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Urgent plea for global protection of springs

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Running head: Spring Stewardship
Keywords: spring ecosystems, biodiversity, habitat destruction, stewardship, climate change
Article Impact Statement: Springs, keystone ecosystems, are rapidly disappearing mainly due to overexploitation and need global protection.

Springs as pivotal ecosystems for people and nature

Springs are natural discharge points from aquifers and the origin of diverse surface-water systems (Glazier 2014; Junghans et al. 2016) (Fig. 1a-d). They are unique and readily distinguished from surface-water-fed wetlands, lakes, streams, and other aquatic ecosystems. Springs harbor a disproportionately high biological diversity (Table 1; Fig. 1e-h) due to their intrasite microhabitat heterogeneity and intersite diversity, which derive from variation in their geological longevity, aquifer geochemistry, and distribution across many climatic zones, geological provinces, and biogeographic regions (Glazier 2014). Discharge, temperature, and geochemistry of springs range from nearly constant to highly variable (Fig. 1a). Some have short subterranean flow paths and brief groundwater residence times, whereas others have flow paths of hundreds of kilometers and residence times of 10^4-10^6 years that provide persistent conditions that allow high levels of evolutionary adaptation and endemism (Stevens & Meretsky 2008; Fensham et al. 2011) (Fig. 1d). We focused on land-surface springs, but underwater (rivers, lakes, oceans) springs also warrant protection (Post et al. 2013).

Near-natural springs provide vital ecosystem goods and services (Knight 2015; Mueller et al. 2017). For example, many farms, ranches, small towns, and several national capitals (*e.g.*, Rome, Vienna, Beirut, Damascus) use springs for potable and agricultural water (Kresic & Stevanovic 2010). Springs also have tremendous cultural, social, and economic significance. They have played important roles throughout human evolution and history (Cuthbert & Ashley 2014). Many of them have substantial recreational value (Glazier 2014; Knight 2015) (Figs. 1a-b), and the economic value of bottled spring water is enormous (Gleick 2010). Most human cultures consider springs places of vital importance for physical and spiritual well-being (Fig. 1k).

Impacts, management, and global conservation status

Although abundant worldwide, many springs are disappearing or are impaired by local to global anthropogenic stressors, including habitat alteration, recreational use, groundwater depletion, pollution, and climate change (Glazier 2014; Knight 2015) (Fig. 1i-m). At local scales, individual springs are directly impaired by flow abstraction and manipulation, road and building construction, vegetation removal, recreation, introduction of non-native species, and particularly by underinformed livestock-management practices. At regional (aquifer) scales, springs are indirect casualties of groundwater overdraft, bottled water extraction, and pollution from mining, agricultural fertilizers, and wastewater disposal, as well as unsustainable land management practices and urbanization. At subcontinental to global scales, aquifers supporting springs are threatened by climate change, which reduces infiltration through decreased high-elevation snowfall and increased low-elevation evapotranspiration. This hierarchy of stressor impacts positions springs as the ecohydrogeological 'canaries in the coal mine' of the Anthropocene epoch .

Increasing levels of groundwater pumping will leave 40-80% of the world's catchments below minimum environmental-flow limits required to maintain ecosystem functioning by 2050 (De Graaf et al. 2019). In recent decades, for example, aquifer overdraft related to rapid human population growth and agricultural irrigation dewatered 195 out of 861 known springs in Jordan: total annual spring discharge decreased from 250 x 10^6 m^3 in 1970 to 135 x 10^6 m^3 today (Fig. 1j) (MWI & BGR 2019). About 33% of the 259,000 km^2 Floridan Aquifer has been appropriated for human uses; existing permitted withdrawals is approximately 50% of the aquifer's recharge, which historically fed more than 1,000 artesian springs in Florida (Knight 2015) (Fig. 1b). High (>95%) estimates of impairment due to recreation and livestock management have occurred in the southwestern United States (Stevens & Meretsky

2008) and in Alberta, Canada (Springer et al. 2015). An estimated 80% of Florida's artesian springs receive groundwater polluted by nitrate nitrogen, and the majority have had native aquatic vegetation replaced by noxious filamentous algae (Knight 2015) (Fig. 1l). In addition to many local-use impacts causing ecological impairment, regional anthropogenic pressures include impacts to aquifers due to drawdown as well as large-scale mining activities in North America (Stevens & Meretsky 2008) and Australia (Fensham et al. 2016).

