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Article *in* Ecological Applications · August 2020

DOI: 10.1002/eap.2218

Ecological Applications, 0(0), 2020, e02218
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Citation: Stevens, L. E., E. R. Schenk, and A. E. Springer. 2020. Springs ecosystem classification. Ecological Applications 00(00):e002218. 10.1002/eap.2218

Abstract. Springs ecosystems are globally abundant, geomorphologically diverse, and bioculturally productive, but are highly imperiled by anthropogenic activities. More than a century of scientific discussion about the wide array of ecohydrological factors influencing springs has been informative, but has yielded little agreement on their classification. This lack of agreement has contributed to the global neglect and degradation of springs ecosystems by the public, scientific, and management communities. Here we review the historical literature on springs classification variables, concluding that site-specific source geomorphology remains the most diagnostic approach. We present a conceptual springs ecosystem model that clarifies the central role of geomorphology in springs ecosystem development, function, and typology. We present an illustrated dichotomous key to terrestrial (non-marine) springs ecosystem types and subtypes, and describe those types. We identify representative reference sites, although data limitations presently preclude selection of continentally or globally representative reference springs of each type. We tested the classification key using data from 244 randomly selected springs of 13 types that were inventoried in western North America. The dichotomous key correctly identified springs type in 87.5% of the cases, with discrepancies primarily due to differentiation of primary vs. secondary typology, and insufficient inventory team training. Using that information, we identified sources of confusion and clarified the key. Among the types that required more detailed explanation were hypocrenes, springs in which groundwater is expressed through phreatophytic vegetation. Overall, springs biodiversity and ecosystem complexity are due, in part, to the co-occurrence of multiple intra-springs microhabitats. We describe microhabitats that are commonly associated with different springs types, reporting at least 13 microhabitats, each of which can support discrete biotic assemblages. Interdisciplinary agreement on basic classification is needed to enhance scientific understanding and stewardship of springs ecosystems, the loss and degradation of which constitute a global conservation crisis.

Key words: classification; conceptual model; dichotomous key; ecosystem; geomorphology; microhabitat; sphere of discharge; springs.

Introduction

Springs ecosystems are places on the Earth's surface that are influenced by the exposure, and often the flow, of groundwater. Springs are widely recognized for their physical diversity, and are abundant point sources of biodiversity and productivity that often have substantial ecological, socio-cultural, and economic function and value (Pliny the Elder AD 77, Perrault 1674, Meinzer 1923, Odum 1957, Botosaneanu 1998, Bonn and Bell 2002, Stevens and Meretsky 2008, Kresic and Stevanovic 2010, Glazier 2014, Hershler et al. 2014, Wynn et al. 2014, Mueller et al. 2017). Springs, as well as groundwater-dependent ecosystem (GDE) ponds and lakes provide headwater baseflow for most natural perennial stream networks in non-ice-dominated landscapes (Junghans et al. 2016). Springs have played central roles in human and cultural evolution (e.g., Broad 2006, Robinson 2011, Cuthbert and Ashley 2014), and many springs provide economically important drinking, agricultural, industrial, and recreational water sources (Gleick 2010, Kreamer et al. 2015). Many farms and ranches throughout the world were founded on, and still rely upon springs, and many villages and towns, as well as at least five European capitals, including Vienna obtain some or most of their public potable water supplies from springs (Kresic and Stevanovic 2010). Thousands of individual springs are protected as local, state, or federal parks globally, many geothermal springs are recreational sites, and some springs play pivotal roles in regional groundwater management policy (e.g., Devils Hole in Nevada; Minckley and Deacon 1991, Deacon et al. 2007). The European Commission (2013) declared travertine-depositing springs to be protected ecosystems and springs in general are protected in Australia and Finland (Zwahlen 2004, Onete et al. 2014, Cantonati

Manuscript received 28 April 2019; revised 7 December 2019; accepted 10 February 2020. Corresponding Editor: Laura Crossey.

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et al. 2016, 2020a, 2020b). Recognized as among the most insular terrestrial ecosystems, Odum (1957) used Silver Springs, Florida as the first location for a comprehensive test and demonstration of Lindeman's (1942) trophic-dynamic principles of ecosystem ecology. Despite their many values, springs nearly everywhere are threatened by anthropogenic groundwater depletion and pollution, and surface habitat modification, management issues that are of critical concern to governmental, public, and conservation organizations, as well as the hydrogeology and ecology science communities (Stevens and Meretsky 2008, Knight 2015, Kreamer et al. 2015; Cantonati et al., 2020a).

Despite a long history of hydrogeological inquiry, beginning with Perrault (1674), and a growing intensity of scientific research (e.g., Glazier 2014), springs conspicuously lack an integrated ecosystem-based lexicon and classification system. Hydrogeologists have trivialized springs ecosystem classification as a tangentially focused perspective, and the ecological community has largely ignored definitive springs hydrogeological and classification issues. Many springs are under private ownership and most are small in size, contributing to springs being over-looked in landscape-scale mapping and inventories. However, springs often are complex, highly individualistic, highly interactive ecosystems, and the absence of a broadly applicable classification system has directly contributed to the lack of attention to them, resulting in an impoverished approach to stewardship, the endangerment and loss of a substantial number of springs and springs-dependent species (SDS, crenobiontic taxa), and global imperilment of these ecosystems.

With at least 2.5 million springs on Earth, and due to their keystone and other eco-socio-cultural ecosystem functions, springs are sufficiently ecohydrologically and socio-culturally influential to warrant classification. Such classification will help clarify and relate springs ecohydrology and ecosystem ecology for management planning and restoration (e.g., Wallace and Alfaro 2001, Thompson et al. 2002, Springer and Stevens 2009, Davis et al. 2011, Kreamer et al. 2015, Stevens et al. 2016a, 2016b, Paffett et al. 2018). Identification of rare types, assessment of ecological integrity, variation in microhabitat roles and distribution, the distribution and evolution of rare, endemic or endangered SDS, and springs cultural, historic, and economic significance are central natural and societal resource management concerns. From a practical standpoint, management of non-natural habitats within a springs type comes at a cost in terms of maintenance and loss of habitat functions. The failure to develop a logical, generally applicable classification also is attributable to the lack of communication between the disciplines of hydrogeology and ecosystem ecology: both disciplines have unique lexicons and conceptual perspectives that relatively few scientists attempt to bridge (Cantonati et al. 2020b). Hydrogeology, landscape location, biotic assemblage characteristics, and policy approaches have failed to provide broadly applicable classification and protection, and an embarrassment of scientific disagreement remains about springs typology. This has resulted in insufficient and inadequate inventory, ecological assessment, and stewardship, and has contributed to the on-going global demise of these critically important ecosystems. A definitive, conceptually grounded, broadly accepted lexicon and classification system is needed to improve basic scientific understanding and provide effective springs ecosystem stewardship guidance (Bedford and Godwin 2003, Stevens and Meretsky 2008, Springer and Stevens 2009). Such classification will benefit cultural socioeconomics and ecohydrological and conservation science (e.g., Perla and Stevens 2008, Hershler et al. 2014, Wynn et al. 2014, Kreamer et al. 2015, Cantonati et al. 2020a, 2020b, Cartwright et al.2020).

Here we briefly review springs classification history and approaches, asserting the primacy of source geomorphology for unambiguous classification, with water quality and other factors providing informative but secondary descriptors. We use this review to formulate a springs ecosystem conceptual model, integrating physical, biotic, and anthropogenic interactions. We then present, describe, and test an illustrated dichotomous key to terrestrial (non-marine) springs geomorphic springs types, modified from Springer and Stevens (2009). We also describe the array of springs-associated microhabitats, which through habitat heterogeneity contribute to observed high levels of biodiversity and tight species packing at springs (Kreamer et al. 2015, Springer et al. 2015, D. Sinclair *unpublished data*). Collectively, these elements help refine the descriptive lexicon and classification of terrestrial springs ecosystems, and provide an improved basis for stewardship decision-making (e.g., Paffett et al. 2018). Our classification system provides the opportunity to (1) recognize relatedness among different types of springs, (2) distinguish how geomorphology influences assemblage composition and ecosystem function, (3) determine where rare or endemic species are likely to occur, and (4) clarify stewardship options, which vary by springs type. We discuss these findings in relation to the development of GDE ecology, and the need for consistent nomenclature and classification in springs ecosystem science, stewardship, and education.

Springs Ecosystem Classification and Approaches

Background

Scientific classification of any target group of objects or species is most useful when it is universally applicable, parsimonious, and based on diagnostic variables that are readily and clearly observable and measurable. Not all variables, features, or characteristics are unambiguously useful in classification, and therefore selection of criteria requires careful consideration. Landform classification of islands, mountains, lakes, rivers, wetlands, and ecosystems has emphasized the use of an array of variables related to geotectonic evolution, geomorphology, geochemistry, biotic assemblage organization, and sometimes management and utility, with varying levels of success (e.g., Wilson 1990, Jackson and Bates 1997, Hutchinson 2004, Dahl et al. 2007, Kresic 2010, Soranno et al. 2010, Buffington and Montgomery 2013, Royle 2014). Among aquatic ecosystems, geomorphic or hydrogeomorphic classification often has been effective, with discrete geomorphic units classified on the basis of physical origin and developmental processes, landform structure, morphometry, and process overprinting or generation (Haskins et al. [1998], but with no mention of springs). Much attention has been placed on applied wetland science, management, and jurisdiction (e.g., Cowardin et al. 1979, Rosgen 1996, Mitsch and Gosselink 2015), with biological and hydrogeomorphic elements used to classify U.S. jurisdictional wetlands, including those in riverine, depressional, slope, mineral or organic soil flats, estuary fringe, and lacustrine fringe settings, but not necessarily springs in those landscapes (Natural Resource Conservation Service 2008). Cantonati et al. (2020b) conclude that the lack of integration between the disciplines of hydrogeology and ecosystem ecology has heretofore stymied springs classification, stewardship, and conservation. Hydrogeological approaches have focused on description of the aquifer up to, but not much beyond the point of groundwater emergence, while ecological description of springs has focused on ecosystem characteristics at and beyond the point of emergence. Thus, these two sciences have had limited overlap and interaction due to discipline-centric foci on different places, processes, and components.

Hydrogeological attempts to classify springs in the past century include those by Fuller (1904, 1910), Thienemann (1907, 1922), Keilhack (1912), Steinmann (1915), Bryan (1919), Meinzer and Hare (1915), Meinzer (1923, 1927), Clarke (1924), Stiny (1933), and others. Keilhack (1912) and Bryan (1919) attempted comprehensive classification based on geologic structure and aquifer characteristics, including groundwater flowpath, but their classes of springs were not definitive. Steinmann (1915) and Thienemann (1922) described three springs types based on flow patterns at the source, including pool-forming limnocrene, flowing rheocrene, and seeping wet meadow helocrene springs. Early classifications schemes often were based on limited geographic mapping, a relatively simple lexicon, and intuitive combinations of physical metrics. While locally descriptive, these classifications did not well describe springs ecosystems typology in their entirety, or in other regions, or at coarser spatial scales. However, Meinzer (1923, 1927) compiled information on the factors affecting USA springs, including flow, water quality, flow drivers (e.g., gravity vs. pressure), water sources, water quality and geomorphic “spheres of discharge” of sources. He quantified flow characteristics, proposing classification within suites of variables, but did not present an overall classification system.

Contemporary physical classification attempts include broad across-spatial-scale approaches down to local-scale approaches. For example, Dahl et al. (2007) used a combination of geomorphologic, geologic, and hydrologic characteristics and processes operating across regional catchment (five types), reach or intermediate (up to eight types), and spatial scale (up to eight scales) to identify at least 17 spatially discrete groundwater–surface-water interactions in Denmark. While useful for classifying that nation’s watersheds, their model tends to emphasize “headwater streams” and riparian zones fed by diffuse groundwater inflow, rather than by springs (a seemingly common approach in fluvial hydrogeology). At a finer spatial scale, Hotzy (2007) used a combination of “water drainage” (i.e., seeping, flowing, ponded, linear, and falling flow categories) and channel bed materials (organic, and fine, coarse, or block materials) to identify 14 springs types in Bavaria. However, his system focused just on the springbrook, rather than the entire springs ecosystem (i.e., not on the associated riparian system or other springs-influenced microhabitats). In addition, his approach did not include several springs types that are common elsewhere (e.g., hanging gardens, hypocrenes, etc.). Again, such classifications may work well synoptically, but not at coarser spatial scales.

