CHAPTER 4
A COMPREHENSIVE SPRINGS CLASSIFICATION SYSTEM:

INTEGRATING GEOMORPHIC, HYDROGEOCHEMICAL, AND ECOLOGICAL CRITERIA

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ABSTRACT

Integration of the hydrological, geological, and ecological characteristics of springs ecosystems provides a much needed means of classifying the types and distribution of these important landscape features. Efforts since the early 1900s have produced general classifications of the physical, chemical, and thermal properties of springs, but these classification systems have varied with the intent of classification needs and the quantity and quality of information collected about the springs. Although classification systems have focused on water up to, and at, the point of discharge, more recent needs have arisen to classify springs beyond the point of discharge for characterizing the geomorphology of the spring channel, the biogeographic context of the spring, associated biota, and cultural values, uses, and management. The lack of a comprehensive springs classification system has resulted in insufficient and inadequate inventories, ecological assessments, and conservation measures for these ecosystems. We present an improved classification system incorporating geomorphic, hydrological, geochemical, ecological, and management criteria of springs ecosystems. We propose that a central database be established to facilitate springs ecosystem inventory, classification, and conservation.

INTRODUCTION

Definition of Springs

Springs are places where groundwater is exposed at the earth's surface, often flowing naturally from bedrock or soil onto the land surface or into a body of surface water (Wilson and Moore 1998). Springs emerge in most of the ecosystems on Earth, including a wide array of subaerial terrestrial settings, and as subaqueous discharge from the floors of freshwater and marine bodies of water. Springs are important ecological and cultural resources, but scientific study and conservation have been hampered by the lack of a comprehensive classification system through which to quantify types of springs (Alfaro and Wallace 1994). Such a classification system would greatly improve understanding of the distribution of different types of springs, and would lay the groundwork for regional, national, and international conservation efforts. The failure to develop such a classification system has undoubtedly played a role in the global demise of these extraordinary ecosystems: recent texts fail to describe the fundamental geomorphic and ecological differences between springs and other kinds of riparian ecosystems (Malanson 1993, Stevens et al., in press), and recent reviews of the services provided by natural ecosystems largely fail to mention springs as important ecosystems (Postel and Carpenter 1997). These oversights are attributable not only to the absence of a synthetic classification system, but also to the limited understanding of springs ecology, poor communication between the sciences of hydrology and ecology, the limited attention paid to groundwater extraction – a form of resource exploitation that we cannot directly observe (Glennon 2002), as well as the ambiguous legal status of springs between groundwater and surface-water laws (Nelson, this volume). Clearly, the need for, and value of such a classification system is great.

Distribution of Springs in the Western United States

Of terrestrial springs named on U.S. Geological Survey topographic maps in the Western U.S., Kansas has the lowest density of springs, 0.0001 springs/km^2. The highest density of springs in the Western U.S. occurs in Oregon (0.018 springs/km^2) and Arizona (0.017 springs/km^2). More than 50 % of springs have not been currently recognized or mapped, particularly in topographically complex terrain, and thus are not located on USGS topographic maps. Also, numerous springs have dried up, or may have been mistakenly assumed to be perennial at the time of mapping. While the distribution and biota of marine geothermal vents have received much recent attention (e.g., Van Dover et al. 2002), there is less information available on that of non-thermal subaqueous springs emerging in marine or freshwater settings.

Springs Classification Systems

Geologists have traditionally classified the physical parameters of springs up to their point of discharge (e.g., Bryan 1919, Meinzer 1923), but little attention has been paid to springs after the point of discharge. Other geochemical, geomorphic, biological, and cultural classification systems have been developed for surface waters and riparian systems downstream from the point of discharge (e.g., Hynes 1970, Rosgen 1996); however, geomorphically based classification systems have largely ignored differences between spring-fed channels and surface-runoff dominated systems, and biologically oriented analyses have either focused on individual springs, or on individual taxa. An integrated springs classification system should include the major physical, biological, and socio-cultural variables. Such a classification system will permit assessment of the distribution of different kinds of springs within ecosystems, thereby improving resource inventory and development of conservation and restoration strategies (e.g., Sada et al. 2001, Stevens and Perla, this volume).

Alfaro and Wallace (1994) and Wallace and Alfaro (2001) updated and reviewed the historical spring classification schemes of Fuller (1904), Keilhack (1912), Bryan (1919), Meinzer (1923), Clarke (1924), Stiny (1933), and others. Of the previously proposed systems, Meinzer's (1923) classification system has been the most persistently recognized. He included 11 characteristics of springs based on various physical and chemical variables. Although Meinzer's (1923) scheme has been widely used, it is not comprehensive. Clarke (1924) considered three criteria to be most important for springs classification: geologic origin, physical properties, and geochemistry. However, none of the classifications proposed thus far include ecologically relevant variables, such as considerations of spatial and temporal degree of isolation, microhabitat distribution, biota, and surrounding ecosystem context. Thus, no comprehensive classification system has yet been developed or accepted (Wallace and Alfaro 2001).

In this paper we build on previous classification efforts and present an integrated springs classification system, with the understanding that testing and refinement of this classification system will require much future work (Table 4.1). We update nine of Meinzer's (1923) classes, integrate Alfaro and Wallace's (1994) recommendations, and then propose additional ecological elements. We propose an organizational structure that integrates springs data, and we reiterate Alfaro and Wallace's (1994) recommendation to develop a global database on springs using this comprehensive classification system. This classification system should permit better management and conservation of springs ecosystems, and the proposed structure should serve as the basis for development of the comprehensive springs database.

