The Ecological Integrity of Spring Ecosystems: A Global Review

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Abstract

Springs are ecosystems influenced by the exposure of groundwater at the Earth's surface. Springs are abundant and have played important, highly interactive ecological, cultural, and socio-economic roles in arid, mesic, and subaqueous environments throughout human evolution and history. However, springs also are widely regarded as being highly threatened by human impacts. Cantonati et al. (2020a) recommended increased global awareness of springs, including basic mapping, inventory and assessment of the distribution and ecological integrity of springs. We conducted a preliminary global analysis on the ecological integrity of springs by reviewing information on the distribution, ecohydrogeology, associated species, kinds and intensity of human uses, and level of ecological impairment of spring ecosystems. We reviewed information on an estimated 250,000 spring ecosystems among 78 countries across much of the world. Available literature on spring ecological integrity is sparse, widely scattered, and spatially erratic, with major gaps in knowledge. We report large differences in the quality and extent of information among countries and continents, with only moderate data availability even among developed countries, and limited information across most of the developing world. Among countries with available data, ecological impairment of springs is everywhere rampant, sometimes exceeding 90% in developed regions. Impairment among Holarctic nations is generally negatively related to distance from human development, elevation, and latitude, but such patterns are less evident in Africa, Australia, and South America. Declining trends in ecosystem condition, compounding threat factors, and spring-dependent population declines, extirpation, and extinctions of plants, invertebrates, fish, and herpetofauna are widely reported. Overall, available information indicates a global crisis in spring ecosystem integrity, with levels of ecosystem impairment ranging from Vulnerable to fully Collapsed. The threats to aquifers and the ecological integrity of springs vary spatially. Many springs are impaired by local impacts due to flow diversion, geomorphic alteration, land use practices, recreation impacts, and the introduction of non-native species. These threats can be reduced through education, rehabilitation of geomorphology and habitat quality, and species reintroductions if the supporting aquifer remains relatively intact. However, springs also are widely threatened by regional to global factors, including groundwater extraction and pollution, as well as climate change. Such coarse-scale, pre-emergence impacts negatively affect the sustainability of spring ecosystems and the aquifers that support them. Improving understanding and stewardship of springs will require much additional systematic inventory and assessment, improved information management, and reconsideration of basic conservation concepts (e.g., habitat connectivity), as well as cultural and socio-economic valuation. Substantial societal recognition, discussion, and policy reform are needed within and among nations to better protect and sustainably rehabilitate springs, their supporting aquifers, and the spring-dependent human and biotic populations that depend upon them.

Introduction

Spring ecosystems are subsurface-surface linked groundwater-dependent systems influenced by the exposure of groundwater at the Earth's surface in subaqueous as well as subaerial environments (Glazier, 2014; Stevens, 2020). Springs are globally abundant, with estimated numbers in the tens of millions, and springs are geomorphologically diverse, ranging from slow diffuse seepage through forest floors to massive karstic outflows. Springs provide headwater baseflows for most streams and rivers in non-ice-dominated landscapes, they sometimes feed lakes, and many emerge in marine profundal settings (Moosdorf, in Stevens et al., 2021a). Perennial springs can have high levels of productivity (e.g., Odum, 1957) and support large numbers and concentrations of spring-dependent taxa (SDT), including many endemic and rare species (e.g., Botosaneanu, 1998; Rossini et al., 2018). Springs also can be highly ecologically interactive, biologically diverse, ecologically individualistic, and socio-culturally significant ecosystems. They often play critical ecological, evolutionary, landscape, socio-cultural, and economic roles both internally and in relation to adjacent landscapes (Stevens and Meretsky, 2008; Krešić and Stevanović, 2010; Glazier, 2014; Cantonati et al., 2020a, 2020b). Despite their importance, springs are highly threatened by human activities: studies of springs and their associated SDT commonly report declining ecological and population conservation status due to direct and indirect anthropogenic impacts, including locally and regionally increasing demands for groundwater, groundwater pollution, habitat modification or loss, SDT population declines and extinction, and global climate change impacts (Rossini et al., 2018; Cantonati et al., 2020a). However, if the supporting aquifer is relatively intact or can be rehabilitated, impaired spring habitats and some SDT populations can be relatively readily rehabilitated (e.g., Rossini et al., 2018).

In response to globally limited conservation attention to springs, Cantonati et al. (2020a) advocated for improved scientific, public, and managerial awareness of these ecosystems across spatial scale, including development of consistent conservation assessment and policy, additional ecohydrogeological research, and the development of practical stewardship methods for springs. Pivotal to their argument was the high bio-cultural value of springs, the imperiled status of these ecosystems, and the need to overcome the deficiency of data on springs distribution and ecological integrity across geo-political boundaries, including in subaqueous marine settings. Recent advances in springs research and conservation are noteworthy: (1) several developed nations (e.g., Australia, Finland, Germany) have elevated national stewardship attention to the natural and socio-cultural significance of springs; (2) the Ramsar Convention on Wetlands (2018) identifies springs as inland wetlands (codes Y and Zg); and the European Union (EU) recognizes travertine-depositing springs as a resource of conservation concern. However, widespread deficiency of information about the distribution and condition of spring ecosystems has heretofore limited international assessment. In this paper we present the first global assessment of the ecological integrity of springs by reviewing information on the distribution, ecohydrogeology, associated species, extent of human use, and level of ecological impairment.

Ecosystem assessment is one of several important steps in ecosystem stewardship (Stevens and Meretsky, 2008):

> Establish long-term administrative context ➔ Inventory and information management ➔ Assessment ➔ Planning ➔ Implementation ➔ Monitoring and feedback.

This formula places individual stewardship components, such as assessment, in context to the goal of sustainable resource management. Over the past decade, the International Union of Conservation of Nature (IUCN) has promoted systematic, comparative assessment of the status of the world's ecosystems, including assessment and modeling of changes in ecosystem distribution, habitat quality, and biotic integrity. The IUCN has used this approach to develop the Red List of Ecosystems (RLE; e.g., Bland et al., 2017), which is well-designed for assessment of broadly distributed ecosystems (e.g., forests, grasslands, lakes, large rivers, or lakes) with known histories of fragmentation and loss of area, physical habitat alteration (e.g., by pollution), and the loss of some species and assemblages. It has been used with modification on European springs (e.g., Finland; Ilomen in Stevens et al., 2021a), but with varied success elsewhere due, in part, to the fundamental deficiency of geographic and assessment data.

An array of practical and conceptual issues complicate the use of IUCN RLE and other approaches spring conservation assessment. In addition to the 10 issues presented in Table 1, spring ecosystem assessment also presents basic conceptual challenges to Western conservation assessment. Improving conservation of abundant, insular, island-like ecosystems like springs may require a "mosaic" approach that provides proportional protection of various spring types. Such an approach also may require the use of metrics that are unique to springs or other archipelago-like ecosystems. And although connectivity often is regarded as an essential goal for habitat and population conservation in large ecosystems, springs are naturally small, insular habitats that often display reduced natural inter-spring connectivity. Springs often may be protected by their isolation from, for example, colonization by invasive aquatic species. Lastly, close evolutionary and contemporary association of humans with springs (Table 1, Issue 8) may require a socio-ecologically integrated ("humans-in-nature") approach that applies specifically to springs assessment. Such conceptual considerations warrant far more scientific and societal discussion before an assessment protocol for springs can be widely accepted.

