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Chapter 9

GROUNDWATER DEPENDENT ECOSYSTEMS – SCIENCE, CHALLENGES, AND POLICY DIRECTIONS

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ABSTRACT

Groundwater Dependent Ecosystems (GDEs) are foci of this planet's biological diversity, living records of cultural heritage, centers of religious ritual and practice, strategic goals of economic aspirations, and have been both the objects and weapons of local and international conflict. They have inspired poetry and the arts, and embody verdant byways in the most inhospitable deserts of the world and of the human spirit. Increasing exploitation of groundwater resources has interrupted the quantity and altered hydrochemistry of these springs and wetlands, creating resource management challenges around the globe. Basic information on GDEs is elusive, as many are in remote locations, and have small areal extent concealed from the resolution of both remote

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sensing satellites and supportive political action. Varying laws, policies, and management practices throughout the world have directed a path forward for GDE sustainability, amid conflicting national ambitions, constrained economic and enforcement capabilities, and lack of basic scientific data.

Keywords: Groundwater Dependent Ecosystems, Springs, Policy, Cultural Significance

INTRODUCTION

In a "Report to Congress - Progress Toward Establishing a National Assessment of Water Availability and Use" (Alley et al. 2013), the work conducted on the U.S. National Water Census and future directions of the program are given a clear and wide-ranging overview. What is remarkable about the document is the limited discussion of groundwater in general, and the relative absence of any discussion of the relationships of ecosystems and groundwater in the vast arid and semi-arid regions of the United States. Criticisms of the Report's drafts, which pointed out there was little or no mention of springs, seeps, groundwater dependent wetlands or river reaches, and subterranean ecosystems, were deemed by the authors to be not in keeping with the overall theme of the report and the technical level to which the report was to be written. That lack of mention of the dependence of ecological systems on groundwater is echoed in the dearth of laws, policy initiatives, scientific study, and public attention on the issue, not only in the U.S., but in many countries throughout the world. Some countries, like Zimbabwe, have robust and holistic water laws, but have difficulties in their implementation and management (Makurira and Magumo 2003). With burgeoning worldwide population, more and more pressure has been put on groundwater for irrigated agriculture, industry, and municipal supply with resultant overdrafts and diminishment of environmental flows and chemistries. For example, over half of India's agriculture is irrigated with groundwater and that fraction is increasing (Dubash 2002), putting pressure on groundwater dependent springs. Immense portions of the planet's population subsist on the limited and vulnerable water that leaks to the surface, or is withdrawn from wells and boreholes. Particularly in dry regions of the earth, the productivity, biological diversity and cultural importance of groundwater dependent ecosystems (GDEs) are often orders of magnitude greater than surrounding dry areas that are not directly supported by groundwater (Odum 1957, Stevens and Meretsky 2008).

Defining and sometimes constraining public perception of these ecosystems are the varied and individual laws of many countries, regions and states. These laws and regulations direct the public policies and management approaches to either recognize or to ignore the relation of groundwater to life-forms it sustains. In turn, scientific research, characterization and monitoring of GDEs relies on funding and supportive public policy. Where clear and sustaining laws, regulations, policies, and monitoring are not available, important ecosystems can suffer and biological diversity can be lost. The efficacy of enforcement of those laws and policies toward natural resource conservation and groundwater dependent ecosystems is key in protection and sustenance of many unique, and sometimes fragile, ecological communities.

Compounding these problems, the locations of springs, seeps, and other GDEs are often not well characterized, even in economically advantaged societies that can apply resources for scientific study. Management of, and policy development for, GDEs cannot go forward if springs, seeps, wetlands, gaining reaches of streams, groundwater-dependent terrestrial ecosystems and phreatophytes, aquifer ecosystems, and cave ecosystems have not been located, identified, surveyed, and monitored. Unfortunately, the basic value of GDEs, and even the existence and enumeration of these unique biotic communities has not been realized in many regions, and the paucity of information constrains public perception that, in turn, drives proper management and policy development. Finally, the definitions of the variety of GDEs are inconsistent and not evenly applied either in law or in practice (Springer and Stevens 2008).

