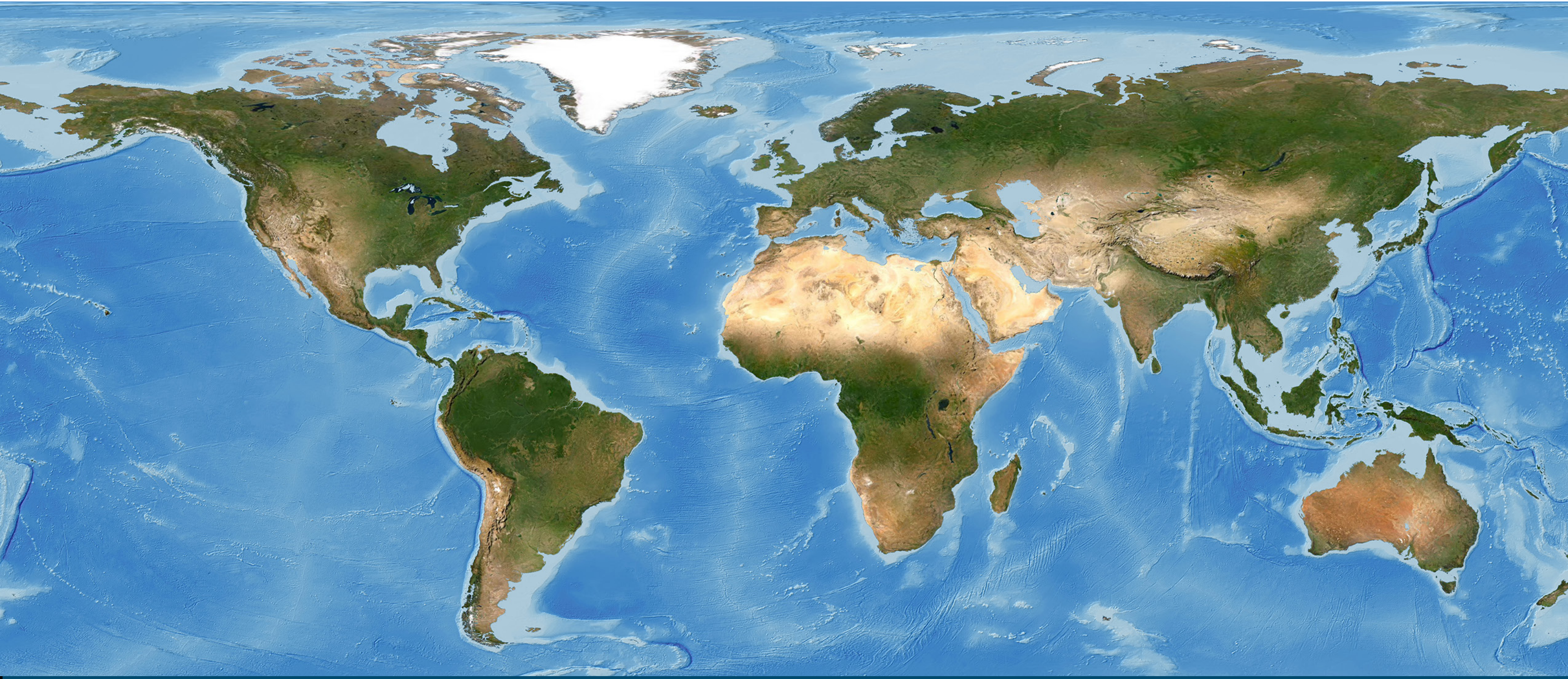

Springs of the World:

Distribution, Ecology, and Conservation Status

Lawrence E. Stevens, Editor

Springs of the World: Distribution, Ecology, and Conservation Status

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Springs of the World: Distribution, Ecology, and Conservation Status

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Executive Summary

Springs have been the focus of attention throughout human evolutionary history, and are nearly universally recognized as highly productive, bio-culturally essential, and economically important ecosystems. While of recognized value and arguably among the most sustainable ecosystems, these ecosystems also have been reported as being ecologically compromised by intensive anthropogenic management. However, the global conservation status of spring ecosystems has not previously been evaluated. To address data gaps, misinformation, and the many uncertainties about the sustainability of aquifer and springs, Cantonati et al. (2020) called for improving public and governmental awareness of spring ecosystems, as well as additional basic mapping, inventory, and assessment to determine the distribution and ecological integrity of springs globally. The impetus for the present work is, in part, in response to their concerns.

In this book we present synopses on the distribution, typology, ecology, anthropogenic uses, and conservation status of >250,000 springs from all continents except Antarctica, from a total of 75 countries and in some cases from multiple states or geologic provinces within countries. This information was derived from our individual studies and from the literature, and serves as the foundation of the first analysis on the ecological status of the world's spring ecosystems, as summarized by Stevens et al. (2021).

