Spheres of discharge of springs

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Abstract Although springs have been recognized as important, rare, and globally threatened ecosystems, there is as yet no consistent and comprehensive classification system or common lexicon for springs. In this paper, 12 spheres of discharge of springs are defined, sketched, displayed with photographs, and described relative to their hydrogeology of occurrence, and the microhabitats and ecosystems they support. A few of the spheres of discharge have been previously recognized and used by hydrogeologists for over 80years, but others have only recently been defined geomorphologically. A comparison of these spheres of discharge to classification systems for wetlands, groundwater dependent ecosystems, karst hydrogeology, running waters, and other systems is provided. With a common lexicon for springs, hydrogeologists can provide more consistent guidance for springs ecosystem conservation, management, and restoration. As additional comprehensive inventories of the physical, biological, and cultural characteristics are conducted and analyzed, it will eventually be possible to associate spheres of discharge with discrete vegetation and aquatic invertebrate assemblages, and better understand the habitat requirements of rare or unique springs species. Given the elevated productivity and biodiversity of springs, and their highly threatened status, identification of geomorphic similarities among spring types is essential for conservation of these important ecosystems.

Keywords Springs classification · General hydrogeology · Ecology

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Introduction

Springs are ecosystems in which groundwater reaches the Earth's surface either at or near the land-atmosphere interface or the land-water interface. At their sources (orifices, points of emergence), the physical geomorphic template allows some springs to support numerous microhabitats and large arrays of aquatic, wetland, and terrestrial plant and animal species; yet, springs ecosystems are distinctly different from other aquatic, wetland, and riparian ecosystems (Stevens et al. 2005). For example, springs of Texas support at least 15 federally listed threatened or endangered species under the regulations of the US Endangered Species Act of 1973 (Brune 2002). Hydrogeologists have traditionally classified the physical parameters of springs up to their point of discharge (e.g., Bryan 1919, Meinzer 1923), but have paid little attention to springs after the point of discharge where they are more interesting to ecologists, conservation biologists, cultural anthropologists, and recreation sociologists. Classification systems that incidentally include springs have been developed for surface waters (Hynes 1970), wetlands (Euliss et al. 2004), groundwater dependent ecosystems (Eamus and Froend 2006), and riparian systems downstream from the point of discharge (Warner and Hendrix 1984; Rosgen 1996). 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 ecosystems, thereby improving resource inventory and development of conservation and restoration strategies (e.g., Sada and Vinyard 2002; Perla and Stevens 2008).

Alfaro and Wallace (1994) and Wallace and Alfaro (2001) updated and reviewed the historical springs 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. Other classifications have been developed for specific types of geomorphology such as karst geomorphology

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(free draining, dammed, or confined springs; Ford and Williams 2007) or classification of karst springs by eight attributes—flow duration, reversing flow, conduit type at spring, geology, topographic position, relationship to bodies of surface water, distributaries, recharge, chemistry, culture/exploitation—(Gunn 2004). Springs, particularly those in arid regions, are renowned as hotspots of biological and cultural diversity, and the presence of endangered or unique species and ethnological and historic resources often greatly influences their management. Therefore, ecological and cultural variables also relevant to springs classification include: size, spatial isolation; microhabitat distribution; paleontological resources; the presence of rare or endemic biota; archeological or traditional cultural resources; and a springs' context to surrounding ecosystems. To date, no comprehensive springs classification system has been developed or accepted (Wallace and Alfaro 2001). Many publications related to springs focus on specific regions that have a limited number of types of springs (e.g., Brune 2002; Scott et al. 2004; Vineyard and Feder 1982; Borneuf 1983). For example, because limnocrene springs of Florida are influenced by karst processes, their classification has focused primarily on the type of spring (vent or seep), whether or not it is onshore or offshore, and the magnitude of the discharge (Scott et al. 2004).

In Springer et al. (2008), previous classification efforts were discussed and an integrated springs classification system was presented, with the understanding that testing and refinement of this classification system requires much further work. Springer et al.'s (2008) organizational structure integrates springs inventory data and reiterates nine of Meinzer's (1923) classes, Alfaro and Wallace's (1994) recommendations, and proposed additional ecological and cultural elements. An organizational structure that integrates springs data and reiterated Alfaro and Wallace's (1994) recommendation to develop a global database on springs using this comprehensive classification system is discussed. The criteria used for classification by Springer et al. (2008) include geomorphic considerations (hydrostratigraphic unit, emergence environment, orifice geomorphology, sphere of discharge, channel dynamics), forces bringing water to the surface, flow properties (persistence, consistency, rate, variability), water quality (temperature and geochemistry), habitats (synoptic climate, surrounding ecosystems, biogeographic isolation, habitat size, microhabitat diversity), springs biota (species composition, vegetation, faunal diversity), and springs management and use. Seeps are considered to be low magnitude discharge springs in this classification system.

