AN ABSTRACT OF THE DISSERTATION OF

William Todd Jarvis for the degree of Doctor of Philosophy in Geography presented on August 2, 2006
Title: Transboundary Groundwater: Geopolitical Consequences, Commons Sense, and the Law of the Hidden Sea

Abstract approved: ____
Aaron T. Wolf

With 97% of the world’s freshwater resources stored underground, the connection between groundwater resources to the metrics of space, scale and time common to the geographic study of natural resources has not been extensively investigated by geographers. While nearly 240 transboundary aquifers are mapped across the world, a potential “tragedy” is brewing due to the poorly structured institutional capacity built within river basin treaties and agreements and River Basin Organizations to accommodate the management and governance of these transboundary aquifers. Regimes to manage or govern groundwater remain weak. On the basis of a survey of 400 freshwater treaties and agreements completed as part of this study, about 15% include provisions for groundwater. Very few of the treaties and agreements address transboundary aquifers, the coastal aquifer systems which serve as the water supplies to an increasing number of mega cities with populations exceeding 10 million people, the types of aquifers that store groundwater and respond differently to intensive exploitation, or the three dimensional boundaries of the resource or user domains. Recognized as a common pool resource, groundwater resources serve as an example of a “pure” common pool resource. This is because of the difficulty in excluding users and because of the subtractability of the resource as groundwater is pumped or artificially drained from the subsurface. Yet the management and governance of groundwater resources is challenging and increasingly conflictive not only due to its hidden nature, but also because of the difficulty in placing boundaries around the groundwater resources and user domains. These domain boundaries are three dimensional and change with time. Drawing these domain boundaries is supremely political and morph with changing social and cultural values. The present work incorporates an interdisciplinarity and broad systems approach to explore the geography of groundwater to provide context to an inventory of global groundwater resources and user domains. On the basis of surveys of international law and national policies focusing on groundwater, a previously unrecognized typology was derived for the boundaries for groundwater resources and user domains. This work found that (1) traditional approaches to defining groundwater domains focus on predevelopment conditions, referred to herein as a *bona-fide* "commons" boundary; (2) groundwater development creates human-caused or *fiat* "hydrocommons" boundary where hydrology and hydraulics are meshed, and (3) the social and cultural values of groundwater users define a *fiat* "commons heritage" boundary acknowledging that groundwater resources are part of the "common heritage of humankind". The significance of this typology is that it is difficult to aggregate demographic, social, and economic data within specific boundaries for groundwater resources for detailed geographic analyses, much less develop international regimes, without agreement on the fundamental unit of analysis. Given the complexity of the geologic and political setting of global groundwater resources, a new paradigm of "post-sovereign governance" was examined as part of this study to assess the applicability of global groundwater governance as opposed to international regimes, including the recognition of the geographic overlap between groundwater and ocean resources through an evaluation of the applicability of a law of the sea model for multilateral collaboration regarding groundwater resources through the Law of the Hidden Sea.

Transboundary Groundwater: Geopolitical Consequences, Commons Sense, and the Law of the Hidden Sea

by
William Todd Jarvis

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented August 2, 2006
Commencement June 2007

Doctor of Philosophy dissertation of William Todd Jarvis presented on August 2, 2006.

APPROVED:

Major professor, representing Geography

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

William Todd Jarvis, Author

ACKNOWLEDGEMENTS

Drs. Aaron Wolf, Roy Haggerty, Brent Steel and J. Mark Christensen from Oregon State University served as my dissertation committee members, and I extend my thanks for their generous suggestions, advice, and the time that they provided from their busy schedules. Dr. Mark Giordano and the International Water Management Institute (IWMI) deserve special acknowledgement for their kind assistance in defining a dissertation topic, for providing leave of his time to serve on the dissertation committee, and for my travel to meetings in Sri Lanka and Kenya. In addition, Joanne van Geest, Melinda Peterson, Marion Anderson, Karen Logan, and the Department of Geosciences helped me in more ways than I can count and went above and beyond the call of duty. For their kind assistance, I offer my heartfelt thanks for their help with acquiring teaching assistantships, international travel funding and arrangements, as well as the administrative processing which often times goes unnoticed but is paramount to the success of any graduate student. My dissertation project could not have been completed without their help. As a Senior Researcher in Water Resources, the Institute for Water and Watersheds also graciously provided funding for travel to support my research and attend conferences. Dr. Kimberly Jensen completed numerous reviews which lead to significant improvements in the dissertation for which I am most grateful.

Permission to use some of the original graphics found in this dissertation were provided by kind permission of the following institutions: The Confederated Tribes of the Umatilla Indian Reservation; BGR – The Federal Institute for Geosciences and Natural Resources in Hannover, Germany in partnership with UNESCO; the American Water Resources Association; the Geological Association of Canada; the University of New Mexico School of Law – the Utton Transboundary Resources Center; Springer-Verlag GmbH – Science and Business Media; and Academic Press – Elsevier. Some graphics were adapted from the U.S. Geological Survey as referenced in the figure caption. The remaining figures were drawn by the author.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

Transboundary Groundwater: Geopolitical Consequences, Commons Sense, and the Law of the Hidden Sea

Chapter One: Introduction

The likelihood and significance of boundary disputes over the territorial integrity of a state and the extent of government control are greater now than at any time since the Second World War, especially with respect to transboundary movements where institutional capacity and international law are in the initial stage of formulation (Anderson 1999). Modern examples of these boundary disputes include the political and strategic dispute regarding the boundary between Israel, the Gaza Strip and the West Bank, the dispute over the boundary between Kuwait and Iraq regarding the economic geography of oil reserves and access to ports, and the territorial and boundary disputes between the countries of the Former Soviet Union. According to Anderson (1999), boundaries have no horizontal dimension, and the crucial dimension of boundaries lies in the vertical plane or subsurface beneath the boundary.

The examination of the transboundary movement of surface water by Wolf and others (2003) identified several "basins at risk" for potential future conflict regarding the general lack of institutional capacity within the 263 international river basins in the world. Less widely recognized are the nearly 240 transboundary groundwater systems or "aquifers"[1] identified by the World-wide Hydrogeological Mapping and Assessment Program (WHYMAP) as described by Struckmeir and others (2006). Many of these underground aquifers are regional in extent with flow paths ranging from meters to hundreds of kilometers across continents, and consequently shared by several countries.

---

[1] The scientific and legal definitions of an aquifer vary from "a permeable rock formation capable of transmitting and yielding usable/exploitable quantities of water" to "a permeable [water-bearing] geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation". Note the legal definition of Yamada (2005) focuses only on the saturated zone. This issue will be discussed more fully later in the text. Other technical terms are defined in the Glossary of Terms found in Appendix A.

Until recently, conflicts over transboundary groundwater have generally focused on contamination of wells (Gleick 2004). Yet concerns over access to water in drought prone regions such as Somalia have a new generation of conflict over groundwater. The Washington Post reported a “War of the Well” between two neighboring clans in Somalia in 2006. Workers of the International Medical Corps reported that “It’s like the start of the water wars right here in Somalia” (Wax 2006). A “Silent Revolution” is occurring where millions of farmers pursue short-term benefits associated with the intensive use of groundwater for agricultural use in India, China, Mexico, and Spain and the need for proactive governmental action is needed to avert water conflicts between neighboring users, user groups, states, provinces, and nations (Llamas and Martínez-Santos 2005). These events, along with the “Silent Trade” of groundwater contaminated with hazardous waste flowing across international boundaries into Lebanon reported by Jurdi (2002), have accelerated interest in managing and governing transboundary groundwater resources.

Pumping of groundwater is among the most intensive human-induced changes in the hydrologic cycle. With dramatic changes in drilling technology, pumping technology and the availability of electrical power over the past 60 years, the number of wells has increased exponentially in many parts of the world (Moench 2004). According to Zekster and Everett (2004), groundwater is the world’s most extracted raw material, with withdrawal rates approaching 600 to 700 km^3 per year. The breakdown of that figure includes the following percentages used per sector: drinking water (65%); irrigation and livestock (20%); industry and mining (15%). With global abstractions of freshwater estimated by Shiklomanov and Rodda (2003) approaching between 4,600 to 5,800 km^3 per year by the year 2025 and comparing this to the estimated volume of groundwater stored in the Earth’s crust approaching 23.4 million km^3, there also exists a perception that humans are using a miniscule proportion of the potential global groundwater resources.

Garret Hardin's "tragedy of the commons" is often referenced in discussions regarding the intensive use of groundwater leading to concurrent declines in water levels, formation pressure declines resulting in the "drying up" of qanats, springs, and geothermal resources, and water quality deterioration at locations across the globe (Hardin 1968; Kerr 1991; McCaffrey 2001; Pimental and others 2004; Jury and Vaux 2005). However, the nexus between common property theory and groundwater management and governance is not entirely clear due to the apparent difficulties in meeting both Elinor Ostrom's design principles of common pool resources and the challenges for "commons" management and governance, especially as it relates to the "open access" problems specific to groundwater resources (Ostrom 1990; Dietz and others 2003). Part of the problem focuses on developing approaches for groundwater management and governance that meet these principles and challenges for groundwater beyond the shallow basins in the United States that have historically served as the early case studies in the governance of groundwater as a common pool resource (Ostrom 1990; Blomquist 1992; Ostrom and others 1999).

Management and governance of groundwater are terms that are often used interchangeably in the literature focusing on the institutional aspects of groundwater resources. Groundwater management has traditionally focused on computer modeling of aquifer systems by hydrologists and water managers to predict hydrologic responses to "stresses" imposed by groundwater development to formulate and implement groundwater rules. Groundwater governance has been defined as a holistic approach of inclusion, taking into account the concerns of water scientists and engineers, policy makers, and groundwater users (Mukherji and Shah 2005). Few practitioners have suggested a coordinated plan of attack to address these management and governance issues for groundwater, due to the lack of knowledge regarding the spatial and temporal response of groundwater systems to intensive use even in the most studied groundwater systems in the world such as the Ogallala or High Plains Aquifer System in the United States. The groundwater governance challenge in transboundary aquifer systems is even more extreme given that only a few have coherent modeling programs in the world. For example, Struckmeir and others (2006) report that of the over 240 transboundary aquifer systems mapped by WHYMAP, only the Guaraní Aquifer System in South America, the Nubian Sandstone Aquifer System in North Africa, the Northwest Sahara Aquifer System, and the Lullemeden Aquifer System in Africa have coherent modeling programs.

In a review of water resources related research in the United States entitled *Confronting the Nation's Water Problems, The Role of Research* the National Research Council (2004) determined that much of the United States federal and state research funding has focused on short-term operational problems. In many respects, such as the renewed interest in building dams in the world, the same could be said of water resources-related research at the global scale. Given the future complexity inherent in water resources research, the National Research Council identified four themes that should be included in water resources research enterprises: (1) interdisciplinarity; (2) broad systems context; (3) uncertainty; and (4) adaptation. Interdisciplinarity acknowledges that questions regarding water resources must now be addressed outside the narrow confines of an individual discipline, and that it is necessary to address water resources problems within the natural and social scientific disciplines. Broad systems context addresses the entities that contribute to a problem, the linkages between the entities, the physical boundaries to the system, and linkages outside the system. Understanding and measuring uncertainty are part and parcel of groundwater resources investigations. Adapting to change is now more than ever a guiding principle for the dynamic natural resource and social environment.

In 2002, the National Groundwater Association suggested that the time had come for the field of groundwater hydrology to adopt a new philosophy by stating:

> “Corporate [Hydrology] must acquire competencies beyond those found in the earth sciences......Corporate must now grow "by acquisition" to deal with the realities of a global marketplace that values water as a commodity and for its in situ services. Integrating

> our traditional areas of expertise in the earth sciences with disciplines such as economics, policy and regulatory analysis, social science, and demographics allow Corporate to profit in several important ways...it gets us a "seat at the table" where decisions will be made about the future of the world...it gives us the chance to explain to a broader audience why ground water is central to the well-being of world populations...it gives license to the overwhelming majority of those doing hydrogeological research to continue to pursue the fundamental understandings" (Ragone 2002:457).

This dissertation attempts to meet the new challenges in the groundwater resources research enterprise by using an interdisciplinary approach integrating geology, geography, and political science to the address the emerging policy issues surrounding transboundary groundwater. I will first examine the history of geography as it relates to the history of the science of groundwater hydrology. This historical assessment establishes one of the linkages to the problem of transboundary groundwater – the connection of space and scale in the geography of groundwater. Likewise, I will build upon these linkages between geography and groundwater by expanding the discussion of space and scale to the management of groundwater as a common pool resource by inventorying the types of groundwater resource and user domains to expand upon the broad systems context of the physical boundaries of the problem of transboundary groundwater. Continuing on the path of broad systems context, I will show that groundwater resources are part of a hydrologic continuum that is connected to the oceans, and that while groundwater is hidden from view, there are many parallels between the ocean and groundwater regarding the uncertainties associated with predicting the hydrologic responses to change, and that perhaps the scientific and institutional lessons learned from managing the oceans can be adapted to groundwater resources.

Research on common pool resources such as groundwater attracts scientists from a broad spectrum of disciplines. Dietz and others (2002) suggest that the research in the commons can best be described as a "drama of the commons…because the commons entails history, comedy, and tragedy". Merriam-Webster defines a drama as “a composition in verse or prose intended to portray life or character or to tell a story usually involving conflicts and emotions through action and dialogue and typically designed for theatrical performance”. [2] The story of transboundary groundwater certainly fits within the definition of a drama.

As this dissertation focuses on groundwater resources, the first section approaches the drama of the commons through a comparative historiography of groundwater hydrology and geography. Recalling that interdisciplinarity determined by the National Research Council (2004) was one of the paradigms for research in water resources, the conventional wisdom over the past 60 years places groundwater resources squarely in the fields of geology and engineering. Yet the spatial and human connections to groundwater use on both the “stygoscape” or “underground landscape” as defined by Stanford and Gibert (1994) and the overlying landscape have long been recognized by geographers. It will be shown that a long tradition of interdisciplinarity exists between the two fields in an effort to dispel the long held myth that because groundwater is a “hidden” resource it is not part of the world studied by geographers.

The second section of the dissertation addresses the “comedy of the drama” by investigating the gap or incongruity between the geography of groundwater and the design principles of common pool resources developed by political scientists. One of the principal challenges between meshing the design principles of common pool resource theory and groundwater management and governance is clearly defining the boundaries for the user pool and the resource domain. The existence of a boundary is the first criterion for the individuality of an autonomous entity. Without clear boundaries of the groundwater resource, Moench (2004) reports that it is difficult, if not impossible, to evaluate the recharge and extraction mechanics associated with groundwater use. Yet a global analysis of international agreements and other legal

---

[2] http://m-w.com/dictionary/drama

instruments finds that the boundaries of groundwater resources and user domains are not differentiated and are traditionally lumped within the confines of a drainage basin, catchment, or watershed. Nations and states sometimes differentiate between groundwater resource and user domains by acknowledging the importance of boundaries in water allocation or protecting water quality. Yet the boundaries designated to preserve geothermal springs, groundwater-dependent ecosystems, and the spiritual boundaries of groundwater-dependent cultural icons are rarely addressed. And there is no recognition that the groundwater resource and user domain boundaries change with time as groundwater resources are developed, as the economics and technology associated groundwater pumping, and as the values of society change with time. My review of international legal instruments for freshwater reveals that groundwater resources are related to political boundaries and river basins in the early to mid 1980s, followed by the physical boundaries of the shared aquifers or related management units in the late 1980s through the 1990s and refined definitions of an aquifer, and the shared aquifer boundaries emerge after 2000. Likewise, on the basis of my examination of management approaches at the nation and state level, I propose a previously unrecognized typology for the boundaries for groundwater resources and user domains.

The third section of the dissertation examines the “tragedy” of the poorly structured institutional capacity built within river basin treaties and agreements and River Basin Organizations accommodate governance of groundwater and transboundary aquifers. Despite many agreements and international laws acknowledging the growing significance of groundwater resources, transboundary aquifers are usually only addressed in a cursory, poorly defined manner due to a lack of consensus regarding applicable international law to international groundwater resources. The literature is replete with references to managing or governing groundwater through Integrated Water Resources Management (IWRM)[3] or Integrated River Basin Management

---

[3] The concept of sustainability and Integrated Water Resources Management were discussed at the International Conference on Water and Environment Issues for the 21st century in Dublin, Ireland in

(IRBM), yet these approaches tacitly imply that the groundwater systems are understood and can be managed in a comprehensive manner by presuming an ability to identify and quantify the nature of surface water – groundwater interactions and to define the boundaries of both hydrologic systems clearly (Moench and others 2003). While the International Groundwater Assessment Center (IGRAC) is in the process of developing the Global Groundwater System[4] for purposes of providing decision makers with a comprehensive listing of management approaches for groundwater by nation or state, the integrated inventory of identified transboundary aquifer systems, the geographic location of the transboundary aquifers within the international river basins, and the freshwater treaty or agreement fixed to the respective international river basin that has provisions for groundwater resources that I compiled for this study is the first of its type for assessing how groundwater and surface water are treated in the emerging arena of transboundary groundwater management and governance.

The fourth section of the dissertation looks at the “comedy of errors” between the governance of groundwater and the oceans and concludes the drama by asking the question: What can be learned from the past that can be applied to the present while incorporating the paradigm shift in water resources research to include (1) interdisciplinarity; (2) broad systems context; (3) uncertainty; and (4) adaptation? While groundwater hydraulic theory dictates that the boundary for the groundwater user domains varies spatially with time, little attention is paid to the vertical dimension of a groundwater resource domain. Much is written about how groundwater and surface water are a single resource (Winters and others 1999), yet the reality of the situation is that shallow groundwater is managed differently than deep groundwater and “fossil” groundwater where groundwater ages range from 100s to 1000s of years due to the lack of active recharge (Foster and others 2005). One

---

1992, the Earth Summit sponsored by United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil in 1992 resulting in Agenda 21.

[4] http://www.igrac.nl/

approach to solving this vexing problem is to adopt the concept of global groundwater regions or the “megawatersheds” model for groundwater catchment areas. Adoption of such a conceptual model for the boundaries of the user pool may serve as the foundation for a global groundwater governance model for the great “Hidden Sea” underlying the visible world (Chapelle 2000). The United Nations Conferences on the Law of the Sea of 1982 (UNCLOS) is the product of decades of negotiations between many sovereign states. Since 1996, the UNCLOS has been a functional reality, arbitrating complex issues pertinent to environmental protection (habitat protection, marine environments and prevention of transboundary pollution), defense, and mining (shared data from mining enterprises). The paradigm shift in the focus of water resources research proposed by the National Research Council (2004) was addressed during the negotiations by the UNCLOS. With 97 percent of the global freshwater resources found as groundwater, I will show that the UNCLOS serves as a template for governing the “underground heritage common to the land” through a “Law of the Hidden Sea”.

Chapter Two: The Geography of Groundwater

Abstract

Geographers traditionally focus on the human-land connection to the surface landscape. Geologists and engineers traditionally investigate the subsurface for the occurrence of groundwater for drinking water, contaminant transport, or dewatering for construction. A common misconception held by some experts in land use management is that groundwater does not have a footprint on the surface landscape and is therefore not important to geographers. This chapter is designed to dispel the myth that groundwater hydrology is strictly a field of study for geologists and engineers using a comparative historiography of geography and groundwater hydrology. I will show that both fields have a common heritage and that some of the early mathematical concepts in groundwater hydrology were developed by geographers. The stygoscape or “hidden landscape” associated with groundwater shapes the surface landscape by creating landforms that geographers study in the physical world, shapes the cultural landscape through identity with groundwater which is of interest to the human geographer, and shapes land use that geographers study in the political world. A rich tradition of interdisciplinarity exists in both fields of study; however, with the governance of groundwater emerging as an important facet of global water resources development, it will be shown that an asymmetry of knowledge exists within groundwater hydrology. The asymmetry of knowledge has reached a point where it is time to fully integrate the resource, user, and institutional perspectives with the physical and chemical facets of hydrogeology - well-trodden ground for resource geographers.

Introduction

Humans’ reliance on groundwater spans over thousands of years. According to Galili and Nir (1993), the oldest well was constructed over 8,000 years ago in Atlit Yam, Israel using dry-stone walling that reached a diameter of 1.5 meters and a depth of 5.5

meters. The Persians constructed horizontal wells or “qanats” several kilometers in length as early as 5,000 BCE[5] (Wulff 1968). The history of groundwater reveals that groundwater was tapped where people were located rather than people locating where groundwater was abundant.

The study and management of groundwater resources has traditionally been left in the hands of geologists and engineers (Mukherji and Shah 2005). The paucity of research on groundwater by geographers suggests some truth to a statement by geographer I. Burton, one of the pioneers leading the quantitative evolution of geography: “Geography has long been a “following” rather than a “leading” discipline.” (Burton 1963). Yet history reveals that some of the early theoretical work in groundwater hydrology was developed by geographers. The two fields of study diverged as the study of groundwater focused on the mathematical theory of groundwater flow while the field of geography became more concerned about the relationship between human and physical phenomena. The asymmetry in the drama between social scientists and groundwater hydrologists that has apparently developed over the past 50 years is best summarized by William Blomquist in his book *Dividing the Waters*:

> “The attorneys recognize and write about how much the physical characteristics of groundwater basins differ, and how much those specific differences matter, while engineers observe how much the legal, economic, and political circumstances of groundwater basins differ, and how much these specific differences matter. For all those involved, it has become clear that much of what needs to be known and taken into account in managing groundwater systems lies beyond the ken of their discipline or profession and that the fundamental problem is how to make use of knowledge not given to anyone in its totality” (Blomquist 1992:25).

A comparative historiography of geography and groundwater hydrology illustrates the historic perception that groundwater was once considered part of the global commons associated with the oceans. Likewise, the historical analysis underscores

---

[5] According to Webster’s Dictionary, CE refers to Common Era, and BCE refers to Before Common Era. http://www.m-w.com/dictionary/

that geographers are an integral part of the solution to the management and governance of global groundwater resources, especially with the convergence of the two fields in the past 50 years. The convergence is due to the perception of groundwater depletion and degradation by human use of groundwater and land use overlying the groundwater resources. With the advent of modern spatial data analysis and visualization technology, the once "invisible" resource domains are now mappable. The circuitous route for an interdisciplinarity approach to water resources research that the National Research Council (2004) recommends for the efficient management and governance of groundwater resources reaches closure for geography and groundwater hydrology in the new millennium.

Groundwater and Geography: A Comparative Historiography

Antiquity

Both the history of groundwater and geographic thought can be attributed to Homer's writings of nearly 3,000 years ago. Martin and James (1993) indicate that ancient scholars consider Homer to be one of the "Fathers of Geography" as a result of his poem the *Odyssey*, while Meinzer (1942) credits Homer with initiating groundwater theory by recognizing the hydrologic cycle – "With Jove neither does King Achelous fight nor the mighty strength of the deep-flowing Oceanus, from which flow all rivers and every sea and springs and deep wells".

The first thousand years of thought in groundwater and geography were shared by the ancient philosophers. During the fourth century BCE, Aristotle developed the "Theory of Natural Places" which defined earth space as the natural space for water. He also developed the theory that subterranean condensation was responsible for springs, apparently ignoring Homer's earlier work on the hydrologic cycle (Meinzer 1942). Little is reported about the development of groundwater theory by others at this time, but it is certain that the Persians understood some of the fundamentals of groundwater flow by virtue of the expansion of qanats in the Middle East during the fourth to sixth centuries BCE (Waterhistory 2003).

The next meeting of the two fields within the first century CE occurred with the work of Roman philosopher Pliny the Elder. From the geographical perspective, Pliny is famous for compiling a geographical encyclopedia (Martin and James 1993). Pliny's contribution to groundwater theory actually was a restatement of the "seawater concept" developed by Greek philosophers – springs are the manifestation of seawater that has been conducted through subterranean channels below mountains, purified through condensation, followed by rising to springs (Meinzer 1942). A new theory of the hydrologic cycle of rain and snow infiltrating the ground surface and eventually discharging as springs was originally developed by Roman architect Vitruvius (Meinzer 1942).

The Middle Ages

The Middle Ages served as a hiatus in developing theoretical concepts in geography in the Christian world with the word "geography" apparently disappearing from the idiom of Christian Europe (Martin and James 1993). The monasteries apparently preserved historical geographic information with the objective of reconciling natural ideas with the Scriptures. Groundwater theory was no exception; philosophers and interpreters of the Scriptures proffered the seawater concept as described in Ecclesiastes 1:7 – "All streams flow into the sea; yet the sea is not full. To the place the streams come from, there they return again" (Meinzer 1942). While geographic and hydrologic theory during the Middle Ages in Christian Europe concentrated on interpreting the work of Aristotle and Ptolemy, Persian scholar Mohammed Karaji described the techniques of qanat builders in the 10th Century CE underscoring that some of the fundamentals of groundwater flow were understood and being developed during the Middle Ages (Martin and James 1993; Waterhistory 2003).

Early Modern Period

While the 13th to 18th centuries can be generally classified as the age of exploration in geography, this same time period served as the founding of groundwater hydrology as a science (Martin and James 1993; Meinzer 1942). DaVinci lived during this period and his natural observations are legendary. DaVinci lived in the town of San Pellegrino located in the mountains north of Milan, the source of the famous San Pellegrino spring water that is sold as bottled water. DaVinci rekindled the concept of the hydrologic cycle developed by Vitruvius nearly 1,400 years earlier. During this time period the field of geography was developing rapidly as maps quickly evolved. However, the development of the hydrologic science did not advance at the same pace. This was due in part by the acceptance of divining or “water witching” in Europe to locate groundwater (Ellis 1917; Meinzer 1942).

Given the uncertainty in the historic literature, Meinzer (1942) followed by Narasimhan (2005) suggest that the science of hydrology may be better attributed to French physicists Palissy, Perault and Mariotte and to the English astronomer Halley during the late 1500s and early 1600s. Palissy was the first to argue that springs were derived by rainfall (Narasimhan 2005). Perault and Mariotte worked on the Seine River basin and ascertained that (1) the quantity of rainfall in the river basin was nearly six times greater that the river discharge, (2) rain and snow percolated into the pores of the earth and accumulated in wells, (3) the flow of springs increased in rainy weather and diminished in drought, and (4) springs with more constant flows were derived from underground reservoirs (Meinzer 1942). Halley made observations on the rate of evaporation from the Mediterranean Sea and calculated that the quantity of water derived from evaporation was sufficient to supply the observed flows of streams discharging into the sea (Meinzer 1942).

The first major convergence between the evolution of geographic and groundwater theory was in the mid 1600s with the Cassini family. Giovanni Cassini was the eldest of four generations of Italian astronomers and geographers who managed the astronomical observatory in Paris, France (Martin and James 1993). Cassini and later generations were primarily responsible for the first topographic survey of France (Martin and James 1993). Cassini developed the hydrostatic theory of artesian pressure – the concept of groundwater stored under pressure in permeable rocks overlain by rocks of lower permeability, which keeps water from flowing at the ground surface until the water bearing rocks are penetrated by a well - before the principles of geology were developed nearly 100 years after his death (Meinzer 1942).

While the pioneering hydrologic theories and mapping work by the Cassinis provide some of the first evidence of groundwater theories being developed by geographers, the concept of the importance of groundwater to a place was developed nearly simultaneously by Bernhardus Varenius in the mid 17th century. Varenius developed the concepts of special geography and general geography. General geography focused on the physical attributes of the earth surface – the wind, the water, the forests, the deserts – fields of study that can be modeled by mathematics. Special geography required the direct observation of the human properties of a place – the relationship between inhabitants of a place with their surroundings. It could be argued that Varenius may have recognized the human-environment interaction or the man-land tradition of American geographic thought as described by Pattison (1964) as it relates to humans and groundwater.

Quantitative hydrology commenced about the same time as geographers recognized that landforms reflect the subsurface rock structures. Bernoulli developed an equation in the mid 1700s permitting the calculation of groundwater velocity about the same time geographer Strachey recognized the relationship of landforms to the subsurface regime (Meinzer 1942; Martin and James 1993). The science of geology evolved quickly with Hutton's principle of Uniformitarianism or the "present is the key to the past" and Smith's pioneering work on geologic mapping and the application to hydrology.

Modern Period

As changes in the foundations in groundwater theory began to change with the advent of the science of geology in the late 1700s and early 1800s, so too did the classical geographic studies. German geographers Alexander Von Humboldt and Carl Ritter are frequently referred to as the catalysts for bringing about the end of the Classical Era in geography and the emergence of the Modern Era (Martin and James 1993). Von Humboldt pioneered much of the research on the human-environmental relationship to water resources. His writings during 1814 to 1825 on the effects of deforestation and the occurrence of springs reveals some of the earliest observations of the human impacts on groundwater systems "When forests are destroyed, as they are everywhere in America by the hands of European planters, the springs are reduced in volume or dry up entirely" (Martin and James 1993:117).

Carl Ritter's work at this same time initiated interest in "scientific geography" and pioneered the concept of earth science. Ritter's earth science differed from Smith's and Hutton's study of geology in one important aspect – Ritter saw the earth as the home of man and harmony of man and the earth as the result of "God's Plan" (Martin and James 1993). Little is mentioned in the historic literature regarding Ritter's philosophy regarding the interaction between humans and groundwater. Chapelle (2002) indicates that rational methods for locating groundwater did not evolve until the 1850s. Given Ritter's belief in the unity of man and nature, coupled with the abundance of research on clairvoyance and the divining rod by European scholars during Ritter's professional life as summarized by Ellis (1917), it is possible that he embraced the concept of a human connection with the hidden resource.

The Modern Ages of Groundwater and Geography dating from the mid 19th century were not only inspired by the establishment of universities that promoted specialized fields of study, but also by the increased needs for natural resources including water supplies as well as river and canal transportation (Meinzer 1942; Martin and James 1993). The fundamental law of groundwater flow through porous media was developed in the mid 1800s by Henry Darcy while working on water projects for Dijon, France. At about the same time, geographer George Marsh recognized the destruction of the land by humans. He followed in the footsteps of von Humboldt by recognizing the widespread changes in the natural environment as a by-product of deforestation (Martin and James 1993). While the scientific community apparently did not pay any heed to Marsh's warning until the early 1900s, the field of groundwater hydrology was rapidly maturing through the recognition of Darcy's law – $Q = KiA$ - a simple relationship determining that the rate of flow of water was a function of the hydraulic conductivity of the filter media (sand), the hydraulic gradient (change in hydraulic head divided by length of flow path used to measure hydraulic head), and cross sectional area. For example, A.J. Dupuit uses Darcy's law as the foundation for predicting the head loss around a well due to pumping in 1865 (Narasimhan 2005). German hydrologist Adolph Theim developed field methods for measuring groundwater flow, ultimately making Germany one of the leading countries to rely on wells and springs for over 85% of its water supplies by 1870 (Meinzer 1942). Groundwater was also recognized for its importance to international water supplies where the term "spring" was used in the Treaty of Limits between Portugal and Spain in 1864, and the term "well" was used in 1888 in the Agreement between the Government of Great Britain and France with regard to the Somali Coast (Matsumoto 2002).

Studies of groundwater in America in the late 1800s were primarily limited to individual state geological surveys and the period of "The Great Surveys" of geologists Clarence King, George Wheeler, John Wesley Powell and others (Meinzer 1942; Martin and James 1993). The formal beginning of groundwater hydrology as a field of specialization was developed by T.C. Chamberlain in connection with his work on artesian wells in Wisconsin in the late 1870s (Meinzer 1942). Chamberlain also developed the concept of "multiple working hypotheses" as it relates to hydrogeologic work (there may be more than one right answer to explain the observed phenomena). It is a concept that underscores the philosophy of interdisciplinarity espoused by the National Research Council (2004), but often overlooked by contemporary geoscientists.

By the 1890s, John Wesley Powell was presenting his landmark work on the arid conditions of western North America and the influence of water on the settlement of the west to the United States Congress. Powell not only wrote on the artesian conditions and groundwater prospect in the arid west (Meinzer 1942), but also apparently was concerned about the human impacts to the land (Martin and James 1992). Within a decade of Powell's warning, geographer Nathaniel Shaler echoed Powell's concerns about the destructive effect of humans on land and nonrenewable resources in 1905 (Martin and James 1993). With the advent of the deep well turbine pump in the United States around 1907, groundwater became an inexpensive alternative to surface water for irrigation in the west and Shaler's prescience was realized by an over-production of groundwater within a few decades (Narasimhan 2005).

Shaler worked with another prominent geologist of the early 1900s, William Morris Davis. Davis was instrumental in developing the field of geography focusing on the evolution of landforms. Davis's formula for describing landforms focused on the structure of the underlying rock (obviously building upon the earlier work of

Strachey), processes such as erosion, dissolution by groundwater (in areas where limestone or karst is prevalent) and gravity, and the stage of the development of the landform at some point in time (Martin and James 1993). And while it appears that the fields of groundwater hydrology and geography converge on a major theme of water resources, the cause and effect of water on the evolution of landscapes, Davis sought a different path. He considered the relationship between humans and the environment – a relationship "between some inorganic element of the earth on which we live, acting as a control, and some element of the existence or growth or behavior or distribution of the earth's organic inhabitants, serving as a response." Davis was promoting the paradigm shift in geographic thought from natural science to environmental determinism and regional studies that predominated geographic thought from 1892 to 1925 (Martin and James 1993). Ellen Semple promoted similar ideas in her discussions of humans and the importance of the earth's environment on patterns of settlement (Martin and James 1993). While the science of groundwater hydrology is connected with the development of human society, the concept of environmental determinism is not consistent with the history of groundwater development. Groundwater was developed where people were located rather than people locating where groundwater was abundant.

Carl Sauer's "regionalism" approach to geography was introduced in 1925 and focused on the investigation of "things associated are on the earth's surface and with the differences from place to place" (Martin and James 1993:346). Heath (1988) indicates that hydrogeologists also recognized the importance of comparative regional studies of similar groundwater conditions in different areas of America as early as 1905. However, the major difference between regionalism as defined by Sauer and by the hydrogeologic community was that Sauer recognized that humans can transform the natural surroundings, creating a "cultural landscape" (Martin and James 1993). Sauer's concepts were prescient as groundwater development transformed desert environments to agricultural landscapes, as well as causing subsidence of the same landscape by virtue of groundwater development.

Post modern Period

While field and regional studies prevailed in the field of geography from 1925 to 1957, this same period saw a rapid maturing of the quantitative era in groundwater hydrology (Martin and James 1993). In the 1930s, Charles Theis developed the "Non-Equilibrium" formula which permitted prediction of the change in water level in the vicinity of a discharging well as water was removed from storage in an aquifer (Theis 1940; Meinzer 1942; Narasimhan 2005). The hydrologic significance of this formula was that the permeability and storage characteristics of the aquifer could be quantified, thus allowing the calculation of the extent of the hydraulic cone of depression or "zone of influence" imposed by extended pumping – the initial recognition of a geographic footprint on the underground landscape. More importantly, Theis's conceptual model also described that wells "capture" groundwater in storage, and that some groundwater was always "mined" from the aquifer during pumping. This fundamental equation and conceptual model served as the cornerstone for assessing the performance of aquifers, groundwater basins, and regional studies completed from the 1950s to today.