THE SIGNIFICANCE OF GROUNDWATER DEPENDENT SPRINGS AND WETLANDS IN HUMAN HISTORY

GDEs and the groundwater that supplies them have been pivotal in human history - our culture, religions, and traditions are intimately linked with these places. Many past and present civilizations have located, and had agriculture flourish, near wetlands including: Egyptian society and the periodically flooding Nile Valley, the Khmer Empire and the Mekong Valley particularly around Tonle Sap (Great Lake) and the ancient hospital of Neak Pean in Cambodia, Rome’s ancient port of Ostia Antica, Spain’s Empúrias in

Catalonia, the ancient western Greek city of Nicopolis in the Amvrakikos Gulf, and Mesopotamian civilization in the Tigris and Euphrates lowlands (Ramsar 2008). Major cities such as Venice, Bangkok, Mexico City, Tunis, Guayaquil, Amsterdam, New York, and New Orleans were established near existing wetlands, although the threat of malaria in some parts of the world have driven human population away from some wetlands (Ramsar 2008). Archaeologically, the anoxic and waterlogged conditions associated with peatlands have yielded valuable historical finds. Ancient ships have been exhumed from Venice and Marseille, and Etruscan age vessels have been recovered from the Hutovo Blato wetland in Bosnia and Herzegovina. Ancient and pre-historic settlements have been discovered in peatlands of the United Kingdom, in Black Sea bottom muds, and under Lake Titicaca. In addition to preserving human relics, the anoxic conditions of peatlands can preserve past plants, insects and pollens, which can serve as valuable indicators of past climate (RAMSAR 2008).

Additionally, springs and wetlands have served as focal points of hostilities, national ambition and war, as both an object of conflict and a strategic tool. For example, Gihon Spring is one of several springs that served as the original gathering locations for what was to become the city of Jerusalem. These springs, located just outside the walls of the early, growing city, were not only major points of sustenance, but were manipulated for strategic military purposes. As mentioned in the King James Bible, when Assyrians were advancing toward Jerusalem in 701 BC, the water flow for these springs was purposely stopped up to impede them (Scofield 1967).

Religiously motivated wars have involved springs and groundwater as strategic tool. In one example during the Crusades in mid-summer of 1187 AD, 30,000 Muslim forces, including 12,000 cavalry, were approached by an army of 20,000 Crusaders at the Horns of Hattin (near Tiberias in present day Israel) having been lured away from the springs at Saffuriya. The Crusaders last sure source of water was a spring at the city of Tur’an, 14 km from their objective of Tiberias. When the Crusaders set out at mid-day, the Muslim leader Saladin ordered two wings of his army to take the spring at Tur’an and cut off the retreat and water source of the advancing army. The then thirsty Crusaders veered toward the springs of Hattin, and they were met and stopped in fierce battle. Saladin’s armies captured or killed the large majority of the Crusaders who had reduced the garrisons of their castles and fortified cities to field their army, making Islamic forces the foremost military power in the Holy Land and prompting a Third Crusade (Gibb 1969, Madden 2000).

Locations of GDEs are often considered as sacred sites, and are crucially important to cultural and religious practice. In ancient Greece, visitors typically stopped at the Castalian Spring near Delphi, which rests in a narrow valley between the "shining" cliffs called Phaedriades, near the Temple of Apollo. Roman poets traveled great distances to receive inspiration at the spring, as did the contestants in the precursors to the modern Olympic Games, the Pythian Games. The spring was also used by supplicants visiting the nearby Delphic Oracle, a cave springs system considered by Hellenes to be the center of the earth, where legend indicates that Apollo slew the chthonic earth guardian monster Python, and a source of divine knowledge and guidance (Broad 2007). Other examples of springs' association with the sacred include the location of monuments to the Babylonian moon goddess Ishtar; the Gallo-Roman Fontes Sequanae at the source of the Seine River in France; the Christian Grotto of Lourdes at the foot of the Pyrénnées in France; the mythic "Fountain of Youth" sought out by the Spaniard Ponce de Léon in Florida, USA; the 7000 year old mineral springs in Bath, England with the Celtic shrine to Sulis and the Roman shrine to Sulis Minerva; and the life-giving fountain and spring waters of Pon Lai and Mount Lao Shan in China (Witcombe 1998).

On the other side of the globe, ancient and modern day Native Americans regard water issuing from the ground as central to their religious beliefs and practices. The hydrologic cycle of indigenous Native Americans is deeply invested with spiritual life. Iconographic analyses across the southern United States and northern Mexico document pictographs of a horned serpent that is responsible for bringing water to the surface of the earth and guarding springs (Phillips et al. 2006, Rea 2008). Also like Delphi, several springs in the southwestern U.S. are considered to be sites where humanity emerged into the world, while at least one Tribe considers a springs complex as heaven, where the spirits of the dead dwell in perpetuity (Hart 1986). The Mayan civilization, in what is now Mexico, viewed caves and cenotes as "doors to the underworld" or U'kux Xibalba. Virtually all indigenous cultures on Earth revere groundwater dependent surface or subterranean flows as sacred places where miracles occur.

Springs have been intensively used by indigenous cultures for >10,000 yr in the U.S, and far longer in Europe, Africa, Asia, and Australia (Haynes 2008). Consequently, springs also emerge as important paleontological and archeological sites for understanding landform, human, and cultural evolution. The affiliation of humans with springs over evolutionary time requires that those involved in spring ecosystem restoration carefully consider the roles of both natural and anthropogenic disturbance (Kodrick-Brown and Brown 2007).