In this paper, the 12 spheres of discharge of springs of Springer et al. (2008) are described in more detail than was included in their manuscript (Table 1). A text description, a sketch and a photograph of each sphere is included, as is a discussion of how each sphere corresponds to equivalent language used by aquatic ecologists, wetland and riparian scientists, or other specialists to describe springs. For spheres of discharge where it is known, a description of how the spheres of discharge of

Table 1 Sphere of discharge and types of springs (modified from Springer et al. 2008) with examples of known springs and references of descriptions of sphere of discharge

Spring type	Emergence setting and hydrogeology	Example	Reference
Cave	Emergence in a cave in mature to extreme karst with sufficiently large conduits	Kartchner Caverns, AZ	Springer et al. (2008)
Exposure springs	Cave, rock shelter fractures, or sinkholes where unconfined aquifer is exposed near the land surface	Devils Hole, Ash Meadows, NV	Springer et al. (2008)
Fountain	Artesian fountain with pressurized CO_2 in a confined aquifer	Crystal Geyser, UT	Springer et al. (2008)
Geyser	Explosive flow of hot water from confined aquifer	Riverside Geyser, WY	Springer et al. (2008)
Gushet	Discrete source flow gushes from a cliff wall of a perched, unconfined aquifer	Thunder River, Grand Canyon, AZ	Springer et al. (2008)
Hanging garden	Dripping flow emerges usually horizontally along a geologic contact along a cliff wall of a perched, unconfined aquifer	Poison Ivy Spring, Arches NP, UT	Woodbury (1933); Welsh (1989); Spence (2008)
Helocrene	Emerges from low gradient wetlands; often indistinct or multiple sources seeping from shallow, unconfined aquifers	Soap Holes, Elk Island NP, AB, Canada	Modified from Meinzer (1923); Hynes (1970); Grand Canyon Wildlands Council (2002)
Hillslope	Emerges from confined or unconfined aquifers on a hillslope (30–60^o slope); often indistinct or multiple sources	Ram Creek Hot Spring, BC, Canada	Springer et al. (2008)
Hypocrene	A buried spring where flow does not reach the surface, typically due to very low discharge and high evaporation or transpiration	Mile 70L Spring, Grand Canyon, AZ	Springer et al. (2008)
Limnocrene	Emergence of confined or unconfined aquifers in pool(s)	Grassi Lakes, AB, Canada	Modified from Meinzer (1923); Hynes (1970)
(Carbonate) mound-form	Emerges from a mineralized mound, frequently at magmatic or fault systems	Montezuma Well, AZ Dalhousie Springs, Australia	Springer et al. (2008); Zeidler and Ponder (1989)
Rheocrene	Flowing spring, emerges into one or more stream channels	Pheasant Branch, WI, US	Modified from Meinzer (1923); Hynes (1970)