Collectively, we report that the ecological integrity of springs is gravely threatened in most regions, particularly in arid and semi-arid regions where water supplies are most limited. The intensity of human impacts on springs and the species and assemblages supported by springs is less clearly identified in the tropics and other humid regions, but generally increases from low to middle latitudes. Human impacts on groundwater availability and quality, local geomorphology, and habitat quality increase with proximity to urban, industrial, and mining development, particularly in regions subject to intensive agriculture. We find that the assumption that springs are only of management concern in arid regions is erroneous: springs everywhere around the world serve many important cultural and socio-economic functions and suffer from generally similar kinds of human impacts.

This effort is, of necessity, a preliminary presentation, because many information and management policy gaps exist, even in countries that recognize the biologically and socio-cultural significance of springs. Basic geographic data and consistent, statistically credible assessment approaches, as well as improved relational and comparative information management are needed everywhere to improve understanding of the distribution, types, associated attributes and species, and ecological status of springs. Existing assessment approaches, such as those proposed by the IUCN's Red List of Ecosystems are laudable, but are complicated by the insular, island-like, and highly individualistic nature of spring ecosystems. Despite many information gaps, our study concludes that springs are globally threatened, and that efforts to maintain springs sustainability must extend to the supporting aquifer, as well as the landscapes into which the springs emerge. Assessment of spring ecosystems should involve random selection of a suitably large number of springs within the study area or nation, with stratification based on the salient variables distinguishing springs types, including geomorphic type, vegetation, and elevation. While challenging to assemble, such data and relational information management are needed to ensure appropriate assessment, prioritization, planning, implementation, and monitoring of stewardship. Our insights into spring ecosystem distribution, ecology, and conservation status reveal that these often critically important ecosystems and their associated species and attributes are highly imperiled globally and warrant significant public, scientific, and managerial attention.

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Key Words

Conservation status, endangered ecosystems, global, groundwater, management, spring ecosystem, springs-dependent taxa, stewardship

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About Springs Stewardship Institute

The Springs Stewardship Institute (SSI) is a 501(c)3 nonprofit organization based in Flagstaff, Arizona. We work to improve communication among land managers to survey, rehabilitate, and steward springs systems. Through collaboration and partnership, and through publications such as this book, SSI strives to improve understanding and management of these critical and endangered ecosystems.

To support this important work, please consider making a tax deductible donation at https://springstewardshipinstitute.org/support.

Prologue

I'd been driving the whole morning across roads on which you wouldn't send your worst enemy, trying to locate Guadalupe Spring. It reportedly emerged in the raw, volcanic woodlands on the north side of Mount Taylor in northwest New Mexico, USA. My GPS on that mid-September morning lead me into a maze of muddy dirt ruts, roads that few locals knew existed, arriving there just before the first winter storm of the season. Although dark clouds were gathering around the mountain to the south, it was still sunny enough to lure me into thinking that a solo spring inventory in this rugged country was a reasonable idea. I crawled in 4-wheel-low out to the edge of a jagged canyon, and bush-whacked my way down into it with a heavy pack, hoping that with all the effort expended this wasn't just another wild-goose-chase to a falsely reported or dewatered spring. Seeing virgin's bower (*Clematis ligusticifolia*) and rock spirea (*Holodiscus dumosa*), and finally willows (*Salix* spp.) on the canyon floor gave me some hope. But my spirits sank when I worked my way to a muddy, cow-trampled pool at the base of a dry waterfall. "Just another tinaja, a runoff plunge pool," I thought with disappointment. Nonetheless, with due diligence, I clawed my way up the waterfall to see if any flow emerged there. No water. I then followed the canyon downstream, discovering to my considerable delight a few tens of meters away, a robust flow of clear, cold water surging up through the basalt cobbles and creating a willow-lined springbrook.

The pool was the upstream-most exposure of water, so I returned there to begin my inventory. Mid-September is the middle of the fall warbler migration, and all about me were dozens of lovely yellow-rumped warblers (*Setophaga coronata*) stopping over briefly on their long journey to Mexico and Central America for the winter. Not having seen more than one or two on my long drive in, I was amazed to see how abundant and unafraid of me they were, with more arriving every few minutes. So desperate were they for a drink and a few insect snacks at this isolated refugium that several very nearly landed on my shoulders as I made my water quality measurements. But my revery in their quiet presence was abruptly interrupted as I heard, and then barely dodged a large lava boulder that crashed right next to me on the canyon floor. It had been kicked off the rim a hundred meters above by a stumbling cow, perhaps one irate at having her spring invaded by a damn scientist. I finished my survey, ascended to the rim, and spent most of the day almost hopelessly lost in the maze of roads, trying to find a route out and back before the impending clouds of winter descended onto the landscape.