Here we provide a preliminary analysis of the ecological condition of the world's springs. We conducted a review of available information on ecosystem distribution, uses, threats, conservation status, and trends at regional, state/provincial, national, and continental scales. We developed summaries of information on the distribution, ecohydrogeology, and level and cause of endangerment of springs (Stevens et al., 2021a). We summarized the results of these literature-based synopses to address, at least qualitatively, assessment of the levels and causes of spring ecosystem endangerment. We use our results to propose strategies for study site selection and a more refined and spring-specific assessment approach to advance research and stewardship that can then be related to RLE assessment. Due to data limitations, our analyses are primarily based on political boundaries, rather than on aquifers or spring types (Stevens et al., 2021b), except in the few studies where such data were available. We regard this initial summarization as a first step in the larger effort to assemble and interpret global information on the ecological integrity of springs: summaries for many nations remain outstanding, and we hope additional authorities on spring ecohydrogeology around the world will become involved in this effort. All such experts are invited to contribute synopses and data to summarize spring conservation status, and update or elaborate upon existing information. The Springs Stewardship Institute website (SpringStewardshipInstitute.org) provides a convenient portal though which to present additional information and references, and through which to update, monitor, and assess the status of the world's springs.

Table 1 Issues that complicate conservation assessment of spring ecosystems.

1. Despite Odum's (1957) seminal trophic analysis of Silver Springs in Florida, scientific recognition and study of springs as ecosystems has been relatively recent, with much and on-going debate among hydrogeologists and ecohydrologists about lexicon, classification, inter-ecosystem interactivity, and conservation significance (Cantonati et al., 2020a, b; Glazier, 2014; Ramsar Convention on Wetlands, 2018; Stevens et al., 2021a).
2. Springs typically are small, insular habitats, usually <0.1 ha in area, and make up little total area within landscapes, typically $<0.01\%$ (Glazier, 2014; Stevens, 2020).
3. Spring density is greater in topographically complex landscapes than in flatland biomes: many emerge on hillslopes, from cliff faces, in heavily vegetated landscapes, or on the floor of streams or lakes, settings that make springs difficult or impossible to detect in remotely-sensed landscape analyses.
4. As a consequence of (2) and (3), springs often go undetected in regional landscape analyses (Cantonati et al., 2020a). Basic mapping data of the distribution of springs is nearly universally low in quality, a geographic data deficiency that constrains ecosystem conservation assessment.
5. Springs are usually mapped as points, but often internally contain a quiltwork of geomorphic microhabitats that are influenced by (e.g., pools, backwalls, terraces, etc.). Each within-spring microhabitat can support discrete assemblages, collectively contributing to intrinsic ecosystem geomorphic diversity and elevated biodiversity (Stevens et al., 2021b).
6. Despite their limited area, springs often are significant, ecologically highly interactive hotspots of biotic and socio-cultural diversity (Stevens and Meretsky, 2008; Glazier, 2014; Cantonati et al., 2020a), and disproportionally contribute to regional ecological integrity as "keystone ecosystems," with considerable complexity of trophic subsidy exchange. Springs of the same type in close spatio-temporal proximity often share low proportions of similar taxa and habitat patches, contributing to low within-spring β-similarity, but high inter-spring γ-diversity (Cantonati et al., 2020b; but see Kodrick-Brown and Brown, 1993 for ordered spring-dependent fish assemblage structure).
7. Intrinsic structural "ecosystem individuality" and within-spring trophic interactivity vary substantially among springs, but has been examined in only a small number of springs and not among spring types. Spring ecosystem studies have been conducted at exceptional sites, such as large limnocrenes (e.g., Silver Springs in Florida, USA; Odum, 1957) or at hot springs, but less often on common and abundant spring types. In addition, long-term monitoring data that establish ranges of natural conditions are rare. Biotic studies often have focused on individual characteristics or SDT, such as individual fish or mollusk taxa, rather than across entire spring assemblages (Stevens, 2020).
8. Spring ecosystems have long, even evolutionary, histories of human use (Stevens and Meretsky, 2008; Cuthbert and Ashley, 2014), requiring reconsideration of the use of "pristine" reference conditions in relation to long-term conservation goals. Establishment of an unaltered baseline condition of springs is often impossible, particularly in Africa, Eurasia, and Oceania/Australasia because of the intensity and duration of Neogene homonin use.
9. Most spring ecosystem research is conducted within local, state, provincial, or (rarely) national boundaries, but not in relation to the supporting aquifers, which often cross multiple jurisdictions.
10. High levels of locally endemic spring-dependent (crenobiontic) algae, plants, mollusks, aquatic insects, other invertebrate phyla, fish, herpetofauna, and some mammals throughout the world indicate that springs and their associated assemblages have been resilient to natural occasional and brief disturbances, including megafaunal wallowing, fire, gradual climate change, and other low-moderate level Pleistocene–Holocene habitat changes and impacts. However, the spate of recent SDT extirpations and extinctions indicates that modern anthropogenic impacts, such as groundwater depletion or pollution often exceed the normal tolerance limits of native SDT, particularly endemic or rare taxa.

Methods

Information sources

The literature on the ecological integrity of springs across broad spatial scales is limited in extent, and is presented in a wide array of reports that vary in accessibility, spatial scope, protocols, and language. These constraints make a review and integration of global information challenging. We developed a collaborative network of authorities from around the world, inviting each to provide a synopsis of available information on the distribution, aquifer sourcing, attributes, goods and services, values, uses, and ecological integrity of springs in their study areas (Stevens et al., 2021a). Many countries and regions remain under-represented, particularly the Russian Federation, China, and many individual countries in South America, Africa, Southeast Asia, and Oceania, as well as in polar regions.

Following development of individual syntheses by the collaborating co-authors, we conducted a meta-analysis to assess the extent and kinds of threats reported to affect springs in the co-authors' study areas, as well as the quality or adequacy of information in relation to the RLE criteria (Bland et al., 2017). RLE criteria include: (A) reduction in geographic distribution; (B) restricted geographic distribution; (C) environmental degradation; (D) disruption of biotic processes and interactions; and (E) quantitative risk modeling analysis. For each criterion in each region or country where data permitted, the status of springs was assessed in relation to eight categories of ecological integrity, including: Not Evaluated, Data Deficient, Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered, or Collapsed. Category scores followed, where possible, recommendations of Bland et al. (2017). However, the severity of data deficiency often precluded quantification so, in many cases only qualitative scores of "low," "moderate," or "high" levels of endangerment were applied.

Anthropogenic threats to springs were described in our individual regional or national write-ups. We analyzed types of anthropogenic disturbances to springs described using a modified Salafsky et al.'s (2008) typology, adding or clarifying several spring-specific stressor subcategories, including: Category 1 Development - subsistence, urban, and industrial water supplies development; Category 2 Agriculture and Aquiculture - direct and indirect livestock use; Category 3 Energy and Mining - groundwater extraction/depletion; Category 6 Intrusion, Disturbance - recreation, balneotherapeutic, spiritual, and scientific uses; Category 8 – Non-native Species - aquatic versus terrestrial invasive species introduction; and Category 9 Pollution - groundwater versus surface water pollution (Table 2).

Table 2 Anthropogenic and natural disturbance factors affecting ecosystems, with examples, spatial scope, and global impact intensity on springs.