THE IMPORTANCE AND CHARACTER OF GROUNDWATER DEPENDENT ECOSYSTEMS

Recognizing that informed policy development and proper management of GDEs can not go forward if the value and existence of these vital resources is undefined, it is crucial that planners and decision-makers understand their importance. Springs are emblematic of the rich diversity and importance of GEDs. Springs are often point-sources of biodiversity within landscapes, providing essential habitat for many endangered species, and supporting untold hundreds of rare or unique plant, macroinvertebrate, fish, amphibian, and some reptile and mammal species. For example, more than 200 species of hydrobioid spring-snails in the genera *Pyrgulopsis*, *Trionia*, and lithoglyphid snails in the genus *Fluminicola* occur in springs and spring-fed stream channels throughout North America, and at least 23 species of in the genera *Jardinella*, *Caldicochlea, Fonscochlea, Trochidrobia*, and *Austropyrgus* are endemic to the Great Artesian Basin of Australia (Hershler 1994; Hershler and Frest 1996; Liu et al. 2003; Perez et al. 2005; Hershler and Liu 2008, 2012; Murphey et al. 2012). Other aquatic gastropod families, such as Physidae also contain large numbers of springs-dependent species (Wethington and Lydeard 2007). Numerous springs-endemic fish also exist in arid portions of the United States and Australia, including the families of Cyprinidae, Cyprinodontidae, Goodeidae, Poeciliidae, Gobiidae, and other families (Kodrick-Brown and Brown 1993, 2007; Echelle, et al. 2005).

Individual springs may support high levels of unique species (e.g., Montezuma Well in central Arizona, USA) (Blinn 2008). Spring-dominated valleys, such as Cuatro Cienegas in northern Mexico and Ash Meadows in southern Nevada, USA, support dozens of unique plant, invertebrate, fish, and other vertebrate species (Hendrickson et al. 2008; Williams 1984). However, there is often little recognition of the extent of endemic species’ dependence on springs. For example, nearly all of the 12 endemic plant species in Ash Meadows, Nevada exist only in groundwater-fed alkaline meadows. In addition, springs sometimes provide important habitat for critical phases of life history, such as overwintering in warm water by Florida manatees, *Trichechus manatus latirostris* (O'Shea and Ludlow 1992), hibernacula of eastern bog turtles, *Glyptemys muhlenbergii* (Carter et al. 1999) in the northeastern U.S. or the in-snail phase of the trematode flatworm *Leucochloridium cyanocittae*, which occurs in Arizona only in *Oxyloma haydeni* ambersnails in springfed wetland vegetation at Vasey's Paradise in Grand Canyon National Park, Arizona, USA (Meretsky and Stevens 2000). The role of spring waters in imprinting among larval fish also may be substantial, but has not been studied to our knowledge.

Some springs are highly productive, and despite their small size, often contain tightly packed assemblages of plants and animals. In a recent study of springs in Kaibab National Forest in northern Arizona, USA, we detected 20% of the entire forest flora in <0.001% of the landscape, representing a remarkable concentration of plant species richness at springs (Ledbetter et al. in press). We found similar results in the Spring Mountains, Nevada, USA (U.S. Forest Service 2012c). Similar species packing has been noted among mosses, aquatic beetles, and avifauna (Grand Canyon Wildlands Council, Inc. 2002), and is a characteristic of subaqueous springs as well (McClain et al. 2003). Thus, everywhere, the high productivity and ecological stability of spring habitats likely contributes to tighter species packing.

Springs that exhibit high concentrations of endemic species are likely ancient systems, and may be trophically strongly structured (Kodric-Brown and Brown 1993; Blinn 2008). The evolution of endemism occurs regularly at springs, arising through relictualization and adaptation cycles related to environmental change: Onset of an altered environmental regime (e.g., desertification, marine or freshwater transgression, or other large-scale environmental changes) may reduce distribution and availability of habitat, enforcing isolation, allele fixation, and local adaptation. In contrast, habitat expansion permits widespread distribution of formerly isolated populations into new habitats. For example, Neogene lakes in the Great Basin of the American Southwest underwent extensive expansions and contractions under changing glaciation-related climates since the Miocene, contributing to the adaptive radiation and now highly localized endemism of spring-snails, pupfish, and aquatic Hemiptera (Hershler and Liu 2008; Echell et al. 2005, Polhemus and Polhemus 2002). Non-native species studies of weedy plants, Gastropoda, crayfish, amphibians, and fish (Stevens and Ayers 2002; Sada et al. 2006). reveal that spring ecosystems are particularly prone to invasion, a condition that has had evolutionary consequences for numerous lineages.