Why does anyone do this kind of work? Just ask any die-hard field biologist. But who wants to hear about yet another global environmental crisis, particularly one linking the status of a basic resource like drinking water to habitat and biodiversity loss and environmental justice? The ecology, distribution, and role of springs in Nature and to humanity is such a story. Spring ecosystems link our most precious and least recognized source of freshwater – groundwater – to the surface world, its ecology, biota, assemblages, and to human evolution, cultural development, and contemporary socio-economics. Springs are not just iconic palm oasis refugia in arid regions, but emerge in an astounding array of forms in environments throughout the globe, nearly everywhere playing ecologically integrative roles in the health, well-being, and economy of natural and human socio-cultural integrity. From "black smokers" erupting as super-heated, deep seafloor geysers and hosting novel phyla and utterly bizarre endemic extremophiles, to acidic alpine Rocky Mountain groundwater-dependent fens supporting predatory *Drosera* sundew plants, springs are extraordinary natural laboratories for understanding evolutionary adaptation and the persistence of life in stressful environments. Springs for me lie at the very heart of natural history – iconic point sources of biodiversity and patches of habitat with remarkable internal and extrinsic ecology, dynamics, and deep relevance to adjacent landscapes. The needless degradation and loss of these abundant point sources of biodiversity and ecological interactivity disproportionally affect people of color, the working class poor, and national and global well-being of nature and humanity.

For all of these reasons, my wife Jeri and I created the Springs Stewardship Institute, a 501(c)3 not-for-profit organization based in Flagstaff, Arizona to provide guidance on how to better comprehend and sustainably manage spring ecosystems. Springs appear to be the most productive ecosystems on Earth, and are renown for supporting a wild array of rare and endemic biodiversity, with likely thousands of poorly known or new-to-science macroscopic life, as well as innumerable microbial life forms. While the biodiversity value of springs is becoming better recognized, their conservation status remains poorly understood. I sit through seemingly endless meetings with large groups of diametrically-opposed stakeholders working to balance societal needs for water with protection of wild places. In great contrast, such work at springs involves relatively few stakeholders and is often relatively simple: if the supporting aquifer is relatively intact, the spring stewards need to come together, agree on how to apportion water use in relation to maintaining the ecological integrity of the spring, and conduct usually very simple, inexpensive management actions. These might include fencing the source while allowing water downstream for livestock, or building a trail to minimize erosion. The conservation approach we follow is in accord with Aldo Leopold's guidance in *A Sand County Almanac and Sketches Here and There* (1949, Oxford University Press): "If the land mechanism as a whole is good, then every part is good, whether we understand it or not. If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering."

Almost everyone knows that "What's good for springs is good for all things". Speaking for the co-authors here, whom I most deeply thank for their expertise and patience, improving understanding of global springs conservation status and sustainable management are critical first steps for informing managers, policy makers, and the public on the diversity, importance, and threatened status of these often small, largely over-looked, but often relativly easily protected ecosystems.

Larry Stevens
Flagstaff, Arizona

Chapter 1

Springs of the World

"On all sides, and in a thousand countries, there are waters bounteously springing forth from the earth, some of them cold, some hot, and some possessed of these properties united..."

(Pliny the Elder: 31.2(2), ca. AD 77)

Introduction

Spring ecosystems are places on the Earth's surface that are influenced by the exposure or emergence of groundwater. Springs are renowned as ecosystems that often have high biological, cultural, historic, and socio-economic importance, not only in arid subaerial settings but also in mesic and subaqueous environments. With global estimates reaching 50 million, springs are abundant, although the area of individual springs is typically small (usually <0.1 ha). Springs are renowned as being among the most productive ecosystems on Earth (e.g., Odum 1957), and in cases when water quality is distinctive and natural disturbance is limited, springs can support high levels of rare and endemic biodiversity (Springer et al. 2014; Kreamer et al. 2015; Rossini et al. 2018). Therefore, springs often function as point sources of biodiversity and as refugia for springs-dependent taxa (SDT), which either require spring habitat(s) for at least one life history stage, or occur primarily at springs. Extrinsically, springs also can be highly ecologically interactive (keystone) ecosystems, with multi-dimensional ecosystem subsidy exchange and supporting many upland taxa (Perla and Stevens 2008; Stevens 2020).

Despite their remarkable ecological attributes, springs everywhere are intensively used for water supplies and other natural resources, and are the focus of recreational and balneological visitation (e.g., Cantonati et al. 2020; Stevens et al. 2021); indeed, springs have been the subject of human attention throughout our evolutionary history (e.g., Ashley and Cuthbert 2014). However, springs nearly everywhere are poorly mapped, heavily appropriated, and their conservation status is generally poorly understood. Despite Odum's (1957) use of Silver Springs in Florida to frame the science of ecosystem ecology, only recently has research on spring ecosystems intensified, but much basic and applied research remains outstanding.

Here we present synopses on the distribution, typology, ecology, anthropogenic uses, and conservation status of >250,000 springs from all continents except Antarctica, from a total of 75 countries and in some cases from multiple states or geologic provinces within countries. This information was derived from our individual studies and from the literature, and serves as the foundation of the first analysis on the ecological status of the world's spring ecosystems, as summarized by Stevens et al. (2021). The synopses presented here are freely available through the Springs Stewardship Institute website (https://SpringStewardshipInstitute.org), with spring ecosystem inventory data readily and securely added into Springs Online (https://springsdata.org). It is our hope that this open, collaborative effort will expand global awareness of the importance of improving public and scientific understanding of springs as remarkable focal points of socio-ecological interactivity that warrant enhanced and collaborative stewardship attention.