In tandem with the developments in well hydraulics was research into regional groundwater motion. In the 1940s, M.K. Hubbert interpreted groundwater systems bounded by groundwater divides and impermeable barriers. Narasimhan (2005) indicates that with the advent of testing underground nuclear devices in Nevada during the 1950s, I. J. Winograd presented early evidence of deep interbasin flows beneath many watersheds and extending over thousands of square kilometers setting the stage for the concepts of "megawatersheds" later posited by Bisson and Lehr (2004). In the 1950s, there was the perception of abundance as the center pivot irrigation system was invented to take advantage of the "unlimited" groundwater resources stored in the Ogallala Aquifer underlying the Great Plains of the midwestern United States (Aucoin 1984). Federal water development projects were undergoing a boom during this decade fitting with what Freeze (2000) describes as the “Age of Carelessness” and the “Throwaway Society”. However, Cressey (1957) recognized it was “time that geographers do something about the world rather than merely to describing what anyone can see” and challenged geographers to get a “seat at the table” to help plan for future water security.

Cressey (1957) recognized that groundwater can be mined by pumping and that groundwater can conquer and push back the desert, but cautioned that the victory may be short-lived. He suggested that geographers should be involved with developing water budgets and posited that the longer that rainwater that recharges aquifers remains underground, the potential for salinization of the groundwater increases, suggesting that groundwater should be utilized as opposed to stored for later use. Cressey also suggested that the knowledge of groundwater hydrology may be more important than surface water hydrology in arid areas and recognized the value of qanats in draining aquifers by gravity. However, he was also cognizant that deep wells only develop an “artificial oasis” and “tend to exhaust ground water resources faster than they accumulate” (Cressey 1957). Cressey suggested that the value of geographers practicing in the 1950s was their use of skills in weighing physical and cultural factors in developing arid lands, and that “wise planning is impossible without a sound geographic inventory.” Tòth (1963) proposed the initial conceptual models of shallow, intermediate, and deep groundwater flow systems that served as the foundation for the conceptual models of continental scale groundwater flow systems developed by Garven (1985).

Both groundwater and geography have experienced what has been termed “eclectic pluralism” from the mid 1950s to the present (Martin and James 1993). Both fields continued to expand in quantitative arenas as computers evolved. Interest in water resources increased during the 1960s, perhaps in response to changes in the perception of natural resources and use that occurred during the 1960s described as the “Age of Awakening” as the Environmental Protection Agency was established (see Freeze 2000; Lucas 1964). Perhaps the first mention of potential conflicts over water appear in the geographical literature with the work of Karan (1961).

The new focus on the environment during the 1960s set the foundations for regulatory changes in America that permitted both fields to study human-environment interactions. During the 1970s geographers were aware of the changing environmental perspectives and regulations during the “Age of Awareness and Action” as described by Freeze (2000). Freeze (2000) characterizes this period as one in which regulations governing clean water, safe drinking water, and resource conservation were established. Borchert (1971) indicated that droughts may occur during the 1970s as a by-product of human induced climate change, thus potentially causing a “dust bowl” comparable to that experienced in the Grasslands during the 1930s. He suggested that the Grasslands farmers’ of the 1960s “faith in luck and water-witching” were important considerations in the behavior of farm settlement and population patterns during the early 1970s, and that “new” drought would require “more wells and deeper wells” as likely adjustments to farms. However, the water ethic for cities located in the Grasslands would also shift towards purchasing land simply for the water rights and groundwater stored beneath the land, and that administrative agencies would eventually have to set priorities between irrigation and urban uses to combat water conflicts (Borchert 1971:20). Borchert believed that the next drought would not only change the geography of the Grasslands, but also the perception of its geography. Muckleston and Highsmith (1978) studied the transformation of the landscape in eastern Oregon associated with irrigation of the Columbia River Basin of the United States. Aucoin (1984), Kromm and White (1992) and Roberts and Emel (1992) completed comparable studies in the High Plains region of the United States.

The evolution of land use planning in the 1960s and 1970s set the stage for Geographic Information Systems (GIS) in the 1980s (Clarke 2001). The 1980s were described as the “Age of Disillusion” by Freeze (2000) as the “Superfund” legislation became law and the fields of groundwater and geography converged once again to undertake the next challenge facing humanity – protecting the high quality of water stored in America’s groundwater basins under amendments to the Safe Drinking Water Act (Bice and others 2000). Groundwater was part and parcel of the land use planning studies and more sophisticated numerical models were developed to analyze groundwater flow.

The 1990s were described as the “Age of Reaction” by Freeze (2000) - a decade typified by the Earth Summit in Rio and the environmental concepts embraced at the time focused on sustainability. Wilbanks (1994) recognizes that sustainable development:

> “…connects remarkably well with our (geographers’) heritage and our strengths as a discipline. It is defined by relationships between human and physical processes. It relates nature-society issues to spatial pattern issues. It can draw from both location theory and social theory. It is linked directly to may of the same questions that underlie society’s recent rush of interest in geography – globalization, environmental problems, and applications of GIS.”

Wilbanks (1994) underscored that during this era of globalization, scarcity, information and democratization geographers are to serve as teachers “who advocate the principles of economic fairness and nature-society balance”. Groundwater hydrologists responded to the sustainability issue by recognizing that many of the previously derived policies on what was considered a “safe yield” from aquifers were not sustainable and suggested that researchers “must cross the boundaries of their individual disciplines…for help in defining a practical context for research. A strong public education program is also needed to improve understanding of the nature and complexity of ground-water resources” (Sophocleous 1997). It would appear that the technical gap between groundwater and geography was beginning to close during the 1990s.

The New Millennium

Looking to the past to help plan the future becomes the focus geography and groundwater in the new millennium. Graf (2001) suggests that ecosystems defined by watersheds provide the most useful geographic units for restoring the physical integrity of rivers – the boundaries of watersheds for determining the boundaries of land management units and "watershed commonwealths" in the west was a notion initially proposed by John Wesley Powell (Hutchison 2000). Many of the problems facing management and restoration on America's rivers cited by Graf (2001) appear similar to the challenges facing extensively exploited aquifers (Llamas and Custodio 2002). As described in more detail in the following sections, one of the largest challenges is the delineation of the spatial boundaries of groundwater resource domains because groundwater flows don not observe state boundaries and depending on the boundary conditions of the aquifer, can often time flow cross watershed boundaries (Matsumoto 2002; Struckmeir and others 2006).

Today, water resources geography is increasingly specialized as compared to the classic river basin studies of the 1920s and 1930s (Platt 1993). And so we reach the final convergence of groundwater and geography. Strassberg (2005) meshes the GIS tools of the geographer with groundwater hydrology with the development of a geographic datamodel for groundwater systems. Shiklomanov and Rodda (2003) followed by Zekster and Everett (2004) inventoried the world groundwater resources for the new millennium. Struckmeir and others (2004; 2006) assembled the first global GIS maps of the groundwater resources of the world and the transboundary aquifer systems of the world to assist in the sustainable management of groundwater. Both intranational and international programs recognize the critical need to collect enormous volumes of spatially-registered data on groundwater (Puri and others 2001; Matsumoto 2002; Glennon 2002; FAO 2003; Struckmeir and others 2004; 2006). Yet because society has not organized around hydrological boundaries, political boundaries serve as one of the largest hindrances to sharing data on surface water and groundwater resources (Robertson 2004).

On the basis of the foregoing discussion, much of the historical "learning" about groundwater focused on the physical and chemical properties of the resource with the social "learning" of the institutional and user perspectives of groundwater management garnering attention only within the past few decades. Groundwater use has changed the socio-ecology of many cultures with the advent of vertical well technology and inexpensive power to pump the resource (Lightfoot 2003; Mukherji and Shah 2005). The uncertainty associated with managing a hidden resource requires rethinking of groundwater management as the intensity of development increases with increased need for food security (FAO 2003). Geographers, economists, and political scientists have recognized the asymmetry of groundwater knowledge (Blomquist 1992; Mukherji and Shah 2005). With global groundwater knowledge historically focusing on development, there is an urgent need for expansion in the knowledge base in groundwater resources, especially through the inclusion of the soft sciences linking economics, policy and institutions to the hard science of hydrogeology and groundwater engineering (see Figure 1). The Alicante Declaration[6] recommended that it was time for the world to develop a comprehensive understanding of groundwater rights, regulations, policy, and uses especially where groundwater crosses cultural, political, or national boundaries (Interacademy Panel 2006). Emerging trends in the geography of groundwater include (1) managing conflict (Adams and others 2003; Thomasson 2005), (2) the "silent trade" of hazardous wastes (Jurdi 2002), and (3) developing and implementing rules and regulations for groundwater management and governance, including the preserving the physical and chemical integrity of aquifers.

---

[6] The Alicante Declaration was developed by the Interacademy Panel (IAP) Water Program during the International Symposium on Groundwater Sustainability (ISGWAS). Alicante, Spain, on January 23rd-27th, 2006.

Conclusions

This chapter used a comparative analysis between the history of geography and groundwater hydrology to dispel the myth that the two fields of study have little to no overlap. On the contrary, the two fields have common beginnings and converged often throughout history. The myth on the divergence of the two fields has focused on the quantitative nature of groundwater hydrology over the past 60 years, whereas during the same time period geographers appeared to become more focused on linking the human aspects to land use and water development through techniques such as GIS.

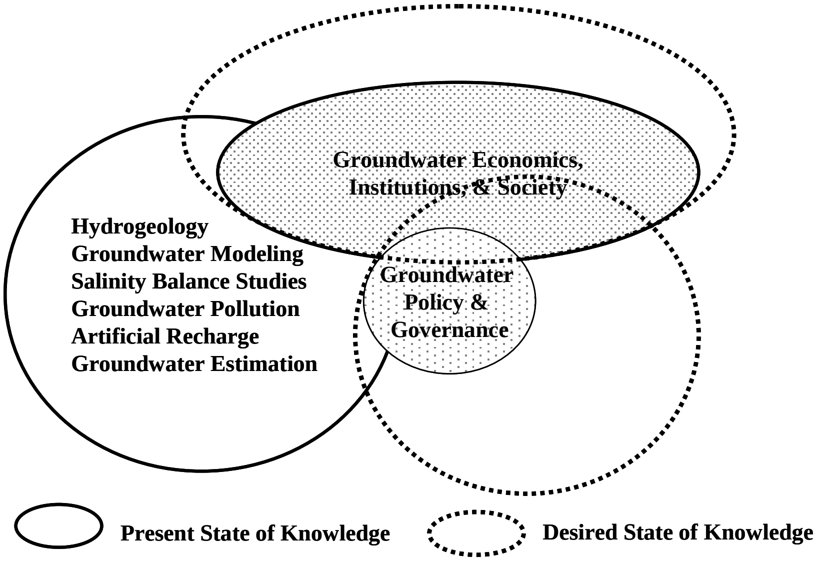


Figure 1. Knowledge Development Challenge of Groundwater Management (modified after Mukherji and Shah 2005. Used with kind permission of Springer).

Accordingly, hydropolitical scientist William Blomquist stated the future of both fields best by indicating “it has become clear that much of what needs to be known and taken into account in managing groundwater systems lies beyond the ken of their discipline or profession and that the fundamental problem is how to make use of knowledge not given to anyone in its totality” (Blomquist 1992:25). Geographers have a rich tradition of using an interdisciplinarity approach to problems in the earth sciences, but they must acquire competencies beyond those found in the traditional arena of geography to effect change in groundwater resources management and governance. Geographers must “grow” into groundwater hydrology by acquiring skills in geology and mathematics to deal with the realities of working in a multi-dimensional environment. Likewise, groundwater hydrologists need to recognize that while increasing the knowledge of the physical, chemical, and biological aspects of groundwater resources is important, the global marketplace demands that increased knowledge be acquired in the disciplines such as economics, policy and regulatory analysis, social science, and demographics typically found in the geographers toolbox. A more focused integration of skills found in geography and groundwater hydrology will get geoscientists a “seat at the table” where decisions will be made about the future of the world.

Chapter Three: Groundwater and the Commons

Abstract

The “tragedy of the commons”, or the lack thereof, as it relates to groundwater resources is a concept that is debated among practitioners in many academic disciplines. Design principles for the management of common pool resources developed over nearly three decades of research on the commons promote the clear definition of the boundaries for the user pool and the resource domain as key to the organization of individuals and groups in managing common pool resources. While groundwater resources have received much attention in the literature on common pool resources, political geographers have been relatively silent on the issues of how boundaries of the groundwater resources and user domains are drawn. This chapter focuses on a two research questions: (1) How are boundaries placed around groundwater resources and user domains?; and (2) Do these boundaries change through time? An interdisciplinarity and broad systems context approach is used to answer these questions where I mesh the principles of common pool resources management developed by political scientists and economists with the principles of geology, hydrology, geography as they relate to boundaries and space. The chapter first addresses the importance of identity and place associated with groundwater resources. This is followed by an inventory of groundwater resource and user domains that are described in the literature. I define a typology of resource and user domains which classifies domains as *bona-fide* boundaries, or naturally occurring boundaries that are traditionally recognized under the concept of the “commons” for groundwater resource domains. The typology further defines two types of *fiat* boundaries or user domain boundaries: the first is the “hydrocommons” or the boundaries associated with meshing hydraulics with hydrology; and the second is the “commons heritage” or the boundaries representing the various social and cultural aspects “using” groundwater resources. I will show that drawing boundaries for the groundwater resource and user domains is technically and politically complex and is value-dependent.

Introduction

Water is the essential substance that continues to be a source of inspiration. In the *Odysseus,* the *Iliad*, the *Bible,* and other fundamental texts, water plays an important part in molding physical and human places and space (Altman 2002; Weir and Azary 2001). The Hopi Nation traditions consider the birth of their people to have been from a spring within the Grand Canyon called the Sipapuni or the "place of emergence" (Hopi Nation 2003). Thermal springs developed by resorts have been sought by the sick for their perceived medicinal powers of healing (Chapelle 2000). Bottled water from springs is perceived to be healthier than tap water; the perception serves as the foundation for a global industry worth billions of dollars per year (Glennon 2002). Variations in groundwater chemistry in aquifers underlying the United Kingdom have been responsible for the establishment of the brewing industry, particularly with respect to the locations of breweries making ales and lagers (Lloyd 1986). "Finding" groundwater is considered by many to be a gift endowed to those with powers of magical divination (Vogt and Hyman 1979). In Islamic tradition, groundwater wells stand for paradise (Fontana 1993).

The use of groundwater has changed landscapes and economies from deserts to irrigated agriculture, from barren landscapes to metropolitan areas such as Las Vegas, Nevada and Tucson, Arizona, from everglades to sunken pits in Florida, and immense valleys that have subsided from meters to tens of meters as measured in the Imperial Valley of California (Cressey 1957; Glennon 2002). The recognition that groundwater can be hydraulically connected to surface water resources is leading to recommendations on policy reforms as increased reliance on groundwater can degrade wetlands, streams, rivers and lakes (Glennon 2002). Conversely, impounding of surface water and its negative impacts on aquifers also is leading to new research by geographers interested in chronicling changes in ancient agricultural landscapes once irrigated by groundwater drained by qanats (Lightfoot 2003).

Geography is considered a spatial science, but the spatial connection to groundwater is not recognized by many geographers. Tobin and others (1989) indicate that geographic research on groundwater "significantly and importantly departs from the neoclassical-economics and political-science approaches to resources management" suggesting the reasons for the relative absence of research in the spatial relationship associated with the use of groundwater resources. Beach (1990) echoed this observation by suggesting that few geographers addressed spatial issues on the sampling and water quality management of groundwater. The spatial problem is multidimensional, incorporating two dimensional spaces traditionally addressed by the geographer through maps, the vertical dimension traditionally the realm of the geologist, and integrating both with time.

Groundwater is becoming an increasingly important source of water for the agricultural, industrial and domestic sectors, yet the academic study of groundwater has developed only over the past 60 years. Groundwater now accounts for more than half of all water consumption in many regions of the world. Much of the current use and future anticipated growth in groundwater use is occurring across intranational and international borders (Burke and Moench 2000; Matsumoto 2002; Struckmeir and others 2006). Despite the rich history of human reliance on groundwater and its profound influence on landscapes, geographical research and institutional collective measures for cooperation focusing on groundwater both domestically and abroad are in an embryonic stage (Matsumoto 2002; Burchi and Mechlam 2005; Yamada 2005).

Given the human-environment interaction with the use of groundwater, coupled with the spatial relations between the two, groundwater management and governance becomes a classic "commons" problem described by Giordano (2003). Dietz and others (2002) indicate that the past 30 years of research in the commons reveals a "drama of the commons…because the commons entails history, comedy, and tragedy". Despite the substantial body of geographic literature surrounding the historical, cultural and political development of boundaries (e.g., Jones 1959; Kristof

1959), it is ironic that few political geographers have addressed the problem of how boundaries are placed around common pool resources, particularly groundwater resources. I hypothesize that drawing boundaries around groundwater resources and users domains is technically and politically complex and is overprinted with values that change with time. I test this hypothesis by asking two questions: (1) How are boundaries placed around groundwater resources and user domains?; and (2) Do these boundaries change through time? I use an interdisciplinarity approach to answer these questions drawing upon common pool resource theory developed by political scientists and economists. This is followed by an analysis of geographical theory specifically on the significance and types of geographic boundaries. I then discuss how groundwater hydrologists define boundaries for groundwater resources and the boundaries that are created through the development of groundwater. Finally, I will show that the legal and legislative boundaries for groundwater resources and user domain boundaries rarely acknowledge the hydrogeologic reality that groundwater flow ignores political boundaries and that the boundaries are transient as the resource is developed, and as social values for groundwater change. What emerges from my research is a typology of boundaries that differentiates between naturally occurring, or *bona-fide* boundaries, in groundwater resource domains, and *fiat* boundaries, or domains created by groundwater users.

Groundwater and the Commons

Groundwater is a resource that is found everywhere. Groundwater use is increasing because it is a “commons” resource, available to anyone with the financial resources to drill, equip, and power a well (Tobin and others 1989; Dietz and others 2002; Moench 2004; Muhkerji and Shah 2005). The commons refers to resources, facilities, or property institutions with some aspect of joint ownership and access. Common pool resources are valued resources that are available to use by more than one person and subject to degradation due to overuse. Buck (1998) further refined the definition of common pool resources to include “subtractable” resources managed under a property regime in which a legally defined user pool cannot be efficiently excluded from the resource domain. Open access common pool resources are those resources with no property rights or definitions on how the resource is used (Dietz and others 2002; Giordano 2003).

Institutions specify who has access to resources and who does not. Common pool resources that do not have institutions governing their use are open access regimes (Dietz and others 2002). Other classes for institutions governing use include (1) private property; (2) common property; and (3) government property. Government property typically refers to a national government that owns the property and directly uses and manages that resource for its own purposes. Or, the resource may be owned by a national, state or local government, but users have rights to access, withdraw, manage, and determine the others that may use the resource. Common property regimes may limit use to cooperatives, extended families, corporations, communities, or other organized user groups. Private propriety management is typically limited to property ownership (Dietz and others 2002).

Groundwater systems are an example of a “pure” common pool resource because of the costly exclusion and subtractability attributes (Dietz and others 2002). Examples of overusing or “privatizing” groundwater include the unintentional poisoning of groundwater by agricultural and industrial wastes that are manifold in nearly every country. An example of the open access problem is that groundwater flow crosses boundaries under natural hydraulic gradients which can be locally perturbed due to pumping, but also in unpredictable ways due to barriers imposed by faulting, by conduits imposed by fractures, or seasonally due to basin switching in aquifers drained by karst. Theis (1940) underscored the subtractability problem in groundwater domains by emphasizing that “all water discharged by wells is balanced by a loss of water…some groundwater is always mined”.

Design Principles in the Management of the Commons

An exhaustive analysis of common pool resource theory as applied to groundwater resources is beyond the scope of this chapter. The topic has garnered international interest for decades, and the interested reader can find an over 378 citations on groundwater in The Comprehensive Bibliography of the Commons in the Digital Library of the Commons[7] maintained by the University of Indiana. Groundwater was one of the common pool resources profiled by the seminal works of Ciriacy-Wantrup and Bishop (1975), Ostrom (1990) followed by Blomquist (1992) Schlager (2004) and Kadekodi (2004). All scholars found that long-term cooperation among users of common pool resources enhanced the success of institutional arrangements. On the basis of over two decades of research on the commons, Ostrom (1990) developed the following eight design principles for the management of common pool resources:

1. Clearly define boundaries for the user pool and the resource domain;
2. Appropriation rules should be developed for local conditions and provisional rules be developed for resource maintenance;
3. Collective choice arrangements should be developed by the resource users;
4. Monitoring programs should be developed for the resource;
5. Graduated sanctions should be developed for "violators" of the rules;
6. Conflict management schemes should be developed;
7. Rights of organized environmental regimes should be respected by external authorities; and
8. Nested enterprises are used to administer the management of the common pool resource.

The National Research Council revisited the commons in *The Drama of the Commons* where seven key challenges of resource management were identified as summarized on Figure 2. The challenges included the following: (1) monitoring the resource and

---

[7] http://dlc.dlib.indiana.edu/cpr/index.php

resource use; (2) low cost enforcement of rules; (3) reconciling conflicts; (4) coping with imperfect knowledge of the resource system; (5) establishing linkages across space and scale; (6) addressing externalities to other resources; and (7) adapting to change. Ostrom and others (2003) provide a summary of the linkages between the design principles for common pool resources and these challenges including the following linkages: (1) monitoring the resource and resource use; (2) low cost enforcement of rules; and (3) reconciling conflicts. Emerging challenges facing the placement of boundaries around groundwater resource and user domains can be linked to coping with uncertainty, establishing linkages across space and scale, addressing externalities to other resources, and adapting to change. All of the challenges are linked to the boundary design principles as discussed in the following sections.

The Boundary Conundrum

Resource domains define the fixed spatial dimensions of resources (Buck 1998). Fish stocks, for example, are natural resources found in the ocean resource domain. Spatial dimensions are used to define property rights which may be held by individuals, groups of individuals, communities, corporations, or nation-states. Rights to natural resource property are not a single right, but are rather composed of a “bundle of rights” such as rights of access, exclusion, extraction, or sale of the captured resource; the right to transfer rights between individuals, communities, corporations or nation-states; and the right of inheritance (Buck 1998). Each “right” has an implied boundary. The spatial extent of a resource affects both the ability of users to develop information and to assess their relative ability to capture the benefits of organization (Schlager, *forthcoming*).

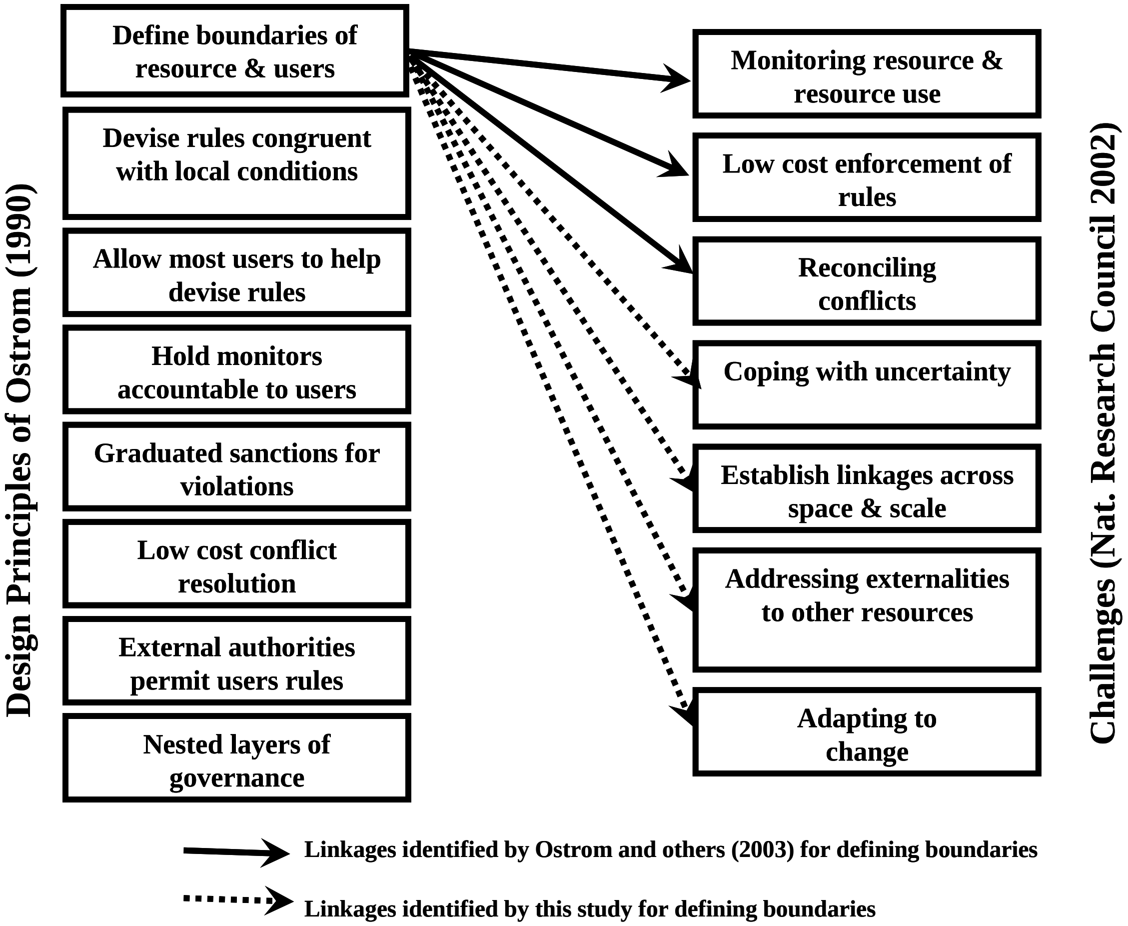


Figure 2. Linkages between design principles defined by Ostrom (1990) and challenges identified by the National Research Council (2002) with added emphasis on boundaries. Used by permission of the American Water Resources Association.

Yet with the assumptions associated with the bundle of rights and implied boundaries comes the fact that the assumptions, knowledge and understandings that underlie the definition of the rights and associated boundaries are uncertain and often contested (Adams and others 2003). For example, the question of identity and its relation to the domains of natural resources is often overlooked (Dietz and others 2002). Choices about water resources are value choices that involve distinct local communities of interest (Blomquist and Schlager 2005). Defining boundaries around water resource domains is “a supremely political act” because they represent different interpretations of key issues such as water quality, water quantity, nature, economics and history

(Adams and others 2003; Blomquist and Schlager 2005:105). The resulting boundaries may range from the international scale, to the national, regional, local, or even the individual scale. These come from the fact that water resources are coupled with the larger reality of a region, including its environmental, social, legal, and economic characteristics.

Why Boundaries Matter

Boundaries are “inner-oriented” or created by the will of a central government, or two or more states in an international setting, with the boundary indicating the limits of a political unit. All that falls within the confines of the boundary has a common bond (Kristof 1959). According to Casati and others (1998), possession of a boundary is one mark of individuality in the ontology of geographic representation. Without a boundary, there can be no separation and control, and without control, it is doubtful where sovereignty in the full sense can be enjoyed (Kristof 1959; Bisson and Lehr 2004). The existence of a boundary is the first criterion for the individuality of an autonomous entity.

Boundaries that correspond to physical differentiations or spatial continuities in territories constitute natural or *bona-fide* boundaries (Jones 1959). Coastlines, rivers, watersheds or catchments, or rock outcrops are good examples of *bona-fide* boundaries for groundwater resource domains. A good example of why boundaries matter in this setting is demonstrated by the definition of the territorial sea in the United Nations Conference on the Law of the Sea (UNCLOS) as described by the United Nations (1982). The exploitation of the riches underneath the high seas, navigation rights, economic jurisdiction, and other matters meant facing one major and primary issue - the setting of limits. According to the United Nations (1982), the clear definition of the line separating national and international waters was paramount to the successful negotiations of the UNCLOS. While the territorial sea had long been recognized in international law, states were unable to agree on the width of this coastal belt until after the UNCLOS.

Regardless of the physical setting of surface water or groundwater resources, boundaries are political in the traditional sense of the concept of a “state” or a sovereign spatial unit that defines who or what is “in” and who or what is “out” be it access to water, what can be located near water, or not using the water to preserve cultural and natural reserves (Blomquist and Schlager 2005:105). And while the geological and geographical areal extent of *bona-fide* groundwater resource domains do contain hydrological causes and effects, they do not necessarily include the social, economic, or other causes and effects.

Fiat boundaries are subjective boundaries demarcated by humans based on judgment and “ease” and represent groundwater user domains. Borders between countries are *fiat* boundaries; conversely, borders of island nations are *bona-fide* boundaries. Most examples of *fiat* boundaries in the geographic world are associated with two-dimensional regions of the globe – many times they can be recognized by the geometric shapes or corresponding with lines of latitude and longitude (Jones 1959). According to Anderson (1999), boundaries have no horizontal dimension, and that the crucial dimension of boundaries lies in the vertical plane or subsurface beneath the boundary. Three dimensional *fiat* objects are created by subterranean volumes of land assigned rights to minerals, the ocean, or groundwater. The capture area of a wellfield or the drainage areas of a qanat or mine are examples of three-dimensional *fiat* boundaries in groundwater user domains (Casati and others 1998).

Maimone (2004) indicates that the spatial, temporal and boundary aspects of groundwater resource domains is important in defining the sustainability of groundwater resources. For example, consideration of the total use of groundwater when compared to the total recharge and discharge that occurs in a regional aquifer may indicate a sustainable groundwater system, yet use of the regional boundary may provide little insight on the local effects to important ecosystems (wetlands or streams) or cultural features (springs with historical or spiritual significance, springs important for therapeutic use, or sources of mineral water). Thus, understanding where withdrawals can be undertaken while incorporating the boundaries of the areas where impacts are to be minimized or maximized is critical in assessing impacts associated with groundwater use. Likewise, Maimone (2004) and Moench (2004) indicate that boundaries of aquifer systems are often critical in defining water budgets or sustainable yield. Boundaries can represent water lost or gained from over- or underlying aquifers, areas of direct recharge, areas of subsurface discharge to coastal areas or lakes and discharge to streams as base flow.

The boundaries of groundwater resource domains and user domains also fluctuate with time. Changes in population, the world’s climate, effectiveness of water treatment and conservation technologies, and social values all affect the rate of groundwater pumping, recharge, and ecological response with time (Ragone *in review*). The types of spatial entities associated with groundwater resource domains not only occupy space, but also sometimes share space with other spatial entities. Wetlands derived from the discharge of groundwater to the surface share space with the surface water resources such as streams, rivers, and estuaries. Conversely, the hydraulic cone of depression associated with pumping of a well field is an immaterial object much like a “shadow” that shares the location with other resources on the overlying ground surface.

While Sutherland and Nichols (2002) report that surveyors assume that good boundaries make good neighbors, the political status and *de facto* contractual concept of these boundaries between two entities sometimes serve as sources of conflict and obstacles for sharing information regarding water resources (Robertson 2004). Likewise, in a global review of local conflict and water, Thomasson (2005) determined that the root causes of water-related conflicts included limited resources, control or the distribution, the quality of the resource, and large infrastructure projects. Boundaries, either political or defining a resource or user domain, are obviously related to the control or the distribution of groundwater; boundaries are used to exclude some users while at the same time providing the appropriators an opportunity to develop information and capture the benefits of organizing within the boundaries (Schlager 2004; 2007).

Similarly, Blomquist and Ingram (2003) report that transboundary groundwater conflicts are often aggravated by the lack of information about the boundaries of the resource domain, resource capacity, and conditions suggestive of the water quality. With all of these potential triggers for conflict, Llamas and Martínez-Santos (2005) report that there are no documented cases where intensive groundwater use in a medium or large-sized aquifer has caused serious social conflicts. Yet despite the setting of boundaries for water catchment systems in Somalia, the “War of the Well” has led to a battle between two clans (Wax 2006).

Inventory of Groundwater Resources Domains

Given the importance of the resource and user domain boundaries in common pool resource management, a search of the groundwater literature was completed to inventory (1) the types of groundwater resource and user domains defined in international legal instruments, and (2) the types of groundwater resource and user domains defined by individual countries. The inventory spanned the last 25 years given the paradigm shift in water resource management worldwide. For example, the Safe Drinking Water Act in the United States was passed in 1984. The concept of sustainability and Integrated Water Resources Management (IWRM) were discussed at the International Conference on Water and Environment Issues for the 21st century in Dublin, Ireland in 1992. The Earth Summit sponsored by United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil in 1992 resulted in Agenda 21 — a comprehensive program of action for global action in all areas of sustainable development. The European Community developed the

Water Framework Directive (WFD) in 2000. The Millennium Development Goals resulted from the United Nations Millennium Summit in 2000. Goal 7 focuses on sustaining our future and confronting the water crisis and the target is cutting by half the proportion of people without access to safe and affordable water before 2015.[8]

The inventory of groundwater resource and user domains is listed in Appendices B and C and is the first of its kind in the literature. It was recognized that it was impossible to develop a comprehensive listing of this information given that some countries may not desire to report this information due to national security, the confidentiality of the procedures, the international relations of the state with neighboring states, commercial and/or industrial confidentiality, and protection of the environment in view of the risk of misuse of the information.[9] The inventory of groundwater resource domains focused on (1) the type of groundwater resource boundaries; (2) the policy emphasis of the boundary; and (3) if the legal instrument or state policy differentiated between shallow and deep groundwater.

Groundwater Resources and User Domains in International Agreements

The general trend within international agreements and other legal instruments listed in Appendix B moves from focusing on groundwater as it relates to political boundaries and river basins in the early to mid 1980s, to recognizing the physical boundaries of the shared aquifers or related management units (groundwater management units, conservation areas and protection zones) in the late 1980s through the 1990s, with more refined definitions of an aquifer and the shared aquifer

---

[8] http://www.un.org/millenniumgoals/

[9] The 1998 Agreement on Cooperation for the Protection and Sustainable Use of Waters of the Spanish-Portuguese Hydrographic Basins lists some of these reasons as a condition of the agreement - see Burchi and Mechlem (2005).

boundaries after 2000.[10] The bulk of the international agreements and legal instruments address groundwaters contributing to surface waters with little to no distinction between shallow and deeper groundwater systems as hydraulically independent systems. The exceptions include (1) the 1986 Seoul Rules on International Groundwaters where aquifers that do not contribute water to or receive waters from surface waters constitute a unique international drainage basin, and (2) the 1994 International Law Commission on Confined Transboundary Groundwater where groundwater is not related to an international water course. Neither of these legal instruments references a depth for the threshold between shallow and deep groundwater. The 2005 Draft convention on the law of transboundary aquifers under development by the International Law Commission and summarized by Yamada (2005) acknowledges the Seoul Rules, as well as non-recharging aquifers which may be construed as "deep" or hydraulically unique from shallow groundwater. Yet none of these agreements or legal instruments explicitly differentiates between multilayered, regional groundwater systems and the shallow, catchment-based groundwater systems that are found on every continent.