A PROPOSED SPRINGS CLASSIFICATION SYSTEM

Geomorphic Considerations

Hydrostratigraphic Unit: Meinzer's (1923) characterization of the aquifer lithology and geologic horizon can be reduced to the rock type(s) of the hydrostratigraphic unit (igneous, metamorphic, or sedimentary; Table 4.1). Sedimentary units can be consolidated rock, or unconsolidated sediments. Seaber (1988) defines a hydrostratigraphic unit as "a body of rock distinguished and characterized by its porosity and permeability." This classification requires that the nature and boundaries of the stratigraphic unit are mappable. As for some other spring classifications, such information may not be available without a detailed investigation of the aquifer. For instance, the spring may issue from a bedrock aquifer, but may travel through one or more other units (e.g., alluvium) before discharging to the surface. Such information may be even more difficult to obtain in deep marine and other subaqueous settings.

Emergence Environment: The environment in which the spring orifice exists varies widely, from the special case of in-cave springs whose flow subsequently may or may not reach the surface, to subaerial emergence in a wide array of geomorphic settings, springs that emerge below glaciers, subaqueous freshwater lentic and lotic settings, on the floor of estuaries, and springs in a wide variety of subaqueous marine settings.

Orifice Geomorphology: Springs orifices occur in several specific geomorphic environments (Meinzer 1923). Groundwater may be exposed or flow from filtration settings (poorly consolidated, permeable materials), or from bedrock fracture joints, or tubular solution passages. We modify the fracture spring list to include springs that exist as groundwater exposed at the surface, but which do not flow above land surface (e.g., Devils Hole in Ash Meadows, Nevada; Table 4.1). We also include stratigraphic contact environments in which springs, such as hanging gardens, emerge along geologic stratigraphic boundaries.

“Sphere of Discharge”: The "sphere" into which the aquifer is discharged as described by Meinzer (1923) was greatly simplified by Hynes (1970) into three different classes (Table 4.1). We re-expand these historical schemes to include 12 classes of springs, some of which are shown in Figures 4.1-4.4 (see also Fig. 6.1). The 12 springs classes include: 1) springs that emerge in caves, and 2) limnocrene surficial lentic pools (see Chapter 6, Fig. 6.1), 3) rheocrene lotic channel floors (Fig. 4.1), 4) mineralized mounds, 5) helocrene wet meadows, 6) hillslope springs (Fig. 4.4), 7) gushets (Fig. 4.3), 8) contact hanging gardens (Fig. 4.2), 9) geysers, 10) artesian fountains, 11) hypocrene buried springs. In addition, we recognize paleosprings, which flowed in prehistoric times, but no longer flow (e.g., Haynes this book; see the Springs Persistence section, below). Some of these springs types are illustrated in Figs. 4.1-4.6. Both Meinzer’s (1923) original and Hynes (1970) classification schemes become complicated if multiple spheres of discharge are present, or if the spring has a highly variable discharge rate and creates multiple spheres over time. Therefore, all major spheres of discharge should be noted during each site visit, and the importance of each should be described.

Channel Dynamics: In the special case of subaerial springs that create or flow into channels, such discharge may support distinct geomorphic characteristics within the channel. If a subaerial flowing spring feeds the stream headwaters and there is little to no runoff contributing to the stream flow, the stream is classified as a spring-dominated stream (Whiting and Stamm 1995). If the spring discharge is relatively constant and permanent, then the morphology of the channel will be distinctive. These types of channels often flow at bankfull stage or slightly above 20 percent of the time (Whiting and Stamm 1995). If the spring discharges to a channel that has significant components of runoff, it is classified as a runoff-dominated stream. Such systems may be classified with stream channel geomorphology terminology, such as Rosgen (1996). Some springs systems have components of both spring- and runoff-domination, such as the spring rills in Ash Meadows, Nevada.

Forces Bringing Water to the Surface

The classes for the forces that bring water to the surface may not be evident on a single visit, or without information on subsurface water from surrounding wells. Meinzer (1923) categorized springs on the basis of the pressure exposing or forcing water out (i.e., gravity, thermal) and other pressures (Table 4.1). Gravity-fed springs systems direct groundwater flow down gradient within the aquifer. Artesian springs discharge water under pressure, or may issue from an aquifer that has an upper confining layer, subjecting the flow to fluid pressures in excess of the pressure due to gravity at the point of discharge. Thermal springs emerge when groundwater comes in contact with magma or geothermally warmed crust, and is forced, sometimes explosively as in geysers, to the surface. Water is forced to the surface by explosive release of CO_2 in the geyser-like “Coke-bottle” springs of Utah. Fluid discharge in submarine springs associated with methane seepage is often forced by diurnal tidal and spring-neap variation in pressure of overlying water (Tryon et al. 2001). Some springs do not flow and therefore are not subject to pressurized discharge, while other springs may have multiple forcing mechanisms. Anthropogenic factors, such as groundwater loading around large reservoirs, may create forces that also affect springs emergence.

Flow

Persistence: Springs may function as refugia across ecological and evolutionary time scales. We follow Nekola (1999) in distinguishing between springs that have recently developed or been exposed to the atmosphere (Holocene neorefugia) versus those that have existed since the Pleistocene or longer (paleorefugia; e.g., Blinn, this book). Nekola (1999) predicted that paleorefugia were likely to exhibit high levels of endemism, unique species, and well-sorted assemblages. In contrast, neorefugia were predicted to support more weedy species, with low levels of unique taxa. His studies of land snails at springs affected or not by Pleistocene ice sheets supported these predictions, and Blinn’s (this volume) study of Montezuma Well in central Arizona provides additional support for the paleorefuge concept. In addition, we consider paleosprings that do not presently flow and may contain important paleoclimate, paleontological or archeological remains (e.g., Hynes, this volume).