Methods

In this compendium we invited experts in regional and national ecohydrogeology from throughout the world to provide brief synopses of the state of knowledge on the distribution and ecological integrity of spring ecosystems in their study areas. These synopses provide information on the hydrogeological and ecological context on the distribution, typology, anthropogenic stressors, present condition, and conservation status of springs and springs-dependent taxa (SDT; crenobiontic taxa), where such information is available from existing literature and the authors' research. In addition, we encouraged our colleagues to include individual case studies. We present these synopses by continent, subcontinent, and region, province or state, and the findings are summarized in

Stevens et al (2021). Thus, we describe the ecological status of springs and SDT in relation to the best available data, where possible in a fashion compatible with International Union for the Conservation of Nature (IUCN) Red List of Ecosystems protocols (Bland et al. 2017).

The differing levels of expertise in the fields of hydrogeology, ecology, cultural anthropology, and socio-economics among our coauthors precludes a consistent format for individual synopses. In addition, information on springs is either unavailable in many parts of the world, or we have not yet encountered knowledgeable experts to supply relevant data. Consequently, these synopses and the global assessment in general remain incomplete and individualistic. Nonetheless, our intent here has been to initiate a compilation of information on the conservation status of spring ecosystems and SDT, and to assess global patterns from that body of information.

We quantified the general forms of anthropogenic disturbance described in the synopses. We used a slightly modified version of the Salafsky et al. (2007) list of ecosystem disturbances that adds several springs-specific stressor subcategories (Stevens et al. 2021). These included: Development (Category 1) - urban, industrial, as well as subsistence water supplies development; Agriculture and Aquiculture (Category 2) – livestock use (both direct and indirect); Energy and Mining (Category 3) - extraction or depletion of groundwater; Intrusion, Disturbance (Category 6) - balneological, spiritual, recreational, or scientific use; Non-native Species Introductions (Category 8) – terrestrial versus aquatic exotic species introductions; and Pollution (Category 9) - surface water or groundwater pollution. We searched for reference to each form of disturbances in each synopsis, and tallied the results by type and region to clarify the frequency of each ecosystem disturbance type. We review and discuss ecosystem assessment methods and specifically the European Union Red List of Ecosystems approach (Bland et al. 2017), and with a conservation focus in relation to capacity for use in prioritization of management implementation.

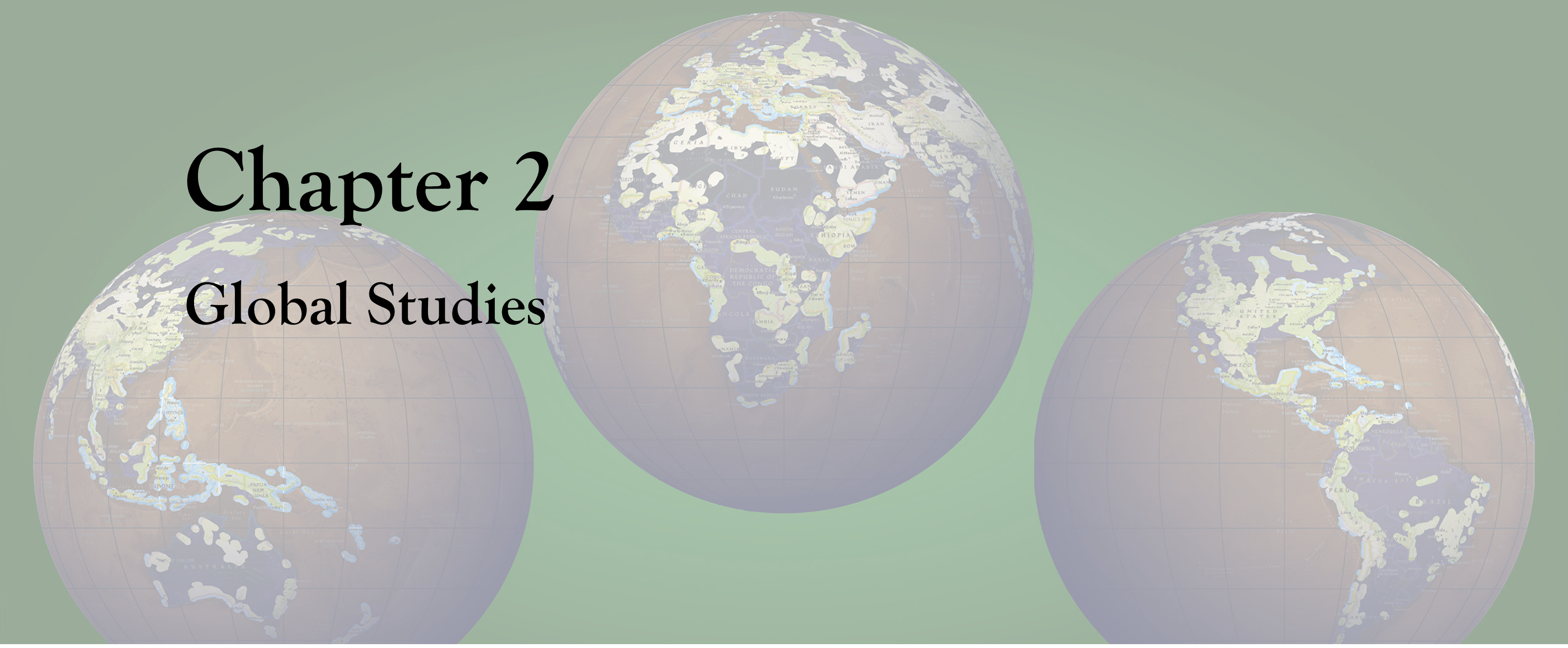
This effort remains a work in progress. We invite other springs researchers whom we have not yet encountered to provide regional synopses on the status of springs in their study areas, and we encourage presently participating colleagues to update their information as new findings and data emerge. Please contact the Springs Stewardship Institute to contribute regional synoptic information or to learn more about this conservation effort.