Past and contemporary springs ecohydrologists have identified eight suites of variables with potential value in springs ecosystem classification, including (1) the geology of the aquifer, (2) springs discharge, (3) water quality (temperature, geochemistry), (4) landscape location, (5) biota (e.g., vegetation, aquatic macroinvertebrates), (6) anthropogenic use and management, (7) source geomorphology, and (8) combinations of those variables (Steinmann 1915, Thienemann 1922, Meinzer 1923, Alfaro and Wallace 1994, Pitts and Alfaro 2001, Hotzy 2007, Spitale 2007, Springer et al. 2008, Springer and Stevens 2009, Kresic and Stevanovic 2010, Glazier 2014, Eamus et al. 2016). Among these many syntheses, Glazier (2014) provided an exemplary recapitulation of the history of classification attempts, succinctly organizing and summarizing potential classification variables. He provided useful cross-referencing of the existing, large, and sometimes contradictory springs ecohydrology lexicon, and an extensive bibliography. However, classification of springs has been subdiscipline specific, and has not much focused on springs as ecosystems, and therefore incorporation of variables critical for ecosystem classification remains outstanding. Below we reexamine and prioritize this list of potentially useful variables to propose a springs ecosystem conceptual model and classification scheme.

Aquifer hydrogeology

Overview.—Aquifer studies contribute greatly to understanding springs emergence and water quality in relation to the tectonic setting, parent bedrock, geologic structure, landscape location, climate, and anthropogenic impacts. While contributing to groundwater modeling, aquifer-based springs typology has usually focused on aquifer processes and geochemistry, variables that often are not directly measurable, poorly differentiate among the surface expression of springs, and which can vary widely among springs within aquifers (e.g., Chapelle 1993, Thomas et al. 1996). As a leading source of potable groundwater supplies, karstic aquifers have received much attention. Karstic aquifers often are characterized by relatively rapid (days to decades), flashy flowpaths through fractured carbonate strata, with flow, water temperature, and geochemistry reflecting parent rock type, surface conditions, flowpath length, and temporal variation (e.g., Schuster and White 1971, Bonacci 1993, Alfaro and Wallace 1994, Cantonati et al. 2007, Kresic and Stevanovic 2010, Goldscheider 2012, Tobin et al. 2017, Calligaris et al. 2018), including ephemeral discharge, and which generate a wide array of emergence conditions. Non-karstic aquifers include non-carbonate sedimentary strata, basaltic and other igneous strata and, more rarely, metamorphic strata. Aquifers have been used to grossly classify springs geochemistry. For example, Dragon and Gorski (2015) described the geochemistry of groundwater in the Wielkopolska region of Poland using factor analysis, finding that boron isotope concentrations indicated upward flow of ancient water, while those of fluoride indicated downward infiltration of younger, and anthropogenically contaminated waters, as well as geochemical differences with adjacent aquifers. Thus, groundwater emergence patterns vary spatially within and among aquifers. While invaluable for groundwater modeling and supply management (see Groundwater Modeling, below), and with potential in secondary description, primary classification of springs based on aquifer characteristics is ineffective.

Flow-based classification

Discharge magnitude.—Springs discharge is an aquifer function that varies widely in magnitude within and among springs, ranging from ephemeral springs with low or highly erratic discharge (e.g., La Fontaine Spring, an erratic cave springs ecosystem that provides seasonal baseflow for the La Morgue River in France), to small seepage sipeocrenes (Glazier 2014), and deep-aquifer springs with highly steady discharge. The largest terrestrial springs in the Northern Hemisphere include Dumanli Spring in Turkey (mean discharge = 5.03×10^4 L/s; Karanjac and Günay 1980), Ra-El-Ain Spring in Syria (mean flow = 3.63×10^4 L/s; Alfaro and Wallace 1994), and other examples provided in Meinzer (1927) and Stevanovic (2010). Large Southern Hemisphere springs include Te Waikoropupū (1.4×10^4 L/s) on the South Island of New Zealand and others.

Meinzer (1923) proposed springs classification based on discharge and discharge variability. However, discharge is inherently difficult to measure in many springs, such as wet meadow ciénegas and GDE fens, hanging gardens, and subaqueous springs (Bauer and Johnson 2010, Sawyer et al 2016, Stevens et al. 2016b), and many springs are naturally ephemeral. Among several problems with Meinzer's (1923) approach to characterizing flow magnitude was his use of a reverse numerical order: "first order" springs were the largest (>2,830 L/s), while the smallest springs were classified as "eighth order" (<8 mL/s). Not only is this scale forced into an unjustified octaval division (perhaps in reference to the western eight-note classical musical scale), it is an illogically reversed-ordinal scale. Springer et al. (2008) recommended simply presenting actual flow measurements, and if the need arose for ordinal scaling, using an intuitive (e.g., $\log_{10}$-transformed) ascending scale. While of relevance to springs ecosystem function, often highly variable and generally poorly measured discharge magnitude within and among springs within aquifers renders this variable intractable for primary classification.

Discharge variability.—Meinzer (1923) considered springs to be perennial if their discharge was constant, and "intermittent" if discharge was interrupted, periodic, or sporadic (episodic) on a seasonal, annual, interannual, or entirely erratic basis. The term "intermittent" has been distinguished from "ephemeral" for consistency with stream terminology, but still has been applied to periodic rheocrenes with highly variable discharge, such as Lilbum Cave Spring in California (Alfaro and Wallace 1994). Meinzer (1923) also proposed springs classification based on discharge variability, which can affect springs geomorphology, ecological stability, and biota. He calculated the discharge variability ratio (DVR), identifying constant (DVR $\approx$ 1), subvariable ($1 >$ DVR < 10), or variable (DVR ≥ 10) levels. Among the limitations of this variable for classification are that it requires generally unavailable long-term discharge monitoring data, and that the DVR of ephemeral springs is undefinable. Also, periodic and other intermittent springs may have highly regular discharge patterns that are not reflected in DVR calculation. Reversing flow springs ("estavelles") change flow direction as the recharge capacity of the supporting aquifer waxes or wanes (Kresic 2010). Thus, like discharge magnitude, DVR can be useful as a secondary descriptor, but is not diagnostic for springs ecosystem classification.

Persistence.—Ecosystem persistence ("longevity") is an evolutionarily important characteristic of springs (Nekola 1999, Cartwright et al.2020). Long-term persistent springs function as paleorefugia (sensu Nekola 1999) across ecological and evolutionary time scales: springs that have persisted since at least the late Pleistocene epoch often support relictual or adaptational endemic species. Montezuma Well in central Arizona, Ash Meadows in Nevada, and Cuatro Ciénegas in Coahuila, Mexico are North American paleorefugial springs or complexes that support high concentrations of endemic species (Stevens and Meretsky 2008). In contrast, recently emerged, exposed, or developed springs arising from, for example, retreating glaciers, dewatered lakes, or wells drilled into confined aquifers, function as neorefugia, supporting recent arrivals of generally weedy colonists. A third group, paleosprings are springs that existed in the distant past but no longer flow, and are identified from geologic or paleontological evidence (e.g., paleotravertine deposits, paleosols). Paleosprings may contain important paleoclimate, paleontological, archaeological, or dendrochronological evidence (e.g., Cuthbert and Ashley 2014, Fuchs et al. 2019). However, determination of the age of individual springs ecosystem often requires considerable research and, while of great interest, springs ecosystem age is untenable as a primary classification variable, particularly within the scale of large landscapes.

Water quality

Overview.—Well prior to Pliny the Elder's (CE 77) pronouncement "…tales sunt aquae qualis terra per quam fluunt qualesve herbarum quas lavant suci," water quality (temperature and geochemistry) was recognized as a function of geology and influences associated biotic assemblages. With regard to springs, water quality is a complex derivative of climate, aquifer lithology, groundwater hydrogeology, and flowpath (Palmer 1911, Bryan 1919, Meinzer 1923, Cantonati et al. 2007). Springs geochemistry regulates ecosystem development, both aquatic and terrestrial biotic assemblage composition and diversity, and can indicate anthropogenic impacts on aquifers, and has long and rightly been regarded as an important suite of variables. However, its utility in springs ecosystem classification remains complex and enigmatic, again relating to the great diversity of variables, non-linear relationships among them, and differences in focus between hydrologists and ecosystem ecologists (Cantonati et al. 2020b).

Temperature.—Multiple water temperature classifications have been developed, primarily based in relation to mean annual air temperature (MAAT) and human use (Waring 1965, Alfaro and Wallace 1994, Springer et al. 2008). Glazier (2014) summarizes 39 thermal classification variables among five categories, including those related to: MAAT, absolute temperature range (cold < 20°C to hyperthermic > 70°C), variation and magnitude (heterothermal to absolutely hot), flora and fauna relationships (hypothermophilous to euthermophilous), and human sensation and therapy (very cold [0°–12°C] to very hot [40°–43°C]). Geothermal waters are influenced by magmatic activity, and include subaerial geysers and highly pressurized profundal submarine and deep lake-floor vent springs that support extremophilic microbes (e.g., Lovalvo et al. 2010). The temperature of non-thermal springs generally reflects groundwater residence time and flowpaths (e.g., Johnson et al. 2012), and nonlinearly influences the presence of specialist aquatic and wetland taxa (Glazier 2012). Thermal variability at the source, and the gradient from source to the first order stream channel also are ecologically important, but are relatively rarely studied (but see Brock 1978, Morrison et al. 2013). Overall, water temperature varies widely within and among aquifers and climate zones, but may be less relevant among ephemeral springs. While of obvious importance to ecosystem ecology, human recreational economics and therapy, but like flow, water temperature varies widely among (and sometimes within) springs, therefore providing only limited, secondary utility in generalized typological classification.

Geochemistry.—Springs water geochemistry has been the subject of intensive study, with early efforts in the United States focused on locating hot springs and minerals, characterizing water types, and pollution (e.g., Peale 1886, Palmer 1911, Clark 1924, Fitch 1927, Meinzer 1927); however, such data are rarely integrated with other ecosystem characteristics. Clarke (1924) classified the waters of mineral springs based on the dominance of ion groups: calcium, carbonate, chloride, magnesium, potassium, sodium, magnesium, sulfate, and combinations of those constituents, as well as silica dioxide, borate, nitrate, and phosphate, and pH. Furtak and Langguth (1986) classified Greek springs as belonging to (1) normal earth alkaline (hydrogen-carbonatic) waters; (2) normal earth alkaline, hydrogen-carbonatic-sulfatic waters; or (3) enriched alkali earth alkaline (primarily hydrogen-carbonatic) waters. Dinius (1987) used an expert decision process to develop an index of surface-water quality to compare levels of pollution in bodies of fresh water using solute concentrations and specific conductance (μS/cm), pH, alkalinity, water color, and [Cl], [O], [NO_3], aqueous [O_2], rare earth elements, stable isotopes, biological oxygen demand, turbidity, and bacterial concentration. In addition, dissolved or gaseous methane, sulfides, and hydrogen can be important indicators in subaqueous freshwater springs. Many studies have used springs geochemistry to describe karstic or deep-aquifer springs sourcing (e.g., Shuster and White 1971, Huntoon 2000, Crossey et al. 2009, Hershey et al. 2010, Springer et al. 2017), and multivariate statistical techniques have revealed spatial and anthropogenic impacts, including as seawater intrusion into coastal aquifers (e.g., Yidana 2010, Retike et al. 2016). However, while essential to understanding springs aquifer sourcing, ecosystem ecology, and utility for human use, like other aquifer and groundwater metrics, springs geochemistry does not readily or unambiguously distinguish springs ecosystems and thus remains of secondary importance in classification.

Groundwater modeling

Hydrogeologic models, including both numerical models (e.g., MODFLOW) and process models (e.g., RHESSys) often are used to estimate aquifer mechanics and the impacts of human activities on groundwater supplies and springs flow (e.g., Scanlon et al. 2003, Tague and Grant 2009, Zurek et al. 2015). Such models require data related to stratigraphy and geologic structure, groundwater inputs (climate, infiltration rates), aquifer characteristics, and groundwater outputs (extraction, springs, streamflow). Groundwater modeling generally uses springs geochemistry and flow as boundary conditions or as output variables, such as line sources of groundwater discharge in analytic element models. Karstic aquifers often are unsuitable for modeling using equivalent porous media flow theory, a common form of numerical model (Anderson et al. 2015). Specific studies have used groundwater modeling to determine the source of springs' source waters, and springs may be useful for modeling aquifer geography, discharge, geochemistry, anthropogenic or climate change impacts, and sometimes GDE aquatic or SDS habitat area (e.g., Gvirtzman et al. 1997, Kresic and Stevanovic 2010); however, classification of the surface expression of groundwater in springs ecosystems generally is of limited interest in groundwater modeling. Thus, while of potential use for classifying aquifers and of much use in groundwater supply analyses, the use of groundwater models to categorize springs ecosystem ecology and classification remains relatively limited.