Disturbance	*Examples for springs*	*Spatial scope*	*Impact intensity*
1. Development			
1.1 Water supplies development	Extraction and use	Local and regional	High
1.11 Potable subsistence supplies, including diversion	Off-source delivery of water supplies	Local	High
1.12 Urban water supplies	Urban potable water supplies (e.g., Vienna)	Regional	High
1.13 Commercial, industrial	Extraction or use for commercial water sources (e.g., water bottling, fish hatcheries, fountains, water sources for construction)	Local and regional	Moderate
1.2 Tourism and recreational development	Geothermal spring resorts	Primarily local	High
1.3 Collateral construction impacts	Non-water supplies construction (e.g., construction of housing or roadways over springs)	Local	Low-Moderate
2. Agriculture and Aquaculture			
2.1 Crops, nontimber	Diverse land and species management issues	Primarily local	Low
2.2 Forestry - tree plantations	Afforestation	Local and regional	Low
2.3 Livestock	Livestock use (grazing, watering, trampling, sedimentation, pollution)	Local	Very high
2.31 Livestock-direct impacts	Cattle watering, trampling, sedimentation, pollution,	Local	Very high
2.32 Livestock indirect impacts - diversion for livestock use	Diversion for livestock watering	Local	Very high
2.4 Wildlife management	Livestock water	Local	High
2.5 Aquaculture	Fish hatcheries	Local	Moderate
3. Energy and Mining			
3.1 Oil and gas	Hydraulic fracturing	Local and regional	Moderate
3.2 Mining	Groundwater pumping from mines; mineral extraction	Local and regional	High
3.21 Mineral extraction	Mineral extraction	Local	High
3.22 Groundwater extraction/depletion	Well drilling, mine draining	Local and regional	Very high
3.23 Water bottling	Bottled water production	Local	Moderate
3.3. Geothermal	Piping, pumping for hydroelectric production and heating	Local and regional	High
3.4 Renewable	Diverse land and species management issues	Primarily local	Low
4.Transportation, Services			
4.1 Roads, railroads, trails	Construction, operation	Local	High
4.2 Utility lines	Construction	Local	Low
4.3 Shipping	Few impacts	Local	Low
4.4 Flight paths	See noise pollution	Local and regional	Low
5. Biological Resource Use			
5.1 Hunting (animals)	Hunting, burning	Local and regional	Very high
5.2 Gathering (plants)	Harvest	Local and regional	High
5.3 Logging	Tree removal	Local and regional	High
5.4 Fishing	Population depletion	Local and regional	High
5.5 Predator removal	Loss of large predators	Local and regional	High
6. Intrusion, Disturbance			
6.1 Visitation	Human presence	Local	High
6.11 Recreation	Human presence, resource removal	Local	High
6.12 Balneotherapy	Human presence, water control	Local	High
6.13 Spiritual uses	Human presence, various uses	Local	Moderate
6.14 Scientific study impacts	Research and scientist visitation; translocation of diseases (e.g., chytrid fungi transmission); over-harvest	Local	Low
6.2 War	Reliance on alternative water sources	Local and regional	Low
6.3 Work	Noise, trampling, etc.	Local and regional	Low

(*Continued*)

Table 2 (Continued)

Disturbance	*Examples for springs*	*Spatial scope*	*Impact intensity*
7. Natural System Modification			
7.1 Fire (frequency, intensity), fire suppression	Burning springs to drive game; increased upland tree cover	Primarily local	High
7.2 Flow regulation	Flow abstraction, general	Local and regional	Very high
7.21 Draining, dewatering	Draining for agriculture or development	Local and regional	Very high
7.22 Inundation	Augmenting flow or inundating the source	Primarily local	Moderate
7.3 Geomorphic alteration	General	Local	Very high
7.31 Focused discharge	Focusing discharge	Local	Very high
7.32 Erosion	Loss of soils, inorganic substrata	Local	High
7.33 Excavation	Tunnelling (e.g., shallow wells, qanats)	Local	High
7.34 Aggradation	Addition of soils, inorganic substrata	Local	Low
7.35 Landform modification	Reshaped landforms	Local	Very high
7.4 Vegetation modification	Removal or planting; afforestation	Local and regional	Very high
8. Non-native Species			
8.1 Invasive NN species	Aquatic, wetland, terrestrial NN spp.	Local	Very high
8.11 Aquatic NN species	Vegetation; Mollusca, crayfish, other invertebrates, fish, amphibians	Local	Very high
8.12 Terrestrial NN species	Vegetation; livestock, pets, other NN wildlife	Local and regional	Very high
8.2 Native problem species	e.g., Beaver, other wildlife	Local and regional	Low
8.21 Native aquatic species	Beaver, muskrat, hippopotamus herbivory, trampling	Primarily local	Low
8.22 Native terrestrial species	Native plant incursion; native bird and wildlife impacts	Local	Low
8.3 Genetic modification	Translocation	Local and regional	Low
9. Pollution			
9.1 Sewage	Groundwater and surface water contamination	Local and regional	High
9.11 Groundwater contamination	Pollution of aquifers	Local and regional	High
9.12 Surface water contamination	Surface water contamination	Local and regional	High
9.2 Industrial/military waste	Groundwater and surface water contamination	Local and regional	Moderate
9.21 Groundwater contamination	Pollution of aquifers	Local and regional	Moderate
9.32 Surface water contamination	Surface water contamination	Local and regional	Moderate
9.3 Agricultural Waste	Groundwater and surface water contamination	Local and regional	High
9.31 Groundwater contamination	Pollution of aquifers	Local and regional	High
9.32 Surface water contamination	Surface water contamination	Local and regional	High
9.4 Solid waste	Garbage disposal	Primarily local	High
9.5 Air pollution	Fugitive dust impacts on photosynthesis	Local and regional	Moderate
9.6 Energy waste (e.g., light pollution, noise, etc.)	Ancillary environmental disruption	Local and regional	Moderate
10. Geologic Events			
10.1 Volcanic eruptions	Aquifer, geomorphic disruption	Local and regional	Low
10.2 Earthquakes	Aquifer, geomorphic disruption	Local and regional	Low
10.3 Avalanche, mudslide (and debris flows)	Burial	Primarily local	Low
10.33 Slope failure	Burial by local rockfall	Local	Moderate
11. Climate Change			
11.1 Climate-related habitat shifts	Upland-spring habitat alteration (e.g., through increased wildfire frequency, severity)	Local and regional	High
11.2 Drought	Increased refugial importance; reduced infiltration	Local and regional	Very high
11.3 Thermal extremes	Springbrook habitat alteration	Local and regional	Moderate
11.4 Storms and flooding	Habitat disruption, burial	Local and regional	Moderate
11.5 Aquifer depletion from reduced infiltration	Reduced discharge	Local and regional	Very high
11.6 Sea level rise	Salinization of near-shore aquifers	regional	High

Modified from Salafsky N, Salzer D, Stattersfield AJ, Hilton-Taylor C Neugarten R, Butchart SHM, Collen B, Cox N, Master LL, O'Connor S, and Wilkie D (2008) A standard lexicon for biodiversity conservation: Unified classifications of threats and actions. *Conservation Biology* 22: 897–911.

We recognize the need for much additional and more refined basic geographic and inventory information to advance this preliminary effort to a more complete global assessment; however, the weight of evidence of impairment presented through these synopses strongly indicates jeopardy conditions and a rapid downward conservation status transition among springs in most nations. Additional data will clarify the extent, loss rate, consequences of spring degradation, and rehabilitation options, but such information is unlikely to substantially change the patterns revealed by our analyses.

Results

Overview

We compiled data on springs provided by the co-authors and from the literature on the distribution, aquifer sourcing, goods and services, threats, and ecological integrity of springs from multiple states or regions within some nations and regions. In all, we compiled reports on >250,000 springs from sometimes multiple states or provinces within 78 countries, on all continents except Antarctica (Stevens et al., 2021a; Table 2; Fig. 1).