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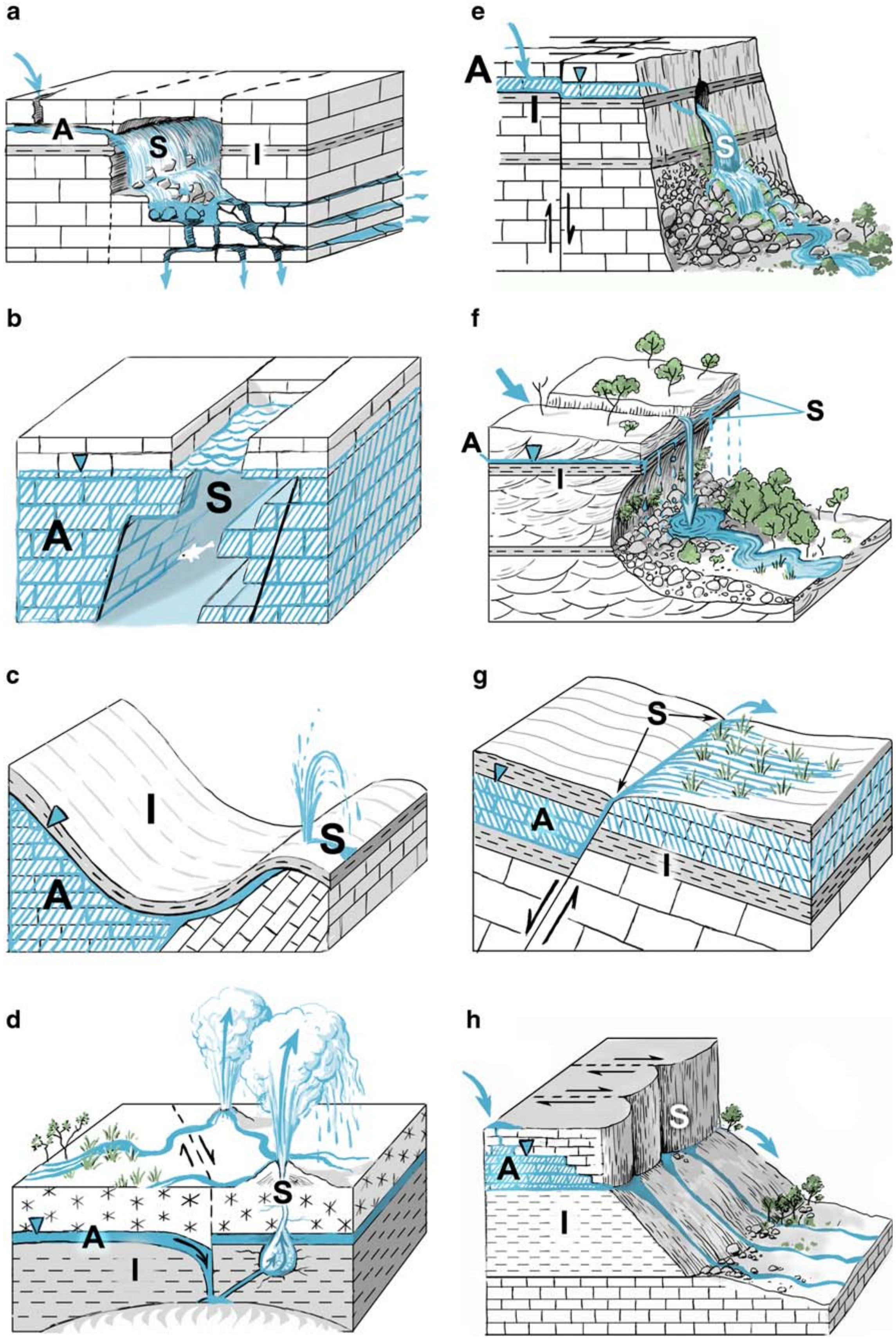

Fig. 1 Sketches of springs spheres of discharge: **a** cave, **b** exposure, **c** fountain, **d** geyser, **e** gushet, **f** hanging garden, **g** helocrene, **h** hillslope, **i** hypocrene, **j** limnocrene, **k** mound form, **l** rheocrene. *A* aquifer, *I* impermeable stratum, *S* spring source. The *inverted triangle* represents the water table or piezometric surface. Fault lines are also shown, where appropriate