Several recently documented extinctions of endemic, spring-dependent species have occurred, mainly due to groundwater drawdown (Rossini et al. 2018). For example, both the Fish Lake springsnail (*Pyrgulopsis ruinosa*) and the riffle beetle (*Heterelmis stephani*) were driven to extinction by local disruption of springs. Fish in the genera *Empetrichthys*, *Cyprinodon*, and *Rhinichthys* were lost through a combination of local impacts and regional groundwater depletion (Miller et al. 1989). Although human use of springs is nearly universal, springs can maintain ecological functionality and habitat for rare species in the face of exploitation. The endemic and endangered Barton Springs salamander (*Eurycea sosorum*) (Fig. 1m), for instance, is maintained in a large spring system that also serves the City of Austin, Texas, as a public swimming facility. Unfortunately, agricultural pollution from the supporting karst catchment is now inducing decreasing oxygen levels that may drive this species to extinction (Mahler & Bourgeais 2013).

Cantonati et al. (2016) provide a comprehensive overview of legislation for the protection of springs worldwide. Among these, the Habitat Directive (Annex I) of the European Union (EU) recognizes only one major spring habitat type, namely Limestone Precipitating Springs (EU-Code 7220); all other types are not considered worthy of protection. Finland is an exception: its springs there are protected under the Water Act and the Forest Act. Australian artesian springs in the Great Artesian Basin are protected under federal law by the Environment Protection and Biodiversity Conservation Act. In the United States, groundwater and springs are scarcely considered in federal legislation, with jurisdiction largely deferred to individual states. Florida, Minnesota, Nevada, New Mexico, Wisconsin, and a few other states have programs that emphasize spring monitoring and protection (Stevens & Meretsky 2008; Knight 2015; Cantonati et al. 2016). Only 5 of 2391 (0.2%) designated Ramsar sites include named springs. Although many Ramsar sites likely contain unrecognized springs, the limited representation of most spring ecosystems may be primarily due to their generally small size.

Plea for improved global stewardship of springs

We propose 4 key objectives for spring protection; each includes several action items.

First, recognize springs as a distinctive group of ecosystems that warrant special conservation attention by reinforcing and amplifying basic understanding of springs as pivotally important conservation targets, and by increasing public and political awareness of springs as crucially important ecosystems and environmental indicators through expanded communication, outreach, popularization, cultural mediation, and informed debate among stakeholders.

Second, explicitly include springs in local, national, and international management directives, including implementation of existing agreements such as the Ramsar Convention, by encouraging the scientific community and the public to lobby decision-making political entities to enact spring-protection legislation.

Third, develop guidelines and collaborative efforts to improve aquifer and spring stewardship across spatial scales. Reinvigorate scientific research to develop conservation criteria and emphasize identification and protection of specific sites, spring-dependent species, and regions of highest conservation value and risk and standardize globally applicable mapping, inventory, and assessment protocols that can be employed in developed as well as understudied regions. Enhance spring and aquifer information management, for example, by linking biological, cultural, and management values and characteristics to data on the geographic distribution, functional and ecological integrity, and vulnerability to human impacts of springs and aquifers. Consider spring indicators of aquifer integrity in all environments. Develop regional and international networks of reference locations with diverse spring types, ideally within the framework of major long-term ecological research networks, such as International Long Term Ecological Research, National Ecological Observatory Network, etc. These sites can serve as research and educational sentinel sites to monitor and test spring-restoration strategies and facilitate management responses to human impacts, including climate change (Stevens & Meretsky 2008).