In addition to their role in regional biodiversity and evolution, springs often function as keystone ecosystems playing disproportionally large roles in adjacent upland ecosystems (Perla and Stevens 2008). Aridland and mesic land springs alike provide essential water, food, and habitat resources for large numbers of invertebrates, fish, amphibians, reptiles, birds, and some mammals. Landsnails, ground beetles, butterflies, and both migrant and nesting birds all are found in great concentrations at springs in the American Southwest. Springs and wetlands also may serve as refugia during drought for terrestrial animal species, and as regeneration hotspots following fire in forested regions (Grand Canyon Wildlands Council, Inc. 2002). Wetlands can clean and filter surface water, serve as sinks for greenhouse gases, and, particularly in estuarine systems, sequester carbon from the atmosphere (Whiting and Chanton 2001; Bridgham et al. 2006). In contrast, some springfed playas may serve as CO2 sources, as alkali soils may oxidize organic matter (Crews and Stevens 2009). Overall, GDEs in general and springs specifically encompass intricate and typically biodiverse ecosystems, and can be found in subaqueous and subaerial settings in marine, coastal, lotic, lentic, wetland, terrestrial, cave, and aquifer environments.

SCIENCE AND GDE ECOSYSTEM CLASSIFICATION

Prior to the 21st Century, the classification and ecology of groundwater dependent ecosystems was largely ignored. However, that information gap is rapidly being filled. In Australia, much attention has recently been devoted to the classification of near-surface GDEs, as summarized in Hatton and Evans (1998) and Eamus et al. (2006). These approaches emphasize the proximity, availability, flux, and quality of groundwater to the surface. The U.S. Forest Service also recently refined classification to improve forest springs inventory of GDEs (U.S. Forest Service 2012a). However, GDE classification is problematic, in part because the phrase encompasses ecosystems deep in the crust to nearly all surface aquatic and some ice-bound environments on Earth: shallow and deep aquifers, springs, streams, rivers, lakes, and oceans may all qualify as GDEs. Among this array of ecosystems, springs are one of the most obvious groups of GDE systems; however, classification of springs has been largely ignored by the public, the scientific community, and most government agencies. Neglect of springs is demonstrated by the near absence of reference to springs in most contemporary texts and textbooks on national or global freshwater ecosystem health, wetland ecosystems, and water resource management. Our review of existing literature suggests several reasons why springs have received so little attention, including issues of definition, scale, and basic understanding.

1) Meinzer (1927) provided guidance on springs hydrology but not ecosystem ecology, and until recently, the inadequacy of an ecosystem-based classification system has precluded discussion of springs types and thwarted mapping. Springer and Stevens (2008) described 12 types of terrestrial springs, of which several also appear to be common subaqueous forms. Spring types vary in abundance in different geologic provinces; however, the absence of a classification system has largely prevented discussion of variation among spring types across spatial scale. Fens in particular have posed conceptual problems for springs classification. Although all fens may qualify as wetlands, not all are groundwater-fed. Those that are groundwater-fed, but exist at low elevations are often called *ciénegas* or *vegas* , while elsewhere they may be called wet meadows, fens, or helocrenes. Classification of springs is important so that rare types can be identified and studied.
2) Springs are commonly overlooked in landscape resource mapping projects because they are usually small and fall within, rather than among, mapping pixels. While highly variable, the average area of individual springs in western North America is 1861 (n = 526; 1 sd = 18962) m^2, with few springs habitat patches larger than 1 ha (Ledbetter et al. 2012). Also, while the mean discharge of western North American springs was11.8 L/s, (n=510; sd=151), the discharge of 62% of springs is in the range of 0.01-1.0 L/s, with a median of 0.07 L/s. Thus, springs are small in area and discharge, and fall below the scale of most landscape mapping efforts and are neglected in remote sensing and floristic mapping.
3) Springs ecosystems have been overlooked by the science community, in part because of their ecological complexity. We note that the often high biological diversity in springs ecosystems is due, in part, to the co-occurrence of up to 13 different microhabitats within some complex springs types, such as Indian Gardens and large gushet springs, like Thunder River, both in Grand Canyon in Arizona. Groundwater-dependence, surface-linkage, microclimate complexity, intricate mosaics of co-occurring microhabitats and associated assemblages, and complex land use histories are characteristics that require detailed interdisciplinary studies. However, such studies are difficult to organize and fund, and with a few exceptions remain largely outstanding. Consequently, there is relatively little literature that integrates information on springs’ ecosystem ecology, and the

> best known text books on wetlands, ecosystem ecology, and the state of the world's ecosystems largely ignore springs. Further, the impacts of drought, water table decline, flow diminishment, and water quality change do not impact all phreatic or wildlife species in the same way, complicating resource management (Eamus and Froend 2006).