Flow Consistency*:* Meinzer (1923) defined two classes of springs perenniality. Springs are considered to be perennial if they discharge continuously, or intermittent if their discharge is naturally interrupted or sporadic. We note that intermittent springs may flow regularly at hourly or daily (e.g., some geysers), seasonally, annually, or inter-annually, or only on an erratic basis. Human impacts, such as groundwater extraction or well drilling, may affect discharge consistency. As with flow variability (below), multiple observations of a spring are required to determine the permanence of discharge.

Rate: Meinzer (1923) developed eight discharge classes by the magnitude of discharge from a spring at the time of measurement; however, his numeric scheme is reversed from the intuitive scale (low discharge should have a low value). We propose reversing this numeric system in a scale that accommodates the full range of springs discharges known, from seeps with near zero flow (a score of 1) to springs with a flow of >10 m^3/s (a score of 8; e.g., Ra-El-Ain Spring in Syria, with a discharge of 36.3 m^3/s, Alfaro and Wallace 1994). Because the discharge of many springs varies temporally, the flow rate class will change depending on the time of measurement. Fluid flow rates are measured in different units by marine hydrogeologists. For marine cold seeps, fluid flow rates range from 10 l/m^2/d (Alaska margin at 5,000 m Suess et al. 1998) up to greater than 1,700 l/m^2/d on the Oregon margin (Linke et al. 1994) with intermediate values off Peru (440 l/m^2/d; Linke et al. 1994; 1,100 l/m^2/d; Olu 1996).

Variability: Springs discharge may be variable at different temporal scales. Short-term variability may be related to loading effects, such as the syphon effect in which filling of groundwater solution channels creates periodic surging of springs discharge. Short-term hydrologic alterations may include individual storms or droughts, while longer-term flow variation may result from interannual climate variation, or Pleistocene-Holocene climate and hydrologic changes. Variability in springs discharge may affect the distribution of associated microhabitats. For these reasons, the classification of discharge variability should be based on repeated discharge measurements, sometimes over long time periods.

Meinzer (1923) considered three levels of springs discharge variability: constant (steady), subvariable, and variable. This classification requires multiple measurements to characterize diurnal, seasonal, annual, inter-annual, and long-term variability. Netopil (1971) and Alfaro and Wallace (1994) used flow duration statistics to calculate a discharge variability ratio (CDR):

$$CDR = Q_{10\%}/Q_{90\%} \qquad \text{Eq. 1}$$

where $Q_{10\%}$ is the high flow exceeded 10% of the time and $Q_{90\%}$ is the low flow exceeded 90% of the time. Of course, calculation of these flow rates requires monitoring over at least a several year period. Steady discharge results in a

CDR of one (extraordinarily balanced), while wildly varying flows may produce CDR >10 (extraordinarily unbalanced; Table 4.1). Intermittent springs have an infinite CDR.

Water Quality

Classification of springs water quality is often specific to an individual study, but several comprehensive approaches have been suggested. Most traditional classifications are based on water temperature and/or the dominance (concentration) of ions.

Water Temperature: Five classes for water temperature in springs have been recognized based on a comparison of springs water temperature with the mean annual air temperature (Table 4.1, modified from Alfaro and Wallace 1994): cold, normal, warm, hot, and superthermal springs. Cold water springs are, by convention, >12.2^{o}C cooler than the mean annual ambient temperature. Spring waters within 12.2^{o}C of the mean ambient temperature may be (but are not necessarily) responding to ambient atmospheric temperatures. This is to be expected in springs that emerge from shallow aquifers and these may have temperatures that vary seasonally with air temperature. Springs with warm (>12.2^{o}C above the mean ambient air temperature, but <37.8^{o}C) and thermal water (>37.8^{o}C) are connected to either very large aquifers with long flow paths, or to geothermal sources of heat. Superheated geothermal springs are commonly reported in tectonically active areas, such as geyser fields or marine sea floor settings. The upper temperature limit presently known for life is 121-130^{o}C for a bacteria-like extremophile Archaea in Pacific Ocean vents (Anonymous 2003). Variability in springs water temperature may also be important, but can only be assessed from multiple visits or by using recording thermistors. Deep submarine springs are typically characterized as cold seeps or hot vents based on their relationship to ambient ocean water temperatures. Because the temperature of seawater in the deep sea is relatively invariant (Gage and Tyler 1991), even small changes above ambient in venting waters represent a significant warming effect with major biological consequences.

Geochemistry: Numerous schemes have been developed to classify water geochemistry, primarily through the surface-water pollution literature, but few studies attempt a comprehensive classification of springs water geochemistry. Clarke (1924) classified mineral springs waters based on the dominance of seven ion groups:

chloride, sulfate, carbonate, combinations of these three constituents, silica dioxide (SiO_2), borate (B_4O_7), nitrate, phosphate, and acidity. Furtak and Langguth (1986) classified Greek springs as belonging to: 1) normal earth alkaline (hydrogencarbonatic) waters; 2) normal earth alkaline, hydrogencarbonatic sulfatic waters; or enriched alkali earth alkaline (primarily hydrogencarbonatic) waters. Dinius (1987) used an expert-based decision process to develop an index of surface-water quality to compare levels of pollution in bodies of fresh water. The twelve variables derived from that analysis include specific conductance (micromhos/cm at 25^{o}C), pH, alkalinity (concentration of equivalent calcium carbonate), water color (platinum units), and the concentrations of chloride and nitrate (NO_3), which may be relevant to springs water-quality classification, as well as several variables that may not be relevant, including dissolved oxygen concentration, biological oxygen demand, and bacterial concentration. Smith (1990) and others consider turbidity to be important to surface waters, and we include it in our list. More recent classifications have emphasized more comprehensive geochemical analyses, rare-earth element analyses (Kreamer et al. 1996), and isotopic analyses, all of which may be informative in distinguishing among springs. Also, more recent studies have emphasized more elaborate statistical analyses (e.g. principal component analysis or cluster analysis; Kreamer et al. 1996) to integrate major and minor element relationships, and such approaches will be fruitful when a large database on springs geochemistry has been developed.