An emerging problem with the definition of resource and user domains in international agreements is the definition of an aquifer. The definition of an aquifer historically has relied on technical attributes of a permeable rock formation capable of transmitting and yielding usable quantities of water to a well or spring. Yet the International Law Commission in their efforts to consider the international law applicable to transboundary groundwater resources defined an aquifer as a permeable [water-bearing] geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation. Eckstein (2004) indicates that the differences between the two definitions are significant in that the legal definition excludes the recharge and discharge areas and restricts an aquifer as only a formation that is water bearing.

---

[10] The exception to this trend is the unique shared aquifer agreement for the Boundary of Franco-Swiss Genovese Aquifer acknowledged in 1978 as summarized by Wohlwend (2002).

Groundwater Resources and User Domains at the Nation-State Level

Recalling that *bona-fide* boundaries reflect naturally occurring boundaries such as rivers, coastlines, and rock outcrops and that *fiat* boundaries reflect human-created boundaries, a temporal trend regarding the recognition of *bona-fide* and *fiat* boundaries such as legislative boundaries for groundwater resource and user domains is not quite as obvious at the national or state level. However, what does become obvious is an evolution of boundaries for groundwater resource domains from a "static" or what may be considered a predevelopment condition, referred to herein as a *bona-fide* "commons" boundary, to a "dynamic" where there is a meshing of hydrology and hydraulics associated with development referred to herein as the *fiat* "hydrocommons" boundary. The recognition of preserving groundwater resources for their social and cultural values as part of the common heritage of humankind is referred herein as the *fiat* "commons heritage" boundary. Figure 3 depicts a summary of the groundwater resource domains within these general categories. Each category will be described more fully in subsequent sections.

The types of groundwater resource domains are generally associated with the main use of groundwater in different countries. According to Zekster and Everett (2004) the three main sectors in global groundwater use include: communities (drinking water), self-supplied industry, and agriculture.

Communities tend to be the main groundwater users in the developed countries of Europe and Russia (Zekster and Everett 2004). In these areas, the type of groundwater user domain includes either areas set aside as reserves (Russia), zones of protection and "respect" (Italy), or "belts" of protection (Bulgaria), and wellhead protection (WHPA) or source water protection areas (SWPA) extending around the water source be it a well or spring in rural and arid areas heavily reliant on groundwater as a drinking water supply in Canada and the United States. A “boundary” for preserving groundwater sources with therapeutic value, such as a source of mineral water, is also recognized, specifically in Poland.

Industry is the prime exploiter of groundwater in nations such as South Korea, Japan, the Netherlands, Norway and the USSR, and the second largest user in other countries such as Germany, Belgium, France, the United Kingdom, the Czech Republic and the former Yugoslavia (Zekster and Everett 2004). The emphasis in groundwater user domains where industrial use is large is focused on allocation. As a consequence, the groundwater resource domains typically focus on political (state, provincial) boundaries to control access to the groundwater resources, drainage areas associated with mining such as in Poland, or catchment and watershed boundaries where IWRM and the WFD are the predominant water management paradigms.

Zekster and Everett (2004) report that agriculture is the most prolific exploiter and user of groundwater both in the developed world chiefly for irrigated farming, and in nearly every developing country outside the humid intertropical zone such as Saudi Arabia and the Libyan Arab Jamahiriya (90%), India (89%), Tunisia (85%), South Africa (84%), Spain (80%), Bangladesh (77%), Argentina (70%), the United States (68%), Australia (67%), Mexico (64%), Greece (58%), Italy (57%), China (54%), among others. The predominant groundwater user domains in areas undergoing intensive use of groundwater for agriculture focus primarily on political boundaries in countries which maintain national control over the groundwater use such as in China. In areas where groundwater is considered private property such as in India, the groundwater user domain is bounded by landownership. Countries with control over the groundwater resources as stewards of water resources owned by the public domain have groundwater user domains that reflect management over extraction such as the aquifer management councils found in Mexico, the hydrographic confederations used in Spain, groundwater management areas, conservation districts, or “control” areas in the United States, or the water user associations in South Africa.

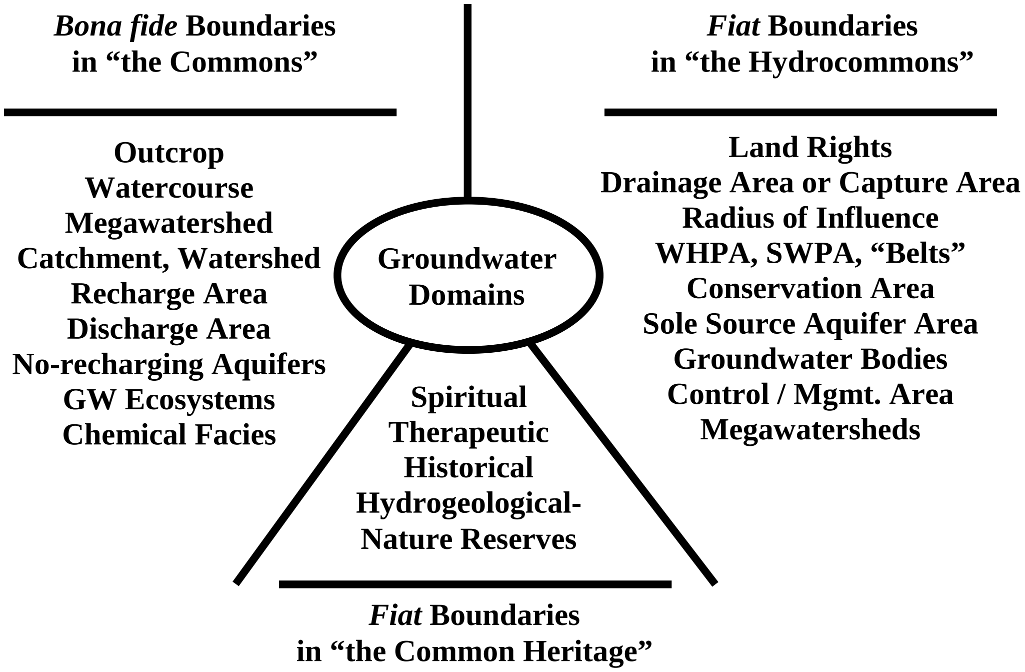


Figure 3. Groundwater resources and user domain typology.

Generalized Observations from Inventories of Resource and User Domains

Groundwater domains designed for "nature" are a recent phenomenon emerging across the globe regardless if the national emphasis is primarily exploitation and ownership of the groundwater. For example, geothermal protection areas are gaining more emphasis in the United States in areas undergoing energy development, particularly near Yellowstone National Park as will be examined in more detail subsequently. In Chile, where mining-related groundwater use is typically at high altitudes within the Andes, there are emerging efforts to protect the high altitude water meadows and other vegetation. Desiccation of soils from agricultural and industrial development of shallow groundwater in the Netherlands has prompted calls for shifting continued groundwater pumping from the shallow aquifers to deeper aquifers to preserve "fragile areas". Likewise, groundwater dependent ecosystems (GDE) along the Mediterranean Sea and the Dead Sea in Israel may lead to establishing "red lines" to protect GDEs.

The acknowledgement of shallow versus deep groundwater resource domains is more prominent at the level of nations and states. The 1995 Oslo 2 Accords[11] recognized the hydrologic differences between the shallow and deeper aquifers when determining the utilization of the regional groundwater resources between Israel and Palestine. The Netherlands designated the deeper aquifers as part of the public domain under provincial control whereas the shallow groundwater is considered property part and parcel of the overlying land. Limited hydraulic connection with surface water is a trait of deep groundwater in the state of Colorado in the United States, and in Poland. India and Pakistan acknowledge that deep aquifers are an opportunity for wealthy agricultural interests and differentiate between shallow and deep wells in well censuses.

Bona-fide **boundaries in the Commons**

The areal distribution of aquifers is a function of the geology of a region. In areas underlain by sand and gravel, the hydrologic boundaries of the sand and gravel aquifers are typically the vertical and lateral extent of the porous materials. In areas underlain by bedrock such as sandstone and limestone, the areal extent of the aquifer is not only defined by how the rocks are folded and faulted, but also by how much of the rocks are saturated. For example, bedrock aquifers located along a mountain range may be only partially saturated where the rocks outcrop and recharge occurs, whereas the areas where the rocks disappear beneath the land surface due to tilting may be fully saturated with water. The hydrologic boundaries in bedrock aquifers are complicated by the degree of saturation and the volume of storage space within the rocks.

The spatial representation of groundwater resource domains on the geographic scale varies across space, scale, time and depth. As depicted on Figure 4, groundwater resource domains are a nested series of spatial and temporal configurations (Gibert

---

[11] http://www.jewishvirtuallibrary.org/jsource/Peace/iaannex3.html#app-40

and others 1994). The megascale domain represents the regional through continental groundwater flow systems which can extend over tens to hundreds of kilometers and depths ranging from 800 meters to three kilometers (Garven 1985; Weiss 2003; Bisson and Lehr 2004; Struckmeir and others 2006). At the macroscale, geomorphologic and hydrologic processes of catchments and watersheds determine aquifer properties, the permeability architecture, and water circulation characteristics. The mesoscale domain incorporates hydrodynamic controls, matter and energy fluxes, and human impacts. Human impacts by intensive exploitation of groundwater for drinking water, irrigation, and energy development are important at this scale. The microscale domain represents short term events such as during the annual hydrologic cycle and at a spatial scale of the pore, fissure or channel (Gibert and others 1994).

Outcrop, Hydrogeologic Regions, Recharge Area, and Discharge Area

Groundwater moves from areas of high hydraulic head towards areas of low hydraulic head. Under natural conditions, water in the aquifer flows from the recharge area towards the discharge area by gravity. Springs represent a discharge area, or areas of low hydraulic head (see Figure 5).

The significance of the boundaries of the outcrop and regional hydrogeologic maps from the perspective of groundwater resource domains focuses on (1) a first-order approximation of what areas recharge the groundwater resource domain, and (2) the storage characteristics of the groundwater system. Recharge is the process by which groundwater is replenished. A recharge area is where water from precipitation is transmitted into an aquifer. Areas which transmit the most recharge into a groundwater system are often referred to as "critical" recharge areas with unique boundaries for land use management. Conversely, discharge areas are locations at which groundwater leaves the aquifer and flows to the surface as springs or water bodies such as wetlands, streams, rivers, lakes or the sea.

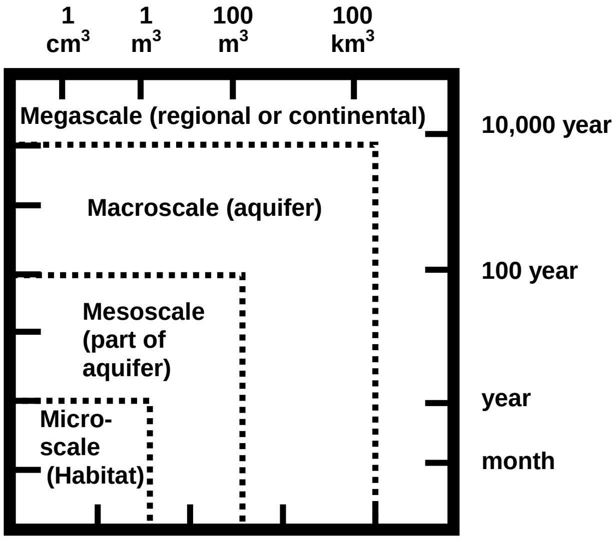
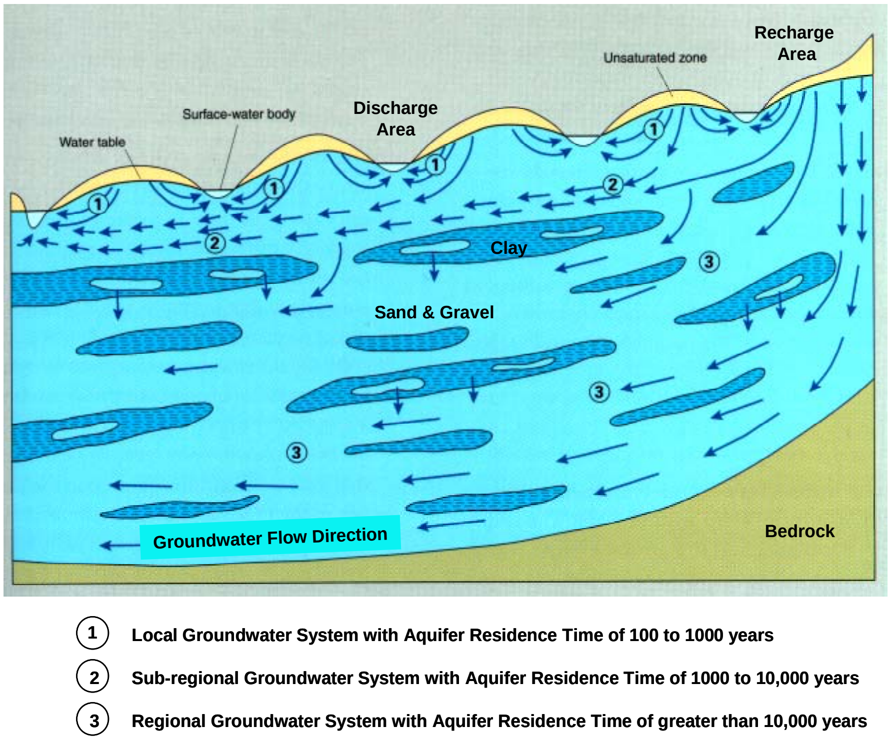


Figure 4. Groundwater resource domains are scale and time dependent. Modified after Gibert and others (1994). Used by permission.

Ostrom's (1990) germinal work in groundwater management in California defined the boundaries of the basin as the groundwater resource domain. The boundaries of the groundwater resource domain were defined by geologic boundaries where readily defined by faults. Geologic faults can sever the hydraulic continuity of the permeable sand and gravel layers or juxtapose sediments against lower permeability bedrock and served as one boundary within the groundwater basins studied by Ostrom (1990). Other boundaries were designated by surficial boundaries or topographic limits where the basin was geologically "unbounded". Conversely, the boundaries focused on the four regions for the Salt Lake Valley Groundwater Management Plan were designed by the Utah Division of Water Rights (2002) to not only protect existing water rights but also water quality and overappropriation in the sand and gravel aquifers.[12] The boundaries of the four regions included not only the geologic boundaries of the basin, but also the discharge areas. Water rights could be transferred from one region to the central area designated as the discharge area, but could not cross from a western region to an eastern region.

---

[12] http://www.waterrights.utah.gov/meetinfo/m062502/slvmgpln.pdf



① Local Groundwater System with Aquifer Residence Time of 100 to 1000 years

② Sub-regional Groundwater System with Aquifer Residence Time of 1000 to 10,000 years

③ Regional Groundwater System with Aquifer Residence Time of greater than 10,000 years

Figure 5. A regional groundwater flow system depicting subsystems at different scales within a complex hydrogeologic framework. Modified from Alley and others (1999) using information from Foster and others (2003).

Maps of rock units considered as aquifers or low permeability confining layers are the most common form of the groundwater resource domain boundary. These boundaries are typically used to represent the groundwater resource domain under static conditions or before large scale development. Depending on the scale of the investigation, the domains may be mapped by individual stratum, series of strata with comparable permeability architecture (e.g. sand and gravel, limestone, sandstone, fractured rock, karst). For example, Sun and others (1997) report that 25 aquifer systems were studied under the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey which was started in 1978 and was completed in 1995. The purpose of this program was to define the regional hydrogeology and establish a framework of background information on geology, hydrology, and geochemistry of the important aquifer systems in the United States. The different aquifer systems were differentiated on the basis of lithology and structural geology.

At the global scale, the International Groundwater Assessment Center (IGRAC)[13] developed a map of global groundwater regions that differentiated 35 regions on the basis of tectonic setting, present-day geomorphology, and the spatial extent of rock formations with contrasting hydraulic properties as part of the consortia of institutions undertaking WHYMAP.[14] Building upon the IGRAC mapping, the WHYMAP further refined the hydrogeologic regions into hydrogeologic units. Careful examination of Figure 6 reveals that at a large scale, the boundaries of the groundwater resources domains are based primarily on permeability architecture. For example, when viewed on a global scale groundwater basins with sedimentary rocks compose 29%, complex hydrogeologic regions compose 20%, and shallow aquifers typically associated with Precambrian igneous and metamorphic rocks compose 51% of the aquifer types in the world, respectively (WHYMAP, written communication, 2006). Table 1 provides a summary of the different aquifer types by continent. It is clear that there are multiple approaches to defining a groundwater resource domain and that scale is an important factor when defining such a domain.

Watercourse

The 1997 Convention on the Non-Navigational Uses of International Water Courses defines watercourse as “a system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and flowing into a common terminus” (McCaffrey 2001:34). While a watercourse can be conceptualized as a watershed associated with a river, a watercourse can also chiefly consist of groundwater, where precipitation within the recharge zone may not be necessarily associated with a surface stream, with the terminus of the water course dependent on the local geology of the groundwater system. The terminus of the “groundwater

---

[13] http://www.igrac.nl/

[14] http://www.bgr.bund.de/EN/Themen/Wasser/Projekte/Berat__Info/whymap/whymap__projektbeschr.html

course" may be the receiving aquifer, a related aquifer, or the sea (McCaffrey 2001:25).

Table 1. Summary of Aquifer Types by Continent (courtesy of WHYMAP personal communication 2006).

Continent	**Aquifer Type**	**Percentage of Continental Land Mass**
Europe	Local and Shallow Bedrock Aquifers	53%
	Complex Hydrogeology	29%
	Groundwater Basin with Sediments	18%
Asia	Local and Shallow Bedrock Aquifers	56%
	Complex Hydrogeology	25%
	Groundwater Basin with Sediments	19%
Africa	Local and Shallow Bedrock Aquifers	50%
	Complex Hydrogeology	8%
	Groundwater Basin with Sediments	42%
North America	Local and Shallow Bedrock Aquifers	61%
	Complex Hydrogeology	26%
	Groundwater Basin with Sediments	13%
South America	Local and Shallow Bedrock Aquifers	44%
	Complex Hydrogeology	11%
	Groundwater Basin with Sediments	45%
Australia	Local and Shallow Bedrock Aquifers	32%
	Complex Hydrogeology	40%
	Groundwater Basin with Sediments	28%

Watershed, Catchment, and Drainage Basin

The watershed, catchment, or drainage basin of a river is the boundary with a long history serving as the boundary for water resources management, particularly within the world's 263 international river basins (Wolf and Giordano 2002). The International Law Association drafted the Helsinki Rules of 1966 and the Seoul Rules of 1986 which identified the international drainage basin as the unit to delineate the geographic extent or surface water and groundwater considered under the rules (Teclaff and Utton 1981; Matsumoto 2002; Eckstein and Eckstein 2003).

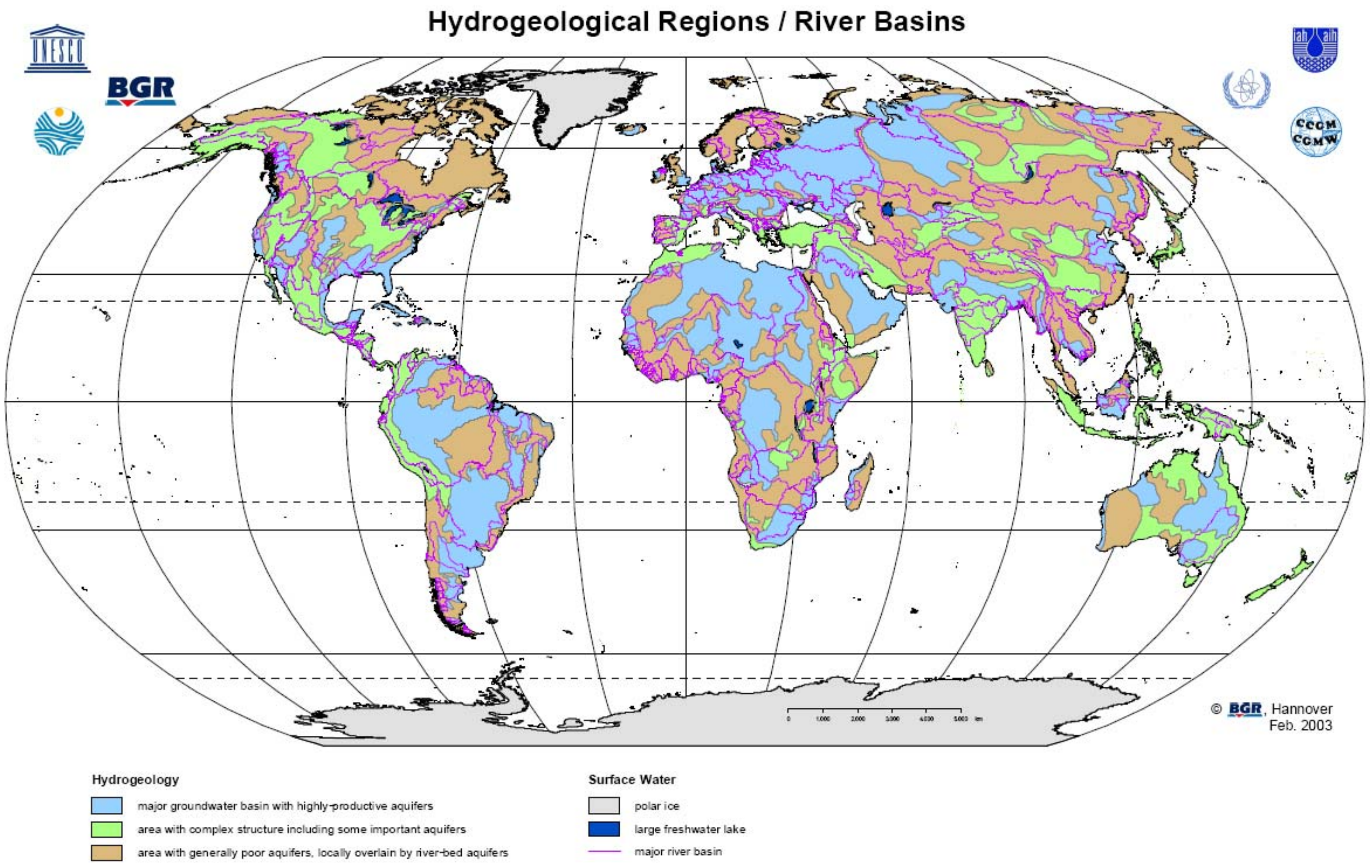


Figure 6. Generalized hydrogeologic regions of the world with outlines of international river basins. The three different colors represent the permeability architecture of the groundwater systems. Note that the groundwater systems cross the boundaries of the international river basins. Adapted from WHYMAP (various years). Used by permission.

Megawatersheds

Bisson and Lehr (2004) define the conceptual model of a megawatershed as a natural complex system of water catchments and drainages linked to tectonism, consisting of three-dimensional surface and subsurface zones linking interbasin groundwater transmission in consolidated fractured bedrock and compartmentalization in faulted, deep sediments. As mappable groundwater resources, megawatersheds may not coincide with surface topography divides, and they may receive recharge from parts of several surface watersheds. Bisson and Lehr (2004) used the megawatershed model to explore and develop groundwater stored in the fractured rocks in Somalia and Trinidad and Tobago.

Within the western United States, the carbonate rocks composing the Great Basin Aquifer System underlying the states of Utah, Nevada, Idaho, and Oregon are targeted for development by the Southern Nevada Water Authority to provide groundwater supplies approaching 0.03 km^3 per year to Las Vegas (Baird 2006; Kirby and Hurlow 2006). The Great Basin Aquifer serves as an excellent example of a deeper megawatershed due to the apparent lack of hydraulic connection between groundwater flows in the nearly 260 surface watersheds that overlie the Great Basin Aquifer System (Schaefer and others 2003).

No-recharging Aquifers or Non-renewable Groundwater

According to WHYMAP (various years) and Zekster and Everett (2004), deep irregularly-recharged aquifers or “fossil” groundwater constitute relevant water management regions because the groundwater systems are not hydraulically linked to a watercourse or are found in areas with little to no precipitation. While Foster and others (2003) argue that groundwater resources are not strictly renewable, there are certain groundwater systems where the period needed for replenishment can be hundreds to thousands of years. Designation of these aquifers is based on groundwater dating using a broad spectrum of isotopes, yielding ages ranging from 10^4 to 10^5 years. Areas of non-renewable groundwater can be found on every continent where rainfall is less than 200 millimeters per year (WHYMAP various years). Large areas of non-renewable or “fossil” groundwater were mapped at the continental scale as part of the WHYMAP project with a large part of the Middle East-North Africa area underlain by fossil groundwater resources.

Groundwater Ecosystems

The hydraulic interaction between groundwater and aquatic ecosystems has long been recognized by groundwater hydrologists. Theis (1940) indicated that groundwater pumped from a well was derived from capturing water in storage within an aquifer, from increased recharge, or from decreased discharge to wetlands and surface water features. In 1972, the United States implemented Section 404 of the Federal Clean Water Act (CWA) which initiated the process of protecting wetlands from pollution and destruction. The Water Framework Directive (WFD-2000/60/EC)[15] for the European Community also recognized the need to protect aquatic ecosystems. Both the CWA and the WFD emphasize terrestrial ecosystems. However, virtually all groundwaters constitute ecosystems ranging from microbes to larger species depending on the permeability architecture of the groundwater system (Gibert and others 1994). As with the boundaries associated with the chemical “facies” of groundwater systems as described in the following section, there also exists the need to delineate the boundaries of groundwater ecosystems (Stanford and Gibert 1994).

Chemical Facies

A groundwater resource domain may also be an area where good quality groundwater is wholly or partially surrounded by poorer quality groundwater (Kalf and Wooley 2005). As part of the WHYMAP, Struckmeir and others (2004; 2006) mapped areas

---

[15] http://ec.europa.eu/comm/environment/water/water-framework/library.htm

at a continental scale where the salinity of groundwater exceeds five grams per liter in Australia, Africa, the Middle East and South America. Similarly, arsenic and fluoride concentrations have been documented to increase as groundwater extraction grows (Moench 2004).

Areas of groundwater contaminated by agricultural, industrial, military, sewage, and municipal wastes constitute a unique chemical facies within a groundwater domain. Hardin (1968) indicates that “the tragedy of the commons” reappears in problems of pollution where “it is not a question of taking something out of the commons, but of putting something in”.

***Fiat* Boundaries in the Hydrocommons**

Focusing primarily on rivers and watersheds, Weatherford (1990) defined the “hydrocommons” as the convergence of hydrology and hydraulics yielding an area defined by the linkages of common water sources. Whether a hydrocommons represents a grounded reality remains debatable, as Weatherford (2003) reports that the “Hydrocommons seems less a reality than a metaphor for the fragmentation of natural resource planning and management” and that institutions fragment the commons because “(1) competing communities of interest and values favor specialized management and particularized accountability and returns, (2) manageability requires bite-sized subject matter, and (3) limited knowledge and lack of integrated knowledge continue to be a barrier”. Yet this fragmentation results in a broad spectrum of user domains, particularly when groundwater resources are concerned.

Land Ownership Rights

Land administration systems traditionally focus on rights to surface ownership under the rules of Roman Law, Napoleonic Civil Code, and English Common Law (Nanni and others 2002). In some countries, land ownership includes not only the ground surface, but also all earth layers below, including all groundwater. The “rule of capture” presides over groundwater ownership in these settings, where the groundwater user is permitted to pump as much water as can be physically captured. Until 1993, the state of Texas prescribed groundwater ownership under the rule of capture for the Edwards Aquifer, one of the most prolific aquifers in the United States (Votteler 2004). Similar definitions are employed in India (Shah 2005), the Netherlands, Germany, the United Kingdom, France, and in Belgium (van der Molen 2004).

Radius of Influence and Capture Areas

Wells drilled into aquifers “capture” water stored in the aquifer by creating artificial discharge areas by lowering the hydraulic head in the vicinity of the well during pumping (Theis 1940). When a well is pumped, the water level is drawn down in the immediate vicinity of the well. This drawdown is referred to as the cone of depression in the vertical dimension; in the planimetric dimension the cone is represented as the radius of influence. The size and shape of the cone of depression and associated radius of influence are a function of the type of aquifer (unconfined versus confined), the physical parameters of the permeable materials open to the well (low permeability materials yield steep cones of depression with small radii of influence) and whether the well is tapping fractured rocks or sand and gravel (fractured rocks typically result in elliptical or irregular shaped radii of influence) (Witten and Horslev 1995: Livingstone and others 1997).

Groundwater flowing toward the well during pumping which is derived from storage in the aquifer is called the “capture area” (see Figure 7). The size of the capture area is not only a function of the hydraulic properties of the aquifer, but also the pumping rate and the duration of pumping.

The geographic significance of both the radius of influence and the capture area is that these can become management areas, requiring policies directing how many wells can be drilled into an aquifer to efficiently exploit the water stored in the aquifer, or protect from overdrafting (Gould and Grant 1995; Livingstone and others 1996). The intersections of radii of influence associated with pumping multiple wells can be compared to the intersection of “water rights domains” in the spatial aspects of open access common pool resources as described by Giordano (2003).

Drainage Areas

Large quantities of groundwater are developed as a by-product of mine dewatering or oil and gas development which can lead to extensive areas of drainage. Likewise, large areas can be drained of groundwater by horizontal water “mines” such as qanats or karezes, found in the tens of thousands throughout the Middle East, which capture groundwater via gravity and drain towards portals (Wulff 1968; Mahdavi and Saravi 2004; van Steenbergen 2004). The convergence of a drainage area with the radius of influence associated with a pumping well can lead to the interference between water users.

Wellhead Protection Areas and Source Water Protection Areas

The United States Safe Drinking Water Act[16] of 1974, as amended in 1996, required public water supply systems to determine wellhead or source water assessment protection areas for wells and springs used as drinking water supplies. A wellhead or source water protection area as defined by nearly every state and province in the United States and Canada, as well as some countries in Europe, is the surface and subsurface area around a well, spring, or tunnel through which contaminants are reasonably likely to move toward and contaminate the drinking water source.

---

[16] http://www.epa.gov/safewater/sdwa/index.html

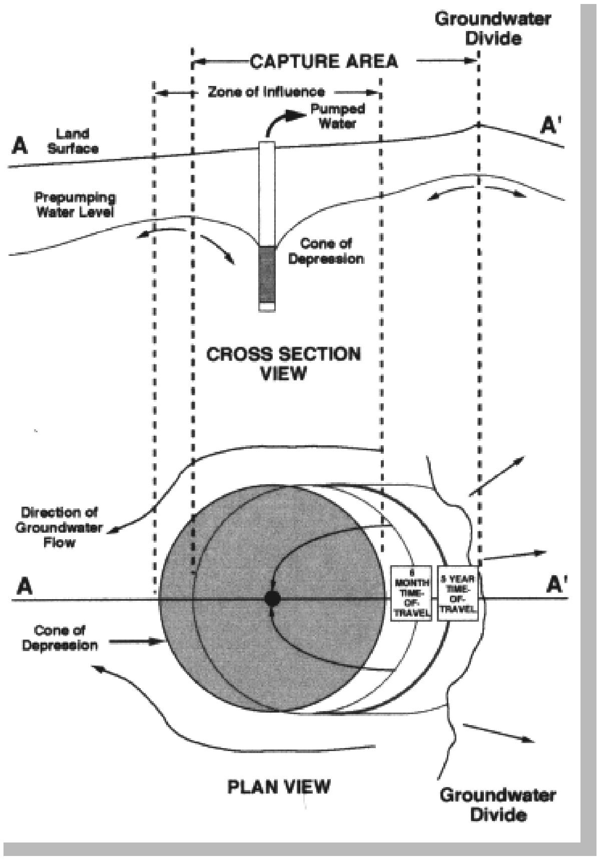


Figure 7. Conceptual model of radius (zone) of influence and capture area associated with pumping a well. Adapted from Livingstone and others (1986). Used by permission of the Geological Association of Canada.

Definition of the groundwater protection areas ranges from an arbitrary fixed radius or "belts" of protection, to groundwater time of travel zones determined from sophisticated computer models, to hydrogeologic mapping using remote sensing supplemented by groundwater tracing with dyes or isotopes (Witten and Horsley 1995). Two domains are commonly used to describe the areas near a well: (1) a fixed radius near the well to protect the area in the immediate vicinity of the well, and (2) the zone of contribution.

Sole Source Aquifer Areas

The Sole Source Aquifer[17] (SSA) program was established under Section 1424(e) of the Safe Drinking Water Act of 1974. The SSA designation authorizes the U.S. Environmental Protection Agency (EPA) Administrator to assess that an aquifer is the "sole or principal source" of drinking water for an area. An aquifer must supply 50% or more of the drinking water for an area to qualify as "sole or principal". According to EPA (1987) and McCabe and others (1997), other criteria for SSA designation includes (1) no economically feasible alternative drinking water sources exist within the area or nearby that could supply all those who now depend upon the aquifer as their source of drinking water, and (2) if the aquifer were contaminated, a significant hazard to public health would result. SSA designation provides for EPA review of federally financially-assisted projects to determine the potential for contaminating an aquifer. Any person can submit a petition; but most petitions are developed by corporations, companies, association, partnerships, state, municipalities or federal agencies. According to the EPA, there are 73 sole source aquifers designated in the United States. The Edwards Aquifer in Texas was designated the first SSA in the United States in 1975 (Votteler 2004).

The delineation of up to five resource domains are required as part of a SSA petition. The project review area serves as probably the most important boundary as this is the boundary which federal financially-assisted projects will be reviewed. Other areas in the petition include the outline of the aquifer and the aquifer service area defined as the area above the aquifer where the entire population served by the aquifer lives. The designated area is the surface area above the aquifer and the associated recharge area. An important, but optional area is the stream flow source area that includes the upstream headwaters of losing streams that flow into the recharge areas. The SSA petitioner is also required to delineate the vertical boundary of the aquifer through

---

[17] http://www.epa.gov/safewater/ssanp.html

longitudinal and traverse geologic cross sections. This requirement is unique among the processes of other groundwater user domains.