Geomorphology

Landscape position.—Several springs classification systems focus on the position or location of the springs emergence within regional landscapes, often including other physical characteristics (e.g., hydrology, geochemistry, vegetation) as secondary descriptors. Bryan (1919) described the influences of aquifer geology, bedrock stratigraphy, slope angle, and groundwater pressure on springs emergence, a geologic structure approach followed by many other hydrogeologists. The European Union (EU) proposed using physical parameters and landform-location–geologic-structure for springs classification (e.g., Bertrand et al. 2012). Fetter (2001) described springs on the basis of geologic structure, identifying depression, fault, contact, fracture, sinkhole, and fracture zone springs, an approach also used by Scarsbrook et al. (2007) to describe New Zealand coldwater springs biodiversity. Refinement of this classification under the EU Groundwater Directive (European Union 2014) focused on subaerial springs (groundwater–atmosphere contact), with springs classes defined by coupling flow velocity and geomorphology to distinguish lentic (spring pool), lotic (spring brooks), and semi-terrestrial (helocrene) springs (Kløve et al. 2011). However, that classification did not consider other common EU springs types, such as hillslope or subaqueous springs. Bertrand et al. (2012) classified Swiss springs ecosystems as only those settings involving a direct groundwater-to-air interface. They coupled hydrogeology, source geomorphology, flow variability, geochemistry, and source and landscape position to describe eight regional springs types, including for example "non-permanent alkaline rheocrene springs," but the general applicability of their model remains untested. Wheeler and Proctor (2003) and Koster and Favier (2005) reviewed mire typology in relation to ecological, geogenetic, and hydrogeomorphic criteria that link landscape location, geochemistry, and vegetation. They reported four classes and eight types, of which only spring mires (quellmoores) were unambiguously GDEs. In the United States, Sada and Pohlmann (2006) coupled description of Great Basin springs in relation to landscape position and other physical characteristics, identifying mountain slope, bajada, and valley floor types. The latter scheme has been used to prioritize springs rehabilitation potential (e.g., Quivara Coalition et al. 2014 in New Mexico).

In general support of the structural geology approach, Naghibi and Dashtpagerdi (2017) found that the best predictors of the location of 842 springs in the Khalkhal region of Iran were altitude, topographic wetness index, slope angle, and faulty density. Freed et al. (2019) reported that springs density in the Crooked River subbasin of the Deshutes River in Oregon was highest for springs discharging from low-permeability rock units. However, description of springs in relation to landscape scale structural geology varies among physiographic provinces and does not distinguish individual springs. Even when coupled with other variables, landscape position is insufficiently site-specific to advance functional classification of springs as ecosystems.

Springs source geomorphology.—The physical geomorphology at, around, and downstream from the point of flow emergence provides the most definitive, site-specific criterion for springs classification. Steinmann (1915) and Thienemann (1922) described pool-forming (lentic) limnocrenes, stream-channel (lotic) rheocrenes, and marsh-forming (generally lentic) helocrenes on the basis of flow velocity from the source. Bryan (1919; in part) and Meinzer (1923) describe those as "spheres of discharge." While this definition captured the attention of other early springs hydrologists, little focus was placed on springs-influenced geomorphology and downstream and peripheral springs-influenced environments. Springer and Stevens (2009) identified 12 terrestrial springs types based on source geomorphology. Here we subdivide their 12 types into six relatively lentic and six relatively lotic groups, and add paleosprings to their list. We refine prior definition of rheocrenes as springs arising within surface flow channels, and we refine their definition of hillslope, helocrene, and mound-forming springs types to each include discrete subtypes. Hillslope and helocrene springs commonly occur in floodplain (rheocrenic) settings, or in uplands away from regular flood scour, with the former subtype (floodplain hillslope springs) strongly influenced by regular flooding disturbance.

Palm oases and GDE swamp forests are forms of helocrenes with tree canopy cover. Mound-forming springs commonly occur as precipitate, ice, and organic mound form subtypes. We note that cave, fountain, gushet, hanging garden, and limnocrene springs also can occur in floodplain vs. upland settings, but such springs are relatively rare compared to floodplain vs. upland hillslope and helocrene springs. Also, all springs types can be created or altered by human actions, so that the modifier "anthropogenic" can be added as a subtype to any springs type. Description of springs types is based on the springs ecological function, so that seepage from a dam would be described as an "anthropogenic hanging garden," or pressurized flow from a well drilled into a confined aquifer would be described as an "anthropogenic fountain." Standardizing this typological nomenclature will improve mapping and assessment of springs types across landscapes and at coarser spatial scales, and facilitate stewardship.

Springbrooks.—Early hydrogeological classifications did not consider springbrooks (springs outflow, flushes) channels or associated riparian microhabitats as ecosystem components. Groundwater emergence in, or production of, springbrook channels generates distinctive fluvial landform geomorphology when springs flow, rather than surface runoff dominates channel dynamics (Whiting and Stamm 1995). The physical (crenal) and coupled ecosystem biocoenosis of source and springbrook are recognized as distinctive aquatic environments (Illies and Botosaneanu 1963, Sada and Pohlmann 2006). Geomorphically, springbrooks typically are straight or erratic, non-symmetrical, and slightly incised, often with flow at or near bank-full stage (Griffiths et al. 2008). Many springbrooks undergo a distinctive transition, from dominance by source flow to dominance by surface flow, including increasing meander symmetry. The point(s) of transition in channel sinuosity and aquatic biota (but not necessarily water temperature or geochemistry) are spatially discrete for each springs ecosystem due to local conditions, adding to the individuality of each springs ecosystems and its responsiveness to variation in environmental interactions and discharge (e.g., Dreybrodt et al. 1992, Scarsbrook et al. 2007, Dumnicka et al. 2013, Morrison et al. 2013). Surface water channel classification systems do not necessarily adequately describe springbrook geomorphology (Stevens et al. 2005, 2016a,2016b). For example, the Rosgen (1996) stream classification system typically categorizes springbrooks as Aa+, A, B, and G channel types, but only rheocrene springs channels that sustain significant surface runoff are well described in that system (Stevens et al. 2005). Similarly, classification of springbrook benthic substrata (e.g., as psammocrenes, rheopsammocrenes, or muddy rheo-helocrenes; summarized in Glazier 2014) is not particularly informative. While not sufficient for ecosystem-level classification, springbrooks are important functional microhabitats, and warrant inclusion in springs descriptions.

Biological classification

Biological variables (i.e., vegetation, aquatic macroinvertebrates, fish, limnology) have been used to differentiate among wetlands and springs types (e.g., May et al. 1995, van der Kamp 1995, McCabe 1998, Wheeler and Proctor 2003, Batzer and Sharitz 2006, Kodrick-Brown and Brown 2007, Soranno et al. 2010). Intensive phytogeographical mapping and description of European fen and mire vegetation has produced a massive classification literature built around diverse concepts, perceptions, and traditions. Wheeler and Proctor's (2003) synthesized that literature, using the term "mire" to include bog, fen, moor, peatland, and mire habitats. They reported that three gradients influenced mire vegetation: pH-based cation concentration (particularly $pH < 5$ or > 6), N and P availability, and hydrology. However, they could not clearly distinguish precipitation-supported (ombotrophic) mires from those supported by groundwater (minerotrophic or geogenous mires, spring-flush fens): mire vegetation intergraded between soligenous (spring-fed) and topogenous (meteoric precipitation-supported depressional) fens. Springs in their review typically were hillslope features that "flush" downslope, becoming stream headwaters or merging into fens. However, mire springs vegetation can be distinctive: a *Carex demissa–Saxifraga aizoides* association was an indicator of spring-flush habitats, whereas a *Carex dioica–Pinguicula vulgaris* association graded between springs and fens. Analogously, wetland vegetation has long been used as a key metric for determining the legal status of U.S. wetlands (Cowardin et al. 1979), which is based on hydrology, vegetation, and soils, and for fens particularly the presence of 40 cm of peat (a characteristic dismissed by Wheeler and Proctor 2003). Wetland status also has been described for many individual plant species, plant associations, and faunal species in other developed countries and continents (e.g., Ellery 2004, Landucci et al. 2015, Australian Plant Society 2018).

D. Sinclair (*unpublished manuscript*) analyzed physical and floristic data from 352 southern Colorado Plateau springs, distinguishing discrete plant assemblages among hillslope, rheocrene, helocrene, and hanging garden springs. However, insufficient data existed to test for floristic differences among uncommon springs types there (e.g., limnocrenes, gushets, etc., sensu Springer and Stevens 2009). Similarly, Springer et al. (2015) attributed the large amount of noise in vegetation analyses to differences among springs in biogeographic history, life history variation among taxa, anthropogenic impacts, and dense plant species packing, which collectively generate high levels of ecosystem individuality.

Springs-supported vegetation can alter both springbrook and confluent stream channel geomorphology. Continuous flow from upland- or floodplain-hillslope springs may promote the growth of dense herbaceous or woody vegetation, potentially altering the power and channel geomorphology of the streams with which they are confluent, sometimes increasing the base level of the channel and reducing the susceptibility of both springbrook and mainstream channels to flood scour. We have observed this phenomenon in many lotic springbrook and mainstream channel confluences throughout western North America.

Aquatic macroinvertebrates in both subterranean and surface settings have been proposed as indicators of differing springs types. Sun et al. (2019) reported that 1,448 aquatic invertebrate SDS could be grouped into three groups of indicators: groundwater subterranean stygobiota, and cold- vs. warm-stenothermic taxa. Stein et al. (2012) reported that German stygoregions (defined on the basis of the distribution of stygobiota) did not relate to surface biogeographic regions, and required a different scheme for groundwater ecosystem classification. Among surface-dwelling invertebrate studies, Glazier and Gooch (1987) analyzed 20 environmental factors, concluding that pH, conductance, and benthic substrata influenced macroinvertebrate assemblages in Pennsylvania springs. Zollhöfer et al. (2000) used multivariate basis habitat and assemblage analysis on 16 variables from 34 Swiss Plateau and Jura Mountains springs to distinguish aquatic source impacts on springbrook macroinvertebrate assemblages. They reported discrimination among springs types based on a mixture of aquifer, source and stream geomorphology, and anthropogenic sorting factors, and identified six types, including karst, lime-sinter, unsintered, linear, alluvial rheocrene, and anthropogenic limnocrene springs. Scarsbrook et al. (2007) identified a suite of eight invertebrate SDS groups among six orders that were indicators of perennial flow in Selwyn River/Waikirikiri drainage springs in New Zealand. Ilmonen et al. (2009) reported that Fennoscandian springs assemblages were spatially organized by coarse-scale latitudinal thermal (climate) regime and fine-scale water chemistry. Weissinger et al. (2012) described aquatic macroinvertebrates among 40 sandstone springs in southwestern Utah, reporting weak differences among taxa, but little evidence of nestedness among assemblages. Their findings contrast with those of Kodrick-Brown and Brown (2007) and Ríos-Arana et al. (2018) who reported strong patterns of nestedness among springs fish species in Australian mound-forming springs and among rotifers in Chihuahuan Desert springs in northern Mexico, respectively. Savić et al. (2017) reported that mayfly, stonefly, and caddisfly assemblages in central Europe were influenced by geochemistry and macrophyte cover, but not by elevation, and that anthropogenically altered (piped) springs differed from rheocrene springs.

Our review of biological differences among springs and springs types indicates compelling insights at regional spatial scales, particularly for conservation purposes; however, a more general, solely biological classification scheme remains outstanding. Most studies have been regional in spatial scale, have focused on individual subsets of taxa, have not included the full array of springs types, or have been inconclusive. Virtanen et al. (2009) examined concordance among bryophytes and aquatic macroinvertebrates in 138 Finland springs, reporting clear differentiation in relation to water quality and substrata, but that the two groups of organisms were poor surrogate indicators of each other. No studies to our knowledge have attempted analysis of a large array of springs types based on the full array of associated aquatic, wetland, and riparian SDS plant, invertebrate, and vertebrate taxa across spatial scale. Thus, although SDS and springs biotic assemblage structure are of great concern, and may be useful as regional indicators of environmental conditions and change, much additional research is needed to develop a broadly applicable biologically based springs classification system.

Management-based classification

Inventory protocols.—Springs inventory protocols and ecosystem models should be founded on appropriate, clearly defined questions, and measurement of variables that illuminate fundamental ecosystem processes and components to test, verify, and refine those ecosystem questions, as well as contribute to classification. Several protocols are actively used in the USA, including: the Nevada Desert Research Institute Springs Protocol (Sada and Pohlmann 2006), the U.S. Forest Service (2012) GDE protocol, the U.S. Bureau of Land Management's Lentic and Lotic Proper Functioning Condition protocols (U.S. Department of Interior 2003 and Dickard et al. 2015, respectively), the U.S. National Park Service (various protocols), the Springs Stewardship Institute's (SSI) Springs Inventory Protocol (Stevens et al. 2016b), and European and Australian springs inventory protocols also have been developed (e.g., Eamus and Froend 2006, Cantonati et al. 2007, European Commission 2013, United Kingdom 2014). Other springs protocols have been proposed, but few are broadly applicable or widely used. All protocols share remarkable similarity in the variables measured, including georeferencing, geomorphology, discharge, geochemistry, biota, and cultural and socioeconomic attributes and values (Stevens et al. 2016b). However, there has been limited consensus on the collaborative or comparative use of inventory protocols in relation to improving springs classification or stewardship of springs and SDS, information management, and resolving stewardship needs and options across local to international political boundaries remains outstanding (Cantonati et al., 2020a).

