GROUNDWATER PROFESSION IN TRANSITION: DISCOVERY TO ADAPTATION[1]

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ABSTRACT

Over the past century and half, groundwater has played an important role in the economic prosperity of the United States. The groundwater profession which has contributed to this prosperity has grown through the contributions of the U.S. and State Geological Surveys, academia, and industry. A century ago, the energies of the profession were channeled towards discovering new sources of groundwater in a largely unexplored land, and exploiting the resources for maximum economic benefit. Experience has since revealed that groundwater systems are finite, and are intimately linked to surface water bodies and the biosphere. A consequence is that aggressive exploitation of groundwater can lead to unacceptable environmental degradation and social cost. At present, the groundwater profession is in a state of transition from one of discovery and exploitation, to one of balancing resource development with avoiding unacceptable damage to the environment. This paper outlines the history of the groundwater profession in the United States since the late nineteenth century, and speculates on what may lie ahead in the near future, as the profession makes the transition from discovering new sources of groundwater to one of better understanding and adapting to nature's constraints.

INTRODUCTION

Over the past century and a half, groundwater has played a major role in the economic prosperity of the United States. Because of the vastness of a newly settled land, unprecedented technological innovation, and unlimited opportunities for acquiring wealth, the groundwater profession initially devoted its energies to discovering new sources of groundwater and exploiting them for maximum economic benefit. Within a few decades, however, mounting evidence indicated that vigorous groundwater development can lead to unacceptable environmental consequences and social cost. Even so, exploitation strategies continued, motivated by overriding economic considerations.

Arguments of economics, nevertheless, could not be sustained indefinitely. The close of the twentieth century saw widespread recognition that groundwater is a fragile resource, vital for

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the sustenance of humans and other living things. Within the hydrological cycle, groundwater is delicately linked with the atmosphere, surface water bodies, and the biosphere. This delicate linkage is often seriously impaired by aggressive development of groundwater resources. At present, we witness a confrontation between a perceived freedom for unlimited prosperity, and a finite natural resource subject to physical laws beyond human control. Having begun with a mission of discovery and exploitation, the groundwater profession is now on a path of learning to balance exploitation for human benefit with competing environmental and social interests.

In the U. S., the groundwater profession has grown through creative contributions of a diverse group: the U. S. Geological Survey, Geological Surveys of different states, academia, industry, and individuals acting as consultants. The purpose of this paper is to look back at the development of the groundwater profession in the U. S., reflect on its present status, and speculate on its near future. A historical account, focusing attention on North American scientific developments in hydrogeology has been published elsewhere (Narasimhan, 2005a).

A BRIEF HISTORY

U.S. Geological Survey

The establishment of the U.S. Geological Survey (USGS) by the Congress in 1879 at the recommendation of the National Academy of Sciences is of special significance. Until then, support for science in the U. S. was largely in the military domain. The creation of the USGS was an initial step in fostering civilian science for social benefit through large-scale governmental support. Thanks to this support, the USGS has, over the succeeding 125 years, been able to contribute to the growth of groundwater hydrology on a scale unmatched by any other institution. Prior to the 1930s, the evolution of groundwater hydrology as a distinct earth science discipline occurred mainly because of the contributions of USGS geologists.

Closely following on John Wesley Powell's (1879) influential report, "Lands of the Arid Region of the United States", water (on the land surface and under the ground), became an important component of the mission of the USGS. In 1902, the surface-water development activities of the USGS were delegated to the newly created U.S. Bureau of Reclamation. With this reorganization, attention to groundwater by the USGS became accentuated.

During the nineteenth century, artesian conditions were widespread throughout the country, and the early geologists devoted much attention to deciphering their nature and behavior. Noteworthy is the work of Darton (1896), who elucidated the hydraulic functioning of the Dakota Sandstone east of the Black Hills in South Dakota, and postulated vertical leakage through confining clay layers. Through systematic geological studies, well inventories, and water budget estimates, others were identifying and defining major aquifer systems around the country, while simultaneously providing technical support on the utilization of groundwater for domestic, agricultural, and industrial purposes. Among these early geologists one may specially mention Walter Mendenhall (1908), who described groundwater conditions in the San Joaquin Valley of California, and Charles Lee (1912), who prepared a detailed water budget for the Owens River Valley in California, accounting for evapotranspiration and spatial distribution of plants.