The aquifer service area, defined by the Sole Source Aquifer program as "the area above the aquifer and including the area where the entire population served by the aquifer lives" was determined to be the capture area for the individual wells. The boundaries of the aquifer or designated area were determined based on hydrogeologic mapping of the area. This defines the area contributing water to the developed aquifer. According to Giordano (2003) the challenge associated with solving the commons problem is “by making the resource and rights domains coincident over time.” By integrating the individual aquifer services areas within the larger SSA petition area, the rights and resource domains can become one with time.

Groundwater Bodies

The Water Framework Directive (WFD) was produced in 2000 by the European Commission to direct the achievement of sustainable management of waters in the European Union Member States. According to the Working Group on Water Bodies (2003), the WFD covers all waters, including surface water, groundwater, transitional, and coastal waters up to one sea mile form the territorial baseline of a Member State. The geographical or administrative unit for water management is the river basin or river basin district (Samper 2005). Groundwaters are associated with a river basin or river basin district. The purpose of the WFD is to prevent further deterioration of and to protect and enhance the state of aquatic ecosystems and prevent inputs of pollution.

A body of groundwater within the WFD refers to a distinct volume of groundwater within an aquifer or aquifers. An aquifer, as defined by the WFD, is a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater. The WFD does not provide explicit guidance on how the bodies of groundwater are delineated beyond that the groundwater bodies should be delineated such that appropriate description of the quantitative and chemical status of groundwater. Unlike other groundwater resource domains, the WFD requires that the groundwater bodies be delineated in three dimensions. The groundwater bodies can be identified as (1) separately within different strata overlying each other in the vertical plane, or (2) as single bodies within the different strata. The final approach to defining the groundwater bodies is up to the individual Member States, but it must be assigned to a River Basin District.

Conservation Areas

Article VII of the Bellagio Model Agreement Concerning the Use of Transboundary Groundwaters proposed in 1989 indicates that Transboundary Groundwater Conservation Areas can be determined by the Commission of the Agreement (Hayton and Utton 1989). While the model agreement is silent with respect to the standards used to develop the boundaries of the conservation area, the emphasis is on (1) the sustained use of the groundwater resource by groundwater withdrawals exceeding recharge to endanger yield, water quality, or diminish the water quantity or quality of interrelated surface water; (2) the impairment of drinking water; or (3) the contamination of aquifer(s).

Legislative Boundaries

In many parts of the United States where large withdrawals of groundwater occur or where water quality has been impaired over large areas, a broad spectrum of tools for local management of groundwater have been developed. Some of these areas have been the result of court orders, others are legislative mandate, and others are created voluntarily (Blomquist 1992; Smith 2003; Votteler 2004). Regulatory controls over drilling, well construction, and pumping are developed in select areas as opposed to an entire county, state, or country is typically vested as a “stand-by” authority to governments. These are important entities in managing groundwater resources used for irrigation at the field level in many parts of the world and function from advisory to managerial and from coordinating to quasi-judicial (Burchi and D’Andrea 2003).

The legislative bodies have a plethora of names such Control Areas, Aquifer Authorities, Management Areas, Natural Resource Districts, Water User’s Group, etc. The boundaries of the districts are generally developed along political boundaries with little regard for the geologic or hydrologic boundaries of the groundwater systems. Many of the “critical” areas are developed due to the perception that continued pumping of groundwater exceeds the long-term natural replenishment of the underground water reservoir leading to “excessive” declines in groundwater levels and/or conflicts between water users, or due to contamination of the groundwater resources. In the High Plains Aquifer of the Central United States, the Natural Resource Districts of Nebraska were formed in response to dramatic lowering of flows in streams and rivers (Aucoin 1984). Comparable efforts to develop legislative authorities and groups are occurring in India, China, Yemen and Mexico (Moench 2004; Mukerji and Shah 2005).

An emerging issue with the designation of groundwater user domains is the question of overlapping jurisdictions. As depicted in Figure 8, the Oregon Water Resources Commission designated groundwater limited areas within the Columbia River Basalt aquifer in where water levels have declined nearly 150 meters in response to intensive use of groundwater for agriculture (Bastasch 1998). However, circular conservation areas have been designated around water supply wells serving as drinking water supplies which preclude the installation of an irrigation supply well within eight kilometers of the water supply well. Careful examination of Figure 8 reveals that the conservation area for wells located near Pendleton, Oregon overlaps the boundary of the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), effectively limiting their access to groundwater for irrigation in the northwestern portion of the reservation. Likewise, the Oregon Department of Water Resources has the regulatory power to designate “critical groundwater areas” which may impose restrictions on pumping from wells located within one mile of a river (Glennon 2002).

Megawatersheds

Just as watersheds and catchments are reshaped, breached and bounded by hydraulics resulting in hybrid surface water resource domains as defined by Weatherford (1990), the extra-basin area enclosing the collection and distribution of imported water to a groundwater resource domain is also part our modern hydrocommons. Aquifer storage and recovery and aquifer replenishment programs that transmit surface water hundreds of kilometers from distant river basins to intensively exploited groundwater basins is becoming increasingly commonplace in the United States (Pyne 1994; Blomquist and others 2004). Injection wells, subsurface dams or “sea cutoff walls” used to control saltwater intrusion in coastal aquifers effectively expand the boundaries of the groundwater user domain oceanward (Sakura and others 2003). Injection wells using treated surface water to replenish depleted basins also expand the boundaries of the groundwater user domain to include the river basin boundaries serving as the source of the injected water. Conversely, the exportation of 0.4 km^3 per year of pumped groundwater to a distant location such as envisioned by Mesa Water[18] a company that anticipates pumping groundwater from the High Plains Aquifer in northern Texas 525 kilometers south to the Dallas-Fort Worth area of Texas, effectively changes the groundwater user boundary for the Dallas-Fort Worth area. The net effect is an expansion of the hydrocommons or the creation of a megawatershed as depicted on Figure 9.

---

[18] http://www.mesawater.com/

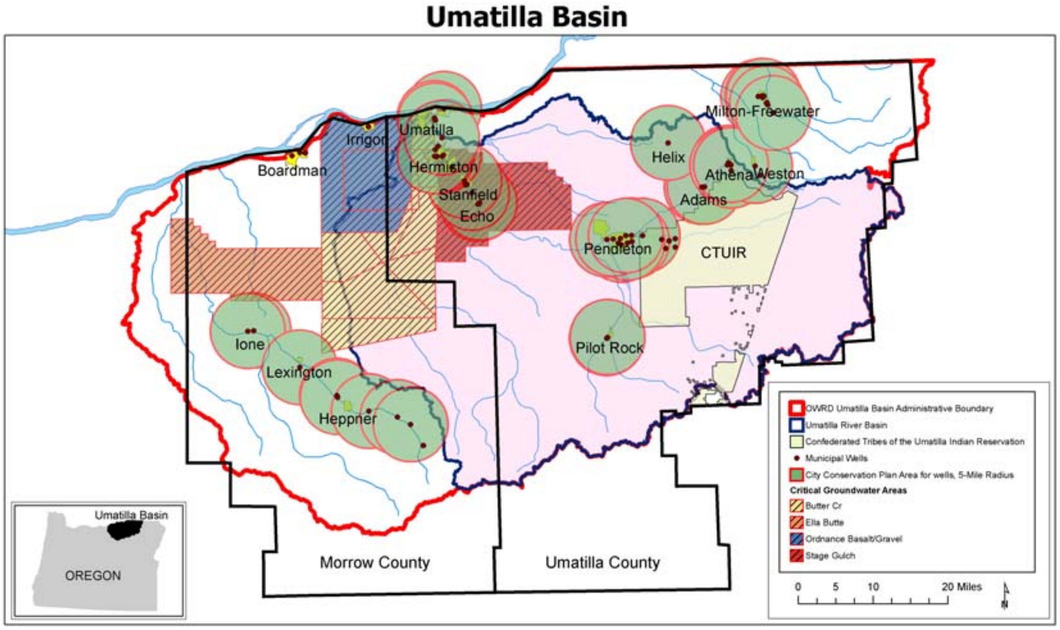


Figure 8. Map of the Umatilla Basin in northeastern Oregon, USA. The different colored regions represent various legislative areas associated with governing groundwater. Note the overlap of the circled areas onto the CTUIR lands. Courtesy of the Confederated Tribes of the Umatilla Indian Reservation. Used by permission.

Fiat Boundaries in the Commons Heritage

Besides the natural or physical boundaries of a groundwater resource domain or the user domain boundaries derived from the exploitation of groundwater, there are natural and human boundaries associated with groundwater. The intensive use of groundwater associated not only with irrigated agriculture or urban use, but often overlooked as a by-product of hydrocarbon or mineral extraction is causing increased awareness of potential impacts to groundwater dependent ecosystems, spiritual resources, therapeutic resources, cultural and historical resources, and geothermal resources. Many of these resource domains could be considered part of the common heritage of humankind or part of the global commons to which all nations have legal access as opposed to international commons which are resource domains shared by several nations (Buck 1998). The groundwater resource and user domains in these settings include, but are not limited to, World Heritage sites, cultural features, and hydrogeologic nature reserves.

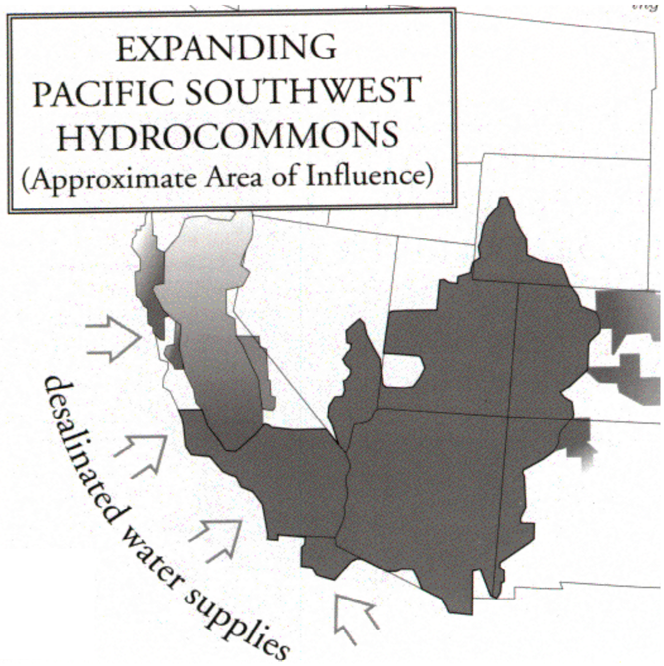


Figure 9. Conceptual model of the "hydrocommons" and megawatersheds in the southwestern United States developed by Weatherford (2003). Note the changing sense of place associated with transbasin diversions of surface and groundwater. Used by permission of the Utton Transboundary Resource Center.

Nature Reserves

In order to protect deep confined aquifers, as well as spring waters and mineral waters used as therapeutic waters as part of a national or common heritage, de Marsily (1994) calls for the creation of "Hydrogeological Nature Reserves". Feitelson (2005) describes the importance of developing thresholds or "red lines" of water levels in wells tapping aquifers draining to Lake Kinneret and the Dead Sea in Israel to protect groundwater dependent ecosystems under the purview of the Israel Nature and National Parks Board from desiccation. Similarly, Glasbergen (2004) reports that the efforts to control shallow groundwater in the Netherlands has lead to extreme desiccation of organic-rich soils in the Netherlands, causing the government to limit the use of shallow groundwater resources and designate “fragile areas”.

The Special Case of Thermal Springs

Springs are a concentrated discharge of groundwater at the ground surface. According to EPA (1997), springs are classified based on the hydrogeologic characteristics with up to eight types recognized in the literature. Springs typically represent the intersection of the ground surface with the water table or potentiometric surface of deeper confined aquifers.

Hydrothermal features are nature reserves that are not frequently considered within the context of groundwater resource domains of common pool resources. Yet, many have been used for thousands of years for therapeutic purposes, are World Heritage Sites, national and state parks, and are spiritually important to some cultures. The Sipapuni is a geothermal spring located at the bottom of the Grand Canyon in Arizona that flows approximately 0.3 liters per second (Loughlin 1983). While the reported flow is miniscule for purposes of use as a drinking water or irrigation water supply, it is considered the place of emergence for Hopi ancestors from the Third World to the Fourth World, yet has no plan for protection of the flow from the spring (Dongoske and others 1997).

Hydrothermal features are increasingly being explored as sources for alternative energy. For example, Kerr (1991) describes the “tragedy of the commons” associated with geothermal energy development at The Geysers, a field of fumaroles located 115 kilometers north of San Francisco, California. Yet after six years of development, the steam pressure decreased and The Geysers is “running dry” because “there are too many straws in the teapot”. Elsewhere in the United States, the world’s largest mineral hot springs located at Thermopolis, Wyoming are at risk of “running out of steam” with reports of declining flows and a decrease in the dissolved mineral content of the waters important for the formation of travertine terraces due to unregulated flows from nearby wells servicing private spas, home development, and oil field development (Prevost 2006). Continuing interest in geothermal development near Yellowstone National Park led to state and federal legislation in the early 1990s to protect the hydrothermal resources in the Park from human activity (Custer and others 1994).

Elsewhere in the world, the Roman hot springs at Bath, England are at risk from dewatering associated with limestone quarrying (Atkinson and Davison 2002). Discoloration of the cotton white travertine terraces at Pamukkale, Turkey, a World Heritage Site, by diversion of the thermal waters for tourist hotel pools, coupled with the lack of sewage systems leading to algae growth on the terraces, has led to conservation efforts (Simsek and others 2000).

Boundaries for groundwater user domains associated with common heritage sites vary from no protection to controlled areas. Like wells, springs have catchment or capture areas. The catchment area of a spring is a function of the discharge and the annual recharge. For example, considering the estimation of catchment areas using the method outlined in EPA (1997) for large springs like those discharging as the geothermal waters at Pammukkale, Turkey where the average flow is 510 liters per second can have catchment areas approaching thousands of square kilometers (Simsek and others 2000). However, only three protection zones have been delineated in and around the boundary of the archaeological site area just to prevent further degradation of the travertine terraces using dye tracer tests and pumping tests (Simsek and others 2000).

The federal strategy for protecting Yellowstone National Park is a simple buffer zone extending 24 kilometers from the Park boundary. The State of Montana strategy differs from the Federal strategy by integrating the cold-water recharge and hot-water discharge into the hydrogeologic conceptual model of the hydrothermal system using the principles developed by Tòth (1963) for groundwater basins, and integrating the location of geologic faults known to exist in the area. Consideration of the geothermal springs in geologically unique areas such as Yellowstone National Park can potentially yield catchment areas to over 15,000 km^2 (Custer and others 1994).

Protection of the Bath Hot Springs is limited to existing statutes which preclude excavations and boreholes in the immediate vicinity of the springs (Atkinson and Davison 2002). However, the dimensions of the buffer zone are not specific. Residents concerned about the declining flows of the Thermopolis Hot Springs are requesting the establishment of a formal control area around the springs, but the challenge associated with defining the boundaries of the control area are obvious "with intersecting underground aquifers that extend over unknown hundreds of square miles" (Prevost 2006).

For the spiritually significant Sipapuni spring in the Grand Canyon, the reported discharge of less than one liter per second indicates a potential catchment area approaching 100 km^2, but the groundwater user domain remains vulnerable due to a lack of federal or state regulations. Likewise, Kemper and others (2003) report that Argentina and Uruguay use deep wells tapping the Guaraní Aquifer for geothermal use to support tourism; consequently, early attention to the boundaries of this groundwater user domain are needed to preserve this common heritage resource.

Conclusions

The boundaries of groundwater resource and user domains change with time. Spatial changes in the groundwater domains changes due to "use" of the resource, either physically in the "hard" sense of developing the resource through pumping or drainage, or through the "soft" sense of changes in the social and cultural values associated with the groundwater resource. Conventional groundwater hydraulic theory dictates that the capture area enlarges as more water is captured from storage in the groundwater system (see Theis 1940). Weatherford (1990) indicates that the biological importance, material utility and spiritual value of water is socially important and multi-faceted, and the relative weight given by a culture or society to each value, and the relationships between values, changes over time. The result is an increase or decrease in the size of the groundwater user domains. While it is tempting to establish a hierarchy of nested structures at successively larger scales, e.g., from micro to macro, they do not reflect the real world geographies of nation states and stateless nations (O'Sullivan 2004).

There is enormous uncertainty involved in the study and management of groundwater resources. Unlike watersheds, the *bona-fide* boundaries of the groundwater resources domains such as coastlines, rivers, watersheds or catchments, or rock outcrops are not easily mappable especially with respect to the location of aquifers and the associated hydrogeologic boundary conditions. *Fiat* or user domains derived from human use of groundwater are difficult to delineate because of the transient character of the boundary. Even with the use of sophisticated numerical modeling of groundwater systems it is not unusual to experience failures or "surprises" in 25 to 30% of the groundwater models and associated *fiat* boundaries (Bredehoeft 2005). It is difficult to delineate the optimal geographical unit for management of groundwater resource, because groundwater resource and user domains depend on (1) heterogeneities in the sediments and rocks composing the groundwater system, (2) the type of groundwater use, (3) the duration of groundwater use, and (4) the values of the groundwater resource users (Stanford and Gibert 1994). Even if the unit can be determined with a high degree of certainty, there is no guarantee of obtaining consensus from states which share a transboundary aquifer (Matsumoto 2002).

In summary, this chapter addressed two research questions: (1) How are boundaries placed around groundwater resources and user domains?; and (2) Do these boundaries change through time? By coupling common pool resource theory developed by political scientists and economists with space theory common to geographers, and integrating the concepts germane to geology and groundwater hydrology to examine international legal instruments for groundwater, a general trend emerges where groundwater is related to political boundaries and river basins in the early to mid 1980s that evolves to recognizing the physical boundaries of the shared aquifers or related management units in the late 1980s through the 1990s. Increasingly refined definitions of an aquifer and the shared aquifer boundaries appear after 2000. Examination of groundwater and user domains at the nation and state level reveals a previously unrecognized typology for the boundaries for groundwater resource domains ranging from a “static” or what may be considered a predevelopment condition, referred to herein as a *bona-fide* “commons” boundary, to a “dynamic” where there is a meshing of hydrology and hydraulics associated with development referred to herein as the *fiat* “hydrocommons” boundary. The recognition of preserving groundwater resources for “users” social and cultural values as part of the common heritage of humankind is referred herein as the *fiat* “commons heritage” boundary.

The implications of these results are important to the governance and management of transboundary groundwater resources. Unlike transboundary river basins where the watershed is the metric for a multitude of analyses, it is difficult to aggregate demographic, social, and economic data within specific boundaries for groundwater resources for detailed geographic analyses without agreement on the fundamental unit of analysis. It is clear that the preconceived notions that the boundaries for groundwater resources and user domains are relatively straightforward to draw are myths. The outcome of this situation is that governing groundwater resources at any scale will be difficult because the spatial extent of the groundwater resources and user domains cannot be determined with a high degree of certainty due to the vagaries in the scientific knowledge of the groundwater systems, as well as the changing social, economic, and cultural values of groundwater resources. The net effect of the multitude and transient nature of the domain boundaries will be disputes between the organizations that determine who is and who is not excluded from the use and benefits of groundwater resources and the actors who desire to use the groundwater resources. Clearly, there are opportunities to mitigate the potential disputes that will arise over the drawing of groundwater resource and user domains. First and foremost is the acknowledgement that the boundaries of the domains are not only a function of the traditional metrics of boundary conditions imposed by geology, hydrology and economics, but also of the nontraditional metrics of the intrinsic, social and cultural value of groundwater. Likewise, it will be important to acknowledge that the boundaries of the groundwater resource and user domains will not remain “static” like a river basin boundary, but rather will be “dynamic”, fluctuating with changes in use and changes in values.

Chapter Four: Geopolitical Consequences of Transboundary Groundwater

Abstract

At the international scale, the statistically significant predictors of conflict over water resources focus on the institutional capacity within a river basin. To assess the potential vulnerabilities of transboundary groundwater systems, this paper examines the extent that bilateral and multilateral water treaties and river basin organizations have made provisions for groundwater in basin agreements. While 240 transboundary aquifers have been identified by international scholars in groundwater resources, only 98 are considered representative of the major transboundary groundwater systems. Reasons for the small number of major transboundary aquifers include (1) the limited geographic extent of the transboundary aquifers, (2) the ongoing efforts to develop conceptual models of some groundwater systems, as well as (3) the ongoing efforts to categorize the type of aquifers by WHYMAP. On the basis of a comparative analysis of the transboundary aquifers with the over 400 basin accords, this study found that approximately 15% of the 240 transboundary aquifers fall within the bounds of a river basin treaty with provisions for groundwater. Groundwater resource administration within River Basin Organizations (RBOs) is weak, even within the most robust international RBOs. In light of these findings, this chapter concludes with suggested policy options for improving transboundary groundwater governance.

Introduction

Over 40% of the world's population relies on transboundary water resources for their secure and stable livelihoods (Wolf and Giordano 2002). Worldwide there are 263 transboundary river basins that cover over 45% of the global landmass (Wolf and Giordano 2002; Wolf and others 1999). Ninety seven percent of all accessible freshwater is found underground.

With annual withdrawal rates approaching 700 km^3 per year, groundwater is the world's most extracted raw material (Zekster and Everett 2004). Dramatic changes in drilling and pumping technology along with the availability of electrical power over the past 60 years have fueled an exponential increase in wells creating the most intensive human-induced changes in the hydrologic cycle (Moench 2004). But the conflicts over groundwater over the past 100 years have generally focused on contamination of wells rather than access to groundwater (Gleick 2004). Yet the first "War of the Well" occurred in Somalia where two clans have clashed over the control of a water well, leading to the killing of 250 people over a period of two years as drought gripped the region (Wax 2006). Llamas and Martínez-Santos (2005) report that millions of farmers in pursuit of the short-term benefits associated with the intensive use of groundwater for agricultural use in India, China, Mexico, and Spain is building a "Silent Revolution" where the need for proactive governmental action is needed to avert water conflicts.

In the face of increasing world population an increasing reliance on groundwater for drinking water, agricultural uses, industrial uses, and as a by-product of mining and energy development, this intensive use of groundwater suggests that human security may be at risk if contiguous nations have not developed institutional capacity to deal with the management and governance of transboundary groundwaters. Like surface water, groundwater ignores political boundaries. The prevailing legal generalizations inadequately fit the hydrogeologic realities (Glennon 2002). A great deal of scientific uncertainty is associated with predicting the hydrologic responses to groundwater development, especially as it relates to the vagaries in storage characteristics and how to establish boundaries for the resource and user domains, all of which are important in developing rules, regulations and conventions. With the 1997 UN Convention on Non Navigational Uses of International Watercourses (UN Convention) serving as the best available legal "tool" to work with in addressing transboundary water issues, it remains unratified, and insufficiently addresses the peculiarities of groundwater (McCaffrey 2001). For example, aquifers "confined" by an overlying layer of lower permeability strata which effectively limits direct hydraulic communication with shallower aquifers and surface water were not covered by the UN Convention. Eckstein and Eckstein (2003) further indicate that the UN Convention also does not differentiate between the types of confined aquifers – “dynamic” confined aquifers that constitute part of the hydrologic cycle versus “static” confined aquifers which are devoid of any connection to a source of recharge. With a worldwide inventory of transboundary groundwater systems underway, along with efforts to develop draft conventions on transboundary aquifers, these gaps need to be addressed to avoid future conflicts over groundwater – the real tragedy over the use of this particular common pool resource.

Past empirical work on the indicators of water conflict have determined that institutional capacity within a river basin, defined as either water management bodies such as River Basin Organizations (RBOs) or treaties, are as important as the physical attributes of a system. Wolf and others (2003:43) tested a working hypothesis regarding the relationship between a change in conditions in a river basin and the institutional capacity to identify basins at risk of potential conflict as “The likelihood and intensity of dispute rises as the rate of change within a basin exceeds the institutional capacity to absorb that change”. A comparable investigation has not been completed for groundwater resources because the 240 transboundary groundwater systems continue to be inventoried by the World-wide Hydrogeological Mapping and Assessment Program (WHYMAP) as described by Struckmeir and others (2006). The objective of this chapter was to undertake a survey of the nearly 400 freshwater treaties archived and maintained in the Oregon State University Transboundary Freshwater Dispute Database (TFDD) to inventory which of the identified transboundary groundwater systems fall within the confines of a river basin with a treaty or agreement. Likewise, an assessment was made to determine which transboundary groundwater systems have strong institutional capacity through RBOs and which RBOs include a groundwater component for the shared management of surface and groundwater resources.

Survey Methodology

The International Freshwater Treaties Database[19] is a searchable database of summaries and the full text of more than 400 international, freshwater-related agreements, covering the years 1820 to 2002. Documents are coded by the basin and countries involved, date signed, treaty topic, allocation measures, conflict resolution mechanisms, and non-water linkages. Both English and non-English language agreements are included. Where available, translations to English of non-English language documents are provided.

The collected agreements relate to international freshwater resources, where the concern is water as a scarce or consumable resource, a quantity to be managed, or an ecosystem to be improved or maintained. Documents concerning navigation rights and tariffs, division of fishing rights, and delineation of rivers as borders or other territorial concerns are not included, unless freshwater as a resource is also mentioned in the document, or physical changes are being made that may impact the hydrology of the river system (for example, dredging of river bed to improve navigation, straightening of a river's course). In large part, the documents in the database concern water rights, water allocations, water pollution, principles for equitably addressing water needs, hydropower, reservoir and flood control development, environmental issues and the rights of riverine ecological systems.

Each of the transboundary groundwater systems identified by Struckmeir and others (2006) was located in a river basin by using either the Web Mapping Tool[20] available from the WHYMAP website or using the map of the international river basins summarized by Wolf and Giordano (2002). From the TFDD document collection, the water treaties for the specific river basin were examined to identify “groundwater” provisions. The keywords used for groundwater provisions were the same as those

---

[19] http://www.transboundarywaters.orst.edu/

[20] http://www.bgr.de/app/whymap/

used by Matsumoto (2002) who completed an inventory of the TFDD document collection to determine that 109 river basin treaties have provisions for groundwater. Matsumoto's inventory included the keywords of aquifer, groundwater, spring, subsoil, underground, wells; this inventory added the keywords of safe yield, shared water resources, fracture, and karst in order to accommodate the type of aquifer system identified by Struckmeir and others (2006).

Survey Findings

The treaties containing groundwater provisions were paired with the transboundary aquifer system as listed in Appendix D. While the preliminary inventory of transboundary aquifer systems by Struckmeir and others (2006) yielded approximately 240 groundwater systems, only 98 of the regionally important transboundary aquifers (> 1000 km^2) and were identified in the preliminary map presented at the 4th World Water Forum held in Mexico City in 2006. Of the 98 regionally important transboundary aquifer systems identified by Struckmeir and others (2006), this survey determined that 36 of these transboundary aquifers can be found within river basins that have treaties that contain provisions to groundwater. Acknowledging the importance of the different storage characteristics of the various groundwater systems identified by Struckmeir and others (2006) as porous, fractured rock, and karst, none of the surveyed treaties recognize the differences between the types of aquifers.

As depicted on Figure 10, the spatial distribution of transboundary aquifers located within river basins with treaties containing provisions to groundwater roughly coincide with the regions underlain by major groundwater basins as reported by WHYMAP (various). The spatial distribution of the transboundary aquifers located within river basins with some provisions for groundwater also coincide with the distribution identified by Matsumoto (2002) who found that the European river basins had the largest distribution of treaties referencing groundwater (35), followed by

Africa (13), Asia and the Middle East (10), North America (4) and none in South America. Three out of the seven (42%) North American transboundary aquifers identified by WHYMAP are located in within a river basin with a groundwater provision embedded in a treaty or agreement. The regionally extensive Guaraní Aquifer System represents the only one out of 20 WHYMAP-identified transboundary aquifers within South America that may be addressed in a freshwater agreement, and groundwater is only vaguely addressed in the Statute of the River Uruguay. Not surprisingly, 10 out of 14 (70%) of the transboundary aquifers identified by WHYMAP in Europe are within river basins with freshwater agreements. Thirty five percent (14 out of 40) of the WHYMAP-listed transboundary aquifers in Africa fall within a river basin with some form of a freshwater agreement. In Asia and the Middle East, nearly 50 % (8 out of 17) of the identified transboundary aquifers are located within river basins with an agreement or other legal instrument with provisions for groundwater.

None of the transboundary aquifer systems located along coastal regions are addressed in the survey of river basin treaties. The vast fresh groundwater resources stored under the ocean floor are also not addressed. Of the few river basin treaties that have provisions for groundwater, none address the spatial and vertical boundaries of the groundwater system. And none refer to the utilization of non-renewable groundwater.

Groundwater and River Basin Organizations

As an adjunct to the treaty survey, the role of River Basin Organizations (RBOs) in addressing groundwater resources was also investigated. Using the comprehensive inventory of global RBOs by Bakker (forthcoming), a survey of this database revealed that none considered groundwater as a major issue of concern. Likewise, a survey of nearly 200 national RBOs by Kemper and others (2005) also reveals that groundwater has uncertain status in most states’ licensing programs and that groundwater has not been fully integrated into the licensing system even in some of the most well-established RBOs such as the Murray-Darling Basin Commission and the Murray-Darling Ministerial Council in Australia.

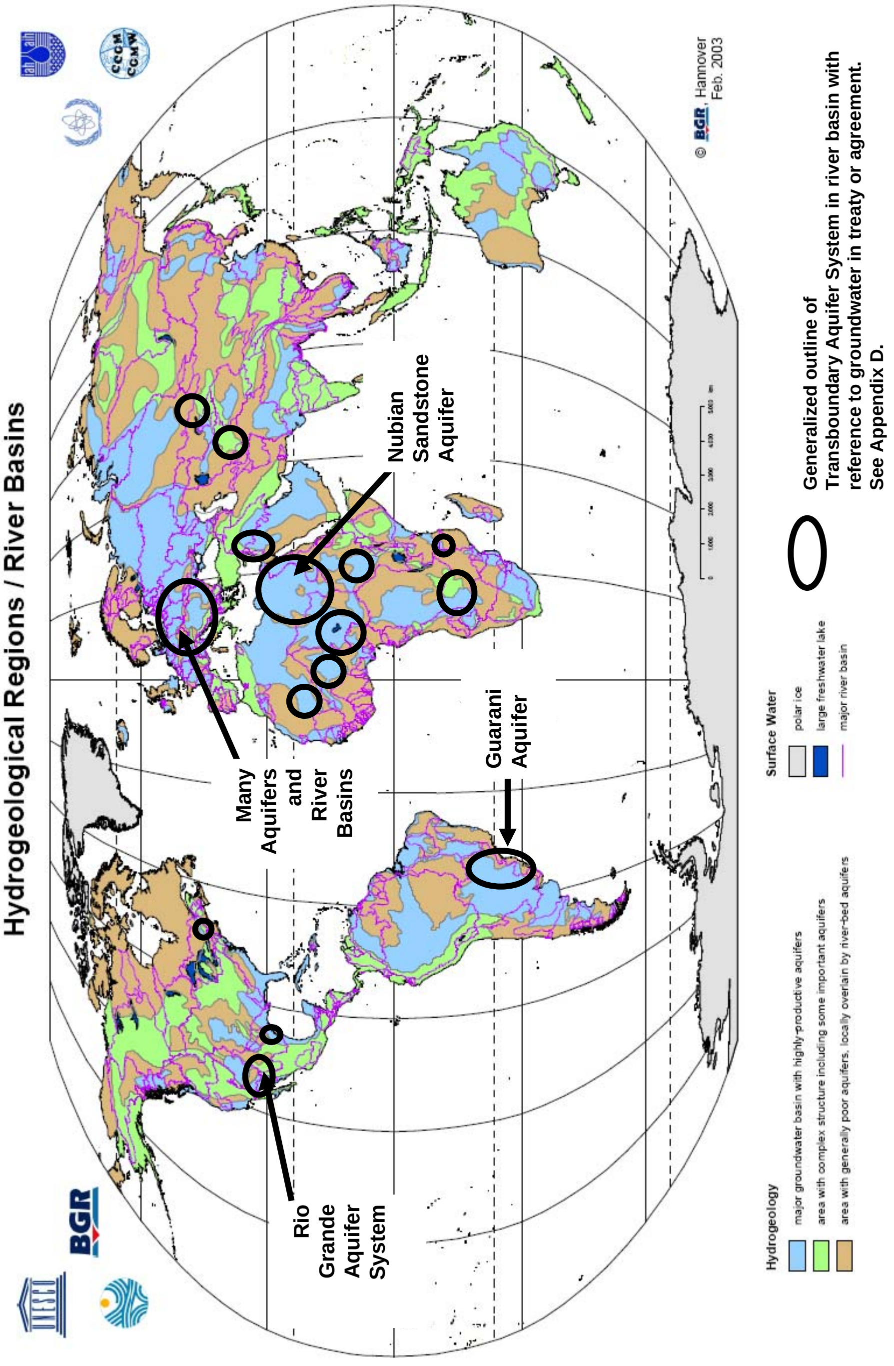


Figure 10. Generalized hydrogeologic regions of the world with outlines of transboundary aquifer systems where river basin treaties have provisions for groundwater. In some cases the outlines encompass several transboundary aquifers within associated subbasins. Modified from WHYMAP (various years) using Struckmeir and others (2006). Used by permission.

Geopolitics of Surface Water versus Groundwater

Politics is about decision making, and geopolitics takes into account the geographical elements that can influence decisions (Bisson and Lehr 2004). With river basins, states are most concerned about flows and what is dependent on flows whether it be for allocation, water quality or ecosystems. For groundwater, Matsumoto (2002) found that the freshwater treaties and agreements archived in the TFDD focus more on the management of specific springs or wells in border areas, or within a particular geographic region such as the Southern Africa Development Community (SADC) as opposed to a specific aquifer system, how much water is stored in the aquifer systems and what "ecosystems", either natural or anthropogenic, are dependent on the change in storage within an aquifer system.

The history of international water treaties regarding surface water is robust with over 400 treaties with the earliest dating back to 2500 BCE following hostilities in Mesopotamia along the Tigris River (McCaffrey 1997; 2001; Wolf and Giordano 2002). The institutional capacity for groundwater is less robust with approximately 48 bilateral and multilateral treaties dating back to 1824 using the listings of treaties compiled by Teclaff and Utton (1981) and supplemented Burchi and Mechlam (2005). Of the 109 freshwater treaties or agreements with provisions for groundwater inventoried by Matsumoto (2002), only the agreement between France and Switzerland regarding the Lake Geneva Basin groundwater is considered truly a unique and successful example of shared groundwater policy dating back to 1978 (Wohlwend 2002; Eckstein and Eckstein 2003; Hardberger 2004). Given the findings that a lack of institutional capacity to absorb change within a basin may increase the likelihood and intensity of disputes suggests that a large number of disputes may occur over groundwater resources and that there should be a way to predict "aquifers at risk" in a manner similar to the prediction of "basins at risk" by Wolf and others (2003).