Fourth, recognize and promote scientifically proven methods for spring conservation and restoration (e.g., use flow splitters and other common-sense practices to allow ecologically important spring sources to persist if flow diversion is deemed necessary), and promote the concept that, if the aquifer is relatively intact, springs respond readily to restoration.

At a global scale, public awareness and active conservation are needed to reverse the conservation crisis facing springs and associated groundwater as human population pressure increases. Given their significance as biodiversity havens for many rare and endemic species, their keystone ecological functionality within landscapes, their extraordinary cultural and socioeconomic values, and the relatively low cost of appropriate management (Knight 2015), improving the stewardship of spring ecosystems and their supporting aquifers will yield substantial environmental advantages and societal benefits.

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Table 1. Examples illustrating spring ecosystems as biodiversity hotspots.

Observation	*Reference*
Disproportionately high species richness of regional pools of springs:	
- >50% of the benthic diatom species known from Central Europe occur in springs on the mountains around Frankfurt am Main, Germany (<1.5% of the surface of the EU)	Werum & Lange-Bertalot 2004
- 25% of the flora of Alberta (Canada) detected at 56 springs (<0.001% of the provincial land area)	Springer et al. 2015
- ca. 80% of the aquatic animal species endemic to the Great Basin (western United States) primarily inhabit springs (many populations are declining due to human impacts)	Hershler et al. 2014
Many species and some genera are spring dependent, including 15% of European water mite species (Fig. 1g)	Gerecke et al. 2017
Springs are refugia for many rare and endemic species, including	
- desert spring fishes in Australia (Fig. 1h) and North America	Stevens and Meretsky 2008
- Bert's predaceous diving beetle (*Sanfilippodytes bertae*) in a few Alberta, Canada, springs	Springer et al. 2015
- 11 species of *Floridobia* silt snails in Florida springs and hundreds of highly endemic truncatelloidean springsnails globally	Hershler et al. 2014
Spring have many red-listed species (e.g., ca. 50% of the diatom species in springs of the Alps)	Cantonati et al. 2012
Springs contain rare and newly discovered taxa, including many kinds of microbes (Fig. 1e), invertebrates, and fishes	Cantonati et al. 2012, Hershler et al. 2014
Spring often contain least-impaired habitat relicts (i.e., sensitive species surviving only in near-natural springs in regions otherwise detrimentally affected by human activities)	Cantonati et al. 2012

Figure 1. Spring ecosystem (a-d) diversity , (e-h) flagship organisms, and (i-m) human impacts: (a) Lison Spring (France), a typical, near-natural karstic spring (photo by N.G.); (b) Silver Springs (Florida), popular tourist attraction since 1878 (photo by J. Moran); (c) Thunder River Springs (Grand Canyon National Park, U.S.A.), a karstic cave gushet spring (photo by J.H. Holway); (d) Elizabeth Springs (Queensland, Australia), habitat for a fish, snail, and 2 plant species known only from this location (photo by S. Richards); (e) newly discovered diatom *Microfissurata paludosa*, typically inhabits bryophytes in seepages and mires (photo by H. Lange-Bertalot); (f) *Flaveria mcdougallii*, occurs at only a few alkaline springs in central Grand Canyon (U.S.A.) (photo by L.S.); (g) *Protzia squamosa*, a water mite found exclusively in European springs (photo by R.G.); (h) red-finned blue-eye fish (*Scaturiginichthys vermeilipinnis*) found in only a few springs in central Queensland (Australia) (photo by E. Tsyrlin); (i) Val Perse Spring (Brenta Dolomites, southeastern Alps) destruction through tapping (photo by M.C.); (j) formerly spring-fed Azraq oasis (Jordan) (photo by N.G.); (k) spring at Jinci temple, where the water supply is no longer natural (photo by N.G.); (l) Manatee Spring (Florida, U.S.A.), where no native vegetation remains (photo by J. Moran); (m) vandalism at Barton Springs (Texas, U.S.A.) (photo by N.G.).