Basic geographic and status data deficiency was reported by virtually all co-authors, among developed as well as developing nations. Nonetheless, nearly all reports included reference to moderate to long-term human association with springs and high levels of impairment (Table 3). Only a few studies reported springs with a conservation status equivalent to the RLE category of Least Concern, and most reported the status of spring ecosystems ranged from Vulnerable to Critically Endangered, including many examples of Collapsed status. In general, the conservation trajectory of springs was downward, with few nations reporting reduction in the intensity of impairment through policy changes or ecosystem rehabilitation activities. Instead, the number of simultaneously operating stressors appears to be multiplying, thus accelerating habitat and species losses. Below we address the major patterns and data inadequacies revealed through our analyses.

Mapping

Spring ecosystem study, assessment, and conservation require adequate understanding of the distribution, status, and importance of springs; however, virtually all co-authors reported geographic data deficiency, and many reported limited confidence in mapping accuracy. Springs mapping simply has not been conducted in most landscapes, and only anecdotal or private information may be available on spring distribution, typology, and status in most regions. Sources of mapping error commonly include the absence of mapping data, mis-mapping spring locations, misnaming or multiple naming of springs, and failure to detect or report the many previously mapped springs that have gone dry or have been obliterated by anthropogenic activities.

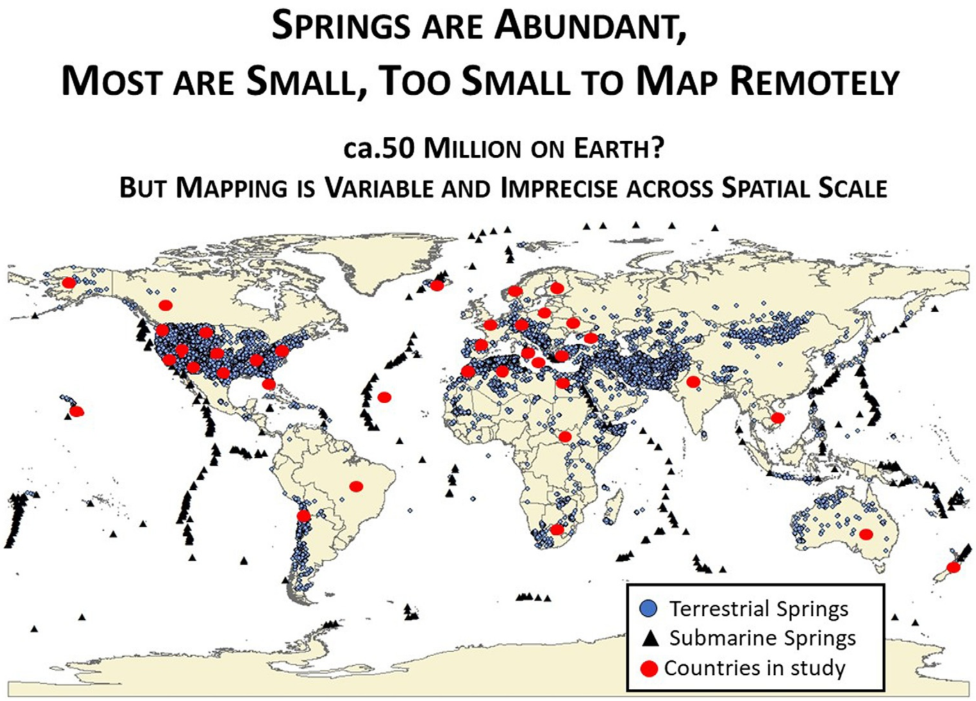

Fig. 1 Preliminary map of the global distribution of springs (black dots are reported terrestrial springs; triangles are reported marine springs). Red dots are states or countries for which co-authors provided data. Map modified from Stevens LE (2020) The spring biome, with an emphasis on arid regions. *Encyclopedia of the World's Biomes* 2: 354–370, doi:10.1016/B978-0-12-409548-9.12451-0.

Table 3 States/provinces, regions, and continents for which data were provided by co-authors, along with area, approximate number of springs, general condition of springs, and impacts on springs described by the co-authors in Stevens et al. (in prep.).

Continent	*Landscape*	*Land Area (km^2)*	*Number of Reported Springs*	*Number of Spring-dependent Taxa*	*Overall or Highest Criterion Endangerment Level*	*Coauthor(s) Report in Stevens et al. (in prep.)*
Europe (EUR)	East-Central Europe	1,045,666	Many	Many	High	Michal Hájek
Europe (EUR)	France, Massif Central	551,695	>440	DD	Moderate-High	Beauger
Europe (EUR)	Germany	357,386	67,279	20	Moderate	Hinterlang
Europe (EUR)	Greece	50,949	3600	DD	High	Mentzafou et al.
Europe (EUR)	Iberian Peninsula	583,254	DD		High	Pascual i Garsaball et al.
Europe (EUR)	Italy	301,340	DD	DD	High	Cantonati et al.
Europe (EUR)	Scandinavia - Finland	338,455	33,000	Few	Low (North), High (South)	Ilmonen
Europe (EUR)	Scandinavia - Iceland	103,000	Abundant	DD	Cold-moderate, Hot-high	Kreiling and Guðmundsdóttir
Europe (EUR)	Scandinavia - Norway	385,207	DD	DD	Low-Moderate	Kapfer, Skaalsveen, and Hassel
Europe (EUR)	Switzerland	41,285	Many	DD	High	Marle
Europe (EUR)	Ireland - Petrifying springs	84,385	Many	DD	High in Lowlands, Low-Moderate in highlands	Lyons
Europe (EUR)	England	244,820	DD	DD	DD	Pentecost
Western Eurasia	Mongolia	1,564,116	DD	DD	DD	–
Western Eurasia	Russian Federation	17,098,242	DD	DD	DD	–
Middle East	Israel	22,145	DD	DD	High	Levine
Africa	North Africa (overview)	30,300,000	DD	DD	High	Saber et al.
Africa	Morocco	710,850	DD	DD	High	Bouchaou
Africa	Siwa Oasis (Egypt)	1600	DD	Dates, other crops	High	Aly
Africa	South Africa	1,221,037	DD	DD	High	Tekere and Tshibalo
Africa	Tanzania	947,303	DD	DD	Moderate-High	Ashley and Norton
Asia	China	9,596,960	DD	DD	DD	–
Asia	India - Indo-Himalayan states	600,000	3560	DD	High	Bhat
Asia	Southeast Asia	4,545,792	DD	DD	High	Holway
Oceania	–	546,863	DD	DD	DD	
Australasia	Australia	7,692,024	Many	Many	Moderate-High	Fensham
Australasia	Australia Great Artesian Basin	1,700,000	Many	Many	Moderate-High	Fensham
Australasia	New Zealand	267,710	Many	Low-moderate	Low-moderate	Death
South America	Brazil	8,515,767	High density	DD	High	Felippe
South America	Northern Chile	105,000	Rare	DD	High	Herrera-Lameli
Central America	General	523,780	DD	Many fish, other taxa	High	Fensham and Guzman
Central America	Mexico	1,972,550	DD	Many	High	Quadri Barba
Central America	Caribbean	222,527	DD	DD	High	Heartsill-Scalley
North America	Canada - Alberta	128,016	Many	DD	Low-Moderate	Springer
North America	USA + CAN-Great Plains	2,900,000	Many	DD	High	Stevens
North America	USA-Arizona	295,234	10,501	>100	High	Stevens et al. (2021b)
North America	USA-California	423,967	21,804	110	High	Stevens
North America	USA Great Basin	541,730	40,000	100+	High	Williams and Sada (2020)
North America	USA + MEX-Colorado River Basin	640,000	20,872	>330	Moderate-High	Stevens et al. (2021a)
North America	USA-Florida	170,312	1132	DD	High	Knight
North America	USA-Kentucky - Green River	104,656	1336	DD	Low-Moderate	Tobin et al.
North America	USA-NV	286,245	25,447	>80	High	Abele (2020) and Williams and Sada (2020)
North America	USA-Northeast	469,630	6785	9	Moderate	Glazier
North America	USA-Ozarks	127,000	6000	355	Moderate-High	Carroll
North America	USA-Pacific Northwest	439,460	DD	DD	Low-Moderate	Perla
North America	USA-Texas	695,662	5600	Many	High	Schwartz et al.
North America	USA-Wisconsin	169,635	400	Several	Moderate	Swanson
Marine Springs	Deep sea (as of 2010)	ca. 1,330,000,000	521	1300	Moderate-High	Stevens
Marine Springs	Shallow coastal	ca. 36,190,000	DD	DD	DD	Moosdorf
Karstic Terrain – Global	Global	ca. 22,545,550	Many	Many	Moderate-High	Goldschneider; Stevanović (2019)

DD = Data deficiency.