Policy-based classification.—Global recognition of the highly endangered status of springs and SDS has highlighted the need for improving management policy (e.g., Hendrickson and Minckley 1983, Shepard 1993, Unmack and Minckley 2008, Kløve et al. 2011, European Commission 2014, Cole and Cole 2015, Kreamer et al. 2015, Zurek et al. 2015, Lehosmaa et al. 2017). Wetland classification policy in the United States has focused on non-GDE wetland hydrology, soils, and vegetation (Cowardin et al. 1979, U.S. Army Corps of Engineers and U.S. Environmental Protection Agency 2020). However, the most recent federal USA wetlands policy specifically excludes GDE wetlands and other springs that lie wholly within state boundaries from federal protection, leaving that focus to individual states and non-federal parties. Policy has been suggested for various habitat or use classification criteria, including conservation ranking on the basis of: extrinsic habitat criteria (e.g., springs type rarity or spatial isolation) vs. intrinsic criteria (e.g.,springs ecosystem integrity, habitat area, springbrook length, the presence of sensitive species, or riparian habitat type); potability and yield; and purpose and type of anthropogenic modification (reviewed by Glazier 2014), criteria that could improve springs stewardship.

As helocrenic wetlands, ciénegas have attracted a great deal of attention in the southwestern United States and Mexico due their conservation value and threatened status (Hendrickson and Minkley 1985). Cole and Cole (2015) proposed a classification system for ciénegas based on current function, stability, and restorability, recognizing functional, restorable, severely degraded, and obliterated ciénegas, and proposing rehabilitation of this springs type as a high priority across the Southwest. GDE fens also have recently received increasing attention. The U.S. Forest Service (2012), and both the U.S.-Bureau of Land Management and the U.S. National Park Service have developed inventory and assessment guidance and protocols for fens under their jurisdiction, with various but differing classification criteria.

European Union (EU) researchers have classified springs in relation to GDE designations as groundwater dependent terrestrial ecosystems (GDTE/GWDTE), groundwater aquatic ecosystems (GDAE/GWDAE), and groundwater-associated aquatic ecosystems (GAAE) under the Natura 2000 habitats list, the European Water Framework Directive (EU 2007), Schutten et al. (2011), the European Commission (2014, 2015), the United Kingdom (2014), and Zurek et al. (2015). Nineteen EU member nations responded to a questionnaire about use of the Natura 2000 habitat description (European Commission 2014). While suggesting consensus on springs classification, that habitat classification does not clearly differentiate EU springs types. Natura 2000 habitat types that support springs range from inland salt meadows to alpine riparian areas, including Habitats 3,190 (lakes of gypsum karst), 7,160 (Fennoscandian mineral-rich springs and springfens), and 7,220 (petrifying springs with tufa formation; European Commission 2013, Onete et al. 2014). The Natura 2000 habitat classification focuses on landscape location and geochemistry, a system that provides relatively little description of, or guidance on many springs ecosystem types. The analysis highlights the uniqueness of precipitate-depositing springs, a springs type that is relatively rare both in the EU and globally. Thus, while of conservation concern, EU springs type definitions do not provide an overarching ecosystem classification system. In addition, European Commission technical reports are conflicted with regard to springs ecosystem description because only one-half of the member nations have adopted the framework for determining quantitative or chemical groundwater–surface-water interactions, and as yet there appears to be no clear framework quantifying springs ecosystem services (Bascik et al. 2009, European Commission 2015).

Summary of springs classification approaches

While the above review of springs classification efforts provides insight and lexicological advancement in springs ecohydrology, all except the local-scale source geomorphology approach fall short with regard to classification of springs as discrete ecosystems. Despite more than a century of debate about organization, lexicon, and hydrological factors influencing springs ecosystem ecology, we are left without the means to clearly distinguish which variables best serve in unambiguous classification of springs as ecosystems, and therefore the ability to differentiate among the relatively large array of terrestrial springs types. Although hydrogeological identification of potential variables has focused on groundwater prior to, and at the point of discharge, the importance of springs ecosystems extends well beyond the point of emergence, downstream and laterally outward from the source. Therefore, springs classification requires consideration of associated springs-influenced microhabitats, such as springbrook channels and associated riparian zones. These factors influence habitat and niche complexity, biogeographic context, associated biota, sociocultural values, uses, and stewardship options.

Although many variables influence springs ecosystems functions, classification based on source geomorphology and expanded from Meinzer's 1923 "spheres of discharge concept" best fits the requirements for typological definition. Source geomorphology appears to be the least ambiguous way to classify springs ecosystems because the characteristics in question are readily observable and quantifiable, the approach is source-site specific, and geomorphology remains relatively stable over time, allowing for repeatability of measurement. This approach focuses on physical habitat configuration and local landform features that can be described and mapped, some of which are commonly encountered at springs and others (e.g., wet, overhanging backwalls) are characteristic of specific springs types. Other variables, such as water temperature, geochemistry, flow dynamics, landscape location, habitat criteria, management- or policy-based considerations, and human use can be applied as additional descriptors, but we recommend source geomorphology as the primary classification variable for springs ecosystems.

In our previous research on springs source geomorphology, we identified 12 discrete types of non-marine springs (Springer et al. 2008, Springer and Stevens 2009). With slight modifications and the addition of subtypes and paleosprings, geomorphic typology successfully discriminates among the array of springs types we have encountered globally. In several cases, landform location criteria have been added to distinguish among sub-types of springs, based on the regularity and xml-style of ecological disturbances and their impacts on springs geomorphology and SDS distribution. This classification system can be used to improve both springs ecosystem science and stewardship, while allowing for inclusion of additional, related ecohydrological characteristics and qualities (Ledbetter et al. 2014; see also *Data Availability*). In the following sections, we: describe a springs ecosystem conceptual model to relate the many physical and biological elements and processes to anthropogenic impacts (above); clarify, refine, and more clearly illustrate springs ecosystem types based on source geomorphology; and describe microhabitat frequency of occurrence within springs types, which contributes to niche and biological diversity.

A Springs Ecosystem Conceptual Model

Conceptual models are important for consolidating and framing understanding the complexities of ecosystem structure, processes, and responses to anthropogenic impacts. Here we present a conceptual springs ecosystem model that characterizes springs as “bottom-up” GDEs, relating interactions among physical tectonic setting, parent rock geology, local-global climate, and aquifer structure and function (Fig. 1). Those regional and aquifer-scale processes influence localized emergence of groundwater and local microclimate conditions. Microclimate effects and site limitations related to the local solar radiation budget, influence interactions between the productivity of the site and its disturbance regime, which together affect its “hospitability” to potential colonists. Collectively, those physical factors and interactions generate the distinctive subsurface-surface-linked geomorphic template on which the biological portion of the ecosystem develops. Biotic development on that template occurs through both passive and active biogeographic processes. Thus, at the top of Fig. 1, a springs ecosystem includes its site-specific assemblage, biodiversity, and trophic interactions. Depending on site characteristics and processes, the springs ecosystem is subject to variation in biotic succession, and evolutionary development over time ($T_1 \rightarrow T_X$).

Springs throughout the non-ice dominated Earth have been subject to hominid influences for $>3 \times 10^6$ yr (e.g., Haynes 2008, Cuthbert and Ashley 2014), although demands for human goods and services have greatly intensified in recent times. Contemporary anthropogenic impacts on springs include pre-emergence regional climate change and aquifer drawdown and pollution, as well as local post-emergence alteration of springs source geomorphology, disturbance regimes, flow, native species assemblages, and the introduction of nonnative species. These impacts feed back to influence subsequent ecosystem characteristics, processes, and developmental trajectory, and range from minor impacts from which the ecosystem can recover to site obliteration or transformation into an entirely different geomorphic state (Fig. 1, red arrows).

In a natural example of change, a single cottonwood (*Populus*) seed can land and germinate at a small, otherwise treeless upland hillslope desert spring. As the seedling grows, the plant begins to transpire, eventually potentially reducing groundwater discharge, and it begins to shade the site, cooling the springbrook water temperature and excluding wetland plant species that require direct sunlight. The tree attracts root- and foliage-feeding, as well as wood-boring, invertebrates, and attracts vertebrate predators, which also may use the tree and springs as habitat. The tree’s annual leaf production creates litter and eventually soil, which in turn support a host of additional invertebrate colonists. The tree may alter site geomorphology by shedding branches that create soil dams and block or pond surface flows. As it grows larger, the tree may transpire all surface water from the site, eliminating aquatic life forms, and transforming the springs ecosystem from a hillslope emergence to a hypocrenic state. The tree may live for a century or more without reproducing successfully at the site, but then may be killed by lightning or be cut down by humans, eliminating its many ecological functions and re-exposing the springs to full sunlight. Thus, single individual can colonize the site through passive biogeographic processes and requires the template of emergent groundwater and undisturbed local site geomorphology for germination and ecesis. It greatly transforms the assemblage and trophic structure during its relatively brief life, all of which changes into a new state after its passing. Of course, far more drastic changes occur when humans appropriate groundwater, habitat, and other resources, or mow, fence pastures for livestock, or construct dwellings on a springs ecosystem.

While our conceptual ecosystem model is admittedly highly simplified, it captures these dynamics, and emphasizes the significance of physical, bottom-up ecohydrogeological processes (sensu Cantonati et al. 2020b) and the centrality of source geomorphology in providing the physical template for ecosystem structure, process,

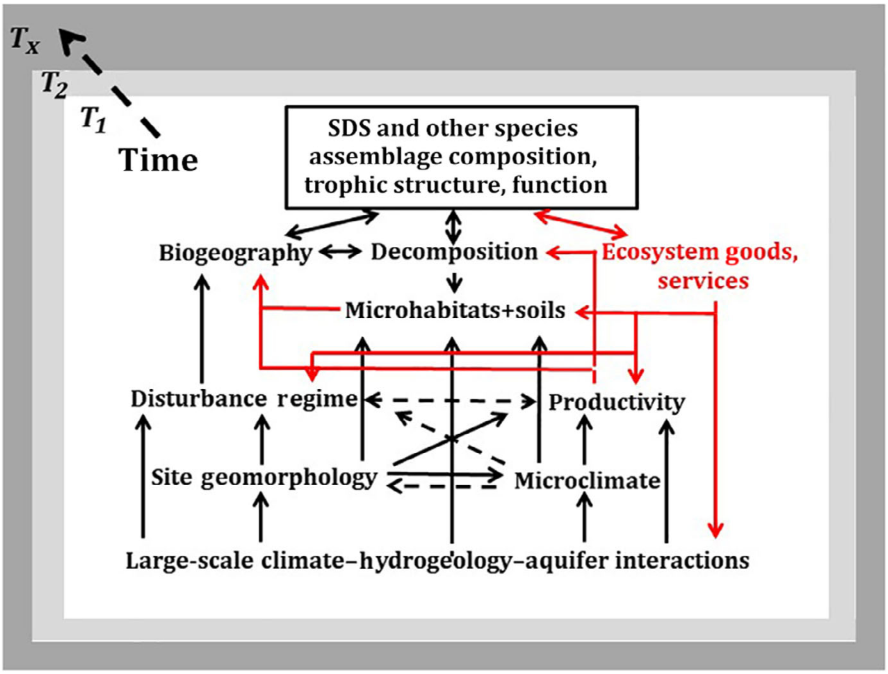

FIG. 1. A springs ecosystem conceptual model. T_1–T_X represent ecosystem states over time (unspecified intervals).

insularity, and susceptibility to human use. Geologic structure, aquifer characteristics, flow, groundwater geochemistry, and other physical variables are foundational to springs emergence location and development, and influence the responsive, changing assemblage composition and structure, and ecosystem trophic structure, as well as potential goods and services. While dependent on bottom-up processes, we recognize that paleorefugial springs can develop powerful trophic cascades and evolutionarily adapted assemblages (e.g., Brock 1978, Nekola 1999, Blinn 2008), Nonetheless, from a conceptual basis, source geomorphology provides the most clear, credible rationale for springs classification.