In spite of their ecological and economic importance, particularly in arid climates, mapping of springs is insufficient. Throughout North America and Europe, tens of thousands of farms, small communities, and many towns and some cities obtain their potable water from springs (Kresic and Stevanovic 2010); however, many of those springs have not been mapped. Only a few states within the U.S. have adequate maps of their springs, despite high densities of springs in montane regions (Stevens and Meretsky 2008). Arizona, Florida, Kentucky, Missouri, Nevada, New York, Utah, and Wisconsin are among the states with moderately good springs maps. Arizona, the second-driest state in the U.S. likely contains the highest concentration of springs, although the total number is still under investigation (Ledbetter et al. 2012). Several geographical information system (GIS) layers exist for Arizona, but none are complete, and each contains features not included in the others. For example, 141 springs are referenced in various databases available for Grand Canyon National Park (National Hydrography Dataset, Geonames, Arizona State Land Office, Arizona Department of Water Resources, U.S Geological Survey maps). However, this is no more than 23% of the known springs there, the others having been reported by independent researchers and in other publications. Unfortunately, such data gaps are the norm, rather than the exception, and springs remain poorly mapped worldwide.

Remote sensing has been promoted as a possible means of accelerating springs mapping. Some springs types are relatively easily detected using remote sensing methods (i.e., helocrene, limnocrene, and some low-gradient hillslope springs in non-forested terrain), while springs types associated with cliffs, caves, and other high-relief landforms (e.g., hanging gardens, gushets) and those emerging in heavily forested landscapes are difficult or impossible to detect using remote techniques. Recognizing these challenges, GDEs were located in the Western Cape of South Africa, using LandSat TM imagery and then mapping and modeling those sites with GIS approaches (Munch and Conrad 2007). Great Artesian Basin springs in Australia were mapped using remote sensing technology with good success (Lewis et al. 2013); however, similar efforts in other regions have met with mixed results. Detection accuracy for western U.S. springs ranged from 50.7% in areas with steep terrain and heavy forest cover (e.g., in the Spring Mountains of southern Nevada) to 83.8% in areas with low topographic relief and large fen wetlands (e.g., in Rocky Mountain meadows; Remote Sensing Applications Center 2012). In such landscapes, rigorous compilation of existing information and structured searching will likely be required to accurately map springs. Much basic mapping still needs to be conducted, both in terrestrial and subaqueous settings.

If surface GDEs are poorly recognized and understood by the scientific community, the public, and policy makers, the importance of subterranean groundwater ecosystems is far less well understood. Humpheys (2006) points out the great variety of life in aquifers, particular karst environments, including "diverse metazoan faunas comprising obligate groundwater inhabitants, largely crustaceans but also including insects, worms, gastropods, mites and fish". Sometimes these are endemic organisms of limited range, are vicariant from closely related biotic strains because of geological sequestration, and may be relictual in lineage, which allows examination of the history of deep aquifers (Humphreys 2006). In arid and/or coastal regions, saline waters can host obligate groundwater fauna (stygobites). Importantly, these ecosystems can be very vulnerable to changes in groundwater flow, quality, or habitat changes.

Clearly, the close relationship of groundwater flow/quality to both terrestrial and aquatic ecosystems is poorly understood by the public, much of the scientific community, and most government agencies. Several cultural factors contribute to this lack of awareness. Historically, the development of nations typically began near regions of available water, often near rivers or in more humid regions (where possible) that were less dependent on groundwater (although many rivers have gaining reaches that are effectively supplied by groundwater). Thus legal development, social awareness, policy actions, and resource management did not typically focus on groundwater in the early development of most nations. This cultural "surface water" focus of early population development is particularly evident in western Africa and South America, where many nations have the first major cities formed in wetter, coastal regions or along rivers, rather than the inland, more remote or drier regions. As populations increased in drier regions, groundwater usage, pollution, and overdraft became more common. Commensurate with arid-lands population growth, the legal, policy-making, and resource management protocols for groundwater and its dependent ecosystems had to evolve after-the-fact, from seats of power often far removed. Even though the population and climate change stresses on groundwater are more evident each year, laws, policies, funding for scientific research, and management strategies for preserving the quality and quantity of environmental flows lag behind and fail to accommodate human demands for drinking and irrigation water.

LAWS, POLICIES AND ENFORCEMENT – A GLOBAL PERSPECTIVE

Crafting and interpreting of water-related laws for the protection of GDEs takes many different forms throughout the world. The overriding legal structure and strictures of each country, and how existing laws are enforced and interpreted, sets the tone for policy decisions and gives a regional context for safeguarding springs, seeps, and wetlands. But many early laws and regulations addressed, at the most, a limited range of groundwater or ecosystem scenarios. The first international legal instrument to address transboundary groundwater was the Helsinki Rules of 1966, issued by the International Law Association. These Rules closely linked groundwater to surface water drainage systems and watersheds, but did not include all groundwater (Salman 2009). According to Lazarus (1997), because of the clear connection of groundwater and surface water, their bifurcation in common-law is, “clearly artificial and at odds with hydrological reality.” He points out that most modern jurisdictions, at the time of his writing, drew no distinction between surface and subterranean waters.