Part of the problem focuses on the lack of a fundamental unit of analysis. Conca (2006:29) indicates that the building of regimes for international river basins use approaches designed for traditional regimes including (1) a territorially-bounded construction of the problem; (2) strong presumptions of state authority; and (3) an "optimistic, universalizing, rationalist understanding of knowledge". Garduño and others (2004) followed by Puri and others (2005) suggest the differences between river systems and aquifers in terms of governance is that river systems are dominated by flow, whereas groundwater systems are dominated by storage. The implications are significant in that the time case of groundwater flow system is orders of magnitude slower, and for upstream-downstream considerations, neither predominates or are fixed in time and space. For the basins at risk study described by Wolf and others (2003) the confines of watershed boundaries served as the unit of analysis. During the course of developing the maps for WHYMAP, Struckmeir and others (2004) recognized that (1) integrated water management either by nation or by river basin is not appropriate especially in arid areas where surface water catchments and deep aquifers are totally different; and (2) aquifers and groundwater systems are to be considered as relevant water management regions in regions where receive little to no recharge is available. Another reason why river basins might not serve as a good metric for regime building focuses on the general lack of certainty associated with groundwater systems as opposed to surface water systems. Conca (2006:22) posits that regimes demand "definitive outcomes to the struggles over knowledge that are apparent to environmental politics" and that regimes tend not to form "when the understandings of a problem and its solution remain highly contested for an indefinite period". Similarly, Struckmeir and others (2006) identified several transboundary aquifers that are located in coastal regions which fall outside of the metric of watersheds. All of these observations imply that watershed boundaries are poorly suited for groundwater resource management and governance.

Yet Garduño and others (2004) indicate that there is no technical reason why groundwater and surface water resource management should not be integrated. They report that because groundwater resources are not manifest in the short-term as "upstream-downstream" conflicts, states and RBOs either overlook or understate the value of groundwater. Garduño and others (2004) followed by Kemper and others (2005) further identify that integrating groundwater into river basin planning often requires addressing constraints presented by compartmentalized legal and institutional frameworks, including (1) water legislation does not address institutional responsibility for groundwater resources or places the responsibility under a different agency than for river basin planning; (2) groundwater user associations are not represented by the river basin planning agency or RBOs; and (3) river basin managers do not have the technical expertise or resources to fully understand the importance of groundwater.

Garduño and others (2004) indicated that specific hydrogeological settings require different approaches to governance. They offer that groundwater systems of limited extent within a river basin catchment may require specific local management plans with recognition that groundwater recharge may be dependent on upstream flow, and downstream river flow may be dependent on aquifer discharge. Other special hydrogeologic settings include river basins underlain by extensive shallow groundwater systems may be fully integrated into a water resource planning and management program. Extensive deep groundwater systems in arid regions where the groundwater system dominates and there is little to no permanent surface water interaction makes establishing a RBO meaningless. Groundwater systems characterized as having patchy distribution, shallow depths, and low production potential should be acknowledged as important to the socio-economic well being of a rural water system to justify attention to the optimum design of wells (Garduño and others 2004).

The type of aquifer system in terms of permeability architecture is important given that fractured rocks and karst have poor storage characteristics. Analyses of the nuances of transboundary aquifers and political boundaries by Barberis (1989) and

Eckstein and Eckstein (2003; 2005) typically address alluvial aquifers or aquifers with homogeneous hydraulic properties. Scholars addressing groundwater legislation and regulatory provisions or the dimensions of groundwater within river basin planning usually assume that the aquifers of concern are porous media and develop management and governance strategies under this limiting assumption (Nanni and others 2002; Garduño and others 2004). Yet given that all but unconsolidated subsurface materials are fractured to some degree, and that fractured rocks typically have unpredictable and poor storage characteristics, the modeling management of these types of aquifers as uniform or mildly nonuniform porous media is inappropriate (Moench 2004; Neumann 2005). The third report on shared natural resources on groundwater resources under development by the International Law Commission included a draft article on monitoring which was designed "For the purpose of being well acquainted with the conditions of a transboundary aquifer or aquifer system…" which describes that the aquifer states agree on a conceptual model of the aquifer. Of the many parameters suggested as key parameters, only the reference to the "flow path" alludes to the nonuniform distribution of the aquifer permeability architecture (Yamada 2005:13).

The development of non-renewable or fossil water under the popular precepts of sustainability is not possible in many groundwater systems because the period for natural replenishment can be hundreds to thousands of years. The volume of groundwater stored in some fossil aquifers is huge estimated to be over 150,000 km^3 in the Nubian Sandstone and 15,000 km^3 in the Arabian Rub-al-Khali basin (Foster and others 2005). The status of nonrenewable groundwater resources in international law is not definitive or comprehensive (Eckstein and Eckstein 2003). The International Law Commission Draft convention of the law of transboundary aquifers addresses non-recharging aquifers under equitable and reasonable utilization, but only with respect to development plan to maximize the long term benefits derived from the use of the groundwater, including the lifespan of the aquifer and well as the future needs of the aquifer states (Yamada 2005). Foster and others (2005) indicate that in addition to assessing the lifespan of the fossil aquifer, consideration should also be given to the impact of the development plan on third parties such as traditional users, related aquatic and terrestrial ecosystems, as well as anticipated groundwater quality changes during the life of intensive groundwater development.

In such regionally extensive aquifers where the boundaries can be well defined, Garduño and others (2004) suggest that Aquifer Management Organizations be developed to include groundwater users, NGOs, professional and drilling organizations, media representatives, and research and training organizations. In light of the above, Abu-Zeid (2002) reports that the Centre for Environment and Development for the Arab Region and Europe (CEDARE) has joined forces with the International Fund for Agriculture Development (IFAD), the Islamic Development Bank (IDB) and the riparian countries of Chad, Egypt, Libya and Sudan for initiating a Regional Program for the Development of the Nubian Sandstone Aquifer System, a transboundary groundwater basin in the North Eastern Sahara of Africa encompassing over 2.2 million km^2. This initiative is the first in the world for the regional management of a shared aquifer which started in 1998 with the signing of agreements between the four countries for regular monitoring and continuous exchange of information.

Of the many international water treaties, few have monitoring provisions, and nearly all have no enforcement mechanism (Chalecki and others 2002). Moench (2004) and Morris and others (2003) indicate that more emphasis should be placed on regular and accountable monitoring of groundwater use, levels, and quality.

Recognizing the limitation in the traditional arenas of water management, Moench and others (2003) suggest rethinking groundwater management approaches as the intensity of development increases with increased need for food security. They recommend moving towards adaptive management strategies that acknowledge existing social trends and responses to a limited number of prioritized groundwater problem areas. Building upon the work of the above scholars, this study also determined that an inadequate understanding or consensus of the socio-political and cultural values of groundwater leads to poor definition of the management or governance boundaries for the groundwater resources.

Conclusions

With groundwater exploitation increasing with growth in population and increasing water needs for food security, and the increased awareness of the hydraulic connection of groundwater for environmental flows, the importance of developing ground rules to govern groundwater cannot be overstated. Yet the research presented in this chapter suggests that regimes to manage or govern groundwater remain weak. Part of the problem rests with the fact that groundwater was not recognized as part of the hydrologic system when freshwater treaties and other agreements were negotiated, resulting in approximately 15% of the treaties and other agreements with provisions for groundwater. The other part of the problem rests with the fact that the boundaries of the transboundary groundwater systems are very different than the boundaries of a watershed; consequently, any treaty or agreement that has a provision for groundwater reflects only a cursory recognition of the groundwater flow system.

Other deficiencies identified by this freshwater treaty survey include (1) the storage characteristics of the groundwater systems are not recognized in the treaties or other agreements, (2) aquifer systems located along coastal regions are not addressed in the survey of river basin treaties, (3) the utilization of non-renewable groundwater remains silent, (4) the vast fresh groundwater resources stored under the ocean floor are not addressed, and (5) there are no provisions for monitoring the groundwater systems. Of the few river basin treaties that have provisions for groundwater, none address the spatial and vertical boundaries of the groundwater system. While the vertical and spatial boundaries present legal complexities associated with developing bilateral and multilateral agreements, the Aquifer Management Organizations such as that developed for the regionally extensive Nubian Sandstone suggest that the boundary obstacles and lack of previous institutional capacity are not insurmountable.

Chapter Five: Groundwater Governance and the Law of the Hidden Sea

Abstract

"Although states are sovereign, they are not free individually to do whatever they want" (Commission on Global Governance 1995). This chapter examines the elements fundamental to the study of groundwater in an international context and proposes the use of possibly the most significant, most complex, and most widely acknowledged international legal instrument negotiated in the past 100 years to groundwater resource governance – The United Nations Convention on the Law of the Sea of 1982 – as a model for the "Law of the Hidden Sea". The complexity associated with assessing groundwater resources, coupled with the regional scale of groundwater flow at depth, the volume of groundwater stored at great depths, along with the hydraulic connection to the oceans, suggests that not all groundwater resources that underlie a sovereign nation should be under the absolute and unlimited control of a sovereign nation. The traditional approaches to transboundary or international groundwater management and governance focus on tying groundwater resources to a drainage basin, yet this approach ignores coastal aquifers which are hydraulically connected to the oceans yet serve as the source of drinking water supplies for the growing megacities found in coastal regions. While the history of institutional capacity regarding the governance of groundwater resources continues to evolve, there is little to no recognition of the vertical stratification of the global groundwater systems.

Introduction

Groundwater represents about 97% of the fresh water resources on the Earth that is available for use by humans. With the increased availability of electrical power, myriad forms of equipment to power pumps, and advances in deep well pumping technology, groundwater is the world's most extracted raw material, with withdrawal rates currently in the region of 600 to 700 km^3 per year and meeting approximately 20% of the current world water needs for all uses combined (Zekster and Everett 2004). At least one-half of the world's population relies of groundwater for basic needs, and sometimes it is the only source of water (Llamas and Custodio 2003). And while groundwater is often considered the ultimate source of high-quality water, it also becomes the ultimate sink of used water (Food and Agricultural Organization 2003)

Groundwater is rarely taken into account in international law and the regulatory regime is “rather crude” given the abundance and vulnerability of the resource (McCaffrey 2001; Burchi and Mechlam 2005). While hundreds of surface water treaties can be reviewed at the Transboundary Freshwater Dispute Database[21] maintained by Oregon State University, provisions for groundwater are only nominally included in the scope of these agreements and other legal instruments if it is "related" to surface waters, or it is not mentioned at all (Matsumoto 2002; Burchi and Mechlam 2005).

In their introductory statements at a National Academy of Sciences Colloquium dedicated to *The Role of Science in Solving the Earth’s Emerging Water Problems*, Jury and Vaux (2005) indicated that institutions for managing international river basins are neither robust nor well developed. With only a handful of transboundary aquifer systems covered by an international agreement specifically designed to deal with groundwater, and with only 36 transboundary aquifer systems located within river basins with treaties containing provisions for groundwater, the development of innovative institutions to govern these commonly held resources is paramount (Jury and Vaux 2005). With this challenge in hand, the International Law Commission has embarked on developing a draft convention of the law of transboundary aquifers (Yamada 2005). Of the few legal instruments that contain groundwater-specific provisions, the type of aquifer storage is rarely addressed, nor are the horizontal and

---

[21] http://www.transboundarywaters.orst.edu/

vertical limits of the groundwater system. None of the legal instruments address groundwaters in coastal regions or groundwater stored under the ocean despite the battle with saltwater intrusion in coastal groundwater basins (Blomquist 1992).

The *bona-fide* boundary between the continents and the oceans has lead to a disconnection of global groundwater governance. Groundwater stored within the global oceanic crust has a mass comparable to that of water in ice caps and glaciers. Often considered peripheral to the Earth's hydrologic cycle, seafloor hydrothermal circulation results in global mass fluxes comparable to that of rivers (Fisher 2005). Growth in human populations along coastal regions is leading to megacities with populations exceeding 10 million and is fueling growing interest in terrestrial-marine interactions along continental margins for many reasons (Howard and Gelo 2003). Groundwater fluxes on continental margins can contribute to the creation of "hardgrounds" - the lithified carbonate sediments found on the sea-floors - and other conditions supportive of healthy fisheries. Pore fluids within sediments along some continental shelves are fresh relative to overlying seawater, and these freshwater fluids extend tens of kilometers from the present-day shoreline (Fisher 2005). The management of water resources in coastal regions and river basins are regulated by a patchwork of treaties, regulatory agencies, and other institutions. Despite the geographic overlap between freshwater and oceans, little attention has been given to the consistency of institutions that regulate these systems (Alcamo 2005). With research in the commons revealing a "drama of the commons" entailing a legacy of apparent tragedies, the lack of acknowledgment regarding the hydraulic connection of groundwater and ocean resources is leading to a "comedy of errors" in the future management of both resources.

Margat (1994) indicates that management of unconfined, shallow aquifers should always be an integral part of local watershed planning and land uses, suggesting that shallow aquifers may be best governed under legal regimes for surface water. McCaffrey (2001) suggests that the different characteristics and behavior of groundwater would seem to justify stricter standards and more stringent protection than is applicable to surface water. The current legal regime governing surface water, as expressed in the UN Convention on the Law of the Non-Navigational Uses of International Watercourses of 1997, may be sufficiently flexible as to be capable of adaptation to the particular requirements of groundwater. But according to McCaffrey (2001) "this situation should prevail only until a special regime can be tailored for international groundwater". Margat (1994) suggests that groundwater management and watershed management of a basin overlying an aquifer can be performed independently of each other in the case of deep, confined aquifers. The recognition that shallow aquifers potentially may be managed differently than deeper aquifers, coupled with the general lack of integrating the geographic overlap between freshwater and the oceans, suggests that a law of the sea model might be applicable not only to geographically-disadvantaged states where water scarcity is a problem as suggested by McCaffrey (1997), but it may also to pertain to the management of deep groundwater as discussed in the following sections.

The Hidden Sea

In the popular literature, Francis Chapelle, a hydrogeologist with the U.S. Geological Survey, defined the enormous volume of water underlying the visible world as the "Hidden Sea" (Chapelle 2000). Given the hidden nature of groundwater, it encompasses space not normally considered within the realm of traditional geographers. Shiklomanov and Rodda (2003) demonstrate that the natural storage of groundwater is determined to an absolute depth of 2,000 meters. Table 2 lists the three vertical zones of groundwater storage and movement summarized by continent. The total storage of groundwater to the 2,000 meter level in the Earth's crust is estimated to be 23. 4 million km^3 with 3.6 km^3 in the first zone, 6.2 million km^3 in the second and 13.6 million km^3 in the third. While there are large local variations, the following descriptions of each zone by Shikmanolov and Rodda (2003) reveal the degree of hydraulic connection with surface water resources:

> 1. A zone of active water exchange is located about the local base level and is highly dynamic. Here the character of the water is most closely related to the nature of the overlying soil and the rock strata containing them and to climatic factors. The effective porosity is about 15%. Rivers are fed mainly from water stored in the first zone.
>
> 2. A zone of less active water exchange is located below this first zone down to an elevation of sea level. This zone is situated below local base levels and the water here is only affected by large rivers which may have deep channels. Drainage of groundwater in this zone is also related to basins and depressions. Where these lie under the sea, the discharge of water from this zone occurs into the sea. The nature of the waters in this zone is determined by the occurrence of aquifers and aquicludes and their juxtaposition in the form of depressions, troughs, synclines, and monoclines forming artesian basins. The effective porosity of this zone is about 12%.
>
> 3. The lower zone lies in the crust from sea level to the absolute depth of 2,000 meters. The water of the upper part of this zone is only influenced by the biggest rivers at depth and by large scale features such as depression in the relief of land and the ocean. In the upper part of this zone, water is fresh or weakly mineralized with saline water and brines below. The effective porosity is 5%.

It is obvious from Table 2 that the geographic distribution of the global groundwater is not uniform. Indeed, some continents could be construed as “geographically disadvantaged” with respect to groundwater resources, regardless of the donation. For example, Australia and Oceania clearly have less groundwater resources than the other global regions. Likewise, the largest percentage of the global groundwater resources is at or below sea level. Yet the bulk international agreements and legal instruments, as well as national laws regarding groundwater, do not differentiate between the different zones of groundwater movement. The European Community Water Framework Directive for delineation of groundwater bodies indicates that groundwater flow at depth may be important to surface ecosystems even though this may be over an extended timescale (Working Group on Water Bodies 2003). The draft convention on the law of transboundary aquifers defines an aquifer as “a permeable geological formation underlain by a less permeable layer” (Yamada 2005). It is becoming clear that “many uses and environmental values (of groundwater) depend on the depth to water – not the volumetric amount of (groundwater) that is theoretically available" (Sophocleous 2003; Ragone *in review*). No generalized guidelines have been proposed to define the depths to the various groundwater systems for purposes of negotiating use of deep groundwater systems.

Table 2. Natural Groundwater Resources in the Upper Layer of the Earth's Crust by Hydrodynamic Zone (modified after Shiklomanov and Rodda 2003).

Continent	**Zone of Groundwater Movement**	**Groundwater Resources (km^3 x 10$^{6)}$**	**Total Groundwater Resources (km^3 x 10^6)**
Europe	Active Water Exchange	0.2	1.6
	Below local base level to sea level	0.3	
	Sea level to -2000m	1.1	
Asia	Active Water Exchange	1.3	7.8
	Below local base level to sea level	2.1	
	Sea level to -2000m	4.4	
Africa	Active Water Exchange	1.0	5.5
	Below local base level to sea level	1.5	
	Sea level to -2000m	3.0	
North America	Active Water Exchange	0.7	4.3
	Below local base level to sea level	1.2	
	Sea level to -2000m	2.4	
South America	Active Water Exchange	0.3	3.0
	Below local base level to sea level	0.9	
	Sea level to -2000m	1.8	
Australia and Oceania	Active Water Exchange	0.1	1.2
	Below local base level to sea level	0.2	
	Sea level to -2000m	0.9	

The Vertical Dimensions of the Hidden Sea

Tòth (1963) provides a hydrogeologic conceptual model of nested regional, intermediate and local groundwater flow systems with horizontal and vertical systems driven by topography based on studies of groundwater basins in Alberta, Canada. Tòth (1999) indicates that each flow system, regardless of its hierarchical position, has a recharge area, an area of through flow and an area of discharge. In the recharge areas, the hydraulic head or mechanical energy in the groundwater system are high and decrease with depth. In discharge areas hydraulic heads are low and increase downward, with groundwater converging and ascending in the area of a springs or streams. Qualitatively, Tòth's model posited that where topographic relief is negligible, deep regional groundwater flow systems would develop. Conversely, local groundwater flow systems would develop where topographic relief was pronounced (Freeze and Cherry 1979).

As depicted on Figure 11, Tòth's model emphasized the importance of deep groundwater systems. In one of his analytical analyses of the conceptual model, he investigated the aquifer depths approaching 3,000 meters while the distance between the recharge areas designated as a drainage divide to the discharge area designated as a stream was approximately 7,000 meters. Tòth's limiting assumptions regarding his model included steady-state conditions for a rectangular, homogeneous flow system under sinusoidal boundary conditions used to imitate a fluctuating water table – a model not unlike some of the groundwater domains assumed for the groundwater basins in California described in the pioneering work on common pool resources by Ostrom (1990) and Blomquist (1992).

Tòth (1963; 1999) showed that numerous local flow cells develop at shallow depths under gravity flow conditions and variations in the water table that coincide with the topography. In a study of the hydrologic relationship of the water table in unconfined groundwater systems, Haitjema and Mitchell-Bruker (2005) developed numerical models using Tòth's conceptual model under different depth scenarios and assuming that the water table closely coincides with the land surface. Their analysis revealed local flow cells circulating to a depth of approximately 305 meters. These modeled local flow cells reasonably represent the local flow cells that may be hydraulically connected to a surface water system such as wetlands or streams. While it is recognized that Tòth's model represents an idealized groundwater flow system, the models by Haitjema and Mitchell-Bruker (2005) provide the first estimates of the vertical dimension that might be applied to shallow groundwater systems that may be governed under a river basin treaty or a groundwater body that is considered part of a watershed administered under the concept of Integrated Water Resources Management or the Water Framework Directive. Consideration that the lifting capacity of conventional pumping equipment capable of exploiting the quantities of groundwater at rates needed for intensive uses such as agriculture or geothermal energy becomes problematic at depths below 550 meters further substantiates the proposal of a vertical dimension for shallow groundwater systems. As a consequence, the deeper groundwater flow systems may be considered separate from the watershed and potentially managed differently than the shallow groundwater system, or considered part of a larger commons.

While Winter and others (1998) argue that groundwater cannot be managed in isolation from surface water, analyses of international groundwater law by Matsumoto (2002), Burchi and Mechlam (2005) and an analysis of river basin treaties and agreements described in previous chapters determined that in most instances where surface water resources are being managed, no significant account is taken of connected groundwater resources (Foster and others 2005). The reality is that there are many examples of managing deep aquifers differently than shallow aquifers; for example, the 1997 UN Convention on Non Navigational Uses of International Watercourses where shallow groundwater is considered part of a watercourse and deeper “confined” aquifers are not legally considered part of a watercourse. Likewise the Netherlands, Israel-Palestine, India, among others, manage deeper aquifers differently than shallow aquifers, some due to hydrogeology, others due to the apparent stress that the aquifers are undergoing and that "pragmatism dictates to tackle them directly” (Foster and others 2005).

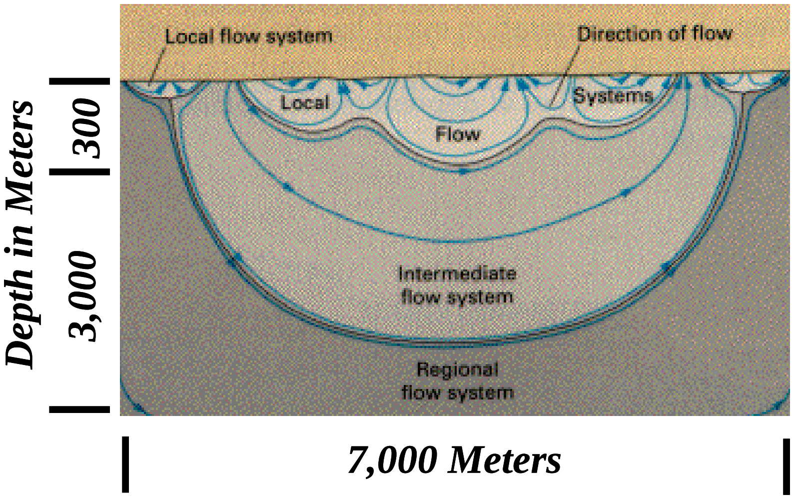


Figure 11. Conceptual model of flow systems in a groundwater basin. Diagram from Winters and others (1998) adapted from Tòth (1963 and 1999) using modeling results of Haitjema and Mitchell-Bruker (2005). Garven (1985) indicates that the horizontal scale for groundwater flow in deep regional systems can approach continental in scale.

Governing the Hidden Sea in the Commons

Under Roman Law, property was considered to exist under four regimes: *res publica*, *res communes*, *res nullius*, and *res privatae* (Buck 1998). *Res publica* focuses on objects where the property rights are held by the government for the beneficial use of the public and included navigable rivers, highways, and territorial seas. In the regime *res communes*, light, air and the deep sea remain accessible by all but cannot be acquired for the exclusive use by an individual or government. *Res nullius* resources have no property rights as they have either been abandoned or no individual has acquired them, but once these objects are possessed, the objects become *res privatae*. While these property regimes categories are well known in the Western world, they are of limited use in labeling common pool resources because they lack dimensions that incorporate the flow of resources from the resource domain (Buck 1998).

Resource domains where common pool resources are found are defined as “the commons” (Buck 1998). Large resource domains that are not under the jurisdiction of one country are either international commons or global commons. Buck (1998) differentiates between the two by indicating that international commons are resource domains shared by several nations, which can exclude others from use - Antarctica is one example. Global commons are resource domains where all nations have legal access and exclusion is more problematic – the oceans are the most commonly thought of, but most complex, of the global commons (Buck 1998).

Where groundwater fits within the management of the commons, global environmental regimes, and international law remains problematic. Chasek and others (2006) indicate that there must be "sufficient concern" within government and the public at large to develop effective global environmental regimes. While Kemper (2004) indicates that practical advances for groundwater management and governance are urgently needed, no "blueprint" for action exists. Many scholars indicate that laws regulating the international use of groundwater are in "embryonic" stages of development (McCaffrey 2001), with transboundary management regimes in their infancy (Matsumoto 2002) and often flouting the scientific principles of hydrology (Glennon 2002). It is beyond the scope of this paper to provide detailed summaries of the history and vagaries of groundwater in international law as the geographic and legal literature is replete with excellent summaries provided by Matsumoto (2002), Nanni and others (2002), Eckstein and Eckstein (2003), Burchi and Nanni (2003), Hardberger (2004), Burchi and Mechlam (2005), and Matthews (2005). Table 3 provides a listing of the progressive levels of groundwater resources management at the national and international levels. With the exception of minimum legal controls over regulation of groundwater observed in countries such as India or China, the general trends in governance models either focus on an integration of groundwater as part of the surface water system as generally practiced in North America or Europe, or on the compartmentalization of groundwater as a unique hydrologic system as practiced in North Africa. Note there is very little acknowledgement of shallow versus deep groundwater systems in the governance models.

Table 3. Levels of Groundwater Resource Governance (adapted from Nanni and others 2002)

Regulation Level	Implications	Limitations	Examples
Minimum Legal Control	No control over groundwater abstractions.	Reduced natural discharge to ecosystems, pollution.	India, China
Local Customary Rules	Groundwater rights defined at local level; mechanisms for local conflict resolution.	Limited controls; no account of impacts to groundwater system, downstream users, water quality.	Pakistan, Iran
Specific Groundwater Legislation	Well construction and groundwater abstraction controlled.	Little consideration may be given to groundwater dependent ecosystems or water quality.	Philippines
Comprehensive Water Resources Legislation	Surface water/groundwater subject to same regulation; both administered by same agency; water quality regulated under separate agency.	Pollution control may be deficient. Little to no recognition of shallow versus deep groundwater systems.	United States, Canada
Fully-Integrated Water Resources Legislation	Integrated catchment/groundwater body; emphasizes public awareness/participation; some transboundary issues recognized.	Best chance of implementing balanced and effective regulation policy. Deep aquifers identified if important to ecosystems or drinking water.	European Community
International Agreement	Water quality protection, allocation, recharge, extraction.	Surface water/groundwater interdependence vaguely recognized. Only one agreement in effect for groundwater.	French Prefect de Haute-Savoie & Swiss Canton of Geneva
River Basin Organization	Management and stakeholder involvement at river basin level.	Marginal recognition of groundwater rights in licensing arrangements.	Murray-Darling Basin, Australia
Aquifer Management Organization	Acknowledgement of limited interaction with surface water resources in arid areas.	Only one in effect for groundwater. No recognition of underlying aquifers.	Regional development of Nubian Sandstone in North Africa
International Conventions	Surface water/groundwater part of international watercourse.	Best chance of international participation. Not ratified. Deeper "confined" aquifers not covered.	Convention on the Law of the Non-navigational uses of International Water Courses
	Transboundary aquifers approach with integration of use and water quality protection.	Draft ongoing by ILC Acknowledges importance of conceptual hydrogeologic model	Draft Convention on the Law of Transboundary Aquifers
	Shallow groundwater connected to surface water. Deeper groundwater part of global commons under "Law of the Hidden Sea"	Depth of shallow and deeper groundwater systems based on simple hydrogeologic model.	Adaptation of the UN Commission of the Law of the Sea proposed in this chapter.

Minimum legal controls serve as the foundation for historical management of groundwater where it was considered the property of the owner of land under Roman Law. This rule also served as the foundation for French Napoleonic Civil Code which until recently was followed by France, Spain, many African and Latin American countries as a result of French and Spanish colonization (Nanni and others 2002). The landowner had the exclusive right to capture groundwater underlying the land subject to similar rights of neighboring landowners. English Common Law permitted the holder of a land title to the exclusive right to use all groundwater not flowing in defined channels. Groundwater flowing in defined underground channels, as well as surface water, were subject to riparian doctrine, where the right to use groundwater was left to the party who held title to the adjacent land. These principles were inherited and modified by those countries using a legal system derived from England. Good examples of this property regime as applied to groundwater include India and groundwater stored in the Edwards Aquifer underlying the state of Texas in the United States (Shah 2005; Vottler 2004). The Edwards Aquifer was managed as a common pool resource with access limited only to landownership, but it is undergoing a transition to a regulated resource under the Edwards Aquifer Authority.

Local customary rules also have historical foundations for groundwater management and governance. According to Teclaff and Utton (1981), Moslem law establishes a close relationship between groundwater and land use. In many Moslem countries, groundwater is viewed as a “gift of god” that could not be privately owned. The ownership of wells in Moslem countries entitles “ownership” of a certain amount of the adjacent land so as not affect the quality or the quantity of existing wells. The *harim*, or “forbidden area” is an unwritten customary law enforced by the local community. *Harim* rules for groundwater are still common in Pakistan and Iran (Nanni and others 2002; van Steenbergen 2004).

With water scarcity and growing concerns over water pollution, legislation is increasingly used to vest water resources in the state to acknowledge a state’s right to the management of water resources. Within the federalist system of the United States, groundwaters are managed under absolute ownership, reasonable use and correlative rights, and appropriation-permit systems. Each state is typically vested with governing all waters, with waters being part of the public domain with users applying for permission for use.[22] Elsewhere, nations are also passing legislation recognizing groundwater as part of the national public domain and even more are incorporating the protection of groundwater as part of their mission. For example, many countries subscribe to the concept of Integrated Water Resource Management (IWRM)[23] where river basins and associated subwatersheds are used as spatial units for data collection and policy formulation is a fundamental geographical notion that has been used as a planning metric since the 1920s (Platt 1993). The European Community has adopted the Water Framework Directive which aims at providing a framework for the protection of the European Community's water resources and in doing so to contribute among other things to sustainable, balanced and equitable water use. However, the development aspects of water in relation to its significance for social and economic development are not mentioned. This is an important deviation from the IWRM approach indicating that the Water Framework Directive is not IWRM.[24]

Reconciliation of water issues in river basins is hampered by the spatial nonconformity of political and physical systems which usually does not conform to the geography of watersheds. Out of basin transfers, water importation, and artificial storage and recovery reflect spatial discontinuities between regions of supply and demand (Platt 1993). WHYMAP (various years) determined that IWRM by nation,

---

[22] Texas and Louisiana are examples of two states operating under the doctrine of absolute ownership, whereas the other states operate under one or a combination of the other management principles.

[23] The concept of sustainability and Integrated Water Resources Management were discussed at the International Conference on Water and Environment Issues for the 21st century in Dublin, Ireland in 1992, and the Earth Summit sponsored by United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil in 1992 resulting in Agenda 21.

[24] http://ec.europa.eu/comm/environment/water/

by catchment or by river basin is not appropriate for groundwater resources particularly in arid areas where the surface water catchments and deep aquifers are totally different. In no-recharge areas where groundwater replenishment is limited to non-existent, these areas are better suited as relevant water management regions (Foster and others 2003).

The New Paradigms of Groundwater Governance

The traditional approach to transboundary water management is sovereign states enter into agreements known as international regimes as a means to maintain sovereignty over actions that may harm their respective environments or economies (Conca 2006; Finger and others 2006). And while this rule-based approach has a strong tradition in surface water resource agreements and treaties, this approach has been less than successful for groundwater resources for many reasons, including (1) the hidden nature of the resource, (2) the lack of monitoring and data collection, (3) the large uncertainty associated with the conceptual models of the groundwater resources, (4) scale mismatches, and (5) deeply rooted conflicts about authority, territory, and knowledge, all leading to a general lack of institutional capacity to accommodate groundwater management and governance. New paradigms for transboundary water management and governance recognize a tiered approach with levels from the global to the local (Dietz and others 2003), acknowledging the role of civil society and markets (Mukherji and Shah 2005), and that the complexity of environmental systems may require a “post-sovereign” or multi-level approach (Karkanninen 2005; Finger and others 2006)

Mukherji and Shah (2005) suggest that the many of the problems associated with managing groundwater resources result from poor governance. They describe governance as used in political science as meaning “de-centering and pluralization of the state into a number of levels that stretch horizontally form civil society and market organizations on the one hand and vertically from the transnational to local self-government institutions on the other" (Mukherji and Shah 2005:338, quoting Chandhoke 2003:2957). Figure 12 diagrammatically portrays their overall concept of governance. Mukherji and Shah (2005) suggest that better groundwater governance of the shallow groundwater resources undergoing intensive exploitation means acknowledging a greater role for markets, civil society, and the local governments, and a much diminished role for the central and provincial governments. Their analysis is silent as to the challenges to governance of the deeper groundwater resources where the flow regimes may extend beyond the traditional boundaries of a watershed and may incorporate the areas of multiple watersheds underlain by deeper megawatersheds which can be continental in scale as described by Garven (1985) and Bisson and Lehr (2004).

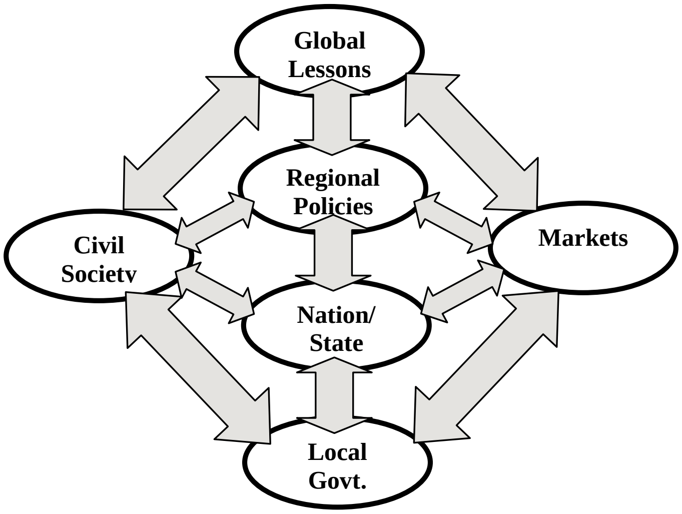


Figure 12. The new and idealized paradigm of governance. Adapted from Mukherji and Shah (2005). Used with kind permission of Springer.

Scale mismatches have been long recognized in transboundary water management as political boundaries that poorly accommodate the scale of the resource (Benevenisti 2002). The scale mismatch is obvious with large surface watersheds and groundwater resource domains extending beyond the boundaries of most individual sovereign nations. Conversely, Karkanninen (2005) argues that sovereign states may be too large to fit the geographical scale of the environmental problem. An example of this mismatch is the management of the North American Great Lakes which drain a region totaling 766,000 km^2. Given that the region is shared by smaller regions located in both Canada and the United States, the environmental management problem may be seen as a sub-national issue rather than a national one for either nation. Karkkainen (2005) goes on to show that the scale mismatch also extends to ecosystems which are poorly matched to political boundaries. Given that Struckmeir and others (2006) identified nearly 240 transboundary aquifer systems, it is obvious that groundwater resources also fall into the scale mismatch category.