Chapter Image Credit

Chapter heading map used data derived from GEBCO ocean bathymetry: General Bathymetric Chart of the oceans (GEBCO). The GEBCO_2014 Grid, www.gebco.net.

Chapter 2

Global Studies



Overview

Several colleagues in this book focus springs-related research on a global scale that transcends the national and continental context of other studies presented here. These include karstic landscapes and both coastal and profundal geothermal marine vent springs. The former research area is relevant because of the extraordinary importance of karstic aquifers for human water supplies: many individual families, communities, small and large urban, metropolitan, and some states and nations around the world reliant on karstic water supplies. Karstic waters support an enormous, but untallied, proportion of freshwater biodiversity, as well as a rich but less well-known subterranean aquifer biota, with many new species of blind and cave invertebrates, fish, and some amphibians. The hydrologic complexity of karstic aquifers makes delineation of groundwater basins difficult. Karstic systems are notoriously flashy, and thus responsive to climate changes that affect infiltration, such as reduction of snowpack. In addition, they and the springs and biota they support also are highly sensitive to, and compromised by pollution, particularly that related to urban and agricultural waste, as well as mining operations.

While shallow marine spring ecosystems have been recognized for centuries, profundal vent springs were only discovered in 1977. The former exist in a wide array of settings and emerge with various geochemical properties, sometimes being anoxic and associated with chemautotrophic assemblages. The latter have received enormous scientific and public attention since their discovery due, in part, to the extreme difficulty of access. Sea floor vent spring studies reveal a great and novel biodiversity, providing insight into extraordinary ecosystem structure, and the extent of adaptation to which springs-dependent extremophiles have evolved in these phenomenally stressful and sometimes unstable habitats. Despite the enormous differences between highly pressurized, anoxic, and ultra-thermal profundal marine sea floor vent springs and terrestrial aridland springs, both can provide sufficient environmental constancy to promote the evolution of endemic microbes, invertebrates, and lower vertebrates. Also, both marine and terrestrial springs often occur as highly insular patches of extremely productive habitat and can be surrounded by vast adjacent areas of low productivity. Clearly, more research, discussion, and comparison of how endemism evolves, and ecosystem disturbance-productivity relationships, and the energetics and subsidy exchange patterns between marine and terrestrial springs are warranted.

Terrestrial Springs

Global Karstic Landscapes

by Nico Goldscheider

Most of the largest springs on our planet are karst springs (i.e., springs emerging from karst aquifers; Kresic and Stevanovic 2010). Karst aquifers consist of chemically soluble rock in which solution processes have created enlarged pathways for preferential groundwater flow (Ford and Williams 2007). Carbonate rocks, such as limestone or dolomite, are the most important karstifiable rocks. Evaporite rocks, such as gypsum, also are karstifiable but are far less important in terms of freshwater resources and springs. Here I focus on springs related to carbonatic karst aquifers, which occupy about 15.2% of the global land surface (Goldscheider et al. 2020). Figure 2-1 presents the global distribution of potential karst aquifers in karstifiable rocks and a selection of the most important karst springs on our planet, in terms of discharge and regional significance (e.g., Australia's largest spring is shown, although it is much smaller than many springs in the Dinaric region that cannot be shown because of their spatial abundance). Table 2-1 presents a summary of these springs and their range of discharge during low-flow and high-flow conditions.

Table 2-1. Selection of the 25 most important karst springs worldwide, in terms of discharge and regional significance, with the range of discharge from low-flow to high-flow conditions (modified after (Goldscheider et al. 2020). The ID designations refer to the map in Figure 2-1 and are taken from the World Karst Aquifer Map (WOKAM); n.d. = not determined.