A comprehensive analysis of springs geochemistry awaits development of the springs database recommended below. Meanwhile, we base our selection of water-quality variables on these few springs studies and on relevant surface-water quality studies. We recommend that eight groups of geochemical variables be measured during springs inventories: major anions and cations (chloride, sulfate, carbonate, calcium, sodium, potassium), minor constituents (iron, borate, silica dioxide, carbonate/chloride, triple waters), pollution indicators (selenium, fecal colliform), useful tracers (stable isotopes, radioactive isotopes, rare-earth elements), alkalinity, total dissolved solids concentration and specific conductance, pH, and nutrient concentrations (nitrate and phosphate).

Fluids associated with hydrothermal vents and cold seeps contain variable concentrations of dissolved or gaseous methane, sulfides, and hydrogen that exert a large influence on chemosynthetic biological processes. These are typically measured in submarine springs to characterize the emerging fluids.

Habitats

Synoptic Climate: Synoptic climate strongly affects springs ecosystem development, processes and biodiversity. Climate variables that are often available or can be regionally modeled include air temperature (seasonality and mean monthly), precipitation (seasonality and mean monthly), and relative humidity. The seasonality index for temperature is the ratio of the mean temperature of the hottest month minus the mean temperature of the coldest month in °C. The precipitation seasonality index is the ratio of the average total precipitation for the three wettest consecutive months divided by average total precipitation for the three driest consecutive months (Bull 1991). While there is no climate relevant to submarine springs, seasonal variation may occur in the ambient water temperature at depths < 200 m, in current strengths, seafloor storms, or in inputs of photosynthesis based production falling to the seabed.

Surrounding Ecosystems*:* The kind(s) of ecosystems that surround springs are likely to influence habitat conditions, colonization, wildlife and human uses, and other springs ecosystem characteristics. In general, steep ecological gradients of environmental stability (disturbance intensity), geochemistry, moisture availability, productivity, and other factors most strongly affect springs biodiversity, endemism, and use (Malanson 1993, Huston 1994, Alexander et al. 1997).

In many springs, the dominant disturbance regime from the surrounding landscape may strongly affect springs microhabitats. Plenet et al. (1992) examined a spring on the Lône des Iles Nouvelles backwater of the Rhône River floodplain. Hypogean (hyporheic) and epigean benthic macroinvertebrates were sampled, and responded to flooding by entering the hypogean zone. Epigean density decreased during high flows, whereas hypogean organisms densities were much more consistent and did not respond strongly to surface flows. Similar levels of influence exist in forest springs, where the regional fire regime may alter springs habitat dynamics (e.g., Stevens et al., this volume). Disturbance regimes in submarine springs may include an increase or decrease in extrusion of new magma at hot vents, slumping, mass wasting or turbidity flows in sedimented margins, storm-driven re-suspension and deposition of sediments. The dominant disturbance regime(s) occurring in the surrounding ecosystem(s) should be noted.

Biogeographic Isolation: Island biogeographic theory provides a convenient framework for understanding species distribution at springs (MacArthur and Wilson 1963; Brown and Lomolino 1998). Colonization is rare and extinction is common in small springs or those that are far from other springs or wetlands source areas. Conversely, colonization is common and extinction is less likely in large springs or those that are near other springs or wetlands source areas. The configuration of springs, such as hanging gardens or travertine springs, along geologic contacts, may result in archipelagoes, a distribution that facilitates colonization and gene flow, and reduces extinction probability. From a biogeographic perspective, the extreme isolation of springs in North America's southern Great Plains indicates that these paleorefugia are likely to support relatively high levels of endemism, and may be excellent sites for biological research and conservation. Island biogeographic theory has yet to be rigorously tested on springs biota at an ecoregional or continental scale. Hydrothermal vent sites tend to occur like strings of pearls along mid-ocean ridges where seafloor spreading occurs. It is believed that planktonic larvae of vent species move between vent sites along the ridge axis, moving in plume-driven superhighways (Mullineaux 1995).

Habitat Size: The area of aquatic, wetland and riparian springs habitats is important to understanding biogeographic impacts on biotic assemblages. We propose that habitat area should be measured, and that an array of eight habitat sizes be determined for each of these three important habitats. The habitat size classes range from extremely small (<2 m^2) to extremely large (>100 ha).

Microhabitat Diversity: In addition to the aquatic, riparian, or terrestrial habitats springs may support, their associated spheres of discharge are capable of creating unique microhabitats for specific species. Microhabitats may be created by specific physical or chemical characteristics, such as temperature, depth of water, dissolved ion or oxygen composition, disturbance regime, or a suite of physical variables. Emphasis on microhabitats is warranted, as some springs microhabitats support high levels of endemic species (e.g., Erman 1992, Sada et al. 2001, Hershler and Sada 2002, Polhemus and Polhemus 2002).

Springs microhabitats that we consider to be important include: cave environments, wet walls, madicolous (fast-flowing water) habitats, hyporheic (saturated subfloor) habitats, open-water pools, spring streams (including those partially or more completely dominated by surface flow), wet meadows, riparian habitats, waterfall spray zones, and barren rock habitats adjacent to springs. Microhabitat diversity may be calculated using standard

Shannon (1948) diversity index (Magurran 2004), using proportion of area of each microhabitat:

$$H' = -\Sigma (p_i * \log_{10} p_i) \qquad \text{Eq. 2}$$

where p_i is the proportion of the total habitat area occurring in habitat *i*. Any logarithmic base may be used for this calculation, as long as the use is consistent, but for ease of interpretation we recommend the use of base 10.