The institutional capacity mismatch for transboundary environmental management is more obvious when one considers the compartmentalized and fragmented nature of traditional water management. For example, water quality management is often separated from the management of water quantity, surface water management is separated from groundwater management, and appurtenant ecosystems or other water-dependent nature reserves are separated from the other water management regimes. Conventional regulatory approaches do not account well for dynamic and complex systems such as surface ecosystems, local livelihood and culture, and water as a market commodity, much less so for the "hidden" groundwater dependent ecosystems, cultures, and livelihoods (Karkkainen 2005; Conca 2006:8).

In addition to the new paradigm for groundwater governance proposed by Mukherji and Shah (2005), Karkkainen (2005), Conca (2006), and Finger and others (2006) posit new paradigms that some complex environmental problems will require rethinking the traditional approach to natural resource management using state-centric regulatory rules. Termed "post-sovereign governance" by Karkkainen or "multi-level governance" by Fingers and others, this new governance model recognizes that state sovereignty remains a key part of the international landscape, but that it exists alongside new forms of multi-lateral transboundary collaboration. The governance model applies both to domestic environmental policy as well as complex transboundary environmental problems, including "transboundary water management" (Karkkainen 2005:73) and by linking "several issues together with water such as biodiversity and climate change" (Finger and others 2006:19).

The post sovereign governance model is a hybrid institutional form built upon three principles. The first principle replaces exclusive sovereign authority under multi-party collaborative governance institutions. Karkkainen (2005) argues that while sovereign states are not excluded from the governance process, non-state actors take on roles as co-authors and co-implementers of environmental policy. The second principle focuses on transnational cooperation extending beyond the one-time-only mutually agreed upon inter-sovereign rules of obligation to building transboundary environmental governance around open-ended, continuous commitments to "do what it takes" to restore ecosystems. The third principle maintains the post-sovereign approach by having the measures extend beyond the traditional hierarchical, or top-down and prescriptive, imposition of rules that bind parties subject to the state's jurisdiction. Karkkainen (2005) argues that such an approach to transboundary environmental governance embraces a mix of non-hierarchical tools that may have little to no formal legal consequence, but still have practical effects in directing the behavior of state and non-state parties.

Acknowledging that scale is an important issue for devising environmental regimes, Young (2003) suggests that higher level arrangements similar to the post-sovereign or multi-level governance models offer opportunities to consider functional interdependencies in large marine and terrestrial ecosystems and to devise regimes based on the precepts of ecosystem management. Those operating at international levels are compelled to devise and promulgate structures of rights and regulatory rules in terms that are broadly encompassing and generic. Moving to higher levels of social organization can open up opportunities for increased efficiency in the use of the resources and for more comprehensive equity. National and international arrangements are needed to manage human activities relating to large marine and terrestrial ecosystems. What is needed is a conscious effort to design and manage institutional arrangements that recognize different types of knowledge and protect the rights and interests of local stakeholders, even while high levels of social organization are required to cope with the dynamics of ecosystems that are regional and even global in scope.

McCaffrey (2001) indicates that the constant movement of water through the hydrologic cycle makes it futile for any state to subject waters under its absolute control. Conversely, he indicates that it would be going too far under the current state of international law to suggest that all freshwater is *res communes*. He argues that it is important to conceive of the hydrologic cycle in this way, however. Most of the water that falls to the land evaporates from the ocean and nearly two-thirds of the ocean lies beyond the limits of national jurisdiction, and is part of the global commons. He further argues that “if the law of the sea can include assistance for developing and geographically disadvantaged states, why should the law of internationally shared freshwater resources not provide assistance for hydrologically disadvantaged states?”

The hydrologic and geographic challenges associated with the ocean policy and governance have many similarities to those anticipated for governing international groundwater resources. For example, the periods of renewal of the oceans and groundwater approach the same order of magnitude with estimates of renewing water stored in the ocean approaching 2500 years and groundwater estimated at 1400 years. The uncertainty associated with numerical modeling of oceans systems leads to “surprises” in approximately 30% of the models (Wilson 2003); whereas Bredehoeft (2005) reports a rate of surprises in models of groundwater systems approaching 15 to 20%. Just as groundwater systems are valued for the vast quantities of water stored or can be disposed of within aquifers, oceans “store” commodities such as minerals from the deep seabed, sources of food from animals, plants and fish, and provide areas for the dumping of waste materials (Sutherland and Nichols 2002). Likewise, the previously held belief that marine spaces are infinite in its resources has in recent times proven to be a myth. The popular literature indicates that the doctrines of capture and reasonable use are leading to a “tragedy of the commons” for groundwater resources (Glennon 2002). However, Llamas and Custodio (2002) indicate that whether the “tragedy” will ultimately fall upon groundwater resources remains debatable.

Young (2003) indicates the marine ecosystems do not conform to any legal or political boundaries however ingenious the effort to delineate them may be. Marine spaces are inherently multi-dimensional and make two-dimensional definition of the rights and domains legally inadequate. The legal interpretations of jurisdiction, administration, and title have broadened the concept of a 3D marine parcel to a complex series of overlapping interests offshore. Many of these boundaries overlap not only at the water surface, but also within the water column and even within the seabed (Sutherland and Nicols 2002). As described in Chapter 3, delineating boundaries around groundwater resource domains face the same challenges.

A Look at the Benefits of Applying the UN Commission on Law of the Sea to the Hidden Sea

Given the similarities in the technical and institutional challenges associated with managing the oceans and groundwater, coupled with the hydraulic connection between both resources, perhaps it is possible to apply the existing regime for the oceans to groundwater resources. The UN Commission on the Law of the Sea (UNCLOS) was originally designed to promote the orderly and equitable regime or system to govern all uses of the sea. According to the United Nations (1982) Malta’s Ambassador to the United Nations, Arvid Pardo, called for “an effective international regime over the seabed and the ocean floor beyond the clearly defined national jurisdiction” in 1967. This set in motion a process that spanned 15 years and saw the creation of the United Nations Seabed Committee that declared that all resources of the seabed beyond the limits of national jurisdiction are the common heritage of humankind.

Referred to by prominent diplomats as “possibly the most significant legal instrument of this [20th] century” and “the most complex international instrument that has ever been negotiated”, UNCLOS starts from the premise that the problems of ocean space are closely interrelated and need to be considered as a whole. It arose from the recognition that traditional sea law was disintegrating and that the international community could not be expected to behave in a consistent manner without dialogue, negotiations and agreement (United Nations 1982). It has been ratified by 149 of the 195 independent members of the United Nations since 1982 with Estonia the most recent in 2005.[25] UNCLOS counts among its supporters groups with such diverse interests as the American Petroleum Institute and the Natural Resources Defense Council (Ravikumar 2000; Los Angeles Times 2004). The United Nations (1982) indicate that wider understanding of the UNCLOS would bring yet wider application.

Recognition of Applying UNCLOS to Freshwater Resources

The application of UNCLOS to freshwater resources is not a new concept. McCaffrey (1997:57) poses an interesting question regarding whether the day is far away where water-poor states assert a “right” to a portion of the water that evaporates from areas of the sea beyond the limits of national jurisdiction. He notes that international law recognized “geographically disadvantaged” states where natural resources were located in global commons such as the issue of living resources and UNCLOS. McCaffrey (1997) cites article 70, paragraphs 1 and 2 of UNCLOS:

> “Geographically disadvantaged States shall have the right to participate, on an equitable basis, in the exploitation of an appropriate part of the surplus of the living resources of the exclusive economic zones of coastal

---

[25] The United States has not ratified the UNCLOS despite the United States Foreign Relations Committee passing for ratification of the treaty 19 to 0 in 2004.

> States of the same subregion or region, taking into account the relevant economic and geographical circumstances of all the States concerned and in conformity with the provisions of this article and of articles 61 and 62 (Article 61 and 62 concern conservation and utilization of living resources)."
>
> "Geographically disadvantaged States" means coastal states, including states bordering enclosed or semi-enclosed seas, whose geographical situation makes them dependent upon the exploitation of the living resources of the exclusive economic zones of other states in the subregion or region for adequate supplies of fish for the nutritional purposes of their populations or parts thereof, and coastal states which can claim no exclusive economic zones of their own."

It is clear that these provisions acknowledge rights for states where geography has created hardships, namely the arid states, but it could be argued that poor hydrogeologic conditions fit into the realm of "geographically disadvantaged".

The implementation of the right of the geographically disadvantaged to sharing of fresh water "would not be a simple matter, but neither would it be impossible" (McCaffrey 1997:58). Two options were presented by McCaffrey for a model of implementation: (1) Part XI of UNCLOS which was designed for allocation of the resources of the deep seabed; and (2) entrusting the Trusteeship Council[26] with the responsibility to determine the equitable share of hydrologically-disadvantaged states with water based upon many factors such as human need, and availability of water from other countries.

---

[26] The United Nations Charter established the Trusteeship Council as one of the main organs of the United Nations and assigned to it the task of supervising the administration of Trust Territories placed under the Trusteeship System. Major goals of the System were to promote the advancement of the inhabitants of Trust Territories and their progressive development towards self-government or independence. The Trusteeship Council was made up of the five permanent members of the Security Council --China, France, Russian Federation, United Kingdom and United States. The aims of the Trusteeship System have been fulfilled to such an extent that all Trust Territories have attained self-government or independence, either as separate States or by joining neighboring independent countries. The Commission on Global Governance's 1995 report recommended amending Chapters 12 and 13 of the United Nations Charter to give the Trusteeship Council authority over the global commons, which consists of oceans, the atmosphere, outer space, and Antarctica (United Nations 1982 and Commission on Global Governance 1995).

Apparently building upon McCaffrey's suggestions regarding how the law-of-the sea model might apply to water scarcity situations, the draft convention on the law of transboundary aquifers incorporates references to UNCLOS to justify some of the draft articles. For example, Yamada (2005) reports that the proposed draft article on bilateral and regional arrangements was developed using the concept of reserving the matter to the group of aquifer states concerned with a particular aquifer is based on the principles set forth in articles 118 (Cooperation of States in the conservation and management of living resources of the high seas) and 197 (Cooperation on a global or regional basis) of the UNCLOS. Likewise, the proposed draft article on the relation to other conventions and international agreements states that "the present Convention shall not alter the rights and obligations of the States Parties which arise from other agreements compatible with the present Convention" and specifically lists article 194 of UNCLOS (i.e., the measures to prevent, reduce and control pollution of the marine environment).

The proposed article with the draft convention on transboundary aquifers focuses on equitable and reasonable utilization as it relates to the proper management of groundwaters. Again the justification of the article focuses on UNCLOS, specifically article 119 where for marine living resources, fishery agreements uphold the maximum sustainable yield principle. Article 18 of the proposed draft convention finds its roots in article 202 (i.e., the scientific and technical assistance to developing States) of UNCLOS**.**

Proposed New Uses of UNCLOS to Groundwater Resources

It is clear that UNCLOS is becoming recognized as a legal instrument with an increasingly wide range of potential applications to freshwater resources. Perhaps the most controversial concept associated with the application of UNCLOS to groundwater is the issue of states' sovereign rights over the natural resources located within their jurisdiction. As outlined in the discussion of equitable and reasonable use in the draft convention on transboundary aquifers, Yamada (2005:8) indicates that "aquifer states are entitled to utilize aquifers and aquifer systems within their territories. It is needless to say that such rights should not be absolute and unlimited". This last statement tacitly implies that some of the groundwater resources with the jurisdiction of a sovereign state may be part of the international or global commons, at least within the eyes of the International Law Commission.

Central to UNCLOS was the setting of limits or boundaries. For example, the United Nations (1982) indicates that the exclusive economic zone (EEZ) was one of the most revolutionary features of UNCLOS because of the impact on the management and conservation of the resources of the oceans. The EEZ recognizes the right of coastal states the jurisdiction to exploit, develop, manage and conserve all resources whether it be fish, the waters superjacent to the seabed and of the seabed and its subsoil (groundwater), oil and gas, gravel, or nodules, to be found in the waters, on the ocean floor and in the subsoil of an area extending 322 kilometers from its shore.

Consideration of Tòth's model of shallow, intermediate and deep groundwater flow systems, coupled with the recognition by Garduño and others (2004) that specific hydrogeologic settings, may require different approaches to governance as opposed to lumping all groundwater under a local management plan. Recalling that the depth of the shallow groundwater flow system using the conceptual model of Tòth (1963) approached 300 meters may suggest a comparable "exclusive economic zone" for groundwater development within a river basin where the river flow is dependent on aquifer discharge. Under this conceptual adaptation of UNCLOS to groundwater resources, the deeper groundwater systems would be considered part of the common heritage of humankind similar to the principles governing the "area" or the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction as outlined in Part XI, Section 2, Article 136 of UNCLOS.

Disputes over the governance of the “common pool” of deep groundwater could also be addressed using provisions within UNCLOS. For example, Part XV of UNCLOS outlines a comprehensive system for the dispute resolution with respect to the interpretation and application of the UNCLOS. The Charter of the United Nations requires states to settle their disputes concerning the interpretation or application of UNCLOS by peaceful means. Parties failing to reach a peaceful settlement are obliged to the compulsory dispute settlement procedures entailing binding decisions, subject to limitations and exceptions contained in UNCLOS. UNCLOS provides for four alternative means for the settlement of disputes: the International Tribunal for the Law of the Sea (ITLOS), the International Court of Justice, an arbitral tribunal constituted in accordance with Annex VII to the Convention, and a special arbitral tribunal constituted in accordance with Annex VIII to the Convention.

ITLOS commenced work in 1996 and has heard 13 cases to settle disputes arising out of the interpretation or implementation of UNCLOS.[27] Some of these cases were related to jurisdiction of coastal states in maritime zones, environmental protection, and conservation of fish stocks. These same types of disputes can easily be envisioned for deep continental groundwater resources, e.g. a dispute over the boundary of the shallow versus the intermediate and deeper zones of groundwater flow, the conservation of groundwater dependent ecosystems, or the flows required to sustain geothermal resources which are part of a national park or World Heritage Site.

While the implementation of ITLOS to disputes regarding deep continental groundwater resources would not be easy, it would not be impossible. The foundation for incorporating groundwater in the commons of global governance is the belief that the world is now ready to accept a “global civic ethic” based on “a set of core values that can unite people of all cultural, political, religious, or philosophical backgrounds” (Commission on Global Governance 1995). And water falling under the precept of a global civic ethic is not a new concept (Conca 2006). In the *Water*

---

[27] http://www.itlos.org/

Manifesto, Petrella (2001) indicated that given the water crisis facing the new millennium, new rules reflecting a revolution in the ways of looking at water and water-mediated solutions among humans and a new means of managing water designed to rebuild solidarity among local communities, across different communities and generations, and that are sustainable in terms of maintaining ecosystems are important. According to Petrella (2001), the founding principle of the World Water Contract is water as a common global resource.

Conclusions

The piecemeal approach to governance of groundwater resources, coupled with the lack of acknowledgment regarding the hydraulic connection of the vast hidden sea of groundwater with the ocean, has lead to a "comedy of errors" when the only difference between groundwater resources in both the terrestrial and marine resource domains are the *bona-fide* boundaries of coastlines. Rather than relying on traditional approaches to groundwater governance as though the resource was like a mineral resource underlying the boundaries of a sovereign nation, this chapter offers a look at how to deal with the complexity associated groundwater resources through an interdisciplinarity approach, integrating what is known about the vertical stratification of the earth's groundwater determined by hydrogeologists and integrating this knowledge with a paradigm shift in natural resource governance developed by political scientists. The "post-sovereignty" and "multi-level" governance model proposed herein for groundwater resources acknowledges the reality that groundwater is hydraulically connected to the ocean and is as complex as the ocean with respect to predictive modeling. Given the existing legal instruments associated with the ocean that fall under the global "contract" of the UNCLOS that has received widespread acceptance from the global community, coupled with the application of UNCLOS to ongoing efforts to develop a legal instrument for transboundary aquifers, it is not unreasonable to assume that UNCLOS or similar "world water contract" or Law of the Hidden Sea could be adapted to incorporate groundwater that is not in direct hydraulic connection with surface water resources. These institutional arrangements would address this need and would address the obvious lack of institutional capacity on deep groundwater and the related ecosystems and cultural resources. According to Conca (2006), transnational forms of water governance are gaining ground, and as Bradley Karkkainen states “They represent the leading edge in a wave of institutional innovation” (Karkkainen 2005:84).

Chapter Six: Conclusions

This dissertation was developed around the four themes that must be included in water resources research enterprises due to future complexity: (1) interdisciplinarity; (2) broad systems context; (3) uncertainty; and (4) adaptation. Research on common pool resources such as groundwater requires scientists from a broad spectrum of disciplines because the commons can best be described as a “drama” composed of different “scenes” including history, comedy, and tragedy. To meet these objectives, an interdisciplinary approach integrating geology, geography, and political science was used to address the emerging policy issues surrounding transboundary groundwater.

The second chapter of this dissertation used a comparative analysis between the history of geography and groundwater hydrology to dispel the “myth” that the two fields of study have little to no overlap. On the contrary, the two fields have a common heritage and converged often throughout history and have become more focused on linking the human aspects to land use and water development through GIS. Geographers have a rich tradition of using an interdisciplinarity approach to problems in the earth sciences, but they must acquire competencies beyond those found in the traditional arena of geography to effect change in groundwater resources management and governance. A more focused integration of skills found in geography and groundwater hydrology will get geoscientists a "seat at the table" where decisions will be made about the future of the world.

Despite the rich tradition of geography in addressing the historical, cultural and political development of boundaries and space, it is ironic that few political geographers have addressed the problem of how boundaries are placed around common pool resources, particularly groundwater resources. The third chapter provided case studies of the technical, political, and social complexities of drawing boundaries around groundwater resources and users domains. Through an examination of international legal instruments for freshwater, groundwater is related to political boundaries and river basins in the early to mid 1980s, followed by the physical boundaries of the shared aquifers or related management units in the late 1980s through the 1990s and refined definitions of an aquifer and the shared aquifer boundaries emerge after 2000. A previously unrecognized typology for the boundaries for groundwater resources and user domains was derived from an examination of management approaches at the nation and state level. Resource domains form a "static" or what may be considered a predevelopment condition, referred to herein as a *bona-fide* "commons" boundary. A meshing of hydrology and hydraulics associated with development or a "dynamic" condition creates a human-caused or *fiat* "hydrocommons" boundary. A *fiat* "commons heritage" boundary recognizes the social and cultural values of "users" of the groundwater resources that are part of the "common heritage of humankind". The significance of these findings is that it is difficult to aggregate demographic, social, and economic data within specific boundaries for groundwater resources for detailed geographic analyses without agreement on the fundamental unit of analysis. This dispels the myth that drawing boundaries around groundwater resources and user domains is relatively straightforward.

Building upon the theme that the commons reflect a drama, the fourth chapter of the dissertation investigated the "tragedy" of the poorly structured institutional capacity built within river basin treaties and agreements and River Basin Organizations accommodate governance of groundwater and transboundary aquifers. This chapter demonstrated that regimes to manage or govern groundwater remain weak. Part of the problem rests with the fact that groundwater was not routinely integrated into freshwater treaties and other agreements were negotiated. About 15% of the freshwater treaties and other agreements had provisions for groundwater. The other part of the problem rests with the fact that the boundaries of the transboundary groundwater systems are very different than the boundaries of a watershed; consequently, any treaty or agreement that has a provision for groundwater reflects only a cursory recognition of the groundwater flow regime. Other deficiencies identified by this freshwater treaty survey include (1) the storage characteristics of the groundwater systems are not recognized in the treaties or other agreements, (2) aquifer systems located along coastal regions are not addressed in the survey of river basin treaties, (3) the utilization of non-renewable groundwater remains silent, (4) the vast fresh groundwater resources stored under the ocean floor are not addressed, and (5) there are no provisions for monitoring the groundwater systems. Of the few river basin treaties that have provisions for groundwater, none address the spatial and vertical boundaries of the groundwater system.

A consensus is growing around the acknowledgement that the institutions for managing international river basins are neither robust nor well developed. This consensus is being fueled by further recognition that the few legal instruments that do contain groundwater-specific provisions, the type of aquifer storage is rarely addressed, nor are the horizontal and vertical limits of the groundwater system mentioned. None of the legal instruments address groundwater in coastal regions or groundwater stored under the ocean despite the battle with saltwater intrusion in coastal groundwater basins. It is clear that the time has come for a paradigm shift in the institutions to govern groundwater resources. The fifth chapter of this dissertation presented a case for "post-sovereign" and "multi-level" governance of groundwater resources given a renewed look at the hydrogeologic distribution of groundwater beneath the world. With the bulk of the global groundwater found at elevations *below* sea level, perhaps it is time to review the "comedy of errors" and the mistaken identity of groundwater as separate from the oceans to more as part and parcel of the sea through a wider application of the United Nations Conventions on the Law of the Sea to the Law of the Hidden Sea.

And so the drama of governing the common pool of groundwater resources comes to an end. This dissertation addressed the "real tragedy" of the commons in groundwater resources – the lack of institutional capacity governing the transboundary movement of groundwater resources both within the traditional framework of freshwater treaties and agreements, as well as legal instruments related specifically to groundwater resources. It also addressed the “history” of interdisciplinarity between geography and groundwater hydrology that revealed a long tradition of collaboration as opposed to the conventional wisdom that the two fields evolved separately. This research also recognized the “irony” associated with the plethora of boundaries around groundwater resources and user domains that has apparently been overlooked by geographers, hydrologists and political scientists concerned with the management and governance of common pool groundwater resources. It also provides a typology for the groundwater resources and user domains recognizing the transient and social nature of the boundary conditions. And finally the dissertation recognized the “comedy of errors” associated with the continued efforts to manage groundwater resources separately from the oceans despite the obvious hydraulic connection, similar hydraulic behavior with respect to time of renewal, and comparable complexities. A new paradigm of groundwater governance is proposed that acknowledges sovereignty issues by offering a conceptual model of the shallow groundwater systems hydraulically connected to surface water systems that could be considered part of a river basin governance, and deep groundwater systems that could be considered part of the global commons and governed under many of the precepts of the United Nations Convention on the Law of the Sea through a Law of the Hidden Sea dedicated to groundwater resources.

Bibliography

Abu-Zeid, K. 2002. Newsletter on the Nubian Sandstone Centre for Environment & Development for the Arab Region & Europe - CEDARE - Nov. 2002 (http://www.inbo-news.org/divers/thonon/CEDARE-NSAS-Article.PDF last accessed on April 17, 2006).

Acosta, O. 2005. Intensive use of aquifers by mining activity in Northern Chile. In *Groundwater Intensive Use*, eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7, pp. 177-185. Leiden, The Netherlands: A.A. Balkema Publishers.

Adams, W.M., D. Brockington, J. Dyson, and B. Vira. 2003. Managing Tragedies: Understanding Conflict over Common Pool Resources. *Science.* 302:1915-1916.

Alley, W.M., T. Reilly and O.L. Franks. 1999. Sustainability of Ground-Water Resources. *U.S. Geological Survey Circular 1186.*

Alcamo, J. 2005. LOICZ (Land-Ocean Interactions in the Coastal Zone) and the GWSP: New Opportunities for Collaboration. *Global Water News.* 2:5-6.

Altman, N. 2002. *Sacred water: The spiritual source of life.* Mahwah, NJ: Hidden Spring or Paulist Press.

Anderson, E.W. 1999. Geopolitics: International Boundaries as Fighting Places. In *Geopolitics, Geography, and Strategy*, eds. C.S. Gray, and G. Sloan. Portland, OR: Frank Cass.

Atkinson, T.C. and R. M. Davison. 2002. Is the water still hot? Sustainability and the thermal springs at Bath, England. In *Sustainable Groundwater Development.* eds. K.M. Hiscock, M.O. Rivett, and R.M. Davison, Geological Society, London, Special Publications No. 193, pp. 15-40. Bath, UK: The Geological Society Publishing House.

Aucoin, J. 1984. *Water in Nebraska: Use, politics, policy.* Lincoln, NE: University of Nebraska Press.

Baird, J. 2006. Lawmakers urged to block Nevada water pumping plan. Salt Lake City, UT. Salt Lake Tribune. April 20.

Bakker, M. Forthcoming, Transboundary floods: conflict, vulnerability, resilience, and institutions. Unpublished Ph.D. Dissertation, Oregon State University.

Barberis, J., 1991, The development of international law of transboundary groundwater. *Natural Resources Journal.* 31:167-186.

Barraque, B.O. 2004. Groundwater Management in France: From Private to Common Property. In *Managing Common Pool Groundwater Resources, An International Perspective*, eds. M. Brentwood and S.F. Robar, pp. 86-96. Westport, CN: Praeger Publishers.

Barrocu, G. and M. Civita. 2004. Groundwater Resources Management in Italy. In *Managing Common Pool Groundwater Resources, An International Perspective*, eds. M. Brentwood and S.F. Robar, pp. 111-121. Westport, CN: Praeger Publishers.

Bastasch, R. 1998. *Waters of Oregon: a source book on Oregon's waters and water management.* Corvallis, OR: Oregon State University Press.

Bauer, C.J. 2004. *Siren Song: Chilean water law as a model for international reform.* Washington, DC: Resources for the Future.

Beach, S.L. 1990. Geographic Sampling Strategies for Groundwater Quality Evaluation. Unpublished doctoral dissertation. University of Minnesota.

Benvenisti, E. 2002. *Sharing Transboundary Resources: International Law and Optimal Resource Use*. Cambridge, UK: Cambridge University Press.

Bice, L.A., R.D. Van Remortel, N.J. Mata, and R.H. Ahmed. 2000. Source Water Assessments using Geographic Information Systems. *U.S. Environmental Protection Agency (EPA), National Risk Management Research Laboratory*.

Bisson, R.A. and J.H. Lehr. 2004. *Modern Groundwater Exploration: Discovering New Water Resources in Consolidated Rocks Using Innovative Hydrogeologic Concepts, Exploration, Aquifer Testing, and Management Methods*: Hoboken, NJ: Wiley Interscience.

Blomquist, W.A. 1992. *Dividing the Waters: Governing Groundwater in Southern California*. San Francisco, CA: ICS Press.

Blomquist, W.A. and H.M. Ingram. 2003. Boundaries Seen and Unseen: Resolving Transboundary Groundwater Problems. *Water International* 28(2):162-169.

Blomquist, W.A., E. Schlager, and T. Heikkila. 2004. *Common Waters, Diverging Streams: Linking Institutions to Water Management in Arizona, California, and Colorado.* Washington, DC: Resources for the Future.

Blomquist, W.A. and E. Schlager. 2005. Political Pitfalls of Integrated Watershed Management. *Society and Natural Resources* 18:101-117.

Borchert, J. R. 1971. The Dust Bowl in the 1970's. *Annals of the Association of American Geographers* 61:1-22.

Bredehoeft, J. 2005. The conceptualization model problem – surprise. *Hydrogeology Journal.* 13(1):37-46.

Bryner, G. 2004. *Western United States Groundwater Law.* The Water Report. Eugene, OR: Envirotech Publications, Inc. p. 9-16. July 15.

Buck, S.J. 1998. *The Global Commons: An Introduction*. Washington, DC: Island Press.

Burchi, S. and A. D'Andrea. 2003. Preparing national regulations for water resources management: principles and practice. FAO Legislative Study 80. Rome, Italy: UNESCO and FAO.

Burchi, S. and M. Nanni. 2003. How groundwater ownership and rights influence intensive use management. In *Intensive Use of Groundwater; Challenges and Opportunities*, eds. R. Llamas and E. Custodio. pp. 227-240. Leiden, The Netherlands: A.A. Balkema Publishers.

Burchi, S. and K. Mechlem. 2005. Groundwater in International Law: Compilation of Treaties and Other Legal Instruments. FAO Legislative Study 86 Rome, Italy: UNESCO and FAO.

Burke, J.J., and M. Moench. 2000. *Groundwater & Society: Resources, Tensions & Opportunities*. New York, NY: UN DESA.

Burton, I. 1963. The Quantitative Revolution and Theoretical Geography. *The Canadian Geographer.* 7:151-162.

Casati, R., B. Smith, and A.C. Varzi. 1998. Ontological tools for geographic representation. In *Formal Ontology in Information Systems,* ed. N. Guarino. pp. 77-85. Amsterdam: IOS Press.

Chandhoke, N. 2003. Governance and pluralisation of the state; implications for democratic citizenship. *Economic Political Weekly.* 38(28):2957-2968.

Chalecki, E.L., P.H. Gleick, K.L. Larson. A.L. Pregenzer, and A.T. Wolf. 2002. *Fire & Water: An examination of the Technologies, Institutions, and Social Issues in Arms Control and Transboundary Water-Resources Agreements.* Oakland, CA: Pacific Institute (http://www.pacinst.org/ reports/fire_and_water/fire_and_water.pdf last accessed May 9, 2006).

Chapelle, F.H.. 2000. *The Hidden Sea: Groundwater, Springs, and Wells*. Westerville, OH: National Ground Water Association.

Chasek, P.S., D.L. Downie, and J.W. Welsh. 2006. *Global Environmental Politics.* Boulder, CO: Westview Press.

Ciriacy-Wantrup, S.V. and R.C. Bishop. 1975. “Common Property” as a concept in Natural Resources Policy. *Natural Resources Journal.* 15:713-727.

Clark, K.C. 2001. *Getting started with Geographic Information Systems.* Upper Saddle River, NJ: Prentice Hall.

Commission on Global Governance. 1995. *Our Global Neighborhood*. New York City, NY: Oxford University Press.

Conca, K. 2006. *Governing Water*: *Contentious Transnational Politics and Global Institution Building*. Cambridge, MA: The MIT Press.

Cressey, G.B. 1957. Water in the Desert. *Annals of the Association of American Geographers*. 47:105-124.

Cusak, G.A. 2004. Managing Water Resources in the Republic of Ireland. In *Managing Common Pool Groundwater Resources, An International Perspective*, eds. M. Brentwood and S.F. Robar, pp. 97-109. Westport, CN: Praeger Publishers.

Custer, S.G., D.E. Michels, W.R. Sill, J.L. Sonderegger, W.Weight, and W.W. Woessner. 1994. Two Strategies for Yellowstone National Park Hydrothermal Protection in Light of Scientific Uncertainty. In *Effects of Human-Induced Changes on Hydrologic Systems*. eds. R.A Marston and V.R. Hasfurther. pp. 821-830. Proceedings, Annual Summer Symposium of the American Water Resources Association.

De Marsily, G. 1994. Hydrogeological nature reserves? *Future Groundwater Resources at Risk*. IAHS Publication No. 22. pp. 403-407.

Dietz, T., N. Dolsak, E. Ostrom and P.C. Stern. 2002. The Drama of the Commons. In *The Drama of the Commons*. eds. E. Ostrom, T. Dietz, N. Dolsak, P.C. Stern, S. Stonich, and E.U. Weber. pp. 3-35. National Research Council. Washington, DC: National Academy Press.

Dietz, T., E. Ostrom, and P.C. Stern. 2003. The Struggle to Govern the Commons. *Science*. 302:1907-1911.

Dongoske, K.E. M. Yeatts, R. Anyon, and T.J. Ferguson. 1997. Archaeological Cultures and Cultural Affiliation: Hopi and Zuni Perspectives in the American Southwest. *American Antiquity*. 62(4):600-608.

Eckstein, G.E. and Y.E. Eckstein. 2003. A Hydrogeological Approach to Transboundary Ground Water Resources and international Law. *American University of International Law Review*. 19:201-258.

Eckstein, G.E. 2004. Protecting a Hidden Treasure: The U.N. International Law Commission and the International Law of Transboundary Ground Water Resources. *Sustainable Development Law & Policy*. V(1):6-12.

Eckstein, Y. and G. E. Eckstein. 2005. Transboundary Aquifers: Conceptual Models for Development of International Law. *Journal of Groundwater*. 43(5):679-690.

Ellis, A.J. 1917. The Divining Rod: A History of Water Witching. *U.S. Geological Survey Water-Supply Paper 416*.

Embid, A. 2005. Legal issues of intensive use of groundwater. In *Groundwater Intensive Use*, eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7. pp. 79-92. Leiden, The Netherlands: A.A. Balkema Publishers.

Environmental Protection Agency (EPA). 1987. Sole Source Aquifer Designation Petitioner Guidance. *Office of Ground-Water Protection, EPA 440/6-87-003*. (http://www.epa.gov/region02/water/aquifer/petition/ last accessed on March 31, 2006).

Environmental Protection Agency (EPA). 1997. Investigation of Hydrogeologic Mapping to Delineate Protection Zones around Springs. *Office of Research and Development, EPA 600/R-97/023*.

Feitelson, E. 2005. Priority rights for nature: a true constraint on aquifer over-exploitation?. In *Groundwater Intensive Use*. eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7. pp. 199-207. Leiden, The Netherlands: A.A. Balkema Publishers.

Finger, M. L. Tamiotti and J. Allouche. 2006. Introduction: Conceptual Elements. In *The Multi-Governance of Water: Four Case Studies*. eds. M. Finger, L. Tamiotti and J. Allouche, pp. 1-42. Albany, NY: State University of New York Press.

Fisher, A.T. 2005. Marine hydrogeology: recent accomplishments and future opportunities. *Hydrogeology Journal*. 13(1):69-97.

Fontana, D. 1993. *The Secret Language of Symbols*. San Francisco, CA: Chronicle Books.

Food and Agricultural Organization of the United Nations (FAO). 2003. *Groundwater Management - The Search for Practical Approaches*. Water Reports No. 25. Rome, Italy: FAO.

Foster, S., H. Garduño, K. Kemper, A. Tuinhof, and M. Nanni. 2005. Making intensive use of groundwater more sustainable – key lessons from field experience. In *Groundwater Intensive Use*. eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7, pp. 105-126. Leiden, The Netherlands: A.A. Balkema Publishers.

Foster, S., M. Nanni, K. Kemper., H. Garduño, and A. Tuinhof. 2003. Utilization of Non-Renewable Groundwater. Briefing Note Series No. 11. Washington, DC. The World Bank.(http://siteresources.worldbank.org/INTWRD/Resources/GWMATE_English_BN_11.pdf last accessed April 20, 2006).

Freeze, R.A. and J.A. Freeze. 1979. *Groundwater.* Englewood Cliffs, NJ: Prentice-Hall, Inc.

Freeze. R.A. 2000. *The Environmental Pendulum*. Berkeley, CA: University of California Press.

Froukh, L.J. 2003. Transboundary Groundwater Resources of the West Bank. *Water Resources Management.* 17:175-182.

Galabov, M. and A. Lichev. 2004. Groundwater in Bulgaria: Resources, Use and Management. In *Managing Common Pool Groundwater Resources, An International Perspective*, eds. M. Brentwood and S.F. Robar. pp. 183-194. Westport, CN: Praeger Publishers.