No matter what the legal format, interpretation of law is crucially important for the preservation of ecosystems. In his seminal 1972 book, “Should Trees Have Standing? – Law, Morality and the Environment ” Christopher Stone argues that affording legal rights or “standing” to natural objects in the world would support their protection (Stone 1972). “Standing” or *locus standi* is defined as “the ability of a party to bring a lawsuit in court based upon their stake in the outcome,” and, “ A party seeking to demonstrate standing must be able to show the court sufficient connection to and harm from the law or action challenged” (USLegal 2014). By affording environmental entities such as trees (or more broadly in our case Groundwater Dependent Ecosystems) “standing”, Stone means that citizens could bring court action on behalf of harmed or threatened natural objects, and he points out that the courts already typically allow guardianship provisions, which permit third-party representation of those with standing who are unable to represent themselves. Countries have not adopted this interpretive legal strategy; however, some seek, through their legal systems to preserve the natural world to varying degrees.

Several nations have devised laws that have direct philosophical links to protection of unique ecosystems, including those habitats sustained by groundwater, but there are many local and regional differences. In particular, Africa is a continent with a variety of water and ecosystem laws, a multiplicity of agency and political support and/or interference, and a range of abilities to enforce existing laws. For example, before the 1990s, South African water law consisted largely of piecemeal allocation of water rights to individuals and private entities, but with the end of Apartheid, fundamental approaches to resources were altered. The South African Water Act of 1998, in addition to establishing availability of clean drinking water as a basic human right, establishes water as an integral part of ecosystem protection. Among the goals of the Act are clear environmental priorities, in addition to general objectives of equitably meeting basic human needs and redressing the results of past racial and gender discrimination. The South African Water Act of 1998 specifies the goal of "promoting the efficient, sustainable and beneficial use of water in the public interest" and even more pertinent to this discussion, "protecting aquatic and associated ecosystems and their biological diversity". It is argued by some authors that this historic water law took some of its early guidance from preceding improvements in Australian water law, but now a few years after its enactment, the roles might be reversed and "Australia can now look to the new South African legal and constitutional framework for inspiration for reforms more geared towards sustainable environmental and social outcomes" (Godden, 2005). The Act allows any citizen to be an environmental advocate.

Other African States have refined their legal framework for water law as well with varying degrees of success for explicit or implicit protection of GDEs. In 1999 Kenya created a "National Policy on Water Resources Management and Development", which was followed by the Water Act of 2002. These initiatives set a tone for integrated water management (Mutinga, 2005), which did not exclude the protection of GDEs and allowed for discussion of the need in Kenya for biodiversity (Khamala 2005). Likewise in 1998, after extended dialogue with stakeholders, Zimbabwe established a new Water Act. Interestingly, both surface water and groundwater are treated as part of one hydrological system in the Act and there are provisions for environmental sustainability. Makurira and Magumo (2003) observed that in the first five years, Zimbabwe's water law had not reached its full potential for several reasons, including financial instabilities, the withdrawal of several donors who initially supported the program, other interfering national initiatives, inadequate agency and institutional linkages and low resources, lack of enforcement of the law, and political obstruction. Botswana's Water Law of 1968 defines underground water as public water, without property right (Lazarus 1997). In Ghana, a Water Resources Commission (WRC) was created by an Act of Parliament (Act 522 of 1996) in order to integrate water resources management and "regulate and manage the country's water resources and coordinate government policies in relation to them" (Odame-Ababio 2003). The Commission's recent groundwater strategy for Ghana has a strong emphasis on resource conservation sustainability and supply for the population, but has little direct emphasis on groundwater protection for ecosystem safety. The Canadian International Development Agency has been providing financial support for the Hydrologeological Assessment Project in the northern regions of Ghana in assistance of WRC efforts. While the Ghanaian WRC is rigorously evolving toward a decentralized stakeholder engagement model for groundwater management, the preservation of GDEs are currently not explicitly stated, nor are stakeholders explicitly assigned to consider GDE sustainability (Ghanaian WRC 2011).