Early in its history, the USGS established a set of publications to communicate its findings to the public. Continuing to this day, these publications constitute a formidable body of open literature on groundwater, covering physical, chemical, mathematical, and biological aspects, field data, research methods, and more recently, public education. The Water Supply Papers, Professional Papers, Bulletins, Circulars, and Open File Reports have helped educate groundwater hydrologists in the U.S. and around the world.

It was Oscar E. Meinzer who had the vision and the philosophical bent to synthesize the findings of his peers of the USGS, and establish groundwater hydrology as an identifiable discipline within the earth sciences (Meinzer, 1923). In a subsequent publication, he meticulously elaborated the connection between groundwater and plants that relied on groundwater for sustenance (Meinzer, 1927).

The publication of a short but enormously influential paper on non-steady flow of water to a well by Charles Theis (1935) opened up a new quantitative direction, complementing descriptive groundwater studies. Theis' work inspired the use of differential equations for analyzing the response of aquifer systems to groundwater extraction through wells. More generally, it catalyzed quantification in groundwater hydrology. Literature on groundwater hydraulics was enhanced by the contributions of Charles Jacob, Hilton Cooper, Mahdi Hantush, Stavros Papadopulos, and John Bredehoeft.

In the area of groundwater chemistry, the necessity for rationally processing vast amounts of water chemistry data being compiled by the USGS geologists inspired Arthur Piper (1944) to invent the trilinear diagram to interpret cation and anion composition of groundwater. A decade later, William Back (1960) formulated the concept of hydrochemical facies to apply Piper's graphical method to interpret spatial variations in groundwater chemistry in the field. The publication, "Study and interpretation of the chemical characteristics of natural water" by Hem (1959) has served for decades as a practical handbook on groundwater chemistry.

At present, groundwater activities of the USGS combine both descriptive geological investigation of groundwater systems on all scales and their quantitative mathematical analysis. As may be expected, increasing attention is now being devoted to the linkages between groundwater on the one hand, and the environment and ecosystems on the other. Attention is also being given to educating the public about the nature and occurrence of groundwater through specially designed publications.

Academia

During the late 19th century, Thomas C. Chamberlin (a geologist), Franklin H. King (a soil scientist), and Charles S. Slichter (a mathematician), all of the University of Wisconsin, were actively involved with the groundwater investigations of the U.S. Geological Survey (Anderson, 2005). Closely following their lead, Daniel W Mead covered topics in groundwater in his hydraulic engineering courses starting from 1904. His text book on hydrology devoted a chapter to the exposition of the geological and hydraulic framework of groundwater (Mead, 1919).

With its coming of age as an identifiable discipline, the 1930s witnessed groundwater becoming a part of academic curricula in universities. Cyrus Tolman of the geology department at Stanford University emphasized the need for geologic investigation and engineering analysis to solve hydrogeological problems (Remson, 2002). With groundwater hydraulics attracting increased attention, groundwater education came to be offered in civil engineering departments as well. By the 1960s, groundwater programs were in place in many of the leading universities around the nation: the University of Illinois at Urbana-Champagne; the University of California campuses at Berkeley, Los Angeles, and Davis; the University of Minnesota; Colorado State University at Fort Collins, Desert Research Institute, Nevada; the University of Arizona; New Mexico Institute of Mining and Technology; Pennsylvania State University, University of Wisconsin, and Princeton University.

The strengthening of the academic programs not only helped train scientists and engineers needed by a growing profession, but also provided significant opportunities for some of the State Geological Surveys to expand their groundwater programs in cooperation with their University systems. The Illinois State Water Survey, The Desert Research Institute, Nevada, and the Geological Surveys of Minnesota, Kansas, Wisconsin, and Nebraska are examples. In Canada, Robert Farvolden led the establishment of a strong groundwater program at the University of Waterloo in 1970.

Apart from Meinzer's (1923) treatise, the first text book on groundwater published in the U.S. was "Groundwater" by Tolman (1937). In addition to training geologists and engineers, Tolman hoped that the book would assist in preparing attorneys for litigation involving subsurface water, and in the development of sound groundwater laws based on scientific principles. The next influential book in the field was David Todd's (1959) "Groundwater

Hydrology". Todd, a civil engineer from the University of California at Berkeley, focused attention on engineering aspects, including groundwater hydraulics, salt-water intrusion, water pollution, geophysical exploration, and related aspects. A widely used textbook on groundwater, focusing attention on geological aspects was "Hydrogeology" by Stanley Davis, then at Stanford University, and Roger De Wiest, then at Princeton University (Davis and De Wiest, 1966). By the 1970s, many environmental problems associated with groundwater development had come to light, including land subsidence, land slides, soil salinization, and groundwater pollution. Clearly, groundwater had to be viewed more broadly than heretofore. To fill the emerging needs, Allan Freeze and John Cherry, both of Canada, published the book "Groundwater" in 1979. This book elaborated the physical and chemical principles governing groundwater within the unifying framework of gravity-driven groundwater flow systems, and gave detailed attention to the vadose zone, which lies between land surface and the water table.