Remote sensing mapping of springs has been difficult (Stevens and Meretsky, 2008). Although spring distribution is rather readily detected in arid flatland environments, such as the Great Artesian Basin of Australia (e.g., Rossini et al., 2018), springs in complex landscapes are difficult to detect because: a) scale issues preclude detection (i.e., springs are smaller than the remote sensing pixel size); b) springs in heavily vegetated landscapes typically escape detection; and c) springs are most abundant in complex topography, often emerging on steep slopes or, in the case of hanging garden springs, beneath overhanging rock ledges, settings that make them virtually impossible to detect using remote imaging. Thus, in many situations, springs are difficult to map without costly and time-consuming field work.

Threats

Despite widespread geographic and assessment deficiency of data on springs, several categories of threats were repeatedly mentioned (Salafsky et al., 2008; Tables 2 and 3; Fig. 2). These include agricultural use, particularly livestock watering; abstraction/diversion for potable supplies; groundwater depletion; groundwater pollution; and recreational use. The overall frequency of threats reported was:

> Agriculture, particularly livestock watering > water supplies development = mining/groundwater depletion > groundwater pollution > climate change = geomorphic alteration = visitation/recreation > non-native species invasion > other threats.

Nearly all synopses reported most or all of these impacts as leading causes of spring habitat and species losses. Livestock watering, domestic potable subsistence, geomorphic alteration, visitation, and non-native species invasion are ubiquitous factors with generally localized impacts. Similarly, extensive use of geothermal waters for heating and energy production [e.g., in Iceland, New Zealand, Winnemucca Nevada (USA), and elsewhere], or recreational and balneotherapeutic uses primarily result in localized impacts. Such local impacts often can be managed through minor actions and at low cost. In contrast, climate change impacts, regional groundwater depletion and pollution, large mining operations, and abstractions of urban potable supplies typically are aquifer-wide or regional impacts (e.g., Knight, 2015). Such coarse-scale impacts may be difficult to remedy without sweeping societal policy and stewardship agreements and policy reforms.

Variation among continents

Europe

Although some European countries, particularly in Scandinavia, place significant attention on conservation of springs, all European collaborators reported deficiency of geographic data, as well as information on habitat degradation and loss over the past multiple centuries. For example, prehistoric and medieval deforestation of Central Europe may have augmented groundwater discharge and spring density (e.g., Hájek, in Stevens et al., 2021a). Contemporary patterns of spring habitat degradation are reported as negatively related to latitude and elevation, with greater ecological integrity among springs at upper elevations, at more northerly latitudes, and at greater distance from human development. Travertine springs are recognized by the EU as a rare habitat type, and have been the subject of recent study, but are often reported to be in declining condition. Although basic recognition, mapping, study, and stewardship of all types of EU springs are needed, the attention paid to travertine springs there demonstrates that governance can improve stewardship for at least one type of spring ecosystem.

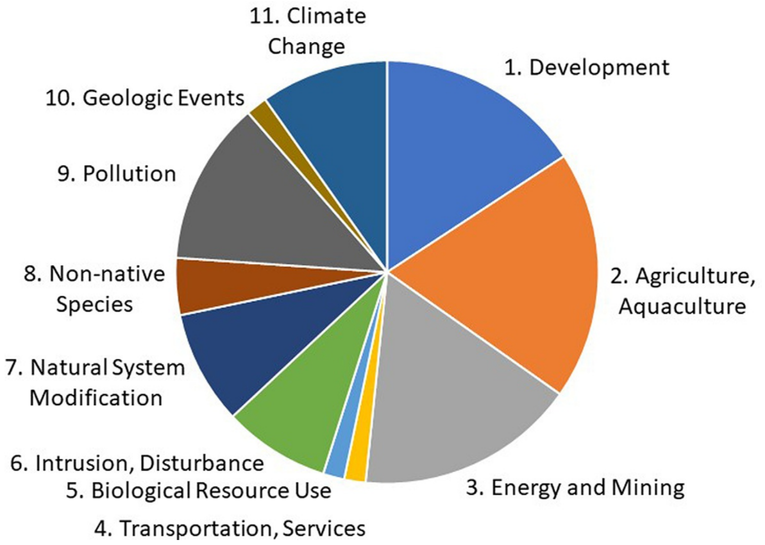

Fig. 2 Pie chart showing relative frequency of anthropogenic and natural disturbances affecting the ecological integrity of springs among regions and continents (data from Stevens et al., 2021a).

Africa and the Middle East

As humanity's homeland, Africa supports springs that likely have been subject to human activities for many tens of thousands of years (e.g., Cuthbert and Ashley, 2014). As in Europe, the Middle East, and likely Eurasia, few large African springs exist that have not sustained substantial anthropogenic impacts over late Neogene time. Recent habitat mapping has been conducted across the continent, as well as in Madagascar (e.g., Thieme et al., 2005). Saharan oases are in a highly endangered state, with some on the verge of collapse due to exploitation of relatively recently discovered Pleistocene aquifers (Powell and Fensham, 2015). Sub-Saharan Sahel wetlands, and African springs and wetlands in general, are critically important for the subsistence of human, as well as avian and wildlife populations, including many poorly known SDT, such as endemic fish and hydrobiid snails (García et al., 2010). Burgeoning human populations, land uses, and both intra- and inter-national conflicts interactively constitute major threats to groundwater and springs throughout Africa, and predicted reduction in precipitation and infiltration due to climate change are exacerbating anthropogenic impacts on springs. Nearly 790,000 km^2 of habitat among 190 Sub-Saharan land units have been designated as Ramsar Convention wetland sites, but basic mapping and long-term monitoring of springs remain data deficient, and spring stewardship often is constrained by other economic urgencies.

Eurasia and India

Although we have yet to encounter substantial information on the distribution and status of springs in the Russian Federation, China, or Mongolia, emerging data from India and other Himalayan countries attests to: (a) the high to enormous intensity of use of springs for subsistence, rural, and urban water supplies; (b) the often degraded status of springs; and (c) growing awareness, concern, research, and interest in rehabilitation of springs. For example, Bhat (in Stevens et al., 2021a) reported that three million springs may occur in the Indian Himalayan Region (IHR), which occupies 600,000 km^2, 15% of India. IHR springs provide many ecosystem services, including drinking water. He estimates that nearly 50 million people in IHR mountain communities rely on springs, with 65,000 (80%) of Sikkim's rural households depending on springs for drinking water and irrigation. Interest in sustainable management and restoration of Indian springs as ecosystems has increased in the past decade. However, data on the distribution and status of springs elsewhere in Southeast Asia remains largely outstanding, although use intensity also is likely high (e.g., Holway, in Stevens et al., 2021a).

