitrate groundwater contamination in Sri Lanka. Nitrate contamination of groundwater from agricultural activities is a worldwide problem. Questions of appropriate loading of nitrate in the fields in relation to crop growth patterns, soil conditions, and the water budget need to be addressed carefully.

The Symposium provides several papers, which look into techniques important in the management of the groundwater resource, and anticipate that they will address all three aquifer functions mentioned earlier in this essay, either directly or indirectly. Other papers provide insight into groundwater exploration techniques and use of rainwater catchments and other artificial recharge techniques in groundwater replenishment. The water quality function of aquifers has not been ignored. Papers describing the groundwater quality in limestones, the occurrence of fluoride in groundwater as well as variations in groundwater composition in an arid climate have been offered for the programme. A paper on the use of shallow aquifers for irrigation in Nepal brings to mind the possibilities of surface water contamination through base flow or surface runoff and the concern of how this aspect of irrigation may be handled in the future. A paper on the overexploitation of groundwater resources in the Kathmandu Valley places the Symposium attendees in the middle of the action, so to speak, as does a paper on the challenges facing hydrogeology in Nepal in the next millennium.

Overexploitation brings to mind a question concerning the long-term benefits for any society. Will the overexploitation provide economic benefits upon which a society might develop other water resources to support itself, or does the overexploitation simply mean that when the "tank" is empty the society will be without water and eventually collapse? Certainly an understanding of geology underlies our attempts to manage the groundwater resource.

In summary, the Symposium provides a cross-section of problems waiting to be answered by hydrogeologists for the benefit of society in the coming years. Each problem may be unique in its details, yet there seem to be worldwide common threads among the various problems. The solution of a particular problem depends upon understanding the geological context within which the problem is found and the geology which influences the occurrence, distribution, and quality of the groundwater. Hence, "Consider the Geology in Hydrogeology."