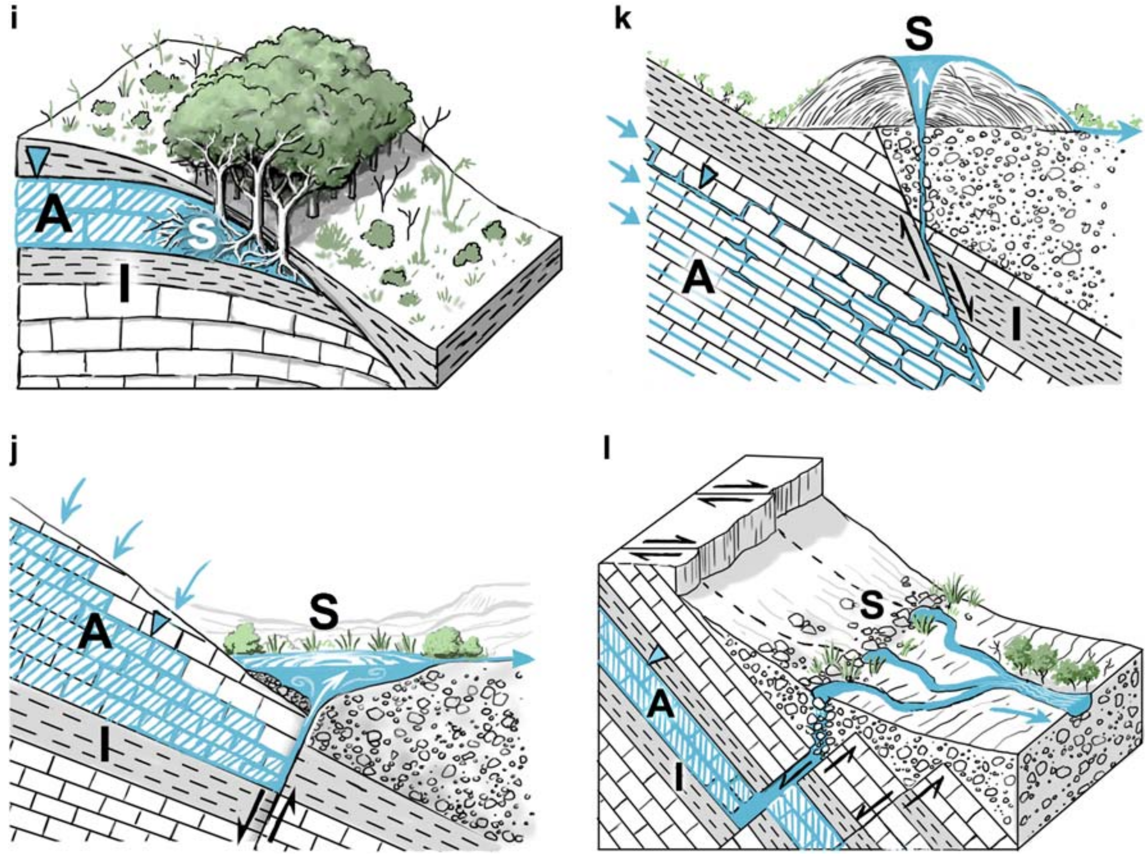

Fig. 1 (continued)

springs create diverse microhabitats which lead to rich and diverse ecosystems is made. Each sphere of discharge has been linked to a conceptual model for springs created by Stevens and Springer (2004) and the array of microhabitats. The success of a future integrated, comprehensive classification system for springs will depend on an inclusive and descriptive set of spheres of discharge coupled with an association of aquatic invertebrates and/or vegetation. However, an insufficient number of comprehensive physical, biological and cultural inventories of springs ecosystems have as yet been conducted to statistically determine these associations.

Background

Conceptual models and classifications systems help organize and categorize complicated natural systems. Various classification systems have been created for various types of hydrological systems. Euliss et al. (2004) created a conceptual framework called the wetland continuum to include factors describing the influence of climate and hydrologic setting on biological communities in wetlands. Although their system is applicable to springs that occur in wetlands, it is not applicable to the many types of springs that do not occur in wetlands. Also, springs only have groundwater discharge, so the wetland continuum concept of Euliss et al. (2004) of recharge is not applicable to springs. Springs occurrence in some geomorphic settings is far more complicated than wetlands (e.g., cliff walls), creating a wide array of microhabitats not observed in wetlands.

Another prominent classification system that includes springs is for groundwater dependent ecosystems (GDE). Three primary classes of GDEs have been proposed (Eamus and Froend 2006). GDE classification tends to focus more on vegetation components of the ecosystem because of the paucity of invertebrate data. The three classes described are: (1) aquifer and cave ecosystems, (2) all ecosystems dependent on the surface expression of flow, and (3) all ecosystems dependent on the subsurface presence of groundwater (Eamus and Froend 2006). As

Fig. 2 Photographs of springs spheres of discharge: **a** cave spring, Kartchner Caverns, Arizona, US, **b** exposure spring, Devil's Hole, Ash Meadows National Wildlife Refuge, Nevada, US, **c** fountain spring, Crystal Geyser, Utah, US—photo by Joel Barnes, **d** geyser, Riverside Geyser, Yellowstone National Park, Wyoming, US, **e** gushet, Thunder River Spring, Grand Canyon National Park, Arizona, US, **f** hanging garden, Poison Ivy Spring, Arches National Park, Utah, US, **g** helocrene, soap hole, Elk Island National Park, Alberta, Canada, **h** hillslope spring, Ram Creek Hot Spring, British Columbia, Canada, **i** hypocrene, 70R mile spring, Grand Canyon National Park, Arizona, US, **j** limnocrene, Grassi Lakes, Alberta, Canada, **k** mound form spring, Montezuma Well, Arizona, US, **l** rheocrene, Pheasant Branch Spring, Wisconsin, US ▶