ID	Name	Country, Region	Low [m^3/s]	High [m^3/s]
A4	Maligne	Canada, Alberta	15.2	40
A18	Ottawa River Caves	Canada, Ontario/Quebec	10	n.d.
A34	Big Spring	USA, Missouri	7	37
A63	Silver Springs Main	USA, Florida	15.3	37
A76	Nacimiento del Rio Coy	Mexico	13.0	236
A91	Negro River Spring	Peru	15.0	n.d.
A98	São Bernardo	Brazil, Goiás	5	n.d.
B1	Cong Springs	Ireland	5	n.d.
B21	Fontaine de Vaucluse	France	4.0	150
B36	Timavo	Italy	30.2	n.d.
B50	Ombla	Croatia	4	138
C3	Dumanli	Turkey	38	50
39	Figeh Spring	Syria	2.5	13
C22	Chehel cheshmeh	Iran	1.9	n.d.
C25	Bobrovaya	Russia, Permskij kraj	1.5	3.0
C26	Panzethnag	India, Kashmir	2.2	3.0
C27	Bolshaja Iret	Russia, Irkutskaja oblast	12	n.d.
C32	Niangziguan	China, Shanxi	8.5	n.d.
C38	Chexinwan	China, Hunan	32.8	n.d.
C64	Zhongzhai	China, Yunnan	37.2	n.d.
C74	Gua Besar	Indonesia	2.2	n.d.
D4	Ayn Zayanah	Libya	5	n.d.
E2	Tobio	Papua New Guinea	85	115
E3	Te Waikoropupu Spring	New Zealand	5.8	21
E5	Blue Waterholes	Australia, New South Wales	.2	2.2

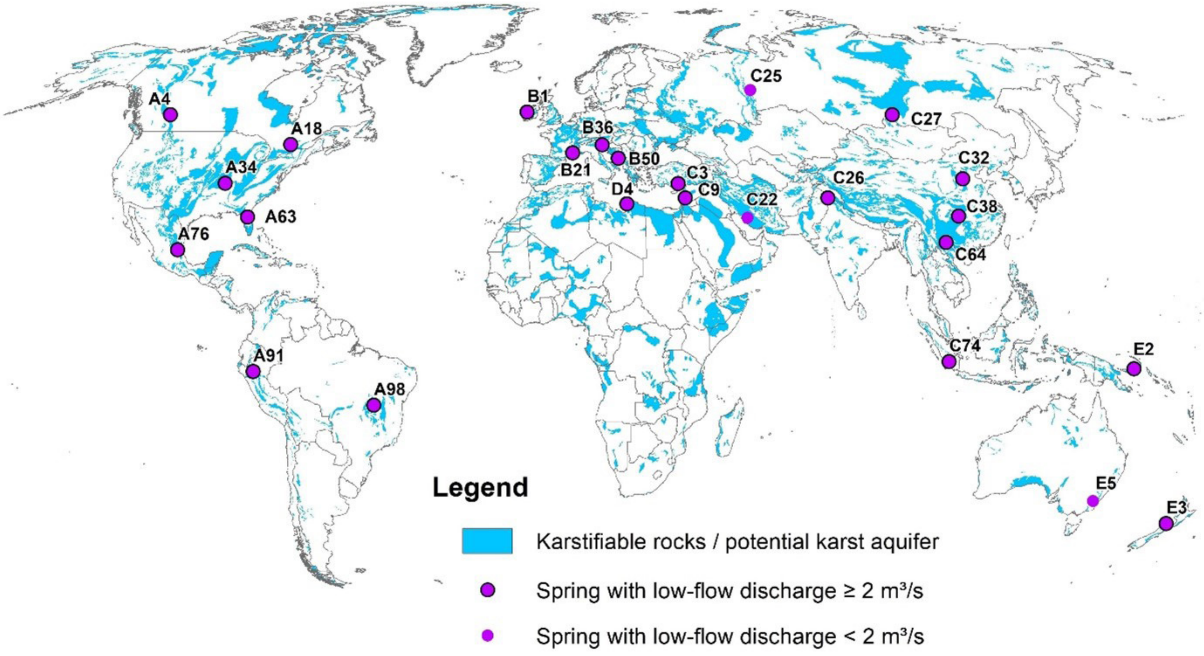


Figure 2-1. Generalized version of the World Karst Aquifer Map with location of 25 selected karst springs on all continents (modified after Goldscheider et al. 2020). The IDs and main characteristics of these springs are presented in Table 2-1.

Karst aquifers form through chemical dissolution of carbonate rock by flowing groundwater containing carbon dioxide (CO_2) from the atmosphere and soil zone. This intense and complex interaction among the atmosphere, pedosphere, hydrosphere and geosphere requires a holistic and ecological approach to groundwater protection (Goldscheider 2019). Karst aquifers can be described as a hierarchical network of drainage conduits, including accessible water caves, which are embedded in, and hydraulically interacting with, a matrix of fractured carbonate rock (Bailly-Comte et al. 2010; Frank et al. 2019). The conduit network generally drains towards large springs that often show rapid and marked variations of discharge and water quality in response to rainfall and snowmelt events (Ryan and Meiman 1996; Winston and Criss 2004).

It is estimated that about 9.2% of the global population is supplied by freshwater from karst aquifers (Stevanovic 2019). A good part of this water supply is based on captured karst springs, such as the water supplies of Rome, Vienna, Montpellier and Damascus (Kresic and Stevanovic 2010). Use of karst spring water for freshwater supplies means reduced environmental baseflow, but usually also involves protection zoning and land-use restrictions to maintain water quality. Other karst aquifers are exploited by means of wells or drainage galleries, resulting in reduced spring discharge. For example, many of the former karst springs on the Arabian Peninsula have run dry due to overexploitation of aquifers (Dirks et al. 2018). Another famous example is the Jinci temple in Shanxi Province, a major cultural site in China. For millennia, it was fed by a karst spring (about 2 m^3/s) that ran dry in 1993 due to aquifer overdraft. Today, the temple complex is supplied by other water sources. Recently, an aquifer rehabilitation program was implemented.