Galili, E. and Y. Nir. 1993. The submerged pre-pottery neolithic water well at Atlit-Yam, northern Israel, and its paleoenvironmental implications. *The Holocene*. 3:265-270

Garduño, H. S. Foster, M. Nanni, K. Kemper, A. Tuinhof, and P. Koudouori. 2004. Groundwater Dimensions of National Water Resource and River Basin Planning. Sustainable Groundwater Management Concepts & Tools, Briefing Note Series No. 10. Washington, DC: The World Bank. (http://siteresources.worldbank.org/INTWRD/Resources/GWMATE_English_BN_10.pdf last accessed April 17, 2006).

Garven, G. 1995. Continental-scale groundwater flow and geologic processes. *Annual Review of Earth and Planetary Science*. 23:89-117.

Geta, J.A., M.A. Garcia-Vera, J.A. de la Orden, J.D. Gomez, J.M. Murillo, M. Vazquez, A. Gonzalez, J.C. Rubio, and M. Martin-Machuca. 2004. Groundwater Management in Spain. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 67-84. Westport, CN: Praeger Publishers.

Gibert, J., J.A. Stanford, M.J. Dole-Oliver, and J.V. Ward. 1994. Basic attribute of groundwater ecosystems and prospects for research. In *Groundwater Ecology*. eds. J. Gibert, D. Danielpol, and J. Stanford pp. 7-40. San Diego, CA Academic Press, Inc..

Giordano, M. 2003. The geography of the commons: Role of scale and space. *Annals of the Association of American Geographers*. 93(2):365-375.

Glasbergen, P. 2004. Common Groundwater Resources and Biodiversity: The Case of the Netherlands. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 123-136. Westport, CN: Praeger Publishers.

Gleick, P. 2004. Environment & Security: Water Conflict Chronology Version 2004-2005. In *The World's Water 2004-2005*. ed. P. Gleick. pp. 234-255. Washington D.C.: Island Press.

Glennon, R. 2002. *Water Follies: Groundwater pumping and the fate of America's freshwaters*. Washington, D.C.: Island Press.

Gordon, F. 2004. Managing Groundwater: Israel, Gaza, and the West Bank. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 202-213. Westport, CN: Praeger Publishers.

Gould, G.A., and Grant, D.L. 1995. *Case and Materials on Water Law (5th Edition)*. St. Paul, MN.: West Publishing Co.

Graf, W. 2001. Damage Control: Restoring the Integrity of America's Rivers. *Annals of the Association of American Geographers*. 91:1-27.

Guanghui, Z. and F. Yuhong. 2004. Groundwater Management in China. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 265-281. Westport, CN: Praeger Publishers.

Haitjema, H.M. and S. Mitchell-Bruker. 2005. Are Water Tables a Subdued Replica of the Topography? *Journal of Groundwater*. 43(6):781-786.

Hardberger, A. 2004. What Lies Beneath: Determining the Necessity of International Groundwater Policy Along the United States-Mexico Border and a Roadmap to an Agreement. *Texas Tech Law Review*. 35(4):1212-1258.

Hardin, G. 1968. The tragedy of the commons. *Science*. 162:1243-1248.

Hayton, R.D. and A.E. Utton. 1989. Transboundary Groundwaters: The Bellagio Draft Treaty. *Natural Resources Journal*. 29:677.

Heath, R.C. 1988. Hydrogeologic setting of regions. In *Hydrogeology, The Geology of North America*. eds. W. Back, J.S. Rosenhein and P.R. Seaber. O-2:1-8. Boulder, CO: Geological Society of America.

Herbich, P., Z. Nowicki, and A. Sadurski. 2004, Groundwater Resources, Management, and Protection in Poland. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 155-164. Westport, CN: Praeger Publishers.

Hernandez-Mora, N. L. Marinez Cortina and J. Fornes. 2003. Intensive groundwater use in Spain. In *Intensive Use of Groundwater; Challenges and Opportunities*. eds. R. Llamas and E. Custodio. pp. 387-414. Leiden, The Netherlands: A.A. Balkema Publishers.

Hopi Nation. 2003. http://www.hopi.nsn.us last visited on May 9, 2006.

Howard, K.W.F. and K.K. Gelo. 2003. Intensive groundwater use in urban areas: the case of megacities. In *Intensive Use of Groundwater; Challenges and Opportunities*, eds. R. Llamas and E. Custodio. pp. 35-58. Leiden, The Netherlands: A.A. Balkema Publishers.

Hutchinson, C.F., 2000, John Wesley Powell and The New West. *Cosmos Club Website*. (http://www.cosmos-club.org/web/journals/2000/hutchinson.html last accessed March 25, 2006).

Interacademy Panel (IAP) Water Program. 2006. The Alicante Declaration. International Symposium on Groundwater Sustainability (ISGWAS). Alicante, Spain, on January 23rd-27th, 2006. (http://aguas.igme.es/igme/ISGWAS/ing/The%20Alicante%20Declaration%20-%20Final%20Document.pdf last accessed May 9, 2006).

Jones, S.B. 1959. Boundary Concepts in the Setting of Place and Time. *Annals of the Association of American Geographers*. 49:241-255.

Jurdi, M. 2002. Transboundary movement of hazardous wastes into Lebanon: Part 2. Environmental Impacts and the need for remedial actions. *Journal of Environmental Health*. 64:15-19.

Jury, W.A. and H. Vaux, Jr. 2005. The role of science in solving the world's emerging water problems. *PNAS*. 102(44):15715-15720.

Kadekodi, G.K. 2004. *Common Property Resource Management: Reflections on Theory and the Indian Experience.* New Delhi, India: Oxford University Press.

Kalf, F.R.P. and D.R. Wooley. 2005. Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeology Journal.* 13(1):295-312.

Kamieniecki, S. and W.D. Grafton, III. 2004. Groundwater Management in Mexico and Mexico City. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 46-60. Westport, CN: Praeger Publishers.

Karan, P.P. 1961. Dividing the water: A problem in political geography. *The Professional Geographer*. 13:6-10.

Karkkainen, B.C. 2005. Transboundary Ecoystems Governance: Beyond Sovereignty? In *Public Participation in the Governance of International Freshwater Resources*. eds. C. Bruch, L. Jansky, M. Nakayama and K. A. Salewicz. pp. 73-87. Tokyo, Japan: United Nations University Press.

Kelbe, B. and B. Rawlins. 2004. Groundwater Management in South Africa. In *Managing Common Pool Groundwater Resources*, *An International Perspective*, eds. M. Brentwood and S.F. Robar, pp. 290-310. Westport, CN: Praeger Publishers.

Kemper, K.E., E. Mestre, and L. Amore. 2003. Management of the Guaraní Aquifer System; Moving Towards the Future. *Water International*. 28(2):185-200.

Kemper, K.E. 2004. Groundwater-from development to management. *Hydrogeology Journal.* 12:3-5.

Kemper, K., A. Dinar and W. Blomquist. 2005. Institutional and Policy Analysis of River Basin Management Decentralization: The Principle of Managing Water Resources at the Lowest Appropriate Level — When and Why Does It (Not) Work in Practice?. The World Bank.(http://siteresources.worldbank.org/INTSAREGTOPWATRES /Resources/Insti&Pol_Analysis_of_RBMDecent.pdf last accessed on March 31, 2006)

Kerr, R.A. 1991. Geothermal Tragedy of the Commons. *Science*. 253:134-135.

Kirby, S. and H. Hurlow. 2006. Proposed Ground-water Withdrawal in Snake Valley. *Utah Geological Survey Notes*. 38(2):1-3.

Kristof, L.K.D. 1959. The Nature of Frontiers and Boundaries. *Annals of the Association of American Geographers*. 49:269-282.

Kromm, D.E. and S.E. White. 1990. Adoption of Water-Saving Practices by Irrigators in the High Plains. *Water Resources Bulletin.* 26(6):999-1012.

Lightfoot, D. 2003. Traditional Wells as Phreatic Barometers: A View from Qanats and Tube Wells in Developing Arid Lands. *Proceedings of the UCOWR Conference: Water Security in the 21st Century*. Washington, DC.

Livingstone, S., T. Franz, and N. Guiger. 1996. Managing Ground-water Resources Using Wellhead Protection Programs. *Geoscience Canada*. 22:121-128.

Llamas, R., and E. Custodio. 2002. Intensively Exploited Aquifers – Main Concepts, Relevant Facts, and Some Suggestions. *Series on Groundwater No. 4*. UNESCO, IHP-VI.

Llamas, R., and E. Custodio. 2003. Intensive use of groundwater : a new situation that demands proactive action. In *Intensive Use of Groundwater; Challenges and Opportunities*. eds. R. Llamas and E. Custodio. pp.13-31. Leiden, The Netherlands: A.A. Balkema Publishers.

Llamas, M.R. and P. Martínez-Santos. 2005. Intensive Groundwater Use: Silent Revolution and Potential Source of Social Conflicts. *American Society of Civil Engineers Journal of Water Resources Planning and Management.* 131(4):337-341.

Lloyd, J.W. 1986. Hydrogeology and Beer. *Proceedings of the Geological Association.* 97(3): 213-219.

Lopez, M. and O. Petit. 2000. Information and Communication Technology as a means to improve stakeholders understanding of the Commons: The case of Groundwater Management in France. Presented at "Constituting the Commons: Crafting Sustainable Commons in the New Millennium", the Eighth Conference of the International Association for the Study of Common Property, Bloomington, Indiana, USA, May 31-June 4. (http://dlc.dlib.indiana.edu/archive/00000294/ last accessed March 30, 2006.)

Los Angeles Times. 2004. Don’t Sink the “Law of the Sea”. (http://www.latimes.com/news/opinion/la-ed-sea3may03,1,3480277.story by subscription)

Loughlin, W.D. 1983. The Hydrogeologic Controls on Water Quality, Ground Water Circulation, and Collapse Breccia Pipe Formation in the Western Part of the Black Mesa Hydrologic Basin, Coconino County, Arizona. Unpublished M.S. thesis. University of Wyoming.

Lucas, R.C. 1964. Wilderness perception and use: The example of the Boundary Water Canoe area. *Natural Resources Journal*. 3:394-411.

Mahdavi, M. and M.M. Saravi. 2004. Groundwater Management in Iran. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 216-225. Westport, CN: Praeger Publishers.

Maimone, M. 2003. Defining and Managing Sustainable Yield. *Journal of Groundwater.* 42(6):809-814.

Margat, J. 1994. Groundwater Operations and Management. In *Groundwater Ecology*. eds. J. Gibert, D. Danielpol, and J. Stanford. pp. 505-521. San Diego, CA: Academic Press, Inc.

Martin, G.J. and P.E. James. 1993. *All Possible Worlds: A History of Geographical Ideas* (3rd Edition). New York, NY: John Wiley & Sons, Inc.

Matsumoto, K. 2002. Transboundary Groundwater and International Law: Past Practices and Current Implications. Unpublished Research Paper, Oregon State University.

Matthews, O.P. 2005. Ground Water Rights, Spatial Variation, and Transboundary Conflicts. *Journal of Groundwater*. 43(5):691-699.

McCabe, W. J., C. A. Job, J. J. Simons, J. S. Graves, and C. J. Terada. 1997. History of the Sole Source Aquifer Program: A Community-Based Approach for Protecting Aquifers Used for Drinking Water Supply. *Journal of Groundwater Monitoring and Review*, Summer 1997: 86.

McCaffrey, S.C. 2001. *The Law of International Watercourses, Non-Navigational Uses.* New York, NY: Oxford University Press.

McCaffrey, S.C. 1997. Water Scarcity: Institutional and Legal Responses. In *The Scarcity of Water, Emerging Legal and Policy Responses.* eds. E.H.H. Brans, E.J. deHaan, A. Nollkaemper and J. Rinzema. pp. 43-58. Boston, MA: Kluwer Law International.

Meinzer, O.E. 1942. Introduction. In *Physics of the Earth-IX, Hydrology*. ed. O.E. Meinzer, New York, NY: Dover Publications, Inc.

Moench, M., Burke, J. and Y. Moench. 2003. *Rethinking the Approach to Ground water and Food Security*, FAO Water Reports 24. Rome, Italy: Food and Agriculture Organization of the United Nations.

Moench, M.. 2004. Groundwater: The Challenge of Monitoring and Management. In *The World's Water 2004-2005,* ed. P. Gleik, Washington D.C.: Island Press, pp. 79-100.

Morris, B.L., A.R.L. Lawrence, P.J.C. Chilton, B. Adams, R.C. Calow, and B.A. Klinck. 2003. *Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management*. Early Warning and Assessment Report Series, RS. 03-3. Nairobi, Kenya: United Nations Environment Programme.

Muckleston, K.W. and R.M. Highsmith, Jr. 1978. Center Pivot Irrigation in the Columbia Basin of Washington and Oregon; Dynamics and Implications. *Water Resources Bulletin*. 14(5): 1121-1128.

Mukherji, A. and T. Shah. 2005. Socio-ecology of groundwater irrigation in South Asia: an overview of issues and evidence. *Hydrogeology Journal*. 13(1):328-345.

Mukherji, A. and T. Shah. 2005. Groundwater socio-ecology and governance: a review of institutions and policies in selected countries In *Groundwater Intensive Use*. eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7. pp. 53-77. Leiden, The Netherlands: A.A. Balkema Publishers.

Nanni, M.S. Foster, C. Dumars, H. Garduño, K. Kemper, and A. Tuinhof. 2002. Groundwater Legislation and Regulatory Provision. Groundwater Dimensions of National Water Resource and River Basin Planning. Sustainable Groundwater Management Concepts & Tools, Briefing Note Series No. 4. Washington, DC. The World Bank. (http://siteresources.worldbank.org/INTWRD/Resources/ GWMATE_English_BN_04.pdf last accessed on April 17, 2006).

Narasimhan, T.N. 2005. Hydrogeology in North America: past and future. *Hydrogeology Journal*. 13(7):7-24.

National Research Council. 2004. *Confronting the Nation's Water Problems: The Role of Research.* Committee on Assessment of Water Resources Research, Water and Technology Board, Division of Earth and Life Sciences: Washington, DC: The National Academies Press.

Neumann, S.P. 2005. Trends, prospects and challenges in quantifying flow and transport through fractured rocks. *Hydrogeology Journal.* 13:124-147.

Ostrom, E., P.C. Stern, and T. Dietz. 2003. Water Rights in the Commons. *Water Resources Impact.* 5(2): 9-12.

Ostrom, E., J. Burger, C.B. Field, R.B. Norgaard and D. Policansky. 1999. Revisiting the Commons: Local Lessons, Global Challenges. *Science.* 284:278-282.

Ostrom, E., 1990. *Governing the Commons: The evolution of institutions for collective action*. Cambridge, UK: Cambridge University Press.

O'Sullivan, D., 2004. Complexity Science and Human Geography. *Transactions of the Institute of British Geographers*. 29(3):282-295.

Pattison, W.D. 1964. The four traditions of geography. *Journal of Geography.* 63:211-216.

Petrella, R. 2001. *The Water Manifesto, Arguments for a World Water Contract.* Reading, UK: Cox and Wyman.

Pimental, D. B. Berger, D. Filberto, M. Newton, B. Wolfe, E. Karabinakis, S. Clark, E. Poon, E. Abbett, and S. Nandagopal. 2004. Water Resources: Agricultural and Environmental Issues. *Bioscience.* 54(1):909-918.

Platt, R.H. 1993. Geographers and Water Resource Policy. In *Water Resources Administration in the United States: policy, practice and emerging issues*. ed. M. Reuss, Selected papers from the American Water Resources Association National Forum on Water Management Policy. pp. 36-54. East Lansing, MI: Michigan State University Press.

Poirier, R. 2004. Groundwater Management in Australia. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar, pp. 250-263. Westport, CN: Praeger Publishers.

Prevost, R. 2006. *Is Thermopolis out of steam?* Casper, WY.: The Casper Star-Tribune, March 16.

Puri, S., L. Gaines, A. Wolf, and T. Jarvis. 2005. Lessons from intensively used transboundary river basin agreements for transboundary aquifers. In *Groundwater Intensive Use*. eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7. pp. 137-145. Leiden, The Netherlands: A.A. Balkema Publishers.

Puri, S., B. Appelgren, G. Arnold, A. Aureli, S. Burchi, J. Burke, J. Margat, P. Pallas, and W. von Igel. 2001. *Internationally Shared (Transboundary) Aquifer Resources Management, Their Significance and Sustainable Management: A Framework Document.* IHP-VI, IHP International Hydrological Programme Non Serial *Publications in Hydrology* SC-2001/WS/40, Paris, France: UNESCO.

Pyne, R.D.G. 1994. *Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery*. Boca Raton, FL: CRC Press..

Ragone, S.E. 2002. Corporate Hydrology: Profit by Growth or by Acquisition? *Journal of Groundwater*. 40(5):457.

Ragone, S.E., A. Rivera, J. Vecchioli, C. Goodwin, L.E. Marin, and O.A. Escolero. 2003. Intensive use of groundwater in North America. In *Intensive Use of Groundwater; Challenges and Opportunities*. eds. R. Llamas and E. Custodio. pp. 287-305. Leiden, The Netherlands: A.A. Balkema Publishers.

Ragone, S.E. In review. The Post-Modern Water Balance and its role in Groundwater Management. Paper presented at the International Symposium on Groundwater Sustainability, Alicante, Spain. January 24.

Ravikumar, S. 2000. Adrift at Sea: U.S. Interests and the Law of the Sea. *Harvard International Review*. Summer 2000:38-41.

Riveria, A. and M. Nastev. 2005. Overview of groundwater resources of Canada. In *Groundwater Intensive Use*. eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7. pp. 157-165. Leiden, The Netherlands: A.A. Balkema Publishers.

Roberts, R.S. and J. Emel. 1992. Uneven development and the tragedy of the commons: Competing images for nature-society analysis. *Economic Geography*. 68:249-272.

Robertson, K.. 2004. Design Considerations for an International Facility to Promote Cooperation Between States Sharing a Common Water Resource: A Feasibility Study on the International Water Cooperation Facility Initiative: Unpublished M.S. thesis, UNESCO-IHE Institute for Water Education, The Netherlands.

Sakura, Y., C. Tang, R. Yoshioka, and H. Ishibashi. 2003. Intensive use of groundwater in some areas of China and Japan. In *Intensive Use of Groundwater; Challenges and Opportunities*, eds. R. Llamas and E. Custodio. pp. 337-353. Leiden, The Netherlands, A.A. Balkema Publishers.

Samper, J. 2005. Intensive use of groundwater in the European Union Water Framework Directive. In *Groundwater Intensive Use*. eds. A. Sahuquillo, J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila, International Association of Hydrogeologists Selected Papers No. 7, pp. 93-101. Leiden, The Netherlands: A.A. Balkema Publishers.

Schaefer, D.H., S.A. Thiros, and M.R. Rosen. 2003. Ground-Water Quality in the Carbonate-Rock Aquifer of the Great Basin, Nevada and Utah, 2003. *U.S. Geological Survey National Water-Quality Assessment Program Scientific Investigations Report 2005-5232.*

Schlager, E. 2007. Community Management of Groundwater. In *The Agricultural Groundwater Revolution Opportunities and Threats to Development*. eds. M. Giordano, and K. Villholth. Comprehensive Assessment of Water Management in Agriculture. Wallingford, Oxon, UK: CABI.

Schlager, E. 2004. Common-Pool Resource Theory. In *Environmental Governance Reconsidered: Challenges, choices, and opportunities*. eds. R.F. Durant, D.J. Fiorino, R. O'Leary. pp. 145-175. Cambridge, Mass: MIT.

Shah, T. 2005. Governing the groundwater economy: comparative analysis of national institutions and policies in South Asia, China, and Mexico. In *Groundwater Intensive Use*. eds. A. Sahuquillo , J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila. pp. 23-51. International Association of Hydrogeologists Selected Papers No. 7. Leiden, The Netherlands: A.A. Balkema Publishers.

Shiklomanov, I.A. and J.C. Rodda (eds.). 2003. *World Water Resources at the beginning of the 21st century*. UNESCO International Hydrology Series. Cambridge, UK: Cambridge University Press.

Simsek, S., G. Gunay, H. Elhatip, and M. Ekmekci. 2000. Environmental protection of geothermal waters and travertines at Pamukkale, Turkey. *Geothermics.* 29:557-572.

Sinha, A.K. and R. Jain. 2005. Intensive use of groundwater in North Gujarat, India. Challenges and opportunities. In *Groundwater Intensive Use*. eds. A. Sahuquillo , J. Capilla, L. Martinez-Cortina, and X. Sanchez-Vila. International Association of Hydrogeologists Selected Papers No. 7. pp. 331-340. Leiden, The Netherlands: A.A. Balkema Publishers.

Smith, Z.A. 2003. Groundwater collective management systems: the United States experience. In *Intensive Use of Groundwater; Challenges and Opportunities*, eds. R. Llamas and E. Custodio. pp. 257-269. Leiden, The Netherlands: A.A. Balkema Publishers.

Smith, Z.A. 2004. Groundwater: The U.S. Experience. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 31-44. Westport, CN: Praeger Publishers.

Sophocleous, M. 2003. Environmental implications of intensive groundwater use with special regard to streams and wetlands. In *Intensive Use of Groundwater; Challenges and Opportunities*, eds. R. Llamas and E. Custodio. pp. 93-112. Leiden, The Netherlands, A.A. Balkema Publishers.

Sophocleous, M.A., 1997. Managing water resources systems: Why "safe yield" is not sustainable. *Journal of Groundwater*. 35(4):561.

Stanford, J.A. and J. Gibert. 1994. Conclusions and Perspective. In *Groundwater Ecology*. eds. J. Gibert, D. Danielpol, and J. Stanford. pp. 543-547. San Diego, CA: Academic Press, Inc.

Strassberg, G. 2005. A Geographic Data Model For Groundwater Systems: Unpublished Ph.D. Dissertation, The University Of Texas at Austin.

Struckmeir, W.F., W.H. Gilbrich, A. Richts, and M. Zaepke. 2004. *WHYMAP and the Groundwater Resources of the World Map*. Special Edition from World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) for the 32nd International Geological Congress. Scale1:50,000,000. Paris, France and Hanover, Germany: BGR/UNESCO.

Struckmeir, W., A. Richts, I. Acworth, G. Arduino, E. Bocanegra, W. Cunningham, A. Droubi, N. de Franca, W. Gilbrich, J. Girman, J. van der Gun, R. Klingbeil, J. Margat, D. Poitrinal, S. Puri, A. Rivera, M. Safar-Zitoun, O. Tujchneider, S. Vasak, J. Vrba, P. Winter, M. Zaepke, H. Zaisheng, and I. Zekster. 2006. *WHYMAP and the World Map of Transboundary Aquifer Systems*. Special Edition from World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) for the 4th World Water Forum. Scale1:50,000,000. Paris, France and Hanover, Germany: BGR/UNESCO.

Sun, R.J., J.B. Weeks, and H.F. Grubb. 1997. Bibliography of Regional Aquifer-System Analysis Program of the U.S. Geological Survey, 1978-96. *U.S. Geological Survey Water-Resources Investigations Report 97-4074.*

Sutherland, M. and S. Nichols. 2002. Marine Boundary Delimitation for Ocean Governance. JS12 Marine Cadastre. Proceedings of the FIG XXII International Conference. Washington, DC. (http://www.fig.net/pub/fig_2002/Js12/JS12 _sutherland_nichols.pdf last accessed April 11, 2006).

Teclaff, L.A. and A.E. Utton (eds.). 1981. *International Groundwater Law*. New York, NY: Oceana Publishers, Inc.

Theis, C.V. 1940. The source of water derived from wells-essential factors controlling the response of an aquifer to development. *Civil Engineering*. 10(5):277-280.

Thomasson. F. 2005. Local Conflict and water: addressing conflicts in water projects. Swedish Water House. (http://www.swedishwaterhouse.se/images/partners /20051017114417Conflicts_Water_Projects_050823.pdf last accessed on March 24, 2006).

Tobin, G.A., D.A. Baumann, J.E. Damron, J.E. Emel, K.K. Hirschboeck, O.P. Matthews, and B.E. Montz. 1989. Water Resources. In *Geography in America*. eds. G. Gaile and C. Willmott. pp. 126-130, Columbus, OH: Merrill Publishing Co.

Tòth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research*. 68:4795-4812.

Tòth, J. 1999. Groundwater as a geologic agent: An overview of the causes, processes, and manifestations: *Hydrogeology Journal.* 7:1–14

Utah Division of Water Rights. 2002. Salt Lake Valley Ground-water Management Plan.(http://waterrights.utah.gov/meetinfo/m062502/slvmgpln.pdf last accessed March 10, 2006).

United Nations. 1982. United Nations Convention on the Law of the Sea of 10 December 1982. (http://www.un.org/Depts/los/convention_agreements /convention_overview_convention.htm last accessed on March 24, 2006).

Van der Molen, P. 2004. Some Microeconomic Aspects of Land Ownership. Paper presented at 3rd FIG Regional Conference, Jakarta, Indonesia, October 3-7. (http://www.itc.nl/library/Papers_2004/n_p_conf/vandermolen_some.pdf last accessed on March 31, 2006)

Van Steenbergen, F. and T. Shah. 2003. Rules rather than rights: self regulations in intensively used groundwater systems. In *Intensive Use of Groundwater; Challenges and Opportunities*. eds. R. Llamas and E. Custodio. pp. 241-256. Leiden, The Netherlands: A.A. Balkema Publishers.

Van Steenbergen, F. 2004. Groundwater Development and Policies in Pakistan. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 227-241. Westport, CN: Praeger Publishers.

Van Steenbergen, F. 2006. Promoting local management in groundwater. *Hydrogeology Journal.* 14:380-391.

Vogt, E.Z. and R. Hyman. 1979. *Water Witching USA*. Chicago, IL: University of Chicago Press.

Vrba, J. 2004. Groundwater Management in the Czech Republic. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 165-181. Westport, CN: Praeger Publishers.

Votteler, T.H. 2004. Raiders of the Lost Aquifer? Or, the Beginning of the End to Fifty Years of Conflict over the Texas Edwards Aquifer. *Tulane Environmental Law Journal.* 15:258-335.

Wax, E. 2006. Dying for Water in Somalia’s Drought. Washington, DC. The Washington Post. April 14.

Waterhistory. 2003. (http://www.waterhistory.org/histories/qanats/ last accessed on March 25, 2006).

Weatherford, G.D. 1990. From Basin to "Hydrocommons": Integrated Water Management Without Regional Governance. Western Water Policy Project (Discussion Series Paper No. 5) sponsored by the Natural Resource Law Center at the School of Law. Boulder, CO: University of Colorado. (http://publish.pdesigner.com /h2olaw/h.jsp last accessed on March 25, 2006).

Weatherford, G.D. 2003. Out of the Basin, Into the Hydrocommons. In *Conference Report and Synthesis on Interstate Waters Crossing Boundaries for Sustainable Solutions, A Multidisciplinary Approach.* eds. M. O'Leary, C. Garcia, and M. Minnis. pp. 40-44. Albuquerque, NM: Utton Transboundary Resources Center, University of New Mexico School of Law.

Wei, M. and D.M. Allen. 2004. Groundwater Management in British Columbia, Canada: Challenges in a Regulatory Vacuum. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 7-30. Westport, CN: Praeger Publishers.

Weir, D.R. and I. Azary. 2001. Quitovac Oasis: A sense of home place and the development of water resources. *The Professional Geographer*. 53:45-55.

Weiss, R. 2003. *Water Scarcity Prompts Scientists to Look Down*. Washington, DC: The Washington Post. p. A.11

WHYMAP - World-wide Hydrogeological Mapping and Assessment Programme. various years. (http://www.bgr.bund.de/EN/Themen/Wasser/Projekte /Berat__Info/whymap/whymap__projektbeschr.html last accessed April 2, 2006).

WHYMAP. 2006. Personal communication from Shaminder Puri. Digital maps.

Wilbanks, T. 1994. Sustainable Development in Geographic Perspective. *Annals of the Association of American Geographers*. 84:541-546.

Wilson, J. 2003. Scientific Uncertainty, Complex Systems and the Design of Common-Pool Institutions. In *The Drama of the Commons*. eds. E. Ostrom, T. Dietz, N. Dolsak, P.C. Stern, S. Stonich, and E.U. Weber. pp. 327-359. National Research Council, Washington, DC: National Academy Press.

Winter, T.C., J. W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and Surface Water: A single resource. *U. S. Geological Survey Circular 1139.*

Witten, J. and S. Horsley. 1995. *A Guide to Wellhead Protection.* Chicago, IL: American Planning Association.

Wohlwend, B.J. 2002. Workshop on harmonization of developing interests in the use of shared water resources, an overview of groundwater in international law, a case study: The Franco-Swiss Genovese Aquifer. (http://www.bjwconsult.com?The%20Genevese%20Aquifer.pdf last accessed March 8, 2006).

Wolf, A.T., S.B. Yoffe, and M. Giordano. 2003. International waters: identifying basins at risk. *Water Policy*. 5:29-60.

Wolf, A.T. and M.A. Giordano. 2002. *Atlas of International Freshwater Agreements*. Early Warning and Assessment Report Series, RS. 02-4. Nairobi, Kenya: United Nations Environment Programme.

Wolf, A. T., J. Natharius, J. Danielson, B.S. Ward, and J.K. Pender. 1999. International River Basins of the World. *International Journal of Water Resources Development*. 15(4): 387-427.

Working Group on Water Bodies. 2003. *Common Implementation Strategy for the Water Framework Directive (2000/60/EC),* Guidance Document No. 2. Luxemborg: Office for Official Publications of the European Commission.

Wulff, H.E. 1968. The Qanats of Iran. *Scientific American*. April:94-105.

Yamada, C. 2005. Third report on shared natural resources: transboundary groundwaters. *International Law Commission.* Fifty-seventh session. United Nations General Assembly Document A/CN.4/551.

Young, O. 2003. Institutional Interplay: The Environmental Consequences of Cross-Scale interaction. In *The Drama of the Commons*. eds. E. Ostrom, T. Dietz, N. Dolsak, P.C. Stern, S. Stonich, and E.U. Weber. pp. 263-291. National Research Council, Washington, DC: National Academy Press.

Young, M.E. 2002. Institutional development for sustainable groundwater management. In *Sustainable Groundwater Development*. eds. K.M. Hiscock, M.O. Rivett, and R.M. Davison. pp. 63-74. Geological Society, London, Special Publications No. 193. Bath, UK: The Geological Society Publishing House.

Zekster, I.S. 2004. Groundwater Management in Russia. In *Managing Common Pool Groundwater Resources, An International Perspective*. eds. M. Brentwood and S.F. Robar. pp. 143-154. Westport, CN: Praeger Publishers.

Zekster, I.S. and Everett, L.G. (eds.). 2004. Groundwater resources of the world and their use, IHP-VI, Series on Groundwater No. 6. UNESCO (United Nations Educational, Scientific and Cultural Organization).

Appendices

Appendix A: Glossary of Terms

The purpose of this Glossary of Terms is to provide a list of terms used in this document and commonly used by groundwater hydrologists and hydrogeologists, as well as some specific terms used in groundwater contamination assessments and groundwater protection. These definitions are adapted from many different sources such as textbooks in groundwater hydrology (for example, Freeze and Cherry 1979) and United States federal and state government guidance documents (for example EPA 1987; 1997).

Alluvium: A general term for clay, silt, sand, gravel or similar unconsolidated material deposited during comparatively recent geologic time by a stream or other body of running water.

Analytical model: A model that provides approximate or exact solutions to simplified mathematical forms of the differential equations for water movement and solute transport. Analytical models can generally be solved using calculators or computers.

Anisotropy: The condition of having different properties in different directions. The condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.

Anticline: A fold in rock strata that is convex upward.

Aquifer test: A test to determine hydrologic properties of an aquifer, involving the withdrawal of measured quantities of water from, or addition of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition. Same as pump test.

Aquifer/Aquifer System: A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield sufficient, economical quantities of water to wells, springs, and drain tunnels.

Aquitard: The less-permeable beds in a stratigraphic sequence that tend to restrict or impede groundwater flow relative to the more permeable beds that serve as aquifers.

Area of influence: Area surrounding a pumping or recharging well within which the water table or potentiometric surface has been changed due to the well's pumping or recharge.

Artesian Conditions: In a confined aquifer, when the water level in a well rises above the top of the aquifer.

Claystone: An indurated clay having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which clay dominates over silt..

Collection area: The area surrounding a groundwater source which is underlain by collection pipes, tile, tunnels, infiltration boxes, or other groundwater collection devices.

Colluvium: Loose, heterogeneous, incoherent mass of soil material and/or rock fragments deposited chiefly by mass-wasting.

Cone of depression (COD): A depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. Its trace (perimeter) on the land surface defines the zone of influence of a well. Also called pumping cone and cone of drawdown.

Confined aquifer: The following criteria are met in order to verify and maintain an upward hydraulic gradient in the producing aquifer: an effective confining layer must exist between the ground surface and the producing aquifer. This confining layer must have a lower hydraulic conductivity than the producing aquifer; and the potentiometric surface of the producing aquifer must remain higher in elevation than the potentiometric surface of the overlying aquifer. If there is no overlying aquifer, then the potentiometric surface of the producing aquifer must remain higher in elevation than the upper surface of the overlying confining layer. These criteria must be maintained during periods of maximum and long-term pumping and seasonal groundwater fluctuations. Not all confined aquifers in nature have an upward hydraulic gradient.

Contact: The surface where two different kinds of rock come together.

Contaminant: An undesirable substance not normally present, or an unusually high concentration of a naturally occurring substance, in water, soil, or other environmental medium.

Contamination: The degradation of natural water quality as a result of man's activities.

Controls: The codes, ordinances, rules, and regulations currently in effect to regulate a potential contamination source.

Dispersion: The spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities within and between pores.

Drawdown: The vertical distance groundwater elevation is lowered, or the amount head is reduced, due to the removal of groundwater. Also the decline in potentiometric surface caused by the withdrawal of water from a hydrogeologic unit. The distance between the static water level and the surface of the cone of depression. A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of groundwater from wells.

Fissure: A fracture or crack in a rock along which there is a distinct separation.

Flow line: The general path that a particle of water follows under laminar flow conditions. Line indicating the direction followed by groundwater toward points of discharge. Flow lines generally are considered perpendicular to equipotential lines.

Flow model: A computer model that calculates a hydraulic head field for the study area using numerical methods to arrive at an approximate solution to the differential equation of groundwater flow.

Flow path: The path a water molecule or solute follows in the subsurface.

Flow System/Hydraulic Boundary: A hydrologic feature that prevents the flow of groundwater. Examples include groundwater divides or low permeability material that impedes groundwater flow.

Flowing Artesian: When the water level in a well rises above and flows at the ground surface.