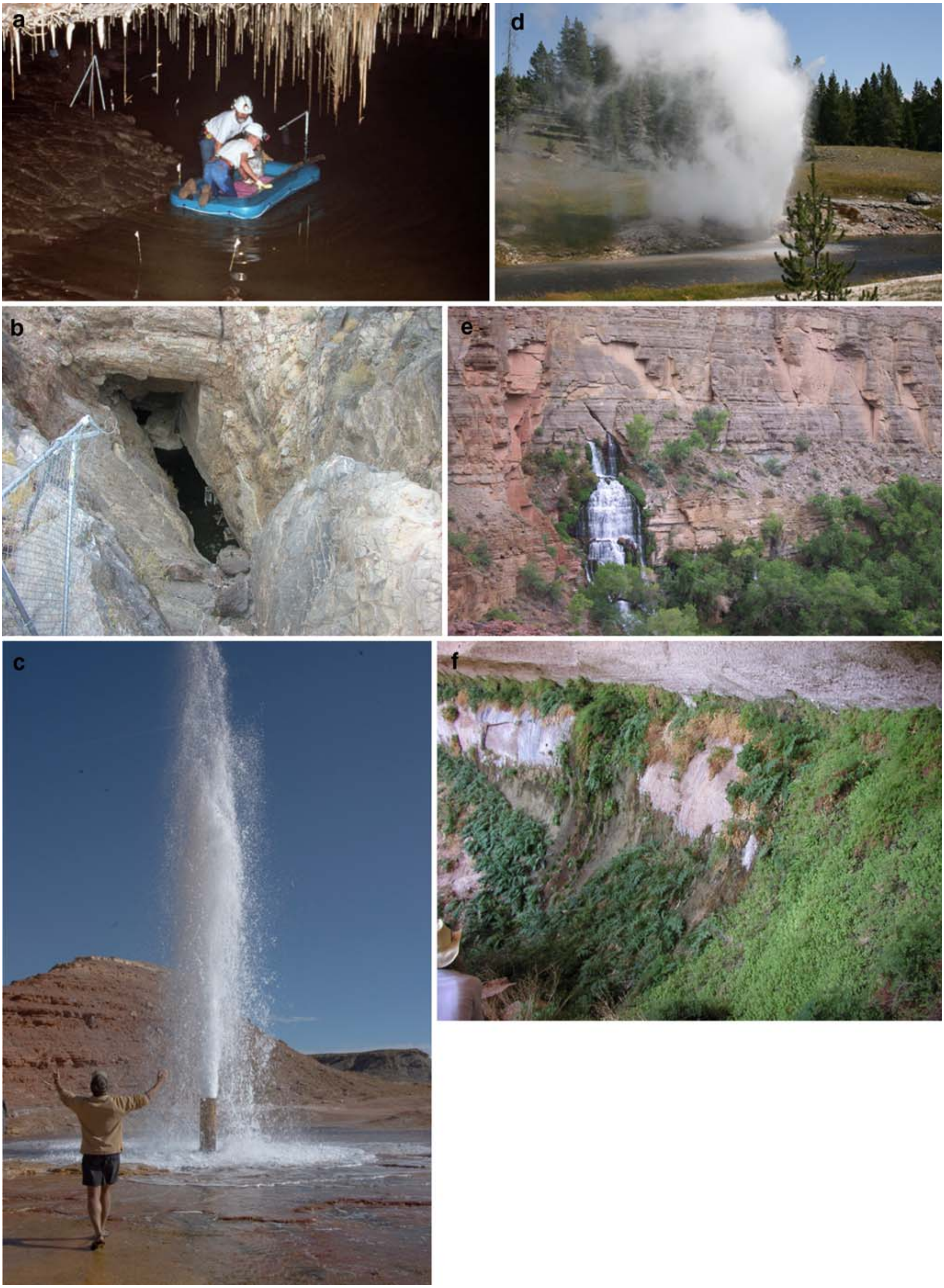
a
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Fig. 2 (continued)

will be demonstrated in this paper and by Meinzer (1923) and Hynes (1970) the spheres of discharge of springs and the associated ecosystems with them are more complex than these three classes. Several notable books about springs ecology that have been published (e.g., Botosaneanu 1998 and Stevens and Meretsky 2008) and Odum's (1957) work on Silver Springs in Florida (which laid the groundwork for much of modern ecosystem ecology) also indicate that springs and their associated ecosystems are more complex than the three GDE classes of Eamus and Froend (2006).

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 (rheocrene, limnocrene, helocrene). Springer et al. (2008) expanded these historical schemes to include 12 spheres of discharge of springs, including: (1) springs that emerge in caves, (2) exposure springs, (3) artesian fountains, (4) geysers, (5) gushets, (6) contact hanging gardens, (7) helocrene wet meadows, (8) hillslope springs, (9) hypocrene buried springs, (10) limnocrene surficial lentic pools, (11) mound forms, and (12) rheocrene lotic channel floors (Figs. 1 and 2; Table 1). In addition, paleosprings are recognized, which flowed in prehistoric times, but no longer flow (Haynes 2008). 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. For example, a mound spring may discharge into a limnocrene pool. In the system of Springer et al. (2008), each sphere of discharge should be described for a spring.

Cave

Cave springs are those that emerge entirely within a cave environment and are not directly connected to surface flow (Figs. 1a and 2a). They are most common in karst terrain. Although there are almost an infinite number of different types of karst features (Ford and Williams 2007), engineering geologists have recommended a classification system for karst that includes descriptions of karst classes (juvenile, youthful, mature, complex, and extreme), sinkhole density, cave size, and rockhead (bedrock) relief (Waltham and Fookes 2003). Cave type springs are most likely to occur in the "mature" to "extreme" karst ground conditions of Waltham and Fookes (2003) where the conduits are sufficiently large enough to allow for emergence and in "free draining or dammed" type karst springs (Ford and Williams 2007). The ecosystems of these types of springs have species and habitats characteristic of biologically active caves, such as those described by Elliott (2007).