Karst regions are characterized by intense groundwater-surface water interactions, with important ecological implications: Surface streams often sink underground via swallow holes, while large springs give rise to important rivers and streams; for example, the entire Upper Danube River in Southwest Germany sinks underground into a karst aquifer during low to moderate flow conditions and reemerges 12.5 km away, at Aach Spring, Germany's largest spring, which is tributary to the River Rhine (Hötzl 1996). The water cave feeding the spring is the northernmost location of an endemic cave fish, highlighting the ecological importance of groundwater-surface water interactions in karst regions (Behrmann-Godel et al. 2017). Endemic species in water caves and karst springs are often threatened by intense land use and contamination in the catchment. For example, the endangered Barton Springs Salamander (*Eurycea sosorum*), which is endemic to Barton spring, Texas, is threatened by declining dissolved oxygen concentrations in the karst spring water resulting from intense agriculture and urban development in its catchment. Potentially, a single severe contamination event generating oxygen levels below the critical threshold could drive this species to extinction (Mahler and Bourgeai 2013).

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Marine Springs

Coastal Marine Springs

by Nils Moosdorf

Springs below the ocean surface that discharge fresh or brackish water ("submarine springs") are a very special environment. Yet they are more abundant than often thought. Submarine springs are particularly abundant in karstic areas, such as the Mediterranean (Fleury et al. 2007), and in volcanic areas like Hawaii (e.g., Knee et al. 2008). Compared to their terrestrial counterparts, submarine springs are much less thoroughly researched. Neither is their total number known (there is not even a register of all major submarine springs), nor do we know discharge volumes or other attributes of most submarine springs. Submarine springs have been used by coastal human populations traditionally, and in some locations this use continues (Moosdorf and Oehler 2017). Uses include drinking water and hygiene, but also spiritual relevance. Many submarine spring locations have legends or other spiritual values attached to them. In addition, submarine springs are favored by fishermen in many locations on the globe because of improved catch rates (Moosdorf and Oehler 2017).

While there are only few biological studies of coastal springs, substantial impacts on benthic ecology throughout the foodchain have been shown (Lecher and Mackey 2018). Very specific and unique ecological conditions occur inside some submarine springs, termed "anchihaline" caves (Pohlman 2011). The marine waters around submarine springs often support increased numbers of fish (e.g., Pisternick eRet al. 2020; Starke et al. 2020), corroborating such reports by fishermen.

Discharge of submarine springs varies in relation to tide and by season, but it can be severely negatively influenced by coastal groundwater pumping, (e.g., in Bahrain: Rausch et al. 2014) or coastal construction (e.g., in Taranto: Parenzan 1969). Yet few examples of impacted submarine springs are reported in the literature since this phenomenon has not been studied. Also, rising sea levels can affect submarine springs (e.g., Ferguson and Gleeson 2012; Masciopinto and Liso 2016), but the degree of impact has yet to be researched. Thus, submarine springs are a unique, highly specialized ecosystems that have not yet been sufficiently understood, but which, like their terrestrial counterparts, are under unknown but potentially substantial risk due to direct anthropogenic impacts as well as climate change. There are no known examples of management or conservation efforts for submarine springs.

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Deep-sea Vent Springs

by Lawrence E. Stevens

Deep-sea marine springs were discovered in 1977 during a submersible submarine expedition to the sea floor near the Galapagos Islands (Ballard 1977). Sea-floor vent springs are submarine hot springs, with temperatures exceeding 370°C. Vent springs generally occur in fields that range in diameter from a few hundred meters to several kilometers. Individual vents emit jets of mineral floc and fine particulate iron sulfide ("black smokers") or calcium and silica ("white smokers"), creating chimney-like precipitate columns (e.g., Parson et al. 1995). These features occur in high frequency, particularly along the mid-oceanic Atlantic and Pacific tectonic spreading ridges, in back-arc spreading zones around the periphery of the Pacific Ocean, and in tropical, temperate, Arctic, and Antarctic waters (e.g., Chown 2012). Not all vent springs occur in profundal waters, and shallow marine vents influence coastal ecosystems (e.g., Tarasov 2006). Vent springs are ephemeral and sometimes cyclical in activity. Individual vents and vent fields vary in age, depending on the tectonic setting, some being short-lived and highly dynamic, while others, such as the TAG hydrothermal mound on the Mid-Atlantic Ridge, may remain active for thousands of years.