Springs Biota

Species Composition: We recommend that all species of plants, invertebrates, vertebrates and other biota observed at the spring during each site visit be recorded, as such information will generally contribute to the inventory. Threatened, endangered and endemic species are most likely to be of immediate management concern, and should be carefully documented. Based on the results of Stevens (unpublished) research in Grand Canyon, a thorough baseline inventory of plants can be conducted in 2-3 site visits, whereas a 95% inventory of aquatic macroinvertebrates may require 5 or more site visits over two or more years, and detection of vertebrates is likely to require even greater survey intensity.

Vegetation: The observer should identify and measure the area of each distinctive patch of vegetation at the spring, and visually estimate the percent cover of each species in each of four strata: ground cover (annual, <1 m in height), shrub cover (perennial, 1-4 m in height), woodland/midcanopy (perennial 4-10 m in height), and tall canopy (>10 m in height). The site should be photographed and aerial photographs should be used if available. A standard Shannon-Weiner diversity index can be calculated using percent cover by stratum in each patch.

Faunal Diversity: Invertebrates have been widely used and tested as indicators of water quality. Excellent metrics have been developed for assessing the health of streams using aquatic invertebrate sampling, such as the Wisconsin Index; the Index of Biological Integrity (Karr 1991) and AusRivAS (Smith et al. 1999); however, no such criteria exist for springs. The wide variation in flow, water quality, microhabitat diversity, and biogeographic issues will render such a metric difficult to develop. Development of such a criteria for commonly occurring springs microhabitats (e.g., limnocrene pools) will depend on analysis of the large database recommended to be collected in this manuscript. Springs that represent extreme environments often support large mats of cyanobacteria, sulfide- or iron-oxidizing bacteria, or consortia of bacteria and archaea. Very often these define the nature of the venting fluids and form the visually dominant life form. We suggest that dominant microbial forms be documented. There is also a growing interest in characterizing microbial diversity through gene sequencing, particular in extreme environment springs were conditions may resemble those of the early Earth or other planets.

Other Habitat and Biological Criteria

Other habitat and biological criteria may eventually be shown useful in springs classification; however, insufficient research has been conducted on many of these topics to warrant their inclusion here. Contemporary springs soils have received limited attention in relation to springs biota and habitats; however, litter accumulation and soil development may occur on low gradient slopes, and may play important roles in some species distributions. Ecological processes, such as productivity and decomposition, are likely to be closely related to biodiversity, particularly in relation to the steepness of the slope gradient across the springs-to-uplands interface (Perla and Stevens, this volume). Also, we presently regard springs ecosystems as being dominated by physical processes and characterized primarily by “bottom-up” ecological processes; however, biological interactions may have as yet unrecognized importance in some types of springs and create important “top-down” trophic cascades. More research is warranted on these and many other springs ecosystem ecology topics. While this may be addressed only in later stages of research, the degree to which spring biota support life forms of the surrounding environments (by exporting production via vagrants) may be important. In the deep sea this is often measured with stable isotopic signatures (Carney 1994, McAvoy et al. 2002).

Springs Management and Use

The land management history, water rights, and other elements of authority may strongly affect geomorphology, flow, geochemistry, and the ecological condition of springs and surrounding ecosystems landscapes, making management and use critical elements of a comprehensive springs classification system (White 1979, Alfaro and Wallace 1994). The authority to manage springs may fall to private, public governmental, or tribal managers, and may be subject to common or legislative law. For example, groundwater use is often governed by common law or precedents established by legal decisions. Groundwater law typically varies from state to state in the U.S., with appropriative water law governing water rights in the western United States, and riparian rights governing water rights in the eastern U.S. and California. In the United States, threatened and endangered species may be protected under the Endangered Species Act, and traditional cultural uses of springs may be governed by federal laws, including the Native American Religious Freedom Act or the Antiquities Act. Federal actions on lands containing federally owned springs take place under the National Environmental Policy Act if contests among multiple stakeholders arise over resource use. Individual states have authority over stream channels and water quality within their borders, and the U.S. Army Corps of Engineers has authority over surface water quality of interstate waters. Jurisdiction over deep-sea springs outside the exclusive economic zone of countries is a more difficult issue. Some guildelines have been developed to establish these as fragile environments protected from damage by energy exploitation and scientists have begun to establish no-research conservation areas to protect certain sites from damage by underwater vehicles.

The wide array of human values of springs includes numerous utilitarian purposes, such as culinary water supplies, livestock watering, municipal or industrial use, recreation, wildlife, conservation, scientific research, or other purposes. Some springs may have had prehistoric or early historic use or modification that should be documented. The impacts of anthropogenic alterations vary by degree and may be classified as undisturbed, partially diverted/disturbed, or fully diverted/disturbed. Full diversion at the point of discharge may not provide any potential for support of dependent ecosystems. "Beneficial uses" may involve partial or complete extraction or abstraction before or after emergence. Springs are also commonly used or regarded in a religious or ceremonial fashion as traditional cultural properties, and such values commonly conflict with extractive utilitarian uses.

Springs Information Management and Database Development

Springs research and classification requires precise measurement of physical, biological, and cultural information, and compilation of those data. The spring should be appropriately georeferenced, photographed, and various physical characteristics should be measured during the spring visit. Elevation and the aspect of the spring should be measured, as these characteristics are likely to be of biological relevance in springs, particularly at higher latitudes. If possible, a solar pathfinder (Solar Pathfinder, Inc. 1994), or similar device should be used to determine the solar energy budget of the site, because aspect influences important physical properties of the study sites, such as temperature, the amount of light available for photosynthesis by wetland vegetation, the duration of freezing in winter, and evaporation and relative humidity in the summer months. The slope (dip angle) of the site similarly should be documented. Some of the proposed classes can be determined through visual observation of a spring during a single visit, but other variables (e.g., flow and geochemical variability) require multiple observations or information in addition to that gathered during a single site visit. Other variables, such as aquifer dynamics, may require additional research and synthesis of numerous studies. Rigorous quality control standards should be applied to the samples and data collected at springs, and these data should be placed in an integrated information management system.