Exposure

Exposure springs are those in which groundwater is exposed at the surface but does not flow, a form of springs sphere of discharge proposed as new by Springer et al. (2008; Figs. 1b and 2b). These types of springs typically occur in the "dissolution" type of sinkholes (Waltham and Fookes 2003), but could form in other types of vertical conduits into an aquifer. A prominent example is Devil's Hole in Ash Meadows National Wildlife Refuge in Nevada. Because of the unique microhabitats of Devil's Hole, that system supports endemic Ash Meadows riffle beetle (Elmidae: *Stenelmis calida*) and Devils Hole pupfish (Cyprinodontidae: *Cyprinodon diabolis*; Deacon and Williams 1991; Schmude 1999). The plight of the latter species has led to special legal and management protection of the associated aquifer.

Fountain

Fountain springs are cool-water artesian springs that are forced above the land surface by stratigraphic head-driven pressure or CO_2 (e.g., Crystal Geyser; Glennon and Pfaff 2005; Figs. 1c and 2c). Discharge at fountain springs, thus, is not driven by thermal processes, such as geysers, but still require a confined aquifer with water pressurized by CO_2, not heat. Other examples of fountains are cold water, submarine seeps of hydrocarbons, carbonates or brine, which may support dense macrofaunal communities such as those in the Gulf of Mexico slope, Sunda Arc, and 30 other known locations on active and passive continental margins through the world's oceans (Cordes et al. 2007).

Geyser

Geysers are globally rare, geothermal springs that emerge explosively and usually erratically (Figs. 1d and 2d). "A geyser is a hot spring characterized by intermittent discharge of water ejected turbulently and accomplished by a vapor phase." (Bryan 1995) There are over 1,000 geysers worldwide, with nearly half of them existing in Yellowstone National Park, WY, USA. (Bryan 1995). Yellowstone has 600 geysers of which 300 erupt frequently. The only other place in the world with more than 40 geysers is the Kamchatka Peninsula of Russia with approximately 200 geysers (Bryan 1995). There are over 10,000 non-geyser hot springs of various types in Yellowstone, many being other spheres of discharge such as limnocrene and helocrene springs. These thermal waters support unique communities of bacteria (Brock 1994).

Gushet

Gushet springs pour from cliff faces and were proposed as a new, unique sphere of discharge by Springer et al. (2008; Figs. 1e and 2e). They typically emerge from perched, unconfined aquifers, often with dissolution enhancement along fractures. Gushets typically support madicolous habitat, which consists of thin sheets of water flowing over rock faces (Hynes 1970; Table 2). All 13 microhabitat types may be present at gushet springs, leading to very diverse ecosystems. Although they occur prominently in areas with steeply dissected topography (e.g., Vasey's Paradise in Grand Canyon, AZ, USA), they can also occur in regions with more modest topography, such as Wisconsin, US, as long as there is sufficient topographic relief to allow for free-falling flow.

Hanging garden

Hanging gardens are complex, multi-habitat springs that emerge along geologic contacts and seep, drip, or pour onto underlying walls (Figs. 1f and 2f). In the southwestern U.S., they typically emerge from perched, unconfined aquifers in aeolian sandstone units. The hydrogeologic processes that lead to these unique ecosystems also control the geomorphologic processes which shape the rock wall or associated canyons. Generally, three types of hanging gardens are recognized (alcoves, window-blinds, and terraces; Welsh and Toft 1981). In the US, hanging gardens support distinctive assemblages of wetland, riparian and desert plants, including some species (e.g., *Primula* spp.) that occur in indirect light on wet backwalls (Welsh and Toft 1981; Wong 1999; Spence 2008).

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Table 2 Estimated likelihood of occurrence of 13 spring microhabitats at 12 terrestrial spring types reported on the Colorado Plateau (data from Springer et al. 2008 and L. Stevens, unpublished observations)

Spring Type	Springs microhabitats													
	Cave interior	Orifice	Hyporheic	Wet wall	Madicolous	Spray zone	Open-water pool	Spring stream	Low-slope wetlands	Hillslope wet meadow	Riparian	Adjacent dry rock	Adjacent uplands linkage	Average microhabitat diversity of a springs type
Cave	5	1	2	5	3	1	5	5				5	5	3.7
Exposure	5	5		1			5		1	1	1	4	3	2.2
Fountain	1	5	2	3	3	3	3	5	3	3	4	5	5	3.5
Geyser	1	5	2	3	3	3	3	4	3	1	3	5	3	3.0
Gushet	4	5	3	3	3	3	4	5	4	3	5	5	5	4.0
Hanging garden	1	3	2	5	3	4	5	5	2	4	5	5	5	3.8
Helocrene	1	2	3	2	2	1	3	3	5	3	5	2	5	2.8
Hillslope	1	2	3	2	2	1	3	3	4	5	5	3	5	3.0
Hypocrene	1		1						3	4	4	5	5	3.3
Limnocrene	1	5		1	1	1	5	5	3	1	5	3	5	3.0
Mound-form	1	5	2	3	3	1	4	5	3	1	3	5	3	3.0
Rheocrene	3	5		3	3	3	4	5	4	1	5	5	5	3.8
Mean microhabitat frequency across springs types	2.1	3.9	2.2	2.8	2.6	2.1	4.0	4.5	3.2	2.5	4.1	4.3	4.5	—