Oceania and Australasia

As in many tropical and subtropical regions, the status of springs throughout most of Oceania is poorly known, although use intensity is likely high, particularly on islands where fresh water availability is limited. In contrast, spring ecosystem distribution and status have been intensively studied in Australia and New Zealand, and that information has been used to improve habitat management. Research on Great Artesian Basin springs in east-central Australia over the past half century has clarified hydrogeology and the distribution of the many spring-dependent taxa there (e.g., Rossini et al., 2018; Fensham, in Stevens et al., 2021a). However, less attention has been paid to the many upland and montane springs that provide baseflow sources for Australian perennial streams and rivers. In New Zealand, many coldwater and geothermal springs retain good ecological integrity where they are protected in the conservation estate, which covers 30% of the nation (Death, in Stevens et al., 2021a). However, much of the remainder of New Zealand is undergoing rapid expansion for dairy farming, and small farmland springs and seeps also are heavily influenced by abstraction of water for agriculture, urban drinking water supplies and, more recently, for water bottling. New Zealand geothermal springs are threatened by steam and hot water extraction for thermal baths and power generation. Thus, groundwater quality and quantity have declined among many New Zealand water sources.

South and Central America, and the Caribbean Region

Although human occupation of South and Central America is far more recent than that of the Old World, springs there have been widely and extensively appropriated for the same purposes, and have sustained the same high levels of endangerment. Brazilian springs sustain intensive impacts from urban expansion, livestock and agriculture use, and deforestation (Felippe, in Stevens et al., 2021a), and mining in northern Chile has affected river discharge and water quality (Lameli, in Stevens et al., 2021a). Springs throughout the Andes are intensively used for these same purposes, and geothermal springs there are popular for recreation and balneotherapy (L.E Stevens, unpublished observations). Mexican springs are similarly intensively used for domestic and small-urban water supplies, as well as for irrigation, and livestock management (Quadri Barba, and Fensham and Rodriguez Guzman, in Stevens et al., 2021a, respectively). Like many Latin nations, Mexico retains water rights at the federal level; however, there has been little evidence of sustainable federal stewardship there or in other Central American nations. Caribbean springs also are surprisingly abundant, and some shallow marine freshwater springs contribute to high productivity of mangrove stands. However, many Caribbean springs are subject to intensive human uses as water supplies and for irrigation and livestock management (Heartsill-Scalley, in Stevens et al., 2021a).

North America

Due to water rights policies, spring management in the USA is largely the purview of individual states, with much of the considerable variation in jurisdiction related to appropriative water rights in the arid western states, versus riparian water rights policy in the more mesic eastern and Pacific Northwest states. Among those states with available data, including Wisconsin and the arid southwestern states of Nevada, Texas, and California, most authors report that springs are in degraded or collapsed condition, with declines and multiple recent extinctions among SDT populations (Swanson, Sada, Schwartz et al., and Stevens, in Stevens et al., 2021a, respectively). Agricultural and industrial pollution has become a leading threat to Florida's springs (Knight, 2015; Stevens et al., 2021a). As in Europe, the extent of habitat degradation and SDT population losses generally appears to be negatively related to latitude, elevation, and proximity to human development, with few springs mapped in Alaska and Canada. Water rights to springs are retained at the provincial or federal level in Canada, where livestock management, fish hatcheries, and other water resource developments threaten springs, particularly at lower elevations and latitudes (Springer, in Stevens et al., 2021a).

Discussion

General findings

Although preliminary, our review and literature synthesis of at least 250,000 springs among 78 nations on all continents except Antarctica reveal poor to moderate adequacy of information, even among developed countries, with limited or non-existent information throughout much of the less-developed world (Tables 1, 3, and 4). Nonetheless, the available data and observations by our coauthors demonstrate that springs are globally widely and intensively used but are generally undervalued, and are in declining ecological condition. The available literature and information on spring ecosystem integrity is sparse, widely scattered, and spatially erratic, with major gaps in extent. Our assessment of the ecological integrity of springs constitutes a new frontier in global conservation awareness and study, one fraught with a deficiency of basic geographic and assessment data, a lack of agreement on classification and appropriate protocols, and one that is challenged by basic conceptual problems in conservation ecology (Tables 1 and 4). We report high levels of ecosystem impairment and habitat loss through local/or and regional pre-emergence and post-emergence abstraction of flow, aquifer depletion and pollution, under-informed livestock and irrigation management, development and urbanization, recreational over-use, and climate change. Nonetheless, we emphasize that improved recognition and stewardship of these typically small but disproportionally important ecosystems at local to international spatial scales are likely to produce substantial ecological, cultural, and socio-economic benefits (Cantonati et al., 2020a; Stevens et al. 2021a).

Despite widespread data deficiency, some information on spring conservation status has been compiled in selected regions (Tables 3 and 5). Such studies in northern Europe and North America generally report increasingly degraded or collapsed ecosystem conditions in proximity to human populations, at lower latitudes, at lower elevations, and in arid regions. However, the temporal scale of human impacts on springs is vast, including evolutionary time scale impacts in Africa, and the construction of long-distance canal and water conveyance systems throughout human history (e.g., the Siloam Tunnel from Gihon Spring into Jerusalem, the Roman aqueducts, the Chinese Grand Canal; Solomon, 2011). Recent advances in deep well drilling and mining technology pose substantial and potentially insurmountable threats even to remote terrestrial springs. Overall, springs are increasingly threatened by groundwater pumping and pollution, under-informed land use and management practices (particularly livestock watering), limited monitoring and information management, as well as inadequate policy and enforcement (Cantonati et al., 2020a).

Assessment

Ecosystem assessment requires documentation, trend detection, and/or modeling of the changing distribution of springs, including accurate mapping, monitoring of discharge, water-quality, habitat, and biota in relation to local and regional stressors, as well as consistent, long-term information management. Spring-specific assessment approaches were reviewed by Paffett et al. (2018). Among those, the Springs Stewardship Institute (Ledbetter et al., 2016) spring ecosystem assessment protocols (SEAP) was the most quantitative and comprehensive system. In addition, the associated Springs Online (springsdata.org) database provides a quantitative, spring-specific ecosystem assessment landscape analysis that can be used to identify trends and prioritize landscape-scale and within-spring management actions. Springs Online combines quantitative inventory data and expert opinion-based assessment of the condition and risks to an array of variables related to the supporting aquifer, site geomorphology, habitat, and biotic properties. These natural resource condition scores are contrasted with anthropogenic impacts and risks, as well as the administrative context (anthropogenic and desired condition factors, respectively). The SEAP allows for detailed or general assessment across all spring types in a management area or a nation, and has been used successfully in a variety of arid and mesic settings to prioritize management actions. It also can easily be used for basic monitoring. However, as Paffett et al. (2018) noted, SEAP analysis only provides technical guidance to the steward, and a more thorough discussion about the practicalities of spring management is needed to clarify options. Although a positive contribution towards improving spring stewardship, the SEAP is habitat-specific and is not well-suited to assessment of other ecosystem types.

Many of our coauthors report that the among-ecosystem approach of the RLE (Bland et al., 2017) is difficult to apply to patchily distributed, insular, island-type ecosystems like springs. However, modified RLE protocols have been used in a few nations to assess spring ecosystem integrity. Due to intensive forestry that affected springs during the last century, springs in southern Finland are considered to be Endangered, although those in northern Finland are in a state of Least Concern (Ilmonen in Stevens et al., 2021a). Also, Knight (in Stevens et al., 2021a) reported that among 32 Florida, USA sentinel springs (among the state's 1090 artesian springs) approximately 50% were Critically Endangered (as evidenced either by declining discharge or biotic assemblage integrity), 40% were Endangered, and 10% were Collapsed. He therefore concluded that all sentinel springs, and therefore likely most springs in the state were either Endangered or in a more dire condition. However, data deficiency is the norm for spring assessment, and only a few regions or nations have sufficient basic mapping, monitoring, and groundwater modeling data on which to base conservation evaluation. This means that many springs are at risk of collapse or have already collapsed, but their associated habitat and SDT losses likely have gone unnoticed.