Integrated information is needed from reconnaissance, classification, and ecosystem health assessment efforts at springs. Considerable time, resources and expertise are needed for detailed classifications of springs, and the impact of climate changes on groundwater dynamics that supply water to springs is but one of many active areas of research. The classification system proposed here should serve as a template for development of a comprehensive global database on springs. Analyses of integrated spatial and temporal data are likely to reveal hitherto unrecognized patterns in springs hydrogeology, distribution, ecology, and conservation, and are likely to result in clarification and modification of data collection protocols.

SUMMARY

Springs are greatly threatened by human impacts and rarely have these productive, biologically diverse ecosystems been managed for long-term, ecological sustainability. Development of the classification system and lexicon proposed here may help clarify the distribution, condition, and conservation of springs ecosystem. Existing classifications of springs have thus far been concerned with water to point of discharge. The physical classifications of Bryan (1919) and Meinzer (1923) require modification because of changes in geologic and hydrologic theory. Biological classification criteria of springs are proposed, with emphasis on the refugial and biogeographic status, ecoregional setting, and steepness of ecological gradients with respect to surrounding upland environments. Management authority and cultural uses of springs are recognized as important variables for status and conservation analyses, although additional understanding of traditional cultural knowledge, history and uses of springs is often needed. Development of a well-managed information management will require rigorous quality control protocols. We recommend the use of the above classification system to develop this global database. Analyses of a large, well managed springs database will provide fruitful future research into springs ecology, and is essential for the conservation and sustainability of these ecosystems.

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Table 4.1: Proposed springs classification criteria and checklist.

Spring Name		Latitude		**Elevation**
Sampling Date	Observers	Longitude		**Aspect**
Map No.	Photo ID No.	GPS Accuracy		**Slope (Dip Angle)**
Comments:				
Class Variable	Type / Criterion	Value / Descriptor	**Check**	**References**
Hydrostratigraphic unit	Parent rock of aquifer(s)	Sedimentary (bedrock or unconsolidated sediments)		Meinzer 1923
		Igneous		Meinzer 1923
		Metamorphic		Meinzer 1923
		Mixed (combination of above)		This study
Emergence environment – Jeri add drop box	Cave	Special case, not usually considered as a spring because it may not be directly exposed to the atmosphere		This study

	Subaerial, by geomorphic setting	Above-ground emergence - note geomorphic setting (e.g., floodplain, prairie, piedmont, canyon floor or wall, mountainside, etc.)		This study
	Subglacial	Above-ground emergence beneath a glacier		This study
	Subaqueous-lentic freshwater	Aquatic emergence into pond or lake - note substratum (organic ooze, silt, sand, rock)		This study
	Subaqueous-lotic freshwater	Aquatic emergence into a stream or river- note substratum (organic ooze, silt, sand, rock)		This study
	Subaqueous-estuarine	Aquatic emergence in an estuary- note substratum (organic ooze, silt, sand, rock)		This study
	Subaqueous-marine	Aquatic emergence in a marine setting - note substrate (e.g., silt, sand, coral,		This study
Orifice geomorphology - – Jeri add drop box	Seepage or filtration spring	Groundwater exposed or discharged from numerous small openings in permeable material		Meinzer 1923
	Fracture spring	Groundwater exposed or discharged from joints or fractures		Meinzer 1923
	Tubular spring	Groundwater discharged from, or exposed in openings of channels, such as solution passages or tunnels		Meinzer 1923

	Contact spring	Flow discharged along a stratigraphic contact (e.g., a hanging garden)		This study
Sphere of discharge – Jeri add drop box	Cave	Emergence in a cave		This study
	Limnocrene - emerges from lentic pool(s)	Emergence in pool(s)		Modified from Meinzer 1923, Hynes 1970
	Rheocrene - lotic channel floor	Flowing spring, emerges directly into one or more stream channels		Modified from Meinzer 1923, Hynes 1970
	(Carbonate) Mound-form	Emerges from a mineralized mound		This study
	Helocrene (marsh) or cienega (wet meadow)	Emerges from low gradient wetlands; often indistinct or multiple sources		Modified from Meinzer 1923, Hynes 1970, this study
	Hillslope spring	Emerges from a hillslope (30-60^{o} slope); often indistinct or multiple sources		This study
	Gushet	Discrete source flow gushes from a wall		This study
	Hanging garden	Dripping flow emerges usually horizontally along a geologic contact		This study
	Geyser	Explosive flow		This study
	Fountain	Artesian fountain form		This study
	Hypocrene	A buried spring where flow does not reach the surface		This study
Spring channel (if any)	Spring-dominated stream	Little external flow impact		Whiting and Stamm 1995

	Intermediate stream	Spring and runoff channel morphologies		This study
	Runoff-dominated stream	Dominated by external flow impacts		Whiting and Stamm 1995
Flow forcing mechanisms	Gravity driven springs	Depression, contact, fracture, or tubular springs		Meinzer 1923
	Increased pressure due to gravity-driven head pressure differential	Artesian springs		Meinzer 1923
	Geothermal springs	Springs associated with volcanism		Meinzer 1923
	Springs due to pressure produced by other forces	"Coke-bottle" springs and springs associated with gas release in deep seated fractures		Meinzer 1923, Shipton et al. in press
	Springs due to pressure produced by anthropogenic forces	Anthropogenic artesian or geyser systems (e.g., hot springs associated with Hoover Dam, Arizona-Nevada)		This study
Persistence	Neorefugium	Holocene (<12,000 yr old), zero endemic species		Nekola 1999
	Paleorefugium	Pleistocene or older ($\geq$12,000 yr old), 1 or more endemic species		Nekola 1999
	Paleospring	Pleistocene but not apparent recent flow, travertine or other paleo flow indicators		This study
Flow consistency	Perennial	Continuous flow		Meinzer 1923
	Intermittent-regular	Regular - flow occurs regularly on hourly or daily (e.g., some geysers), seasonally, annually, or interannually		Meinzer 1923; this study