A Key to Springs Types

Morphology-based dichotomous keys are universally used in biological taxonomy to distinguish among taxa (e.g., Hagedorn et al. 2010), but are less commonly employed in geomorphology. Dichotomous keys require clear definition of observable features, and are organized to repeatedly divide groups into distinguishable subgroups to ultimately and unambiguously identify a single unique form. Several dichotomous keys have been proposed to classify springs and wetlands ecosystems. Bryan (1919) used aquifer hydrogeology and pressure, landscape location, and source geomorphology to develop a dichotomous key to springs types. Although highly insightful, the initial steps of his key focused on aquifer structure and groundwater sources, data that can be prohibitively difficult to obtain. Also, the first steps of his key largely negate subsequent steps: “Associated with volcanism or volcanic rocks; water commonly hot, highly mineralized…Grade from gas vents into springs of normal temperature indistinguishable from those due to other causes” (Bryan 1919: 559).

United States wetlands classification has been dominated by jurisdictional policies focused primarily on non-GDE wetland hydrology, soils, and vegetation, the description of which has been formulated into a nationally used dichotomous key (Appendix E in Cowardin et al. 1979). However, U.S. federal wetlands delineation is focused on surface water ecosystems, not GDEs, and although few would dispute that springs are wetlands, that key scarcely mentions springs. Most springs types except limnocrenes and rheocrenes key to Cowardin et al.’s (1979) “palustrine” (marsh-forming) type, unfortunately including vegetated gushets and hanging gardens (sensu Springer and Stevens 2009), which are petric, cliff-dominated springs. That key includes macrophytic vegetation as an element, although wetland vegetation may or may not exist at some springs types (e.g., gushets, geysers). Further challenges in their key include habitat size as a criterion, and self-contradictory statements, such as “…vegetation… is contained within a channel… or not…” (Cowardin et al. 1979: Appendix E:44). Thus, even if springs were to become legally regarded as wetlands in the United States, the Cowardin et al. (1979) key would not provide the appropriate foundation for classification. Non GDE- U.S. wetlands classification and assessment has progressed into ever more complex concepts, lexicon, and jurisdictional conflicts over the past four decades (e.g., Dorney et al. 2018, Mažeika et al. 2019, U.S. Army Corps of Engineers and U.S. Environmental Protection Agency 2020), showing little promise of resolution, and springs have remained largely unprotected. Thus, development of definitive descriptive keys to springs types have largely failed, delaying and weakening scientific and societal attention to these important ecosystems.

Based on the above issues, we developed a geomorphologically based classification key that clarifies and expands on the sphere of discharge concept emphasized by Meinzer (1923), Springer et al. (2008), and Springer and Stevens (2009; Table 1), extending the spatial scope to include the habitat primarily influenced by the springs emergence. Such a key requires clear definition and identification of morphological features, including factors related to the groundwater–surface-water contact mechanism (aquifer contact), how groundwater is expressed (e.g., lentic vs. lotic), the surrounding, downstream, and riparian geomorphology of the springs emergence and springbrook, and both habitat structure and ecological function. Water flow, geochemistry, biota, anthropogenic impacts, and ecosystem goods and services are of recognized importance, but generally remain as secondary descriptors of the springs ecosystems.

Many physical hydrogeologic, landscape location, and water quality variables help refine where, what, when, and through which mechanisms groundwater reaches, or is forced to the surface. Those variables can be used to describe the supporting aquifer and can be useful for groundwater modeling (e.g., Johnson et al. 2012), but only contribute secondarily to description and classification of springs as ecosystems. Description of several springs sub-types is enhanced by considering the role of landscape location in relation to the disturbance regime (e.g., lying within or outside a floodplain).

DESCRIPTION OF TERRESTRIAL SPRINGS ECOSYSTEM TYPES

We re-describe and refine the lentic and lotic springs types proposed by Springer and Stevens (2009), and provide improved illustrations of those types (Table 2; Figs. 2, 3). We emphasize the need for precision in language when describing springs ecosystems, focusing on ecological structure and function. Many springs can be described as a single type; however, because springs commonly emerge from multiple sources in close proximity (the reason we prefer to use the plural form, "springs" throughout this paper), they often can be more precisely described as a primary type with co-occurring secondary and tertiary types. For example, a ciénega or GDE fen wet meadow helocrene may contain an anthropogenic open-water pool created for livestock watering. Based on the habitat area, the primary ecosystem function of such a site is as a helocrene, with a secondary function as a limnocrene created by human action. Thus, such a springs ecosystem would be described as an anthropogenic limnocrenic helocrene. We recognize that this specificity can be readily described in English, but that such descriptive combinations may be less succinct in other languages.

While we recommend source geomorphology as the primary descriptive approach for springs classification, we recognize that different ecohydrological projects require further refinement of springs groups. For example, region-specific classification systems have been proposed for springs water temperature and groundwater geochemistry in mires, fens, petric springs, biota, and in relation to anthropogenic use, policy, and management (Cowardin et al. 1979, Moore 1984, Zoltai and Vitt 1995, Wheeler and Proctor 2003, Glazier 2014, Retike et al. 2016, Peterka et al. 2017). We recommend that, depending on the project questions and spatial scale of inquiry, researchers use the approaches and tools provided here to identify the springs type, and then refine the type using additional classification criteria.

With respect to identifying specific springs as reference sites for ecosystem studies and restoration comparisons over time, it likely will be most informative for researchers and stewards to select representative examples of springs at regional or biome scales. However, many more springs need to be systematically inventoried before truly representative reference sites can be selected. Among the examples cited in Table 2 are springs that illustrate key characteristics of each springs type, and we invite our colleagues to suggest other well-protected sentinel sites around the world to improve this list.

TESTING THE KEY

We tested this springs ecosystem classification key (Tables 1 and 2) by randomly sampling 1–56 non-sensitive North American springs of each type for which data were available in Springs Online (Ledbetter et al. 2014; see also *Data Availability*), and for which sufficient ancillary data were available for analysis (Table 3). In all, we keyed out 244 springs among 12 major types, to determine whether and how accurately the key correctly identified springs type. Because of differences in information availability, sample size varied among types, with information on fountain and geyser springs limited to only a few cases. Overall, we report that 87.5% of springs were correctly identified using the key, and that keying success varied by springs type.

The utility of this analysis was threefold. First, it is obvious that more inventories are needed on several rare springs types, including exposure, fountain, geyser, gushet, and mound-form springs. Second, the exercise clarified which types were less easily distinguished, and we used the analysis to refine the key. Third, in relation to the previous issues, several new, basic insights were gained in relation to springs ecosystem ecology. For example, misclassification of hypocrene springs as hillslope or mound springs was due, in part, to information limitations, as well as to interaction between water table depth and anthropogenic impacts. Hypocrenes are

TABLE 1. Dichotomous key to terrestrial springs types. Numbers guide the user stepwise through the options in the key.

No.	Alternative	Springs type
1	Groundwater expression of flow emerges within a cave (a water passage, often through limestone or basalt, with an aperture sufficient to allow human passage), before emerging directly into the atmosphere, or subaqueously into a surface pool or channel. Lentic and/or lotic flow conditions can exist.	cave
	Groundwater expression of flow emerges or emerged in a subaerial setting (direct contact with the atmosphere), including within a sandstone alcove or subaqueously (beneath a body of water), but not from within a cave. Lentic and/or lotic flow conditions can exist.	2
2	Groundwater is not expressed at the time of visit (the springs ecosystem is not flowing; the soil may be moist but is not saturated.	3
	Groundwater is expressed at the time of visit; saturation, seepage, and/or flow are actively expressed (water and/or saturated soil is evident. Lentic and/or lotic flow conditions can exist.	5
3	Evidence of prehistoric groundwater presence and/or flow exists (e.g., paleotravertine, paleosols, fossil springs-dependent species, etc.), but no evidence of contemporary flow or aquatic, wetland, or riparian vegetation.	paleospring
	Not as above; lentic and/or lotic flow may exist.	4
4	Soil may be moist, but is not saturated, by groundwater. Groundwater is expressed solely through wetland or obligate riparian vegetation. Lentic flow conditions prevail.	hypocrene
	Groundwater is expressed through saturated soil, or as standing or flowing water. Lentic and/or lotic flow conditions can exist.	5
5	Groundwater is expressed, but discharge is primarily lentic (standing or slow-moving). Flow does not emerge on the floor of a stream channel, although it may emerge on a channel margin or floodplain terrace. Downstream flow may be absent or very limited.	6
	The majority of groundwater discharge flows actively within and/or from the site, and flow is primarily lotic (fast-moving).	11
6	A usually low-gradient patch of shallow groundwater or saturated fine sediment or soil, with subaerial emergence, and usually strongly dominated by hydric soils and emergent wetland vegetation, but sometimes can include woodland or forest vegetation (e.g., palm oases, GDE swamp forests). Lentic flow conditions predominate.	7 (helocrene)
	Subaqueous flow creates an open, lentic body of water, typically more than a few square meters in area, not within a mineral (usually travertine)-precipitating or travertine-dominated landscape, and sometimes without outflow.	8
7	A GDE wet meadow with seepage emerging from the margin of an active surface flow-dominated channel (floodplain), and subject to regular flood scour by the stream channel into which it feeds.	floodplain (rheocrenic) helocrene
	A GDE wet meadow with seepage emerging outside and away from an active surface flow-dominated channel (floodplain), and not subject to flood scour by a stream.	uplands helocrene
8	The groundwater table surface is exposed as a pool with standing water, without a focused inflow source, and with no outflow.	exposure, including many prairie pothole springs
	A pool with one or more focused, often subaqueous inflow sources, and generally with outflow if not frozen. Lentic flow conditions predominate.	9
9	An open pool not surrounded by one or more springs-created mineral, ice, organic mound (e.g., not within a travertine, ice, or organic deposit). Lentic flow conditions prevail, but lotic flow also may occur in the springbrook.	limnocrene
	The springs are surrounded by, and have contributed to the formation of a mound composed of mineral precipitate (e.g., travertine), ice, or organic matter; lentic flow conditions generally prevail.	10
10	The springs are surrounded by, or emerge from a mound composed of carbonate or other mineral precipitate. Both lentic and lotic flow conditions can occur.	precipitate (carbonate mound)
	The springs are surrounded by, or emerges from a mound composed of ice in an ice-dominated landscape. Flow may be seasonal; and both lentic and lotic flow conditions can exist.	ice mound (e.g., pingo, aufweis)
	Springs mound is composed of organic matter, such as decomposing vegetation. Lentic flow conditions generally prevail.	some GDE helocrene fens
11	Springs flow emerges explosively, driven either by geothermally derived or gas-derived pressure. Lotic flow conditions generally prevail.	geysers, including both geothermal and "coke-bottle" (CO_2 gas-driven geysers)
	The springs flow emerges non-explosively, by the action of gravity. Both lentic and lotic flow conditions can exist.	12
12	Artesian flow emerges from one or more focused points, rising 10 cm or more above ground level due to gravity-driven head pressure, before flowing from the source. Both lentic and lotic flow conditions can occur.	fountain (artesian)
	Flow emerges from focused point(s), but without substantial artesian rise above ground level. Both lentic and lotic flow conditions can occur.	13

Table 1. (Continued)

No.	Alternative	Springs type
13	Flow emerges from within a near-vertical or overhung, cliff-dominated bedrock surface, and not within an established surface flow channel (although a surface channel may exist on top of the source cliff). Lotic flow and cliff seepage conditions prevail.	14
	Not as above.	15
14	Focused lotic flow emerges (sometimes from a cave) and immediately cascades, usually in madicolous sheet of whitewater flow down a bedrock cliff face. This springs type may include unvegetated bedrock wall surfaces and adjacent colluvial slopes.	gushet
	Flow emerges along a near-horizontal geologic contact, dripping along a seepage front and often creating a wet backwall behind or within a bedrock overhang. If a surface channel exists above the source area, a plunge pool and runout channel are likely to occur. This springs type may include unvegetated seepage patches on near-vertical or overhung bedrock walls, as well as adjacent colluvial slopes. Both lentic and lotic flow conditions can occur.	hanging garden
15	Relatively focused flow emerges within a surface flow-dominated channel, which upstream may be a dry channel or a perennial stream (in which case the springs may be subaqueous). Channel terraces can exist in unconsolidated marginal sediment deposits. Lotic flow conditions generally prevail. The springs are subject to stream channel flood scour.	rheocrene
	Relatively focused flow emerges from a non-horizontal, generally non-bedrock-dominated slope that does not have an upslope surface flow channel. In some cases, these springs may emerge from the base of a cliff, but not from the cliff itself. Both lentic and lotic flow conditions can occur.	16 (hillslope)
16	Focused flow emerges from the margin of an active surface flow-dominated channel terrace (floodplain), and the source is subject to regular flood scour by the stream into which it feeds. The springs and springbrook channel(s) may be strongly influenced by mainstream flood disturbance. The slope angle of the source may be < 20°, and both lentic and lotic conditions may exist.	floodplain (rheocrenic) hillslope
	Focused flow emerges on relatively steeply sloping uplands, the slope angle of which generally lies between 20° and 60°. The springs are not associated with an upslope channel and not subject to bottomland stream channel flooding. The springbrook channel, if any, rarely contains prominent flood terraces. Both lentic and lotic conditions can exist.	upland hillslope

Note: Springs types are based on those identified by Springer and Stevens (2009), but also include paleosprings, differentiate between floodplain and upland sub-types of helocrene and hillslope springs, and distinguish three subtypes of mound-form springs not included in their original list.

springs with sufficiently near-surface groundwater to support phreatophytic vegetation, but which do not express surface flow. In contrast, ephemeral springs (which are not a geomorphic springs type per se) can generate hypocrene-like conditions due to temporally fluctuating water tables and other hydrogeomorphological processes. Hypocrenes occur naturally and can be confused with helocrenes (the latter are distinguished by the presence of saturated surface soils), but hypocrenes also develop as a consequence of aquifer pumping and groundwater depletion, anthropogenic impacts that initiate regionally characteristic, as well as biome and springs-type specific hydrarch succession (e.g., Cartwright et al.2020).