Table 4 Summary of impacts listed referenced by co-authors among various regions and continents.

Continent or Area of Study	*1. Development*	*2. Agriculture, Aquaculture*	*3. Energy and Mining*	*4. Transportation, Services*	*5. Biological Resource Use*	*6. Intrusion, Disturbance*	*7. Natural System Modification*	*8. Non-native Species*	*9. Pollution*	*10. Geologic Events*	*11. Climate Change*
Global Karstic	1		1						5		1
Marine			1			1			1	1	3
Europe	10	7	6	1	1	4	4	1	9		9
Africa	5	4	2			1	1		3		1
Mid-East	1	1	1			1	1	1	1		1
Asia	1		1								
Australasia	3	5						1			
South America	1	2	3		1	1					
Central America		1	1	2		2				1	1
North America	7	16	15		1	6	11	5	4	1	2
Total	29	36	31	3	3	16	17	8	23	3	18

The ecosystem disturbances listed are related to Table 2.

Modified from Salafsky N, Salzer D, Stattersfield AJ, Hilton-Taylor C, Neugarten R, Butchart SHM, Collen B, Cox N, Master LL, O'Connor S, and Wilkie D (2008) A standard lexicon for biodiversity conservation: Unified classifications of threats and actions. *Conservation Biology* 22: 897–911.

Table 5 Technical, societal, and governance issues that constrain spring assessment and overall stewardship across spatial scales.

1. *Inadequate mapping:* The quality of mapping data in most regions throughout the world is low to very poor. The paucity of such data makes it difficult to assess spring conservation status, which is likely to vary by spring type, proximity to developed areas, as well as many other factors.
2. *Limited inventory and assessment:* Although much information exists about spring hydrogeology for water supplies management in many regions, relatively few nation-wide inventories and assessments of spring ecosystems and SDT have been conducted. Improved comparative spring ecosystem information is needed for establishing conservation priorities and identification across aquifers and at landscape and national scales.
3. *Agreement on assessment protocols:* The RLE approach provides an excellent standardized assessment protocol for comparing conservation status among ecosystem types; however, it may not provide sufficient resolution to improve spring stewardship. A spring-specific assessment protocol, such as that provided by the Springs Stewardship Institute (Paffett et al., 2018) may provide prioritized within- and among-springs stewardship guidance. Such a spring-centric protocol can subsequently be expanded to inform comparative ecosystem assessment.
4. *Inadequate information management:* Consistent, quality-controlled, secure information management is needed for archival and analysis of existing information and trend assessment, but such need has scarcely been mentioned in assessment protocol discussions. We recommend that those interested in improving comprehensive spring ecosystem information management examine Springs Online (SpringsData.org; Ledbetter et al., 2016).
5. *Under-appreciated anthropogenic association and valuation:* Due to the evolutionary and intense contemporary association of humans with springs, assessment should include consideration of the socio-cultural context and valuation in which the spring ecosystem exists.
6. *Exploitative water use policies:* Throughout the world, spring use and water rights have long been subject to exploitative political and industrial decision-making, which often fail to recognize the need for sustainable stewardship. Exploitation and depletion of the Ogallala Aquifer in the North American Great Plains and the vast fossil aquifers of North Africa, and elsewhere, have been undertaken for short-sighted consumptive purposes that can only result in long-term depletion of regional water supplies. We regret to report that several co-authors expressed concern for their personal and professional safety by contributing to this assessment, and several others declined to participate because their governments refused to permit such collaboration. We greatly appreciate and laud the brave scientists who place scientific integrity over personal security to report truthfully on the status of spring ecosystem in their regions.
7. *Prior habitat and species losses:* Many regional conservation analyses of springs have been conducted long after significant anthropogenic impacts have occurred, impacts that may have fully eliminated springs and associated SDT that existed prior to detection or study. The magnitude of such losses is uncertain.
8. *Inadequate response timing:* By the time a decline in groundwater level or water quality has been detected, it may be too late to prevent spring ecosystem collapse. Therefore, an assessment status of Vulnerable or Near Endangered may serve as a more useful conservation warning about potential ecosystem collapse than does a status of Endangered.

Due to the inherent difficulties of mapping springs in complex, and particularly forested terrain, and until reliable technology emerges, we recommend that landscape managers conduct a statistically reliable inventory and assessment to detect the frequency and ecological condition of spring ecosystems and spring-dependent taxa in their study area. A stratified random selection of a sufficient number of springs of the types existing in the landscape is preferred; however, mapping data are usually so poor that such a suite of springs cannot be defensibly selected. In addition, conducting such an assessment in a complex terrain may be logistically unfeasible. An alternative approach is to select a suite of sentinel sites and determining the proportional level of endangerment among them. This approach has been used successfully among large, well-known limnocrenes in Florida, USA, and likely can be applied to assessment of protected travertine-depositing springs in the EU. However, the conservation status of other, more abundant spring types will remain unknown without specific inquiry.

Assessment approaches should employ protocols that allow for repeated inventory data to be readily translated into assessment, prioritization, management planning and implementation, and monitoring feedback. The results of such efforts should be scientifically credible and should be shared in public forums, as well as with neighboring regions and nations to enhance engagement and education of managers and the public regarding the distribution, status, and extent of endangerment of springs.

Spring-dependent taxa

Spring-dependent taxa include a surprisingly broad array of biota, including diatoms, non-vascular and vascular plants, many invertebrate phyla, as well as fish, herpetofauna, and other vertebrates (e.g., Stevens et al., 2021b). High levels of habitat uniqueness and local adaptation characterize many aquatic and riparian SDT and assemblages, Some SDT are intolerant of even slight modification of discharge, water quality, and other habitat quality changes. Although some SDT can tolerate simple, low-moderate levels of natural physical disturbance, few are resilient to major anthropogenic changes related to declining discharge, water geochemistry, livestock-induced habitat loss, the introduction of non-native predators, or simultaneously interacting environmental alterations. Spring assemblages subject to such changes quickly degrade or collapse as habitat integrity degrades, leading to extirpation or extinction of highly endemized taxa, such as truncatelloidean springsnails (e.g., Hershler et al., 2014), Australian spring fish species (e.g., Fensham in Stevens et al., 2021a), and other SDT. For example, Sada (in Stevens et al., 2021a) notes a dozen recent SDT extinctions in the Great Basin Desert of southwestern North America. Thus, the pathways to habitat and assemblage collapse from ecologically intact conditions tends to be short and steep, and once started is often irreversible. Spring habitat and assemblage composition are inseparably coupled, in a fashion that differs from large, widespread ecosystems like streams and rivers, which typically sustain a greater natural range of within-ecosystem variability.