Occurrence likelihood: *missing* microhabit does not occur at that springs type, *1* very low likelihood of occurrence, *2* low likelihood, *3* moderate likelihood, *4* fair likelihood, *5* high likelihood of occurrence at that springs type. Average diversity values were calculated for within and among springs types

Helocrene

Helocrene springs usually emerge in a diffuse fashion in cienega (marshy, wet meadow) settings (Figs. 1g and 2g). Hynes (1970) distinguished these types of springs as different from the limnocrene type springs described by Bornhauser (1913). What are described as soap holes or mud springs in Alberta also are examples of helocrenes. A soap hole or mud spring is “a part of the land surface characterized by a local weakness of limited extent underlain by a mixture of sand, silt, clay, and water” (Toth 1966). The formation of these springs is similar to that of quicksand. In the semi-arid regions of Alberta, Canada where these occur, groundwater discharge is typically saline, leading to the occurrence of halophytes. Other helocrenes may have fresh water, but low oxygen concentrations, and support species characteristic of wetlands, or they may have thermal waters and primarily support bacteria. Other helocrene springs may have hypersaline water and support marine relict taxa that may occur far inland on continents at great distances from the ocean (Grasby and Londry 2007). The wetland continuum of Euliss et al. (2004) provides further classification of helocrenes.

Hillslope

Hillslope springs emerge from confined or unconfined aquifers on non-vertical hillslopes at 30–60° slopes, and usually have indistinct or multiple sources (Figs. 1h and 2h). Hillslope springs were proposed as a unique sphere of discharge by Springer et al. (2008) because of the diverse array of microhabitats they support (12 of 13 common microhabitat types; Table 2). The diversity of hillslope springs is generally negatively related to the slope gradient, and is strongly influenced by aspect, although those relationships have yet to be rigorously quantified.

Hypocrene

Hypocrene springs are springs in which groundwater levels come near, but do not reach the surface (Figs. 1i and 2i). Discharge from the springs is low enough that evaporation or transpiration consumes all discharge and there is no surface expression of water. In the wetland continuum of Euliss et al. (2004), hypocrene springs would represent a site with the lowest amount of discharge and the lowest inputs of atmospheric water. Investigations of this spring type indicate that they most commonly support halotolerant and drought-tolerant plant species; species that support few herbivorous invertebrates.

Limnocrene

Limnocrene springs occur where discharge from confined or unconfined aquifers emerge as one or more lentic pools (Figs. 1j and 2j). The term was first used by Bornhauser (1913) and then reinforced by Hynes (1970). Limnocrene springs exist in both the wetland continuum and GDE

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classification systems. Although limnocrene springs may have pond and aquatic species, their relatively uniform temperature and chemistry may cause different species to be present than in an adjacent surface-water dominated water body. Montezuma Well in central Arizona is a limnocrene pool in a collapsed carbonate mound spring; the harsh, uniform water chemistry there appears to support the highest concentration of endemic species of any point in North America (Stevens 2007).

Mound form

Mound-form springs emerge from (usually carbonate) precipitate mounds or peat mounds (Figs. 1k and 2k). They are extensively known and described for the Great Artesian Basin in central Australia and from other limited areas of Western Australia, and also in North America (Knott and Jasinska 1998, Springer et al. 2008). Travertine-forming mound springs are often located along active magmatic or fault systems and therefore may be hot, or in the case of "black smokers" hyperthermic, waters, and these systems may emit large volumes of CO_2 from endogenic water sources (Crossey et al. 2008). Mound-form springs often support high numbers of endemic species because of the unique quality of the water or because of their importance as a water source in arid regions where they commonly occur (Knott and Jasinska 1998; Blinn 2008).