Other springs types presented minor sources of confusion to the field staff who tested the key. Gushets occasionally were confused with hillslope and hanging garden springs. Those errors were attributable to recognition of the presence of primary vs. secondary types (e.g., gushets at hillslope and hanging gardens often were secondary springs types). Hanging garden springs that occurred in deeply overhung rock shelters occasionally were confused with cave springs, and carbonate mound-form springs occasionally were confused with limnocrenes (the former are distinguished by the presence of travertine or other mineral precipitates). Most cases of confusion were attributable to insufficient familiarity on the part of the staff with springs geomorphic diversity, and can be corrected with more intensive training in springs type recognition. Otherwise, the springs types described and illustrated above appear to be readily recognizable, and demonstrate that this classification key is useful for springs inventory, assessment, and stewardship planning.

Springs Geomorphic Microhabitats

Habitat heterogeneity has long been recognized as an important contributor to species richness and diversity (Simpson 1948, Hutchinson 1953). Some springs types, particularly larger hanging gardens, gushets, and hillslope springs, have higher levels of geomorphic diversity due to the co-occurrence of multiple geomorphic microhabitats (Table 4; Figs. 2, 4). Such features are landform components of the springs ecosystem, develop from various physical processes, and are subject to various environmental forces. Pools, springbrook channels, hyporheic zones, wet or dry bedrock walls, madicolous zones (shallow sheets of racing white water), and other microhabitat types can occur in close proximity, and may contain entirely distinct assemblages of organisms that may or may not interact with those in other

Table 2. Springs type definitions, common subtypes, alternate names, and examples, corresponding to Figs. 2 and 3.

Springs type	Definition	Common subtypes	Comments and alternate names	Examples
1. Cave	Gravity-driven groundwater emergence within a cave (a conduit with an aperture sufficient to allow human entrance), from tubular, fissure, or joint geologic structure(s) before reaching the atmosphere (Meinzer 1923, Fetter 2001), or from an anthropogenically excavated tunnel; common in karstic and igneous terrains (e.g., central Europe, American Ozarks). Lotic and lentic flow conditions commonly co-occur.	Perennial; ephemeral; anthropogenic.	Cavern springs; in-aquifer (Colvin et al. 2007), cavern, or fissure springs; hydropetric (EU); incorrectly classified as palustrine springs in Cowardin et al. (1979) Appendix E, including Bureau of Land Management Proper Functioning Condition methods key; some lava tubes; recognized as a springs form by Schutten et al. (2011), and as surface expression of groundwater by Eamus et al. (2016); if anthropogenic, qanāt (Arabicized Persian of kanāt to ghundat, ~ falaj ~ kārīz ~ kārēz), an excavated underground channel or tunnel that transfers water from a spring or well to a flow capture point.	Cave Spring, Cave & Basin National Historic Park, Alberta, Canada (natural; Springer et al. 2015); Miskolctapolca Bath Cave, Miskolc, Hungary (partially anthropogenic)
2. Exposure	The aquifer is exposed to the atmosphere, but typically does not flow; these lentic water bodies occur in fracture, contact, or depression structural contexts (Sloan 1972, Meinzer 1923, Fetter 2001).	Perennial, ephemeral; anthropogenic (e.g., mines, quarries, livestock watering tanks).	Depression, hole, lake, pond, prairie potholes (in part).	Devils Hole, Death Valley NP, Nevada, USA; some volcanic maars (perhaps some of the Katwe-Kikorongo Volcanic explosion crater lakes in Uganda); Lac de Gahsa, Tunisia (appeared in 2014)
3. Fountain	Lotic flow-focused, gravity-driven, artesian upwelling through a fracture or tubular geologic pathway, with groundwater rising substantially (e.g., >10 cm) above the surrounding land surface (Meinzer 1923).	Perennial; ephemeral; anthropogenic fountains are created by drilling into a confined artesian aquifer.	Semi-terrestrial (Kløve et al. 2011); palustrine or rarely, lacustrine (Cowardin et al. 1979: Appendix E key (including BLM PFC); recognized as a surface expression of groundwater by Eamus and Froend (2006), as a springs form by Schutten et al. (2011), and described in Utah (Keleher and Rader 2008).	Peirene Fountain, Corinth, Greece (Robinson 2011); Franklins Fountain, Cache County, Utah
4. Geyser	Gas (steam or CO_2) or geothermally driven eruption of groundwater, often from a mineral precipitate mound; lotic conditions prevail but pools also commonly occur.	Ephemeral; anthropogenic result from well drilling into geothermal or CO_2-producing strata and aquifers.	Recognized as a surface expression of groundwater and as a springs form by Schutten et al. (2011), but incorrectly keying to a palustrine or riverine wetlands in Cowardin et al. (1979: Appendix E key), including PFC methods (U.S. Department of the Interior 2003, Dickard et al. 2015).	Old Faithful, Yellowstone NP, Wyoming, USA; Onikobe Geyser, Naruko Onsen, Japan
5. Gushet	Flow-focused, gravity-driven, lotic groundwater emergence on a nearly vertical cliff and in a plunging cascade of madicolous flow.	Cave, hillslope, mound-form, rheocrene, travertine springs.	Fracture (Fetter 2001), fissure, or joint springs (Springer et al. 2008). Incorrectly keying to a palustrine wetlands in Cowardin et al. (1979: Appendix E key) and including BLM PFC methods. Cliff spring (Bertrand et al. 2012); hydropetric (EU); recognized as a surface expression of groundwater and as a springs form by Colvin et al. (2007) and Schutten et al. (2011).	Thunder River, Grand Canyon National Park, Arizona, USA (Springer et al. 2008); Laguna del Laja Cascadas del Rio Laja, Province Biobío, Chile; Termas de Baños, Baños, Ecuador (geothermal)
6. Hanging Garden	Diffuse, gravity-driven groundwater emergence along a horizontal or near-horizontal geologic contact between an aquifer (typically sandstone or basalt) and an underlying aquitard (usually	Ephemeral, hillslope, mound-form, rheocrene; anthropogenic (e.g., cliff seepage	Seepage or contact springs (Bryan 1919, Meinzer 1923); incorrectly keying to a palustrine wetlands in Cowardin et al. (1979: Appendix E key); contact and fracture or fracture zone system (Fetter 2001, Bryan 1919); a cliff spring (Bertrand et al. 2012); a	Weeping Wall, Zion National Park, Utah, USA

Table 2. (Continued)

Springs type	Definition	Common subtypes	Comments and alternate names	Examples
	shale or siltstone); both lentic and lotic flow conditions can exist.	downstream from some dams).	hydropetric spring (EU); a surface expression of groundwater by Earmus and Froend (2006); and a terrestrial spring by Colvin et al. (2007); recognized for their distinctive geomorphology and flora (Malanson 1980, Welsh and Toft 1981, Welsh 1989, Spence 2008, Weissinger et al. 2012, D. Sinclair, *unpublished data*).	
7a. Floodplain (rheocrenic) helocrene (not illustrated)	Diffuse-flow, gravity-driven, low-gradient, lentic, marsh-forming wet meadows that arise on stream channel or lake margins, and are subject to regular stream scour or inundation by regular lake stage fluctuation; these seepage springs may arise from a buried geologic contact or structure.	Fountain, floodplain hillslope, limnocrenic margins; precipitate (hygropetric) or organic mound, mire forming in rheocrenic setting (rheo-helocrene or fluvial marsh, often with little or no peat due to high flood frequency); some palm oases (Cornett 2008).	Ephemeral (non-permanent); fracture springs (Bryan 1919, Meinzer 1923); ciénegas (when below ~2000 m (Meinzer 1923, Cole and Cole 2015); GDE fens (Bedford and Godwin 2003); fluvial marshes and emergent and scrub-shrub wetlands (Cowardin et al. 1979); sinkholes (Fetter 2001); Pleistocene lakebed wetlands if groundwater is expressed at surface (Cole and Cole 2015; semi-terrestrial (Kløve et al. 2011); GWDTE fen, wet slack (ephemeral; Schutten et al. 2011); ephemeral GCE marshes (Boulton 2005); moss–lichen and emergent and scrub-shrub wetlands (Cowardin et al. 1979); dispersed flow wetlands; permanent or non-permanent waters characterized as alkali, acid, salt pan, or gypsum ("lakes with large bacterial mats"; European Commission 2013, Bertrand et al. 2012); bryophyte-dominated travertine helocrenes or petrifying springs with tufa formations or Fennoscandian mineral-rich springs and springfens (European Commission 2013, Onete et al. 2014); mires (multiple subclasses; European Commission 2013, Wheeler and Proctor 2003); monsoon-driven or snowmelt-driven ephemeral slope wetlands; mineral-rich peatlands (noted for endemic species); iron-rich GCE fens; palm oases (Cornett 2008); and in permafrost- and ice-dominated high latitude settings as aufweis; not to be confused with rheohelocrenes (flowing wet meadows; Glazier 2014).	e.g., Hance Rapid Spring, Grand Canyon, Arizona (Stevens et al. 1995)
7b. Upland helocrene	Diffuse-flow, gravity-driven, low-gradient, lentic, marsh-forming, wet meadows that form in uplands, away from regular stream scour; wet meadows that generally arise from seepage associated with buried geologic contacts or structure.	Hillslope fountain; limnocrene margins; developing precipitate (hyrgropetric) or organic mound; peatland fens or mires can be GDEs in rheo-topogeneous (flowing	Ephemeral (non-permanent; Boulton 2005); fracture springs (Meinzer 1923, Bryan 1919); ciénegas (when below ~2,000 m (Meinzer 1923, Cole and Cole 2015) or GDE fens at higher elevations (Bedford and Godwin 2003); palustrine marshes and emergent and scrub-shrub wetlands (Cowardin et al. 1979); sinkholes (Fetter 2001); Pleistocene lakebed wetlands if groundwater is expressed at surface (Cole and Cole 2015; semi-terrestrial (Kløve et al. 2011); GWDTE fen, wet slack (ephemeral;	Empire Ciénega, Tucson, Arizona, USA; Bobolice Alkaliine Fen, Chociel Valley, Poland (Osadowski et al. 2018)

Table 2. (Continued)