Information management

Although variables such as flow, groundwater chemistry, SDT populations and other biological characteristics often are measured in terrestrial springs (but with more difficulty in subaqueous springs), such data are widely scattered through the literature, and often are managed in a non-collaborative fashion (for exceptions, see Ledbetter et al., 2016; Goldscheider et al., 2020), and the Ramsar Convention on Wetlands (e.g., 2018). Information management is essential not only to archive baseline conditions and determine normal ranges of variability, but also to provide stewards with clear options for archiving and reporting upon spring data. The complexity of spring ecosystem information requires extensive and careful forethought about database design to ensure ready access to high quality, relational, and secure information. To be most useful, spring information should be archived into a standardized, relational database that is capable of protecting sensitive information, as well as storing geographic and bibliographic information for long-term monitoring and stewardship. For example, Ledbetter et al. (2016) created Springs Online (springsdata.org), a spring ecosystem information management system as a secure, freely available, password-protected platform into which spring stewards can readily archive, synthesize, monitor, and report upon virtually any type of information gathered on the springs they oversee. Also, the karst hydrogeology community has created the World Karst Map and website, containing data on >400 karst springs (Goldscheider et al., 2020). Unfortunately, governing agencies and NGOs typically attempt to develop their own "in-house" databases, which generally are not shared externally and which often suffer from inflexibility and limited reporting capacity.

Enhancing spring sustainability

Many springs are regarded as groundwater-dependent wetlands, and can be designated under the intergovernmental Ramsar Convention on Wetlands of International Importance (Ramsar Convention on Wetlands, 2018). Such designation can provide important levels of conservation and protection. Several hundred of the >2400 Ramsar sites contain springs, but very few individual springs have been designated as Ramsar sites. This may be related to the generally small size of most springs (Cantonati et al., 2020a): the mean area of Ramsar sites is 106,181 ha, and the smallest site appears to be Ile Alcatraz in Guinea (1 ha); however, the average area of most springs is generally far less, ranging from <0.001 to 0.2 ha (Glazier, 2014; Stevens et al., 2021b). Their small size is generally insufficient to provide sufficient habitat for large numbers of waterbirds (Ramsar Group B Criteria 5, 6) or high proportions of fish species (Group B Criteria 7, 8); however, springs often qualify under the convention as Group B Criterion 9 "supporting individual endemic wetland or aquatic, non-avian animal species, primarily invertebrates." Prominent individual springs, such as Montezuma Well and Moapa Warm Springs in the American Southwest, and Dalhousie and the Edgbaston/Myross complex in the Great Artesian Basin of Australia clearly qualify as Ramsar sites because they support "...representative, rare, or unique example[s] of a natural or near-natural wetland type." They also qualify under Criterion 9, each having at least five endemic species found nowhere else. Designation of individual springs also may be limited by the administrative burden to the steward to prepare the initial designation and subsequent monitoring reports. Nonetheless, Ramsar designation provides an internationally recognized conservation tool for enhancing protection of springs as wetlands.

Springs also should be regarded in the context of drainage or catchment organization. Springs have been considered as "zero order streams" in drainage networks, and as headwater sources contribute critically important baseflow to most, if not all of the world's rivers that arise in non-ice-dominated landscapes (Stevens et al., 2021b). In a review of the status of the world's rivers, Feio et al. (2021) list the following factors that promote sustainable stewardship: (a) a strong mandate; (b) political context; (c) adequate governance and funding; (d) clearly defined objectives; (e) management well fit to the purpose; (f) enhanced trust and communication; (g) public support; (h) adequate ecological and technical knowledge; and (i) clear, well-reported metrics of success. These stewardship elements also apply to springs. Feio et al. report that at least 44% of the world's rivers are at risk due to human activities, and our data indicate levels of impairment of springs at nearly double that value. Therefore, integration of springs into drainage network concepts also may help focus attention on the role and status of these critically important headwater ecosystems.

Conclusions and recommendations

Springs are threatened across the globe because of local and regional impacts, including: subsistence to urban water supplies appropriation, aquifer depletion and contamination, livestock management, geomorphic habitat alteration, recreation, and the introduction of non-native and invasive species, as well as climate change and consequent reduction in groundwater recharge. Contributing to the severity of this mélange of threats and impacts is the inadequacy of basic mapping data, ecosystem inventory and assessment, and collaborative information management. Improving spring stewardship has become an urgent global need, but remains little-recognized by the public and governance (Cantonati et al., 2020a). Both the Ramsar Convention on Wetlands (2018) designation, and inclusion of springs into general conceptual river basin models will help frame assessment and conservation approaches for springs. However, both systems may reduce attention to spring ecosystems to mere components of larger classification systems, obscuring or trivializing the importance of springs, which heretofore have received far too little direct conservation attention. Therefore, based on suggestions by Stevens and Meretsky (2008) and Cantonati et al. (2020a), we make a suite of recommendations regarding improvement of spring ecosystem stewardship (Table 6) to expand attention to springs across local, regional, national, continental, and international spatial scales.

Table 6 General recommendations to spring stewards on conservation of springs at all spatial scales, from local to international (following Stevens and Meretsky, 2008 and Cantonati et al., 2020a).

1. Improve basic mapping and classification of springs at the national scale.
2. Select, inventory, and monitor spring discharge, water quality, habitat, and biota, and enhance long-term protection of those sites.
3. Develop regional and national groundwater models incorporating spring distribution and data on trends on discharge, water quality, habitat, and biota.
4. Support and enhance basic and applied spring ecosystem research.
5. Remediate and rehabilitate springs, particularly those of recognized biological or socio-cultural/historical importance.
6. Develop lists of SDT across spatial scale, monitor their population status, and protect them and the springs at which they occur to prevent further extinctions.
7. Conduct assessments across spatial scale to determine the cultural and socio-economic significance of springs.
8. Develop and maintain a collaborative, relational information management system in which to archive and report upon spring ecosystem characteristics and trends.
9. Synthesize and publish results in the peer-reviewed and popular literature.
10. Develop public education and outreach programs to improve public and managerial appreciation and protection of springs.
11. Develop and enact policies to protect and rehabilitate springs and the groundwaters that support them.
12. Make field technology (e.g., flow splitters) available and provide incentives to improve the ecological functionality of springs and balance ecological and economic development, where such development is warranted.

We regard springs as important indicators of groundwater sustainability and essential headwaters of rivers. We warn that as springs and surface waters are consumed or polluted, depletion of fossil or slowly recharging aquifers can result in insurmountable water shortages. Aquifer depletion is already occurring across the Great Plains Ogallala aquifer and in Arizona, southern California, and Texas in the USA (Stevens and Schwartz et al. in Stevens et al., 2021a). Overdraft of the Nubian aquifer system in North Africa, the world's largest aquifer, has already resulted in the loss and abandonment of some North African desert oasis communities (Powell and Fensham, 2015). Such losses are having dire economic and societal consequences, not only for the over-consuming regions, nations, or groups of nations sharing those aquifers, but also on the adjacent lands to which refugee human and other SDT populations must retreat to survive. Similarly, poorly regulated mining operations and under-informed agricultural practices that contaminate aquifers render them unfit for consumption and ecosystem support in perpetuity. Of course, the burden of water shortage impacts will always fall hardest on the poor and those least able to escape these human-caused catastrophes.

Throughout human history, civilizations have risen and collapsed in relation to the availability of fresh water (Solomon, 2011). Access to clean water is a basic human right, and therefore, ensuring the sustainability of freshwater supplies must be a primary goal of governance. A thorough inventory and assessment of springs throughout the world is long overdue, and that information should be used to prioritize, plan, and rectify national and international spring stewardship challenges and the populations they support. Springs are not only important as focal bio-cultural, ecological, and socio-economic hotspots in all lands and seascapes, but also are windows into the world's most precious water source: its aquifers. We posit that improved attention to, and sustainable stewardship of springs will help educate humanity about the needs and benefits of conserving these essential ecosystems, the many species and habitats they support, and the groundwater supplies on which the future of humanity is likely to depend under a changing global climate.

Acknowledgments

We thank our home institutions for their support. We also thank the editors of Imperiled World Biomes for advisement in the preparation of this manuscript. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

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