Industry

Academic research in groundwater has in general been characterized by a theoretical flavor as compared with the practical day-to-day needs of the industry. Therefore, the groundwater industry has historically organized itself to meet its own educational, training, professional certification, continuing education and other needs. Here, the phrase "industry" includes groundwater exploration, assessment, and development by drilling and manufacturing enterprises, consulting companies, and individual consultants.

In 1948, the National Water Well Association (NWWA) was founded to fill the needs of water-well drilling industry and those of groundwater contractors. At about the same time, a few states such as California, Oregon, Texas and New Mexico commenced their own groundwater associations. Initially, the focus of NWWA was on drilling and construction of water wells, and it soon started the Water Well Journal, which continues to be a leading industry resource. With increasing interest in the science of groundwater, the journal "Groundwater" was introduced in 1963, intended for groundwater hydrologists. In response to the growing importance of groundwater contamination during the 1970s, NWWA introduced in 1981 the journal "Groundwater Monitoring and Remediation". These journals are devoted to covering technical aspects of groundwater that are of direct relevance to the field practitioner. Doing justice to its expanded interests in groundwater as a resource, the NWWA was renamed, "National Groundwater Association" in 1991.

The educational contributions of what used to be Edward E. Johnson Inc. of St. Paul, Minnesota deserves mention. After several name changes through the decades, this company, founded in 1904, is now known as Johnson Screens. To disseminate practical knowledge about water-well drilling and groundwater development, the company started distributing "Johnson National Driller's Journal" in 1929 to drillers, faculty members, government officials, and others interested in groundwater. The popularity of this journal led to the publication, "Groundwater: its development, uses and conservation", (Bennison, 1947) that covered geological aspects of groundwater occurrence and movement, well hydraulics, exploration for groundwater, drilling and construction of wells, pumping equipment, water treatment and water conservation. This book was revised and reissued as "Groundwater and Wells (Anonymous, 1966), which has since seen many reprints and revisions. In retrospect, this book clearly reveals the aspirations of the drilling industry towards a wise utilization of groundwater resources. Between Tolman's book in 1937, and Todd's book in 1959, "Groundwater: its development, uses and conservation" filled an important niche in groundwater education.

Consultants and Consulting Engineering companies have contributed significantly to the growth of the groundwater profession. Some consulting companies have been started by persons with prior association with the USGS or the universities. Some consultants are active faculty members, for whom consulting provides a means of being connected to practical problems of the field. In addition to providing expertise on projects, consultants also regularly conduct workshops and other training courses designed to provide continuing education to practicing groundwater professionals. Space does not permit a more detailed discussion of this topic, except to state that consulting companies and consultants constitute an integral part of groundwater resources development in the U. S.

PUBLIC PERCEPTIONS AND POLICY

The groundwater profession plays an important role in society. The recognition that groundwater is intimately linked to the environment was latent in the enactment of many environmental acts by the U.S. Congress and the many State legislatures during the 1960s and 1970s. The upshot is that groundwater hydrologists are now routinely required to prepare assessments or environmental impact statements before approval is granted for any groundwater project of significance.

That water and waterways are vital for the survival of all humans was recognized by the U.S. Congress as far back 1787 when it passed the Northwest Ordinance. This Ordinance established the doctrine of public trust as a guiding principle in the management of natural resources. Inspired by the Northwest Ordinance, most states of the Union have constitutionally recognized the notion that water is owned by the people, and that the State holds water in trust for the people. Despite this philosophical foundation, the ownership and use of groundwater have been subject to ambiguous interpretation over the past century and a half.

During the 19th century, courts in many states considered groundwater to be an occult, mysterious phenomenon, not amenable to rational understanding. As a result, groundwater was largely treated as private property of the overlying land owner. At the turn of the twentieth century, in a dispute between neighboring land owners during a drought period, a California court ruled that hardship due to decreased well yields should be shared by the neighbors, in proportion to their prior usage. This principle is referred to as correlative rights. Although scientific knowledge of groundwater and its role in the hydrological cycle became well established by the 1920s, the perception of groundwater as private property has continued to influence water policy. Starting from the 1980s, environmental groups have had much success in invoking the public trust doctrine to curb private water rights. But, such successes were in regard to surface water. The doctrine has not yet been successfully extended to groundwater.