Springs type	Definition	Common subtypes	Comments and alternate names	Examples
		depressional) settings or as soligeneous mires or peatlands, or marginal seepage slopes (Wheeler and Proctor 2003, Rocchio 2006); potentially including rheohelocrene (flowing wet meadows; Glazier 2014); palm oasis; GDE swamp woodlands or forests.	Schutten et al. 2011); moss-lichen and emergent and scrub-shrub wetlands (Cowardin et al. 1979); dispersed flow wetlands; permanent or non-permanent waters characterized as alkali, acid, salt pan, or gypsum ("lakes with large bacterial mats"; European Commission 2013, Bertrand et al. 2012); bryophyte-dominated travertine helocrenes or petrifying springs with tufa formations or Fennoscandian mineral-rich springs and springfens (European Commission 2013, Onete et al. 2014), or spring mires (quellmoore; Koster and Favier 2005; rheo-topogeneous (flowing depressional) or soligeneous mires, marginal seepage slopes, and other classes (Wheeler and Proctor 2003, Rocchio 2006, European Commission 2013); mineral-rich peatlands (noted for endemic species); iron-rich GCE fens; palm oasis (Cornett 2008); GDE forested wetland or swamp forest; and in permafrost- and ice-dominated high latitude settings as aufweis; not to be confused with meteoric precipitation-fed ephemeral slope wetlands or vernal pools.	
8a. Floodplain (rheocrenic) hillslope	Channel margin floodplain (rheocrenic) hillslope springs emerging within the 100-yr flood return stage elevation of the adjacent stream or river, and reflecting the disturbance dynamics and vegetation of that stream; gravity-driven focused or diffuse groundwater emergence on nearly flat to steeply sloping channel margins; may include high gradient ciénega habitat; flow often is focused at bottom of the springs ecosystem); sometimes occurring as travertine-forming springs; lotic and lentic flow conditions can co-occur.	Ephemeral; rheocrene; anthropogenic (e.g., pipe or ditch leakage).	Seepage area, fracture spring, fissure spring, joint spring, contact spring (Meinzer 1923, Bryan 1919); palustrine wetlands (Cowardin et al. 1979); GDE slope wetlands and mires (hangmoores; Koster and Favier 2005); headwater slope wetlands (Quivira Coalition et al. 2014); semi-terrestrial or terrestrial cliff springs (Colvin et al. 2007, Kløve et al. 2011, Schutten et al. 2011, Bertrand et al. 2012), and as surface expression of groundwater (Eamus and Froend 2006); if travertine depositing, occurring as petrifying springs with tufa formations (Onete et al. 2014).	Big Springs, Ozark National Scenic Riverways, Missouri, USA
8b. Upland hillslope	Gravity-driven focused or diffuse flow groundwater emergence generally on slopes of 15°–60° (may include high gradient ciénegas), with flow often focused at bottom of the springs ecosystem), and sometimes as travertine-forming springs; upland hillslope springs emerge outside of stream channels and therefore are not subject to fluvial flood cyclicity; lotic and lentic flow conditions can co-occur.	Ephemeral; anthropogenic (e.g., pipe or ditch leakage).	Seepage area, fracture spring, fissure spring, joint spring, contact spring (Bryan 1919, Meinzer 1923); palustrine wetlands (Cowardin et al. 1979); GDE slope wetlands and mires (hangmoores; Koster and Favier 2005); headwater slope wetlands (Quivira Coalition et al. 2014); semi-terrestrial or terrestrial cliff (base) springs (Colvin et al. 2007, Kløve et al. 2011, Schutten et al. 2011, Bertrand et al. 2012); if travertine depositing, occurring as petrifying springs with tufa formations (Onete et al. 2014).	Watridge Karst Spring, Spray Lakes Provincial Park, Alberta, Canada (Springer et al. 2015)
9. Hypocrene	A flow-focused, gravity-driven, shallow confined aquifer, with groundwater expressed through	Mound-form; anthropogenic (due	Palustrine wetlands (Cowardin et al. 1979); not recognized except in the form of Pleistocene lakebed	Colorado River Mile 70L Hypocrene Springs, Grand

Table 2. (Continued)

Springs type	Definition	Common subtypes	Comments and alternate names	Examples
	wetland vegetation but not as surface emergence of flow; occurring naturally, but usually not ephemeral; supporting perennial wetland and woody riparian vegetation; also commonly developing as groundwater tables decline through aquifer overdraft, causing hydrarch succession from aquatic and wetland vegetation, to riparian, and ultimately upland vegetation.	to groundwater depletion).	wetlands where groundwater is not expressed at the surface (Quivira Coalition et al. 2014); subsurface presence of groundwater; Australian *Banksia* woodlands fed by subsurface waters (Zencich et al. 2002), or River Red Gum forests fed by subsurface waters (Catelotti et al. 2015); not to be confused with terrestrial ecosystems that occasionally rely on groundwater (Hatton and Evans 1998, Boulton 2005, and Kløve et al. 2011).	Canyon National Park, Arizona, USA
10. Limnocrene	Focused flow, gravity-driven, pool-forming, generally lentic, forming from fissure, depression, or contact contexts (Meinzer 1923, Odum 1957); Can contain acidic (e.g., some GDE bogs) or geothermal waters (e.g., Dianas Punchbowl, central Nevada and other Great Basin geothermal lakes; prairie potholes are sourced, in part, from groundwater, and some are examples of limnocrenes; ephemeral limnocrenes are recognized; limnocrenes can be confused with carbonate mound springs.	Perennial; ephemeral; anthropogenic (GDE livestock watering tanks, mine pits, quarries, etc.); perennial GDS pools and lake; paleosprings; lacustrine GDE mires; rheolimnocrene (springbrook channel pools; Glazier 2014).	Depressions, sinkholes (Bryan 1919, Meinzer 1923); lacustrine wetlands or aquatic bed wetlands (Odum 1957, Cowardin et al. 1979); GDE ponds, pools, tanks, quarries (anthropogenic), or lakes (Colvin et al. 2007, Kløve et al. 2011, Schutten et al. 2011, Bertrand et al. 2012); acid limnocrenes (Bertrand et al. 2012); prairie potholes (northern Great Plains in North America (Sloan 1972; ephemeral GDE pools in Ireland, referred to as turloughs, existing across a dry-wet continuum (Visser et al. 2006), and not to be confused with U.S. vernal pools, which are sourced from surface water.	Silver Springs, Marion County, Florida, USA (Odum 1957); King Spring, Ash Meadows National Wildlife Refuge, southern Nevada
11a. Mound, mineral precipitate	Diffuse or focus, gravity-driven inflow resulting in precipitation of secondarily derived minerals, from or around which groundwater emerges and usually flows, potentially with both lentic and lotic flows,	Precipitate mounds can form in depression, sinkhole, tubular, fissure, fracture, or joint geologic structures (Meinzer 1923, Fetter 2001, Bryan 1919); erroneously keying to riverine or lacustrine wetlands in Cowardin et al. (1979); often called ponds or lakes (Schutten et al. 2011).	Collapsed mound; geyser; fountain; iron fen; limnocrene; depression, sinkhole, tubular, fissure, fracture, or joint springs (Bryan 1919, Meinzer 1923, Fetter 2001); paleosprings; ponds or lakes (Schutten et al. 2011); potentially ephemeral.	Montezuma Well, Rimrock, Arizona, USA (Blinn 2008)
11b. Mound, ice (not illustrated)	Diffuse flow, gravity-driven, generally lentic; forming in permafrost-dominated landscapes by seepage and freezing of emerging groundwater.	Helocrene, limnocrene (when melted).	Artesian ice mounds, pingos = ice mound upthrust or hydrolaccolith (van Everdingen 2002), cryolaccoliths, cryocrenes; aufweis (groundwater ice sheet).	–
11c. Mound, organic (not illustrated)	A diffuse flow, gravity-driven, generally lentic flow resulting in deposition of organic matter	Helocrene, hillslope, limnocrene.	Mound-forming fen; patterned fen (Cooper et al. 2002).	Mount Emmons Iron Fen, Gunnison County Colorado, USA

Table 2. (Continued)

Springs type	Definition	Common subtypes	Comments and alternate names	Examples
	(e.g., peat mound) that creates a dome form, from or around which groundwater emerges.			
12. Rheocrene	Focused flow, gravity-driven, lotic groundwater emergence in an established channel (a channel exists upstream from the source); emerging on the floors of dry channels or subaqueously in perennial streams; emergence is due to geologic structural constraints on the groundwater flowpath,	Cave, geyser, gushet, hanging garden, helocrene, hillslope, limnocrene, mound-form; most periodic springs and some estavelles occur as rheocrenes; some in-channel palm oases (Cornett 2008); anthropogenic (urban effluent releases and dam tailwaters quasi-function as rheocrenes).	Channel or flowing riverbed springs, derived from fracture, fissure, contact, or seepage geologic structures (Bryan 1919, Meinzer 1923, Alfaro and Wallace 1994, Fetter 2001); lotic springs (Kløve et al. 2011); classified as riverine wetlands, streambed wetlands (with no flowing water), unconsolidated shore wetlands by Cowardin et al. (1979), and as perennial or ephemeral alkaline or acid rheocrene streams (Bertrand et al. 2012); not classified by Quivara Coalition et al. (2014), but hinge-felling wetlands that generate helocrenic conditions in a dammed channel can be rheocrenes; permanent (perennial) riverine aquatic, river baseflow springs (Hatton and Evans 1998, Boulton 2005, Colvin et al. 2007, Schutten et al. 2011, Bertrand et al. 2012); as alluvial forest springs (European Commission 2013); recognized by Eamus and Froend (2006) as GDEs, and as supporting terrestrial fauna; rhythmic or periodic (AKA breathing heart, ebb and flow, pulsing, or siphon) springs can be rheocrenes (Huntoon and Coogan 1987, Mather 2013); some channel palm oases (Cornett 2008).	Subaqueous Lava Tube Spring, upper Rio Grande River, northern New Mexico (Bauer and Johnson 2010); Periodic Spring, Wyoming (Huntoon and Coogan 1987); Villa Pliniana Spring, Como, Italy (Pliny the Eder 77)
13. Paleospring (not illustrated)	A flow-focused, gravity-driven, now-dry but much formerly a flowing, carbonate, or other springs ecosystem type, typically pre-Holocene in age, and bearing fossilized evidence of past ecosystem function; limnocrenes and collapsed carbonate-mound springs may contain evidence of paleosprings fossils as well; paleosprings may be identified by past, or current, mineral deposits if emanating from karst terrain, or paleopeat deposits.	Travertine deposits, carbonate mound.	Fossil springs; quaternary cauldron springs (Haynes 2008); fissure, fracture springs (Bryan 1919); paleotravertine springs (e.g., Blackwood et al. 2017).	Central Arbuckle Mountains, Oklahoma, USA; marine Great Blue Hole, Lighthouse Reef, Belize

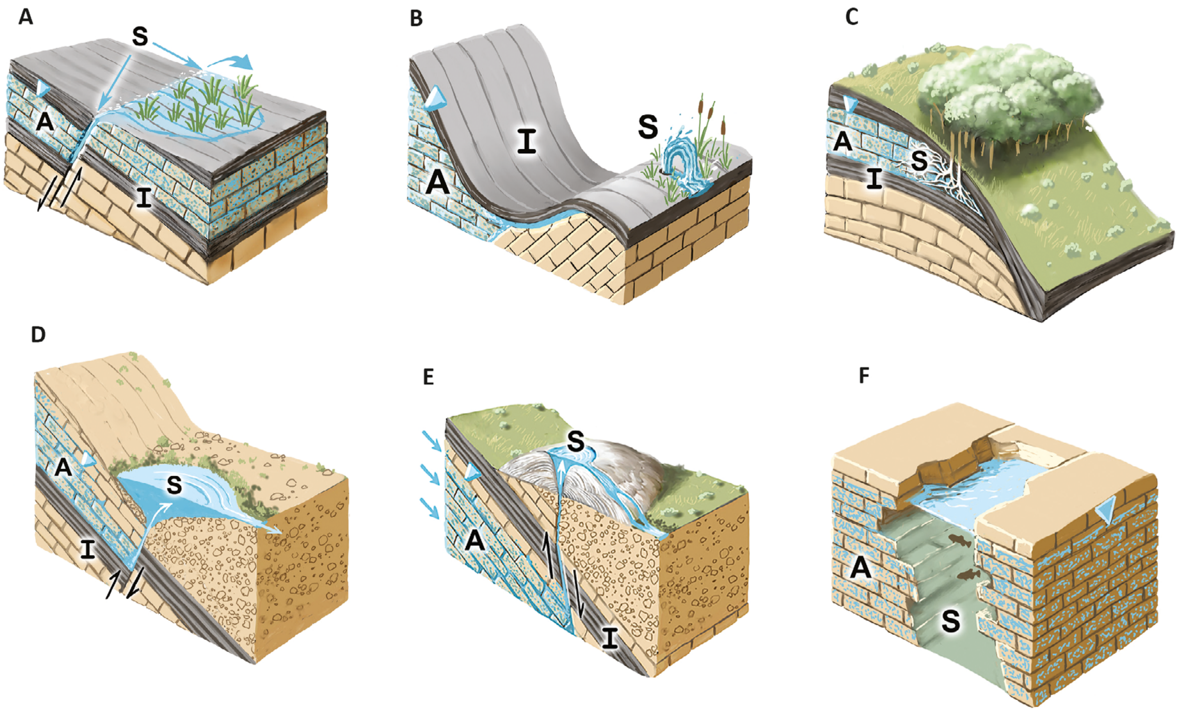

FIG. 2. Lentic springs types, including (A) helocrene, (B) fountain, (C) hypocrene, (D) limnocrene, (E) mound-forming, and (F) semi-lotic fountain springs. A on each figure stands for aquifer, I, impermeable infiltration barrier (aquitard); S, surface groundwater expression (springs source). Illustrations conceived by L. E. Stevens and redrawn from Springer and Stevens (2009) by Victor Leshyk.