Legal protection of springs and other GDEs takes different forms in other countries. In the United States, the Endangered Species Act of 1973 (ESA) is a major force that has been exercised many times to protect ecosystems and threatened species (Nelson 2008). In interpreting the law and responding to legal challenges, the U.S. Supreme Court ruled, in a landmark and precedent-setting case, that "the plain intent of Congress in enacting" the ESA "was to halt and reverse the trend toward species extinction, whatever the cost" (Tennessee Valley Authority vs. Hill 1978). The U.S. Fish and Wildlife Service (FWS) and the National Oceanic and Atmospheric Administration (NOAA) administer the ESA. Australia developed its own Endangered Species Protection Act in 1992, which was subsequently strengthened with replacement by the Environmental Protection and Biodiversity Conservation Act of 1999 (enacted in July of 2000). Australia also has instituted a National Strategy for Ecologically Sustainable Development, a National Water Quality Management Strategy, and the Water Act of 2007, which includes provision for groundwater and environmental flows. In many ways, the broader view of ecosystem protection, afforded in Australian law, can allow better overall management than the legal drivers in the U.S. that directs a more piecemeal, endangered-species by endangered-species, non-integrative approach.

Various, and sometimes different legal approaches and definitions have historically been applied to both surface waters and groundwaters that support

GDEs. Many nations place water in the public trust, at either provincial/state or federal levels. Provincial or state regulation of interstate aquifers may require complicated political negotiations that may fail to achieve sustainable management of those aquifers. However, there are numerous examples of nations with an integrated, holistic approach that treat both above and below ground waters as part of the same hydrologic cycle. For example, the Israeli Water Law of 1959 confers all water, both above and underground to the State; likewise, the Spanish Water Law of 1985 defines groundwater resources as public property (Lazarus 1997). Broad-reaching legal definitions of water are contained in the New Zealand Resource Management Act of 1991 that protects water in all forms, both above and below ground, as does the Alberta (Canada) Water Resources Act of 1979, amended in 1981. The British Colombia Water Act of 1979 (Canada) a "stream" is characterized as "a natural watercourse or source of water supply, groundwater, a lake, river, creek, spring, ravine, swamp and gulch" (Lazarus 1997).

The European Union actively recognizes that there is not enough information on GDEs, and has created policies and funding to advance a scientific groundwater research effort under the European Communities Framework Programmes for Research and Technological Development. Specifically the Framework 7 (FP7) directive includes a sub-program with an acronym of GENESIS, funded at 7 million Euro, which supports and encourages research on groundwater and GDEs in the European Research Area (ERA). The project timeline is April of 2009 to the end of March 2014, and includes participating institutions from 17 countries (CORDIS 2014). A particular appreciation of the EU effort, that groundwater dependent ecosystems need to be better understood in Europe, is advancing both scientific understanding and public awareness of these vulnerable spring and wetlands. Even in laws and legal constructs preceding these more recent actions, European nations recognized surface and groundwater as interconnected, with an example being the German Federal Water Amendment Act of1986 (Lazarus 1997).

There have been many international initiatives addressing water related ecosystems in the last half century. Three of the most influential are the Ramsar Convention of 1971, the already mentioned European Union's Water Frame Work Directive (WFD; EU Directive 2000/60/EC), and the Brisbane Declaration of 2007. The former was written and adopted by participating countries at a summit in Ramsar, Mazandaran, Iran and takes an expansive approach to protect and influence the future of wetlands. The broad definition of wetlands in Article 1.1 of the Convention is "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar 2014). This broad definition focuses on surface water, including even salt pans, fish ponds and rice paddies, but also recognizes the importance of groundwater. A Ramsar list of "Wetlands of International Importance" now numbers 2,171 sites, covering 207,291,271 hectares with many in the United Kingdom and Canada. According to the Ramsar website (Ramsar 2014) there are 168 contracting parties, as opposed to only 21 original signatory nations in 1971. The European Union's Water Frame Work Directive has perspectives that fundamentally redefine the approach to bodies of water, both above and below ground. The Directive promotes attainment of "good statPa Der Vang <pdvang@stkate.edu>

us" through an assessment aimed at a water body's ecology and chemistry. An important part of the determination of groundwater status is ascertaining the potential impairment of ground-water dependent terrestrial ecosystems (Krause 2007). A strength of the directive is its holistic and inclusive approach, its main weakness likely that it is organized around surface river basins which do not always conform to aquifer boundaries. The more recent Brisbane Declaration was released at the 10th International River Symposium and Environmental Flows Conference, held in Brisbane, Australia, in September 2007. Although the Declaration is a powerful and urgent call to the global community for the defense of imperiled freshwater and estuarine ecosystems, there is scant mention of groundwater dependent habitat. The Declaration does, however, emphasize "environmental flows", both in quantity and quality, as a factor crucial to the future of GDEs.