Meanwhile, alarmed by excessive depletion of groundwater resources and associated environmental/ecological impacts, many states (e.g. Arizona, Colorado, Nebraska, Texas) have enacted legislation to mandate coordinated use of surface water and groundwater. These legislative actions are ultimately founded on the premise that water is held in trust by the State for the people, and that water shall be put to beneficial use, without waste. With almost a century of vigorous exploitation motivated by property rights, the implementation of coordinated use of surface water and groundwater is not an easy task. Many land owners who have historically held rights to groundwater continue to seek legal protection of their rights. Change is an unavoidably slow process.

NEED FOR A MEETING OF MINDS

What then is the current status of the groundwater profession in the U. S., and where might it be headed? At present, roughly half of the nation's water-supply needs are met by groundwater. The nation's sources of groundwater, and its major aquifer systems have largely been identified and catalogued. The technology of groundwater extraction has advanced enough so that the resource can be produced at extremely rapid rates. However, groundwater development is constrained, not by our ability to extract groundwater, but by the vulnerability of the resource system to depletion and degradation, with drastic long-term consequences to society.

The science of groundwater hydrology is now progressing along two lines. The first is one of characterizing and understanding the behavior of aquifer systems across the nation in ever increasing detail with observational tools of great sophistication. We now have the ability to observe groundwater history unfold in real time. The second is one of using mathematical models to quantitatively analyze groundwater systems. Although there was great excitement about the potential power of these mathematical tools a few decades ago, the enthusiasm has moderated. It is now recognized that mathematical models are of greater value as tools capable of providing insights about the historical behavior of groundwater systems through hypothesis testing, than as tools of precise prediction. Many factors contribute to this, including limitations of conceptual foundations, difficulty of access to observation, complexities of scale, interactions among a multitude of processes, lack of knowledge of forcing functions, and so on.

Groundwater systems are revealing themselves to be a vital part not only of the hydrological cycle but also the nutrient cycle. These cycles are interlinked delicately and in such complex ways that groundwater development strategies have the potential to impact the linkages adversely. Rather than attempting to precisely predict their future, which is a formidable computational task, a more realistic approach is to aim at utilization of groundwater resources based on strategies that are amenable to adaptation, should unacceptable impacts be observed. A corollary is that continuous and sustained monitoring of groundwater systems must become an essential component of water management. The challenge is to mobilize observational and computational tools to achieve this purpose.

This raises a profound issue of science and society coming together. For two centuries, the U. S. has reveled in its personal freedom and prosperity. However, this human notion of prosperity directly confronts groundwater systems subjected to immutable natural laws. Ultimately, nature demands consideration of social responsibilities. Clearly, science and society must have a meeting of minds before one can attempt to resolve the complex water management issues in some equitable way. What may be the elements of such a meeting of the minds?

In a recent editorial in Groundwater, Narasimhan (2005b) identified a set of three tenets that can reasonably serve the purpose of achieving a consensus among those interested in use of groundwater resources. The first is that groundwater systems are subject to physical laws that are beyond human control. The second is that these resources are vital for the existence of humans, and that human actions have the potential to seriously impair these resources if due care is not exercised. The third is that our current values of social justice require that groundwater resources be not monopolized by an individual or groups of individuals. They have to be shared equitably by present and by future generations.

Of the three, the first two are reasonably self-evident. But, the third entails societal values which can change with time. Although we currently accept democracy and social justice as noble values to guide society, it is not quite certain how nations may respond if they are subjected to unforeseen stress on their natural resources such as, for example, a century-long drought.

CHALLENGE OF TRANSITION

Can unlimited freedom and the power of technology come to terms with the delicate interconnectedness of earth systems? Experience with the growth of groundwater development in the U. S. suggests that nature imposes definite restrictions on human aspirations. This is reflected in the fact that the groundwater profession understands its client's interests, while simultaneously being cognizant of its social responsibility. These two precepts may not always be aligned. The profession is in transition from solving well-defined, narrow problems of science to far less well-defined problems involving interactions between science and society. Fortunately, these larger issues are already part of serious debate within the profession. There is reason for optimism that the profession has what it takes to face these challenges and progress towards judicious usage of the nations's groundwater resources in the short term and the long term.

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