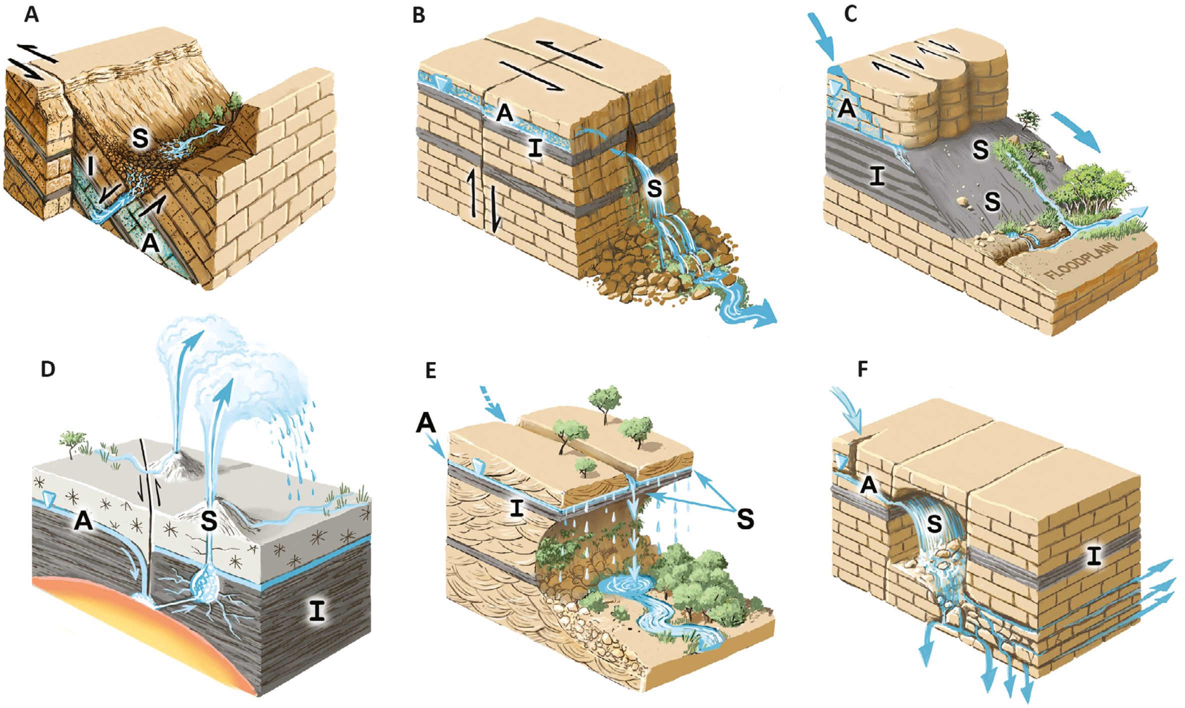

FIG. 3. Lotic springs types, including (A) rheocrene, (B) gushet, (C) floodplain vs. upland hillslope, (D) geyser, (E) hanging gardens, and (F) cave springs. A on each figure stands for aquifer, I, impermeable infiltration barrier (aquitard); S, surface groundwater expression (springs source). Illustrations conceived by L. E. Stevens and redrawn from Springer and Stevens (2009) by Victor Leshyk.

Table 3. Testing results of the springs ecosystem dichotomous key (Table 1) based on source geomorphology.

Type	Correct	Total	Percent correct
Cave	13	13	100.0
Exposure	4	5	80.0
Fountain	1	1	100
Geyser	1	1	100
Gushet	13.5	16	84.4
Hanging garden	27	31	87.1
Helocrene	28	32	87.5
Hillslope (floodplain vs. upland)	47	56	83.9
Hypocrene	12	13	92.3
Limnocrene	25.5	30	85.0
Mound (carbonate, organic)	14.5	16	90.6
Rheocrene	26	30	86.7
Total	212.5	244	87.5

Notes: Randomly selected non-sensitive springs were selected of 12 terrestrial springs types, and tested to determine whether the key correctly identified them. Sample sizes vary in relation to availability of information on individual springs types.

microhabitats, but which collectively contribute to the biodiversity of the individual springs ecosystem. Microhabitat heterogeneity can be measured as the number and area of microhabitats through the use of diversity metrics, such as the Shannon-Weiner diversity index, or through more complex geometric edge-effect methods (Stevens et al. 2016b).

Microhabitat diversity at springs has ecological consequences for springs ecosystems and stewardship. After accounting for expected species-area effects, microsite diversity has been shown to be positively related to vascular plant richness, as well as land gastropod diversity at springs in western North America and elsewhere (Spamer and Bogan 1993; Springer et al. 2015, Ledbetter et al. 2016). Thus, the area of the springs-influenced habitat and microhabitat heterogeneity are important variables influencing springs biodiversity. Such relationships also can influence stewardship planning and implementation, as larger, more geomorphologically diverse springs may warrant increased management attention. However, isolation also may an important management consideration, as isolated springs may play larger roles as keystone ecosystems, particularly in arid regions.

Conclusions

The need for scientific agreement on the classification of springs is great and long overdue. Nearly all springs ecosystem authorities around the world expound on the biodiversity, socioeconomic importance, and profoundly imperiled status of these ecosystems (Fensham and Fairfax 2003, Stevens and Meretsky 2008, European Commission 2015, Kreamer et al. 2015, Knight 2015, Cantonati et al. 2016; Cantonati et al., 2020a. Nonetheless, springs remain remarkably poorly mapped and inventoried throughout most regions of the world, a failure that stymies analysis of rare springs types, the distribution and status of springs-dependent species, and the refugial potential of springs under changing climates (Stevens and Meretsky 2008, Cartwright et al.2020). The lack of scientific consensus on springs classification has constrained compilation of basic information on springs ecosystem ecology, diversity, distribution, importance, status, and threats. This, in turn, has led to the lack of public and governmental awareness of, and attention to springs, directly contributing to the global demise of these important ecosystems (Cantonati et al., 2020a).

Springs ecosystem classification based on source geomorphology is the least ambiguous means of differentiating among diverse springs types. Expanding Meinzer's (1923) "sphere of discharge" approach to include the entire springs-influenced, geomorphologically defined, source area provides the opportunity for spatially explicit physical description of springs ecosystems. Other classification approaches, such as those proposed for aquifers, flow, water quality, landscape location, biota, and management/policy approaches, are insufficiently explicit to distinguish discrete springs types. For example, landscape location approaches do not distinguish individual springs types, and biotic approaches (e.g., those based on algae, macrophytic vegetation, or aquatic macroinvertebrates) in success, in part due to contrasting patterns of nestedness among some taxa and idiosyncratic patterns among others. Habitat area also is important, but neither it nor anthropogenic use clearly distinguish discrete springs types. We note that humans have manipulated many springs, and can create any springs type, some of which have the functional attributes of springs. Our source geomorphology classification approach also readily lends itself to description of ecosystem change over time, including the manner and extent of anthropogenic alteration, and it allows for spatial quantification of associated microhabitats. Such information is critical for informed stewardship assessment, planning, implementation, and monitoring (e.g., Paffett et al. 2018).

Our classification system provides the opportunity to (1) recognize relatedness among different types of springs, (2) determine where rare or endemic springs and SDS are likely to occur, (3) distinguish geomorphology influences on assemblage composition and ecosystem function, and (4) clarify stewardship options, which vary by springs type and influence management planning, implementation, monitoring, and maintenance (Stevens et al. 2016a). The Springer and Stevens (2009) classification system has been successfully used by the U.S. Forest Service in its national springs inventory program (U.S. Forest Service 2012), and by more than a dozen U.S. Bureau of Land Management and U.S. National Park Service land units, as well as on several large Tribal and Department of Defense reservation, other federal land units, by the states of New Mexico and Nevada, and in

TABLE 4. Probability of occurrence of different geomorphic microhabitats among springs types: Lo, low; Med, medium; Hi, high likelihood of occurrence.

												Wet meadow gradient		Occurrence		
Spring type	Backwall	Cave	Channel (wet)	Colluvial slope	Hyporheic or sublacustrine bio-zone	Madicolous flow	Mound	Pool	Sloping bedrock	Spray (mist), drip, or splash zone	Fluvial, palustrine, or lacustrine terrace or margin (peripheral wetlands)	Low	High	Likely	Possible	Unlikely
Cave	med	hi	hi	lo	lo	med	lo	med	hi	med	med	lo	lo	3	5	5
Exposure	med	lo	lo	med	med	lo	lo	hi	hi	lo	med	lo	lo	2	4	7
Fountain	lo	lo	med	med	lo	lo	med	med	med	med	med	hi	lo	1	7	5
Gushet	med	hi	hi	hi	med	hi	lo	med	hi	hi	hi	med	med	7	5	1
Geyser	lo	lo	med	lo	lo	hi	hi	med	hi	hi	med	med	lo	4	4	5
Hanging garden	hi	lo	hi	hi	med	med	lo	hi	hi	med	hi	lo	med	6	4	3
Helocrene	lo	lo	med	lo	med	lo	med	med	lo	lo	hi	hi	med	2	5	6
Hillslope-floodplain	med	lo	hi	med	hi	med	lo	med	med	lo	hi	med	med	3	7	3
Hillslope-upland	med	lo	hi	hi	med	med	lo	med	med	lo	hi	med	med	3	7	3
Hypocrene†	lo	lo	med	med	lo	lo	med	lo	med	lo	hi	med	med	1	6	6
Limnocrene	med	lo	hi	med	med	lo	lo	hi	med	lo	hi	hi	lo	4	4	5
Mound-Form																

(precipitate)‡medlohimedmedlohihihilohimedmed553Rheocrenemedlohimedhilolohimedlohimedlo445High likelihood1283222563930---------Medium likelihood8047743762477---------Low likelihood41113478118036---------

[†] Hypocrenic conditions often occur with distance away from the source, and in response to declining groundwater table stage elevation, either from natural decreases in recharge or due to anthropogenic depletion.

[‡] Microhabitat characteristics of chemical precipitate mound-form springs data are presented here, but not those of organic- or ice-mound springs due to a lack of available data.

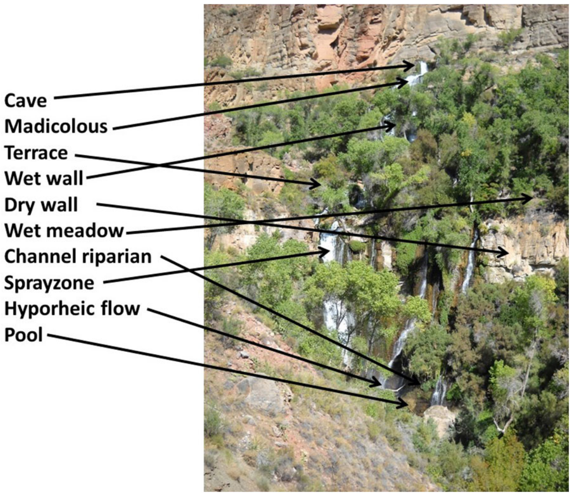

FIG. 4. Springs geomorphic microhabitats at Thunder River Spring, Grand Canyon, Arizona, USA.

Canada and Mexico. Thus, interest and use of this synthetic approach to springs classification system is growing, and we welcome consideration and testing of it.

Society looks to ecologists and hydrogeologists to provide a clear, unified definition, lexicon, classification, and management guidance to improve understanding and best practices for conservation and management of springs, as well as the aquifers that support them. Rather than legislating management of springs, improved stewardship may be more harmoniously achieved in a non-jurisdictional fashion by promoting education and incentivizing springs owners to better balance sustainable ecosystem management with socioeconomic uses and needs. However, the foundation of such policy advisement must include scientific ecohydrogeologcial consensus on lexicon and classification, interdisciplinary agreement that is needed to prevent further degradation and loss of essential groundwaters and their remarkable, species-rich, and highly threatened surface expression as springs.

ACKNOWLEDGMENTS

Funding for portions of this manuscript was provided, in part, by the U.S. National Park Service (for an early version of the conceptual model), the New Mexico Environment Department (Contract ID 18-667-2060-0011), and through joint support from the U.S. Bureau of Reclamation and U.S. Fish and Wildlife Service Landscape Conservation Cooperative (R13AP80031). We thank the Museum of Northern Arizona and its Springs Stewardship Institute staff, particularly Jeri Ledbetter, Gloria Hardwick, Andrea Hazelton, Jeff Jenness, Alek Mendoza, and Tierney Schipper for assistance with testing the key and for administrative, geographic, and editorial support. Victor Leshyk graciously redrew the springs illustrations. We also thank Northern Arizona University School of Earth & Sustainability for supporting A. E. Springer's research. G. Rink, L. Crossey, and two anonymous reviewers provided insightful and much-appreciated comments on earlier versions of the text.

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DATA AVAILABILITY

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.r2280gb9w