Rheocrene

The term rheocrene was first coined by Bornhauser (1913) to describe springs where discharge emerges as flowing streams (Figs. 1l and 2l). Spring-fed streams are also referred to as springbrooks or spring runs. The term was continued as a special habitat of running waters by Hynes (1970) because of the relatively uniform temperature and the de-oxygenated groundwater contribution to the stream. Springer et al. (2008) further recognized that there is a continuum between channels which are springs discharge dominated and those that are dominated by surface runoff. These longitudinal changes in flood-related disturbance, water quality, and geomorphology strongly direct evolutionary processes. Springflow-dominated springs may be sufficiently stable habitats to allow for evolutionary microadaptation, and ultimately speciation, whereas surface flow-dominated systems are typically occupied by weedy, generalist species (McCabe 1998). The different types of channels along this continuum are distinctively different, in turn influencing the types of microhabits that exist in them (Griffiths et al. 2008).

Distribution of spheres of discharge

To date, comprehensive inventories following the protocols of Springer et al. (2006) have been conducted for 244 springs of the Colorado Plateau (Springer et al. 2006) and the Verde Valley of Arizona (Flora 2004) and for 48 springs in Wisconsin (Swanson et al. 2007) in the US. The sphere of discharge was determined for each of the springs on the Colorado Plateau and Wisconsin during those inventories. Although cave, exposure, and fountain springs are known or likely exist in these regions, they have not yet been comprehensively inventoried (Table 3). Geyser springs are not known to exist in those regions. Results of comprehensive inventories of selected springs in the two counties in Wisconsin conducted by Swanson et al. (2007) determined that 40% were helocrene, 38% were rheocrene, 13% were hillslope, 2% were limnocrene, and 8% had other spheres of discharge. Analyses of global distribution of spheres of discharge of springs will not be accomplished until global inventories are conducted and databases constructed.

Threats to springs ecosystems

Springs are among the most threatened ecosystems (Stevens and Meretsky 2008). Primary anthropogenic impacts include groundwater depletion and pollution, alteration of source area geomorphology, and diversion of runout flows. Excessive groundwater pumping presently threatens the flows and biota of springs in the Edwards Aquifer in Texas (McKinney and Watkins 1993), the Verde River watershed in central Arizona (Haney et al. 2008), the hot springs of the Bruneau River in Idaho (US Fish and Wildlife Service 2002), Ash Meadows in Nevada (Deacon and Williams 1991) and the Owens Valley in California (Minckley and Deacon 1991), and elsewhere in the US. Groundwater pollution threatens water clarity of many Florida limnocrene springs (Scott et al. 2004). The Environmental Protection Agency requires that groundwater used for potable water supplies not be exposed to the atmosphere, a management strategy that often results in the capping of springs and obliteration of the source area. Fencing that focuses livestock into source areas, and diversion of runout streams to watering troughs or ponds are two very common practices throughout the Western US. A survey of springs not protected by the US National Park Service in northern Arizona revealed that more than

Table 3 Spheres of discharge of springs inventoried on the Verde Valley of Arizona and the Colorado Plateau (Springer et al. 2006; Flora 2004)

Sphere of discharge	Number inventoried	Percent of total inventoried
Cave	0	0
Exposure	0	0
Fountain	0	0
Geyser	0	0
Gushette	2	0.820
Hanging garden	29	11.8
Helocrene	38	15.6
Hillslope	31	12.7
Hypocrene	1	0.410
Limnocrene	13	5.33
Mound-form	2	0.820
Rheocrene	128	52.4
Total	244	100

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93% were moderately to severely ecologically impaired (Grand Canyon Wildlands Council 2002).

Conclusions

As Brune (2002) noted, “The study of springs is a borderline discipline, because springs are the transition from groundwater to surface water. Hence they have been studied to some extent by groundwater specialists and to some extent by surface-water specialists.” Because springs research is typically conducted by researchers from only one specialty or locality, there has grown a proliferation of different and varying classification and description systems for springs specific to that specialty or locality. This paper is an attempt to allow hydrogeologists to reclaim the description and classification of springs, as well as to inform that classification with information from other disciplines, particularly ecology and evolution. For example, springs in arid regions are hotspots of endemism: the highest concentrations of unique species in North America are found in the pool-forming springs of Ash Meadows (Nevada), Montezuma Well (Arizona), and Quatro Cienegas (Coahuila, Mexico; Stevens and Meretsky 2008).

The 12 spheres of discharge of springs, their descriptions and sketches included in this paper may allow springs researchers from many disparate specialties to share a common language and simplified visualization of these springs types. Also, hopefully, this paper may lead to a more thorough discourse in the literature of the shortcomings of this proposed system, leading to improvement over time. With a common language for springs, it may be possible to better focus limited research, management, and restoration resources onto spring types that are most at risk or most threatened.

When more comprehensive, integrated, springs ecosystems inventories are conducted, including analysis of species distribution among different spheres of discharge, an international database is built, and large-scale statistical analyses are conducted that include the species present along with the sphere of discharge, it will be possible to associate characteristic plant and animal assemblages with those spheres of discharge, and to clearly define a comprehensive springs classification system.

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