HYDROLOGIC PREDICTION, ECOLOGICAL EVALUATIONS, AND THE FUTURE OF GROUNDWATER DEPENDENT ECOSYSTEMS

The solutions to GDE protection lie in increased scientific scrutiny, shifts in the tectonic plates of public perception, and strengthened policy decisions. Recent scientific advances and better monitoring of GDEs, speed the process. Traditionally, a comprehensive assessment of the chemistry and physical properties of groundwater issuing to an ecosystem is a necessary first step. Along with traditional groundwater tracking, tracing and dating techniques, new methods are actively being proposed to establish flow source and potential vulnerabilities to host springs (Kreamer et al. 1996; Johannessonn et al. 1997; Ingraham et al. 2001; Heilweil et al. 2014). These techniques use water quality parameters to track and trace groundwater status, movement, sustainability, and age. The proper amount and chemistry for individual GDEs varies, and several researchers such as Eamus and colleagues (Eamus et al. 2006a; Eamus et al. 2006b) have proposed methodologies for determining the groundwater flow and quality needed to successfully supply an ecosystem.

The development of organized and methodical GDE assessment techniques have been a major managerial advance in the last decade. Recent refinements in springs classification and monitoring allow a more systematized approach to their evaluation with Springer and Stevens (2008) developing 12 different spring types based on their hydrogeological setting and spheres of discharge. Boulton and Hancock (2006) have looked at groundwater-dependent rivers, determining both the degree of dependency, and the influence of upwelling hyporheic waters on the physical and chemical riverine processes. They discuss the important management implications of understanding and predicting the baseflow contributions to river biota and its quantitative sustainability. Integrative groundwater ecosystem assessment is put forward by Stuebe et al. (2009) and the Springs Stewardship Institute (SSI 2014) pointing out the need of determining natural background, establishing bioindicators (perhaps microbial populations) for understanding ecosystem health, and attempting to gain correlation between abiotic and biotic variables.

One recent, exciting example of an organized GDE inventory protocol comes from the U.S. Forest Service. In an organized effort to promote the best available information and science, three intensity levels of GDE inventory and monitoring were established (USFS 2012a; USFS 2012b). The first level is geared toward referencing the location and extent of GDEs. The second involves the description of major attributes of GDEs such as flora and fauna, the hydrogeologic setting, factors which could perturb the site. The third level centers on gathering extremely quantitative spatial and temporal information to characterize physiochemical aspects of a GDE. The approach includes considering business required analysis and protocols (USFS 2010). These guides address many considerations including: 1. pre-field survey activities such as mapping, remote sensing, and gathering geographic information, 2. field survey activities such as use of a Management Indicator Tool, georeferencing, transect layout and describing the geology, soil, hydrology, vegetation aquatic and terrestrial fauna, and any natural and anthropogenic disturbance, and 3. post-field activities such as laboratory analyses, information verification and data interpretation. These protocols have been used and documented at many sites.

Another new management tool is the classification of ecosystem resilience and/or vulnerability. For example, originally, simple and subjective desktop methods for GDE assessment were available such as a 5- or 10-point scale ranking of uniqueness, vulnerability and priority (Nature Conservation Council 1999; Sinclair Knight Mertz 2001; Murray et al. 2003). Since that time, more comprehensive and complicated modeling approaches have been used. An evaluation of ecosystem resilience was made in regions transected by the Qinghai-Tibet railway in China using GIS, and using a neural network to analyze ecosystem risk (Chen et al. 2007). In their studies of wetland vulnerability in the U.K. and Ireland, Krause et al. (2007) put forward an ecohydrogeological framework for assessing groundwater dependent terrestrial ecosystems, including both their chemical and ecological status. This is accomplished by distinguishing wetlands based on controlling ecological, hydrological, chemical and hydrogeological characteristics, and then assessing the potential and risk of damage. The SSI (2014) springs ecosystem assessment protocol advances these concepts and approaches further, by using quantitative data and expert opinion to provide springs stewards with within- and among-site management priorities.

Perhaps more daunting is the challenge of changing community perceptions. GDEs can be negatively viewed as breeding grounds for mosquitoes and other pests, unutilized land that should be drained, swampy areas that attract detrimental and nuisance wildlife and create odors that degrade the value of surrounding land, and/or resources that should be piped to another place. Many communities do not recognize the connection between groundwater overdraft, and surface water diminishment, while others can not appreciate the link between groundwater and surface water quality.

The push to increase public appreciation and understanding of GDEs is moving forward, and many groups are joining in this effort. For example, the International Association of Hydrogeologists has established a “Groundwater and Ecosystems Network” to raise public awareness and promote the welfare of GDEs, hoping to positively influence local, national and international policy (IAH 2014). Protection of wetlands through the efforts of the Ramsar Convention are increasingly broad and effective, and the Springs Stewardship Institute (2014) is working to advance interaction and training among springs managers to improve understanding and management of these resources (Ramsar 2014; Spring Stewardship Institute 2014). Many wildlife societies are joining in the effort to protect groundwater, which issues into areas of unique biological diversity and habitat. The success of these and similar activities will be key in preservation of these priceless oases, scattered around the globe, that provide such rich and varied habitats for groundwater dependent species, human cultural resources, and essential ecosystem functions.

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