	Intermittent-erratic	Flow occurs only on an erratic basis, can be noted with vegetative indicators		This study
	Intermittent-dry	No flow at all times of measurement		
Flow rate (mean)	Unmeasurable	No discernable flow to measure		This study
	First	<0.12 gpm (<10 ml/s)		Modified from Meinzer 1923
	Second	0.12 - 1.0 gpm (10 - 100 ml/s)		Modified from Meinzer 1923
	Third	1.0 – 10 gpm (0.10 - 1.0 L/s)		Modified from Meinzer 1923
	Fourth	10 – 100 gpm (1.0 - 10 L/s)		Modified from Meinzer 1923
	Fifth	100 - 448.8 gpm (10. - 100 L/s)		Modified from Meinzer 1923
	Sixth	448.8 - 4,488 gpm (0.10 - 1.0 m^3/s)		Modified from Meinzer 1923
	Seventh	4,488 - 44,880 gpm (1.0 - 10. m^3/s)		Modified from Meinzer 1923
	Eighth	>44,880 gpm (>10 m^3/s)		Modified from Meinzer 1923
Flow variability (CVR = Q10%/Q90%)	Steady (extraordinarily balanced)	1.0 - 2.5		Meinzer 1923, Netopil 1971, Alvaro and Wallace 1994
	Moderately (well) balanced	2.6 - 5.0		Meinzer 1923, Netopil 1971, Alvaro and Wallace 1994
	Balanced	5.1 - 7.5		Meinzer 1923, Netopil 1971, Alvaro and Wallace 1994
	Moderately unbalanced	7.6 - 10.0		Meinzer 1923, Netopil 1971,

				Alvaro and Wallace 1994
	Highly unsteady (extraordinarily unbalanced)	> 10.0		Meinzer 1923, Netopil 1971, Alvaro and Wallace 1994
	Ephemeral	Infinite		This study
Water temperature	Cold	Below mean annual ambient temperature		Alfaro and Wallace, 1994
	Normal	Within 12.2°C of the mean ambient temperature		Alfaro and Wallace, 1994
	Geothermal - warm	>12.2°C warmer than mean annual ambient temperature but <37.8°C		Alfaro and Wallace, 1994
	Hot	Significantly warmer than mean annual ambient temperature 37.8° C-100°C		Alfaro and Wallace, 1994
	Superheated (usually pressurized)	>100°C		This study
	Ambient temperature	Taken at time of spring water temperature measurement, temperature at time of measurement varies with daily mean temperature		This study
Dominant cation type	Magnesium type	Magnesium (Mg) is dominant cation		after Back 1966
	Calcium type	Calcium (Ca) is dominant cation		after Back 1966
	Sodium type	Sodium (Na) is dominant cation		after Back 1966

	No dominant type	No dominant cation		after Back 1966
Dominant anion type	Sulfate type	Sulfate (SO_4) is dominant anion		after Back 1966
	Bicarbonate type	Carbonate (CO_3) and bicarbonate (HCO_3) are dominant anions		after Back 1966
	Chloride type	Chloride (Cl) is dominant anion		after Back 1966
	No dominant type	No dominant anion		after Back 1966
Minor constituents	List of minor constituents	For example, borate, iron		Meinzer 1923, Clarke 1924
Pollution indicators	Polluted - mineral	For example, selenium, fecal coliform		This study
	Polluted - biological	For example, fecal colliform		This study
	Polluted - human	For example, debris		This study
	Polluted – multiple	Combination of three above		This study
Tracers	List of tracers	For example, stable isotopes, radioactive isotopes, rare-earth elements		Kreamer et al. 1996
Alkalinity	List value			Clarke 1924, Furtak and Langguty 1986
Total dissolved solids or specific conductance	Hyperfresh	0 to 100 mg/L TDS		This study
	Fresh	100 to 1,000 mg/L TDS		Fetter 1994
	Brackish	1,000 to 10,000 mg/L TDS		Fetter 1994

	Saline	10,000 to 100,000 mg/L TDS		Fetter 1994
	Brine	> 100,000 mg/L TDS		Fetter 1994
pH	Acidic	$pH < 5.0$		This study
	Moderately acidic	$5.0 < pH < 6.0$		This study
	Neutral	$6.0 < pH < 8.0$		This study
	Moderately basic	$8.0 < pH < 10.0$		This study
	Basic	$pH > 10.0$		This study
Nutrient concentrations	Low nitrate	NO_3-N < 0.3 mg/L		This study
	Moderate nitrate	0.3 < NO_3-N < 5 mg/L		This study
	High nitrate	NO_3-N > 5.0 mg/L		This study
	Low phosphate	PO_4 < 50 µg/L		This study
	Moderate phosphate	50 µg/L < PO_4 < 500 µg/L		This study
	High phosphate	PO_4 > 500 µg/L		This study
Mean annual air temperature	Pergelic	Mean annual temperature < 0^{o}C		Bull 1991
	Frigid	0^{o}C < mean annual temperature < 8^{o}C		Bull 1991
	Mesic	8^{o}C < mean annual temperature < 15^{o}C		Bull 1991
	Thermic	15^{o}C < mean annual temperature < 22^{o}C		Bull 1991