Footwall: The lower side of a horizontal or inclined rock body or fault. If the fault has dip-slip translational movement along a normal fault, the footwall block is upthrown; the footwall block is downthrown along a reverse fault.

Fracture: A general term for any break in a rock, which includes cracks, joints, and faults.

Groundwater barrier: Rock or artificial material with a relatively low permeability that occurs (or is placed) below ground surface, where it impedes the movement of groundwater and thus may cause a pronounced difference in the heads on opposite sides of the barrier.

Groundwater basin: General term used to define a groundwater flow system that has defined boundaries and may include more than one aquifer. The basin includes both the surface area and the permeable materials beneath it. A rather vague designation pertaining to a groundwater reservoir that is more or less separate from neighboring groundwater reservoirs. A groundwater basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries.

Groundwater divide: Ridge in the water table, or potentiometric surface, from which groundwater moves away at right angles in both directions. Line of highest hydraulic head in the water table or potentiometric surface.

Groundwater mound: Raised area in a water table or other potentiometric surface, aerated by groundwater recharge.

Groundwater source: Any well, spring, tunnel, adit, or other underground opening from or through which groundwater flows or is pumped from subsurface water bearing formations.

Hanging wall: The upper side of a horizontal or inclined rock body or fault. The hanging wall is downthrown along a normal fault with dip-slip movement; the hanging wall is upthrown along a reverse-slip fault.

Head, total: Height of the column of water at a given point in a groundwater system above a datum plane such as mean sea level. The sum of the elevation head (distance of a point above datum), the pressure head (the height of a column of liquid that can be supported by static pressure at the point), and the velocity head (the height to which the liquid can be raised by its kinetic energy).

Heterogeneity: Characteristic of a medium in which material properties vary from point to point.

Homogeneity: Characteristic of a medium in which material properties are identical throughout.

Hydraulic Conductivity (K): A coefficient of proportionality describing the rate at which water can move through a permeable medium. It is a function of the porous medium and the fluid.

Hydraulic Gradient (i): Slope of a water table or potentiometric surface. More specifically, change in head per unit of distance in a given direction, generally the direction of the maximum rate of decrease in head. The difference in hydraulic head divided by the distance along the flowpath.

Hydrogeologic methods: The techniques used to translate selected criteria and criteria thresholds into mappable delineation boundaries. These methods include, but are not limited to, arbitrary fixed radii, analytical calculations and models, hydrogeologic mapping, and numerical flow models.

Hydrogeologic unit: Any soil or rock unit or zone that because of its hydraulic properties has a distinct influence on the storage or movement of groundwater.

Impermeable: Characteristic of geologic materials that limit their ability to transmit significant quantities of water under the head differences normally found in the subsurface environment.

Indurated: A said of a rock or soil hardened or consolidated by pressure, cementation, or heat.

Interference: The result of two or more pumping wells, the drawdown cones of which intercept. At a given location, the total well interference is the sum of the drawdowns due to each individual well. The condition occurring when the area of influence of a water well comes into contact with or overlaps that of a neighboring well, as when two wells are pumping from the same aquifer or are located near each other.

Isotropy: The condition in which the properties of interest (generally hydraulic properties of the aquifer) are the same in all directions.

Leakage: The vertical flow of groundwater; commonly used in the context of vertical groundwater flow through confining strata.

Limestone: A bedded sedimentary deposit consisting chiefly of calcium carbonate.

Mudstone: An indurated mud having the texture and composition of shale, but lacking its fine lamination or fissility; a blocky or massive fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal..

Nonpoint source: Any conveyance not meeting the definition of point source.

Normal fault: A fault, with an angle usually between 45-90 degrees, at which the hanging wall (upper block) has moved downward relative to the footwall (lower block).

Permeability: Capacity of a rock or soil material to transmit a fluid.

Piezometric surface: See potentiometric surface.

Point source: Any discernible, confined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, animal feeding operation with more than ten animal units, landfill, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include return flows from irrigated agriculture.

Pollution source: Point source discharges of contaminants to ground water or potential discharges of the liquid forms of "extremely hazardous substances" which are stored in containers in excess of "applicable threshold planning quantities" as specified in SARA Title III. Examples of possible pollution sources include, but are not limited to, the following: storage facilities that store the liquid forms of extremely hazardous substances, septic tanks, drain fields, class V underground injection wells, landfills, open dumps, landfilling of sludge and septage, manure piles, salt piles, pit privies, drain lines, sewer lines, and animal feeding operations with more than ten animal units.

Porosity: The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Potable water: Suitable for human consumption as drinking water.

Potential contamination source: Any facility or site which employs an activity or procedure which may potentially contaminate ground water. A pollution source is also a potential contamination source.

Potentiometric Surface: A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

Pump Test: A test to determine hydrologic properties of an aquifer, involving the withdrawal of measured quantities of water from, or additional of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition.

Radial flow: The flow of water in an aquifer toward a well.

Recharge area: Area in which water reaches the groundwater reservoir by surface infiltration. An area in which there is a downward component of hydraulic head in the aquifer.

Residual soil: Unconsolidated or partly weathered material, presumed to have developed in place (by weathering) from the consolidated rock on which it lies.

Reverse fault: Fault with a dip greater than 45 degrees at which the hanging wall (upper block) appears to have moved upward relative to the footwall (lower block).

Sandstone: A cemented or otherwise compacted detrital sediment composed predominantly of quartz sand grains.

Shale: A laminated sediment in which the constituent particles are composed of clay. Same as mudstone, except mudstone may be composed of a percentage of silt and may or may not be laminated.

Siltstone: An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which the silt predominates over clay.

Thrust fault: Fault with a dip of 45 degrees or less in which the hanging wall (upper block) appears to have moved upward relative to the footwall (lower block).

Time of travel (TOT): The time required for a particle of water to move in the saturated zone from a specific point to a groundwater source of drinking water.

Unconfined Aquifer: Any aquifer that does not meet the definition of a confined aquifer. An aquifer over which there is no confining strata and the water table forms the upper boundary.

Well field: An area containing two or more wells supplying a public water supply system.

Wellhead protection area (WHPA): The surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field.

Wellhead: The physical structure, facility, or device at the land surface from or through which groundwater flows or is pumped from subsurface, water-bearing formations.

Zone of Contribution (ZOC): The area surrounding a pumping well, spring, or tunnel that encompasses all areas and features that supply groundwater recharge to the well spring, or tunnel.

Appendix B: Listing of Groundwater Resources Domains in International Agreements

Parties or Agency	**Agreement or Policy**	**Type of Groundwater Resource Boundary**	**Emphasis**	**Shallow versus Deep Groundwater?**	**Reference**
British Columbia/Washington	Memorandum of Understanding 1996	Exterior boundaries of Abbotsford/ Sumas	Allocation		Burchi and Mechlem (2005)
Israel and Jordan	Treaty of Peace 1994	Territorial	Allocation, Quality, Nature Reserves		Burchi and Mechlem (2005)
Israel and PLO	Interim Agreement on West Bank & Gaza Strip 1995	Boundaries of Eastern Aquifer, North-eastern Aquifer, Western Aquifer & Gaza Strip	Allocation		Burchi and Mechlem (2005)
Mexico and US	Agreement of Cooperation 1985	International boundary	Water quality		Burchi and Mechlem (2005)
Niger-Nigeria	Agreement of Cooperation 1985	Shared river basins	Allocation	Underground waters contributing to surface waters	Burchi and Mechlem (2005)
Spain-Portugal	Agreement on Cooperation 1985	Hydrographic basin	Allocation, Water quality, Pollution prevention; Ecosystems; Exchange of information	Underground waters contributing to surface waters	Burchi and Mechlem (2005)
Idaho-Washington	Interagency Agreement on Coordinated Management 1992	Boundary of Pullman-Moscow Aquifer	Modeling areas; Allocation		Burchi and Mechlem (2005)
South Australia-Victoria	Border Groundwaters Agreement 1985	Designated area along border	Allocation; Water quality		Burchi and Mechlem (2005)
Australia-New South Wales-South Australia-Victoria	Murray-Darling Basin Agreement 1985	River basin	Planning and mgmt.	Affluent connected with river	Burchi and Mechlem (2005)
Australia-Queensland-South Australia	Lake Eyre Agreement 2000	Lake basin	Planning and mgmt.	Sub-artesian waters dependent on surface flows	Burchi and Mechlem (2005)
Australia-Australian Capital Territory-New South Wales-Northern Territory-Queensland-South Australia	Intergoverment Agreement 2004	River basin; Groundwater Management Units; Groundwater Trading Zones	Allocation; Water Markets; Planning and mgmt; Indigenous, social, spiritual access		Burchi and Mechlem (2005)

Parties or Agency	**Agreement Or Policy**	**Type of Groundwater Resource Boundary**	**Emphasis**	**Shallow versus Deep Groundwater?**	**Reference**
The State Council of the Republic and Canton of Geneva and The Prefect of Haute-Savoie	Arrangement on the Protection, Utilisation and Recharge of the Franco-Swiss Genevese Aquifer 1978	Boundary of Franco-Swiss Genevese Aquifer	Recharge and water use; Pricing; Water quality		Wohlwend (2002)
European Community Law	Council Directive Concerning Protection of Waters 1991	Vulnerable Zones	Protection against pollution		Burchi and Mechlem (2005)
Austria, Bulgaria, Croatia, Germany, Hungary, Republic of Moldova, Romania, Slovakia, Ukraine, European Economic Community	Convention on Cooperation for the Protection and Sustainable Use of the River Danube 1994	Protection zones for existing and future drinking water supplies	Protection against pollution		Matsumoto (2002)
European Community Law	Directive 2000/60/EC Establishing Framework for Community Action in Water Policy 2000	Body of groundwater assigned to a river basin	Designation of status based on quantitative and chemical status; Protected areas	Deep aquifer identified if important to surface ecosystems and drinking water supply	Burchi and Mechlem (2005); Working Group on Water Bodies (2003)
UN Economic Commission for Europe	Charter on Groundwater Management 1989	"Aquifers" at risk; groundwater protection zones (recharge areas); wellhead protection zones	Strategies for economic and ecological value; preservation of water quality	Deep-well injection of wastes; research programs should focus on both unsaturated zones and "deep-lying aquifers"	Burchi and Mechlem (2005)
International Conference on Water and the Environment	The Dublin Statement 1992	Groundwater "aquifer"	Links land and water use across aquifer		Burchi and Mechlem (2005)
UN Conference on Environment and Development	Agenda 21 – Chapter 18 1992	Catchment or sub-basin; Water Users Groups; Protection Zones in recharge and abstraction areas	Integrated water resources development and management		Burchi and Mechlem (2005)
UN International Law Commission	Resolution on Confined Transboundary Groundwater 1994	Groundwater not related to an international water course		Implies recognition of deep groundwater	Burchi and Mechlem (2005)

Parties or Agency	**Agreement Or Policy**	**Type of Groundwater Resource Boundary**	**Emphasis**	**Shallow versus Deep Groundwater?**	**Reference**
UN Economic Commission for Europe	Guidelines on Transboundary Groundwaters 2000	Zoning; Protection zones in current and future abstraction areas	Pollution prevention; Allocation; Wetlands	Implies recognition of deep groundwater	Burchi and Mechlem (2005)
Convention on Wetlands	Resolution VIII.40 – Guidelines for use of Groundwater Compatible with Conservation of Wetlands 2000	Wetlands	Acknowledges role of groundwater in maintaining the ecological function of wetlands		Burchi and Mechlem (2005)
International Law Association	Seoul Rules on International Groundwaters 1986	International drainage basin; Recharge areas	Allocation; protection	Aquifers that do not contribute water to or receive waters from surface waters constitute a unique international drainage basin	Burchi and Mechlem (2005)
	Bellagio “Model Agreement Concerning the Use of Transboundary Groundwaters” 1989	“Border region” or area within a mutually agreed upon distance from the mutual boundary set forth in annexed map; Reserved groundwater within border regions; Transboundary groundwater conservation areas	Allocation; Protection; Control	Shallow – as defined by interrelated surface water where the quantity or quality is affected by the outflows from or inflows to transboundary groundwater	Burchi and Mechlem (2005)
International Law Commission	Convention on the Law of the Non-navigational uses of International Water Courses 1997	International watercourse	Allocation		McCaffrey (2001)
International Law Association	Berlin Rules on Water Resources 2004	Catchment drainage basin; Vulnerability maps	Allocation; protection	Applies to both aquifers that are connected to surface waters and aquifers that are not connected to surface waters	Burchi and Mechlem (2005)

Parties or Agency	**Agreement Or Policy**	**Type of Groundwater Resource Boundary**	**Emphasis**	**Shallow versus Deep Groundwater?**	**Reference**
International Law Commission	Third Report on Shared Natural Resources: Transboundary Groundwaters or "Draft Convention on the Law of Transboundary Aquifers" 2005	Applies to only saturated zone of aquifer and to "extent" and "geometry" of aquifer boundaries with parts situated in different States	Utilization; Protection of ecosystems, recharge and discharge zones, and protection from pollution	Applies to both aquifers that are connected to surface waters and aquifers that are not connected to surface waters; and non-recharging aquifers	Yamada (2005)

Appendix C: Listing of Groundwater Resources User Domains by Nations and States

Country	Institutional Attributes	Type of Groundwater Resource Boundary	Emphasis	Shallow versus Deep Groundwater?	Reference
AMERICAS					
Mexico	National public domain	Watersheds; Aquifer Management Councils	Allocation		Kamieniecki and Grafton (2004); Muhkerji and Shah (2005)
Canada	Provincial public domain	Aquifer; Hydrostructural domains; Wellhead Protection Areas	Quality		Livingstone and others (1986); Wei and Allen (2004); Rivera and Nastev (2005)
United States (select states) • Arizona • California • Colorado • Nebraska • Oregon • Texas • Utah • Wyoming	State public domain	Aquifer Management Areas; Designated Basins; Regional Aquifer Systems; Wellhead Protection Areas; Source Water Protection Areas; Control Areas; Groundwater Management Areas; Geothermal Protection Areas; Sole Source Aquifers	Allocation; Quality; Nature reserves	Colorado specifically differentiates types of groundwater.	Aucoin (1984); Blomquist (1992); Blomquist and others (2004); Bastasch (1998); Ragone and others (2003); Smith (2003; 2004); Sun (1997); Glennon (2002); McCabe and others (1997); Bryner (2004); Custer and others (1994); Utah Div. of Water Rights (2002); Votteler (2004)
Costa Rica	National control	Drainage basin	Open access (No controls)		Kemper and others (2005)
Brazil	State public domain	Drainage basin	Allocation		Embid (2005); Kemper and others (2003); Kemper and others (2005)
Argentina	Provincial public domain	Drainage basin; Groundwater use restriction zone	Allocation; Water quality		Foster and others (2005); Kemper and others (2003)
Chile	National public domain	"Vegas" or water meadows; "Bofedales" or High Andes phreatophytes	Allocation; Nature Reserves		Acosta (2005); Bauer (2004)
EUROPE					
Ireland	Open access	Agenda 21 councils	Allocation, Water quality		Cusack (2004)
Spain	National public domain	Hydrographic confederations or river basins	Allocation		Geta and others (2004); Mukherji and Shah (2005); Hernandez-Mora and others (2004)
France	National public domain	Catchments; Outline of aquifer	Allocation		Barraque (2004); Lopez and Petit (2000)

Country	Institutional Attributes	Type of Groundwater Resource Boundary	Emphasis	Shallow versus Deep Groundwater?	Reference
EUROPE					
Italy	National public domain	Zone of absolute defense; zone of respect; zone of protection; zone of normal springs	Water quality; Allocation		Barrocu and Civita (2004)
Netherlands	Private property and provincial public domain	Provincial boundaries. Nature reserves or "fragile areas"	Allocation; Water quality	Shallow groundwater by rule of capture. Deep groundwater by provincial permit.	Glasbergen (2004)
Poland	National control	Main Groundwater Reservoirs; Hydrostructural units; Basin balance unit; Drainage areas for mining, industrial, and municipal Therapeutic	Allocation	Deep groundwater based on limited contact with river network.	Herbich and others (2004)
Czech Republic	National control	Hydrogeological Zones; Protected Recharge Areas; Wellhead Protection Areas	Allocation; Water quality		Vrba (2004)
Bulgaria	National public domain	Basin or catchments; Belts of Protection	Allocation; Water quality for drinking water and mineral water		Galabov and Lichev (2004)
MIDDLE EAST					
Israel, Gaza, West Bank	National control in Israel; Joint sharing between Israel and Palestinian Nat. Auth.	Outcrop boundaries; Basin boundaries; Political boundaries; Geochemistry; Depth	Allocation; Nature reserves	Deep aquifers designated by Oslo 2 Accords for Israel; Shallow aquifers for Palestinian Nat. Auth.	Froukh (2003); Gordon (2004); Feitelson (2005)
Iran	Traditional local laws; National control	None	Allocation		Mahdavi and Saravi (2004)

Country	Institutional Attributes	Type of Groundwater Resource Boundary	Emphasis	Shallow versus Deep Groundwater?	Reference
MIDDLE EAST					
Arabian Peninsula (Oman, Yemen)	National public domain; Traditional local laws	Aquifer; Drainage basin; Wellhead Protection Area (1 km radius)	Allocation; Water quality		Young (2002); Foster and others (2005); Van Steenbergen (2006)
ASIA					
Russia	National control	Approved reserved areas	Allocation		Zekster (2004)
Pakistan	Provincial control (?); Land ownership; Traditional harim rule	Dug well free zone up to 5 km from kareze in some areas. Prohibited zone near kareze or qanat (250 meters in silty soils; 500 meters in gravel soils); Provincial authorities	Access; Monitoring	"Deep" aquifers recognized as opportunity for rich farmers.	Van Steenbergen and Shah (2003); Van Steenbergen (2004); Mukherji and Shah (2005); Van Steenbergen (2006)
India	"Rule of Capture" or Private property	Land ownership	Availability	Census of wells differentiates between shallow versus deep wells.	Sinha and Jain (2005); Mukherji and Shah (2005); Shah (2005)
China	National control	Provincial; County; Township; Village	Allocation		Guanghui and Yuhong (2004); Mukherji and Shah (2005); Foster and others (2005); Shah (2005)
Philippines	National public domain	"Circle of influence" spacing based on rate of withdrawal	Allocation	Shallow – as defined by interrelated surface water where the quantity or quality is affected by the outflows from or inflows to transboundary groundwater	Burchi and D'Andrea (2003)

Country	Institutional Attributes	Type of Groundwater Resource Boundary	Emphasis	Shallow versus Deep Groundwater?	Reference
AFRICA					
South Africa and SADC	National public domain	Catchment Management Areas; Water User Associations; Subterranean Water Control Areas	Allocation; "Reserves" for basis human needs and environment; "Usable" portion; Watercourse		Kelbe and Rawlins (2004); McCaffery (2001)
OCEANIA					
Australia	States public domain	Groundwater provinces	Allocation		Poirer (2004)

Appendix D: Transboundary Aquifer Systems

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	**Countries sharing this Aquifer System***	**Type of Aquifer System***	**River Basin (from Wolf and Giordano 2002)**	**Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)**
AMERICAS				
Okanagan-Osoyoos / Grand Forks	Canada, USA	Porous	Columbia	
Poplar	Canada, USA	Porous	Mississippi	
Estevan	Canada, USA	Porous	Nelson-Saskatchewan	
Chataeauguay	Canada, USA	Fissured/Fractured	St. Lawrence	Protocol Amending the 1978 Agreement Between the United States of America and Canada on Great Lakes Water Quality 1987
Basin & Range Aquifer System	USA, Mexico	Porous	Colorado	Mexico-US Agreement on the Permanent and Definitive Solution to the Salinity of the Colorado River (Minute No. 242) 1973.
Rio Grande Aquifer System	USA, Mexico	Porous	Rio Bravo-Rio Grande	Treaty between the United States of America and Mexico relating to the utilization of the Waters of the Colorado and Tijuana Rivers and of the Rio Grande 1944; and International Boundary and Water Commission United States and Mexico Observation Of The Quality Of The Waters Along The United States And Mexico Border (Minute No. 289) 1992
Gulf Coast Plain Aquifer System	USA, Mexico	Porous	None	
Masacre / Arbonito / Pedernales	Haiti, Dominican Republic		Artibonite / Massacre / Pedernales	

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	**Countries sharing this Aquifer System***	**Type of Aquifer System***	**River Basin (from Wolf and Giordano (2002)**	**Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)**
AMERICAS				
Various Aquifer Systems	Mexico, Guatemala, Belize, Honduras, Nicaragua		Grijalva / Hondo / Yaqui / Belize	
Honduras – Nicaraqua Aquifer System	Honduras, Nicaraqua		None	
Nicaragua – Costa Rica Aquifer System	Nicaragua, Costa Rica		San Juan	
Sixaola / Coto	Costa Rica, Panama		Sixaola / Chiriqui / Changuinola	
Jurado	Columbia, Panama		Jurado	
Tachira / Paranaguachon / Carrapia / Mongui / Cretacio	Columbia, Venezula		None	
Llanura Rio Arauca / San Antonio-Cucuta / Rio Pamplonita / Guayabo / Carbonera / Mirador	Columbia, Venezula		Orinoco	
A-Sand / Cosewijne / Zanderij	Guyana, Suriname, French Guiana		Essequibo(?)	
Costeiro	Brazil, French Guiana		Oiapoque / Oyupock	
Tulcan	Columbia, Ecuador		Patia / Mataje / Zarumilla	
Ica / Machala / Zurumilla / Tumbes	Brazil, Columbia, Peru, Ecudor		Amazon	
Solimoes	Brazil, Peru, Bolivia		Amazon	
Ignimbritas Cordillera Ocidental / Conordia-Escitos / Caplina-La Yarada / Laguna Blanca-Maure	Boliva, Peru, Chile		Lake Titicaca-Poopo System; Cancuso / Lauca	
Silala / Ascotal / Ollague	Bolivia, Chile		Concuso/Luaca?	

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	Countries sharing this Aquifer System*	Type of Aquifer System*	River Basin (from Wolf and Giordano (2002)	Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)
AMERICAS				
Yrenda-Toba-Tarijeno Aquifer System	Paraguay, Argentina, Bolivia	Porous	La Plata	
Pantanal / Lslas	Brazil, Bolivia, Paraguay		La Plata	
Guarani Aquifer System	Brazil, Paraguay, Argentina, Uruguay	Porous; Fissured/Fractured	La Plata	Statute of the River Uruguay 1975
Chile-Argentina Aquifer System	Chile, Argentina		Aysen – Baker (?)	
El Condor	Chile, Argentina		Gallegos-Chico	
EUROPE				
Carbonfierous Limestone Aquifer	France, Belgium	Karst	Ysur	
Northwest Germany / Netherlands Aquifer	Germany, Netherlands	Porous	None	
Northeast Germany / Pommeranian Aquifer	Germany, Poland	Porous	Vistula / Wista / Oder / Odra	Agreement between the government of the Polish People's Republic and the Government of the Union of Soviet Socialist Republics concerning the use of water resources in frontier waters 1964
East Prussian Aquifer	Russia, Poland, Lithuania	Porous	Lielupe	
Latvia / Lithuanian / Estonia Aquifer System	Latvia, Lithuania, Estonia	Fractured/Fissured, Karst	Parnu / Guaja / Salaca	
West Russian Aquifer System	Russia, Latvia, Belarus	Porous, Fractured/ Fissured, Karst	Daugava / Dneiper / Volga	Draft Agreement on Water Quality Management of Zapadnaya Dvina/Daugava River Basin 1997

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	**Countries sharing this Aquifer System***	**Type of Aquifer System***	**River Basin (from Wolf and Giordano (2002)**	**Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)**
EUROPE				
Southwest Russian Aquier System	Russia, Ukraine	Porous, Fractured/Fissured, Karst	Don / Dneiper / Volga	Agreement between the government of the Republic of Kazakhstan and the government of the Russian Federation concerning the joint use and protection of transboundary waters 1992
Upper Rhine Graben	Germany, France	Porous	Rhine	Convention on the Protection of the Rhine Against Chemical Pollution 1976; Convention on the Protection of the Rhine 1998
Forealpine Depression / Northern Limestone Alps	Germany, Austria, Switzerland	Porous, Fractured/Fissured, Karst	Rhine / Danube	Convention on the Protection of the Rhine Against Chemical Pollution 1976; Convention on the Protection of the Rhine 1998 Convention on Cooperation for the Protection and Sustainable Use of the Danube 1994
Upper Rhine Graben	Germany, France	Porous	Danube	Convention on Cooperation for the Protection and Sustainable Use of the Danube 1994
Dinarides (numerous aquifers)	Croatia, Slovenia, Bosnia and Herzegovina, Serbia and Montenegro	Fractured/Fissured, Karst	Danube	Convention on Cooperation for the Protection and Sustainable Use of the Danube 1994

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	**Countries sharing this Aquifer System***	**Type of Aquifer System***	**River Basin (from Wolf and Giordano (2002)**	**Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)**
EUROPE				
Pannonian Basin	Hungary, Romania, Ukraine, Solvakia, Austria, Solvenia, Croatia, Serbia and Montenegro	Porous	Danube	Convention Between The Government Of The Socialist Federal Republic Of Yugoslavia And The Government Of The Romanian People's Republic Concerning The Operation Of The Iron Gates Water Power And Navigation System On The River Danube, Signed At Belgrade 1963
Cretaceous Aquifer	Bulgaria, Romania	Karst	Danube	Convention on Cooperation for the Protection and Sustainable Use of the Danube 1994
Moldovian Aquifer System	Moldova, Ukraine, Romania	Porous, Fractured/Fissured	Danube / Sarata	Agreement between the government of the Republic of Moldova and the government of Ukraine on the joint use and protection of transboundary waters 1994
AFRICA				
Tindouf Aquifer	Algeria, Morroco		Dra	
Errachidia Basin	Algeria, Morroco		Daoura / Dra	
Northwest Sahara Aquifer System	Algeria,Libya, Tunisia	Porous, Fractured/Fissured	None	
Mourzouk-Djado Basin	Chad, Libya, Niger		None	
Nubian Sandstone Aquifer System	Chad, Egypt, Libya, Sudan	Porous, Fractured/Fissured	Nile	Exchange of Notes Constituting an Agreement' Between the United Kingdom of Great Britain and Northern Ireland and Egypt Regarding the Utilisation of Profits From the 1940 British Government Cotton Buying Commission and the 1941 Joint Angloegyptian Cotton Buying Commission to Finance Schemes for Village Water Supplies 1946

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	**Countries sharing this Aquifer System***	**Type of Aquifer System***	**River Basin (from Wolf and Giordano (2002)**	**Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)**
AFRICA				
Senegalo-Mauritanian Basin	Gambia, Guinea-Bissau, Mauritania, Senegal		Atui / Senegal	
Taoudeni Basin	Algeria, Mali, Mauritania		None – southern area in Niger	Convention creating the Niger Basin Authority 1980
I'Air Cristalline Aquifer	Algeria, Mali, Niger		Niger	Convention creating the Niger Basin Authority 1980
Tin-Seririne Basin	Algeria, Niger		Niger	Convention creating the Niger Basin Authority 1980
Liptako-Gourma Aquifer	Burkina Faso, Niger		Niger	Convention creating the Niger Basin Authority 1980
Iullemeden Aquifer System	Mali, Niger, Nigeria		Niger	Agreement between the Federal Republic of Nigeria and the Republic of Niger Concerning the Equitable Sharing in the Development, Conservation and Use of their Common Water Resources 1990
Chad Basin	Central African Republic, Chad, Cameroon, Niger, Nigeria		Lake Chad	Convention and Statutes relating to the development of the Chad Basin 1964
Coastal Sedimentary Aquifer	Ghana, Cote d'Ivoire		Komoe / Bia	
Coastal Sedimentary Aquifer	Benin, Nigeria, Togo		Mono	
Upper Nile Basin	Ethiopia, Sudan		Nile	Framework for general co-operation between the Arab Republic of Egypt and Ethiopia 1993
Awash Valley Aquifer	Djbouti, Ethiopia		Nile	
Rift Aquifers	Kenya, Tanzania, Uganda		Lake Turkan / Lotagipi Swamp	

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	Countries sharing this Aquifer System*	Type of Aquifer System*	River Basin (from Wolf and Giordano (2002)	Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)
AFRICA				
Ogaden-Juba Aquifer	Ethiopia, Kenya, Somalia		Juba / Shibeli	
Mount Elgon Aquifer	Kenya, Uganda		Lake Turkan / Lotagipi Swamp	
Merti Aquifer	Kenya, Somalia		Juba / Shibeli	
Coastal Sedimentary Basin	DR Congo, Angola	Porous	Congo / Zaire	
Congo Intra-cratonic Basin	DR Congo, Angola	Porous, Fractured/Fissured	Congo / Zaire	
Kagera Aquifer	Tanzania, Uganda		Nile	Agreement to initiate program to strengthen regional coordination in management of resources of Lake Victoria 1994
Kilimanjaro Aquifer	Kenya, Tanzania	Fractured/Fissured	Lake Natron	
Coastal Sedimentary Basin	Kenya, Tanzania	Porous	Umba	
Karoo Sandstone Aquifer	Mozambique, Tanzania	Karst, Fractured/Fissured	Ruvuma	
Coastal Sedimentary Basin	Mozambique, Tanzania	Porous	Ruvuma	
Coastal Sedimentary Basin	Angola, Namibia	Porous	Kunene	
Cuvelai Basin	Angola, Namibia	Porous	Cuvelai / Etasha	
Northern Kalahari / Karoo Basin	Angola, Namibia, Botswana, Zambia	Porous, Fractured/Fissured	Zambezi	Agreement on the action plan for the environmentally sound management of the Common Zambezi River system 1987
Nata Karoo Subbasin	Namibia, Botswana, Zimbabwe	Fractured/Fissured	Zambezi	Agreement on the action plan for the environmentally sound management of the Common Zambezi River system 1987
Medium Zambezi Aquifer	Namibia, Mozambique, Zimbabwe		Zambezi	Agreement on the action plan for the environmentally sound management of the Common Zambezi River system 1987

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	Countries sharing this Aquifer System*	Type of Aquifer System*	River Basin (from Wolf and Giordano (2002)	Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)
AFRICA				
Shire Valley Alluvial Aquifer	Malawi, Mozambique		Zambezi	Agreement on the action plan for the environmentally sound management of the Common Zambezi River system 1987
Southest Kalahari / Karoo Basin	Botswana, Namibia, South Africa	Porous, Karst, Fractured/Fissured	Okavango	Agreement between the Governments of The Republic of Angola, The Republic Of Botswana, and The Republic of Namibia on the establishment of a permanent Okavango River Basin Water Commission (Okacom) 1994
Ramotswa Dolomite Basin	Botswana, South Africa	Karst	Limpopo	
Tuli Karoo Subbasin	Botswana, South Africa, Zimbabwe		Limpopo	
Limpopo Basin	Mozambique, South Africa, Swaziland		Limpopo	
Incomati / Maputo Basin	Mozambique, South Africa, Swaziland	Porous	Incomati	
Coastal Sedimentary Basin	Namibia, South Africa	Porous	Orange	
Karoo Sedimentary Basin	Lesotho, South Africa	Fractured/Fissured	Orange	

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	Countries sharing this Aquifer System*	Type of Aquifer System*	River Basin (from Wolf and Giordano (2002)	Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)
ASIA				
Upper Jezira / Mesopotamia	Iraq, Syria, Turkey	Porous, Fractured/Fissured	Tigris-Euphretes Shatt al Arab	
Eastern Mediterranean	Israel, Jordan, Lebanon, Palestinian Teritory, Syria	Porous, Karst, Fractured/Fissured	Nahr El Kebir; An Nahr Al Kabir Wadi Al Izziyah; Jordan	Johnston Negotiations, 1955; Treaty Of Peace Between the State of Israel and the Hashemite Kingdom of Jordan 1994; Annex III to the Israeli-Palestinian interim agreement on the West Bank and the Gaza Strip: protocol concerning civil affairs 1995
Hauran and Jabal Al-Arab (basalts)	Jordan, Saudi Arabia, Syria	Fractured/Fissured	Wadi Al Izziyah; Jordan	Agreement between the Republic of Syria and the Hashemite Kingdom of Jordan concerning the Utilization of the Yarmuk Waters 1953
Syrian Steppe	Iraq, Jordan, Saudi Arabia, Syria	Fractured/Fissured	Jordan	Agreement between the Republic of Syria and the Hashemite Kingdom of Jordan concerning the Utilization of the Yarmuk Waters 1953
Eastern Arabian Peninsula	Bahrain, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, UAE, Yeman	Porous, Fractured/Fissured	None	
Ertix River Plain	Russia, Kazakhstan	Porous	Ob	Agreement between the government of the Republic of Kazakhstan and the government of the Russian Federation concerning the joint use and protection of transboundary waters 1992

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	Countries sharing this Aquifer System*	Type of Aquifer System*	River Basin (from Wolf and Giordano (2002)	Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)
West Altai	Russia, Kazakhstan	Porous, Fractured/Fissured	Ob	Agreement between the government of the Republic of Kazakhstan and the government of the Russian Federation concerning the joint use and protection of transboundary waters 1992
Yili River Basin	China, Kazakhstan	Porous	Ob; Pu Lun T'o	Agreement between the government of the People's Republic of China and the government of Mongolia on the protection and utilization of transboundary waters 1994
Yensei Upstream	Russia, Mongolia	Porous, Fractured/Fissured	Lake Ubsa-Nur; Har Us Nur	Agreement between the government of Mongolia and the government of the Russian Federation on the protection and use of transboundary waters 1995
Heilongjiang River Plain	Russia, China	Porous	Amur	
Central Asia	Kazakhstan, Krgyzstan, Uzbekistan, Tajistan, Turkmenistan, Afghanistan	Porous, Karst Fractured/Fissured	Aral Sea; Tarim	Agreement on joint activities in addressing the Aral Sea and the zone around the Sea crisis, improving the environment, and ensuring the social and economic development of the Aral Sea region 1993
India River Plain	India, Pakistan	Porous	Indus	
Southern of Himalayas	India, Nepal	Porous	Ganges – Brahmaputra - Meghna	
Ganges River Plain	Bangladesh, India	Porous	Ganges – Brahmaputra - Meghna	

Name of Transboundary Aquifer System (Struckmeir and others 2006)*	**Countries sharing this Aquifer System***	**Type of Aquifer System***	**River Basin (from Wolf and Giordano (2002)**	**Treaty Referencing Groundwater Issues listed in Transboundary Freshwater Dispute Database (2006)**
South Burma	Burma, Thailand	Fractured/Fissured	Salween	
Mekong River Plain	Thailand, Laos, Cambodia, Viet Nam	Porous	Mekong	
New Guinea Island	Indonesia, Papua New Guinea	Porous, Fractured/Fissured	Tami; Sepik; Fly; Tjeroaka-Wanggoe	