	Hyperthermic	Mean annual temperature > 22°C		Bull 1991
Air temperature seasonality	Nonseasonal	Seasonality index < 2		Bull 1991
	Weakly seasonal	2 < Seasonality index < 5		Bull 1991
	Moderately seasonal	5 < Seasonality index < 15		Bull 1991
	Strongly seasonal	Seasonality index > 15		Bull 1991
Mean annual precipitation	Extremely arid	Mean annual precip. < 50 mm		Bull 1991
	Arid	50 mm < mean annual precip < 250 mm		Bull 1991
	Semi-arid	250 mm < mean annual precip. < 500 mm		Bull 1991
	Semi-humid	500 mm < mean annual precip. < 1,000 mm		Bull 1991
	Humid	1,000 mm < mean annual precip. < 2,000 mm		Bull 1991
	Extremely humid	Mean annual precip. > 2,000 mm		Bull 1991
Precipitation seasonality	Nonseasonal	1 to 1.6, seasonality index		Bull 1991
	Weakly seasonal	1.6 to 2.5, seasonality index		Bull 1991
	Moderately seasonal	2.5 to 10, seasonality index		Bull 1991
	Strongly seasonal	Seasonality index > 10		Bull 1991
Growing season length	Short	Number of degree days > xx		This study
	Medium	Xx < number of degree days < xx		
	Long	Number of degree days > xx		

Surrounding ecosystem(s)	Terrestrial	Barrenlands		This study
		Grasslands		This study
		Herblands		This study
		Shrublands		This study
		Woodlands		This study
		Forest		This study
	Freshwater	Lentic		This study
		Lotic		This study
	Marine	Euphotic (shallow) - note substrata (e.g., silt, sand, coral)		This study
		Aphotic (deep)		This study
	Urban/suburban/rural	Note human development		
Biogeographic isolation	Nearest spring very near	<1-100 m between springs		This study
	Nearest spring nearby	100 m -1 km between springs		This study
	Moderately isolated	1-10 km between springs		This study
	Isolated	10-100 km between springs		This study
	Highly isolated	>100 km between springs		This study
Habitat size (habitat area of associated aquatic, wetland,	Extremely small	$<2\ m^2$		This study

riparian areas)				
	Very small	2-10 m^2		This study
	Small	10-100 m^2		This study
	Medium-small	100-1,000 m^2		This study
	Medium-large	0.1-1.0 ha		This study
	Large	1-10 ha		This study
	Very large	10-100 ha		This study
	Extremely large	>100 ha		This study
Microhabitat diversity: $H' = -\Sigma (p_i * \log p_i)$	Cave	Permanently dark zone		This study
		Twilight zone		This study
		Entrance		This study
	Wet wall	Wet , seeping, or dry wall(s)		This study
	Madicolous	Falling or fast flowing stream water		This study
	Hyporheic	Habitat beneath the floor of the stream		This study
	Open-water pool(s)	Mud, ooze, sand, gravel, boulder, or bedrock-floored pond		This study
	Spring stream(s)	Fine-grained (sand or silt) floor		This study
		Gravel floor (note embeddedness of gravels)		This study

		Cobble-boulder floor		This study
		Bedrock floor		This study
	Wet meadow	Cienega - low slope wetlands		This study
		High slope wetlands		This study
	Riparian	Note area by vegetation cover type		This study
	Spray zone	Areas watered by spray from waterfalls		Gressleson et al. 1987, this study
	Barren rock	Cliffs, slopes, or relatively flat		This study
	Microhabitat diversity	Shannon diversity index calculated using proportion of each microhabitat area		Shannon 1948
Biota	Plant species richness	Species observed with percent cover of each species in each major vegetation patch by stratum - ground, shrub, mid-canopy=woodland, and tall canopy; note any sensitive species		This study
	Vegetation diversity $H' = -\Sigma (p_i * \log p_i)$	Shannon diversity index, using percent cover for each stratum in each patch		Shannon 1948
	Invertebrate species richness	Number and species observed; note any sensitive species		This study
	Invertebrate diversity $H' = -\Sigma (p_i * \log p_i)$	Shannon diversity index, using quantitative measures of diversity for aquatic and terrestrial taxa separately		Shannon 1948

	Animal species richness	Number and species observed; note any sensitive species		This study
	Animal diversity $H' = -\Sigma (p_i * \log p_i)$	Shannon diversity index, using quantitative measures of diversity for aquatic and terrestrial taxa separately		Shannon 1948
Land use management	Land ownership	Federal, state, local, private		This study
	Legal authorities	Applicable laws, including water rights and environmental protection laws		This study
	Land use history	Land use history should be referenced or compiled		White 1979
	Prehistoric/early historic Use/modification	Document any use of spring by prehistoric or early historic cultures		This study
	Primary use	Culinary, livestock watering, recreation, religious, wildlife, conservation, research, other		This study
	Secondary use	Culinary, livestock watering, recreation, religious, wildlife, conservation, research, other		This study
	Other uses	Culinary, livestock watering, recreation, religious, wildlife, conservation, research, other		This study
	Groundwater modification	Extraction, augmentation, pollution		This study
	Emergent flow regulation	Dewatering, abstraction, diversion, pollution		This study

	Microhabitat modification	Piping, fencing, tanks, ponds, spring house, etc.		This study
	Surrounding ecosystem health	Condition of surrounding ecosystem		This study
Information management	Metadata criteria	Data management criteria and authorities (Federal, state, local, private)		This study
		Location and forms of original data		This study
		Data quality control protocols		This study

Fig. 4.1: Rheocrene springs in GCNP, AZ: a) Hermit Creek Spring, b) Monument Creek Spring.

Fig. 4.2: A hanging garden spring, Cliff Spring, NPS, Arizona.

Fig. 4.3: A gushet spring: Vaseys Paradise, NPS, Arizona.

Fig. 4.4: A hillslope spring: Lower Butte Fault Spring, Nankoweap Canyon, NPS, Arizona.