Deep-sea vent springs are renowned for supporting a wide array of often highly adapted chemoautotrophic microbes and micro- and macro-invertebrates (Karl 1995; Van Dover 2000, 2002; Van Dover et al. 2002). Rather than relying on photosynthesis-generated energy, these organisms obtain energy through the oxidation of inorganic minerals. Deep-sea vent SDT biota include a remarkable diversity of chemautotrophic or autotroph-consuming microbes, Cnidaria, Annelida, Mollusca, and crustaceans. However, seafloor vents are ephemeral and as vent activity wanes, the associated assemblages undergo biotic succession, with sulfide-dependent taxa replaced by non-vent organisms, although inactive vent assemblages may derive much of their ecosystem energy subsidy from nearby active vents within the field (Erickson et al. 2009). We also note that the ecology of profundal anaerobic chemautotrophic coldwater seeps are gaining substantial research attention (e.g., Levin et al. 2005; Thurber et al. 2013; Goffredi et al. 2020).

Deep-sea mining impacts may be occurring widely, with many marine sea floor springs considered for copper, zinc, silver and gold mineral extraction (e.g., Van Dover 2011). Other impacts on these intriguing ecosystems involve those related to scientific investigation, stimulating the call for appropriate conservation ethics and protocols (Godet et al. 2011). However, the extent and intensity of deep-sea vent spring disruption due to anthropogenic impacts, as well as ecological recovery processes remain largely unknown.

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Chapter 3

Europe

Overview

European springs have influenced and been used by humans over a multi-millennial time frame, with greatly increasing impacts on aquifers and springs in recent historical times (Meinzer 1934; Adams 1938; Kresic and Stevanovic 2009). Use of springs as ambush sites for hunting, and reverence for them as sacred sites undoubtedly characterized the earliest European cultures. However, as hunting and gathering lifeways transitioned into agricultural and then urban settlements, human needs for clean, reliable water sources led to extensive anthropogenic settlement at, and exploitation of clean groundwater provided by springs. While generally consumptive, some anthropogenic development may have increased springs density. For example, prehistoric and medieval deforestation of Central Europe may have augmented groundwater discharge and springs density there (e.g., Hájek, below). Pliny the Elder (ca. 77) wrote extensively about the many remarkable array of springs in the Mediterranean region, apparently believing, like the Greek natural philosophers before him, that such groundwater was somehow derived from seawater and subterranean condensation. Pre-Christian reverence and balneological respect for springs were appropriated by Catholicism, and remained sufficiently robust that regard for springs as special places reappeared relatively quickly following the Reformation (Johansen 1997). However, a burgeoning European population and technological improvements, such as the use of the water wheel and the invention of the steam engine and electric pumps resulted in intensifying exploitation of springs, as well as other water sources (Solomon 2009).

European understanding of the cyclicity of springs hydrogeology linking groundwater to precipitation was recognized by Greek naturalists (Aristotle 1984), but was clarified by European writers and scientists during the Enlightenment (Karterakis et al. 2007). Pierre Perrault (ca. 1611-1680; Perrault 1874) calculated that surface water influx was adequate to explain the flow of the River Seine, and went on to hypothesize about the origin of springs. Edmund Halley (1691) and Antonio Vallisneri (1715) supported and refined Palissy's (1580, in LaRoque 1957) hypothesis, concluding that spring waters were ultimately derived from infiltrating meteoric sources. Subsequent and ever-increasing demands on water supplies, improving well-drilling technology, and pollution have led to the dewatering or contamination of many European springs. In response, groundwater information is being compiled and made available in many nations, with databases like the Base de Données des Limites des Systèmes Aquifères (BDLISA; brgm.fr) providing national hydrogeological information and tools in France. Intensive catchment-wide analyses also are emerging to reveal climate change impacts. As one of many such efforts, a 50-year record of monitoring weather and streamflow in the Réal Collobrier catchment in southeastern France has revealed climate-change reduction in western Mediterranean precipitation (Folton et al. 2019 and literature therein), which with increasing temperature and evapotranspiration, will reduce infiltration and potential groundwater discharge. Thus, hydrology emerged as a scientific discipline from the Enlightenment and has matured to point of understanding and prediction of the future of its essential groundwaters.

Such attention to groundwater has elevated awareness regarding the importance springs, not only as important socio-cultural features, but also as indicators of environmental integrity. Some European countries (particularly in Scandinavia) now regard springs ecosystem integrity as a national concern, and the European Union (EU) has recognized travertine-depositing springs as a protected ecosystem (Cantonati et al. 2016). Reverence for springs is reflected in the work of many European ecologists, with remarkable contributions to ecosystem ecology and biodiversity by Botosaneanu (1998), Margalef (in Prat et al. 2019), and many of the coauthors of this book. Such policy and scientific attention increase public awareness of springs, helping bring much-needed basic appreciation, support for research, and encouragement for improved stewardship. However, nearly all of our European collaborators report deficiency of geographic, typological, and conservation status data. Existing data collectively indicate high levels of habitat degradation and loss, with degradation negatively related to latitude, elevation, and proximity to heavily-used rural agricultural, industrial, as well as urban areas. To address data gaps and uncertainties and recover ecological integrity, Cantonati et al. (2020) called for improving public and governmental awareness of spring ecosystems, as well as additional basic mapping, inventory, and assessment to determine the distribution and ecological integrity of springs globally. The impetus for the present work is, in part, in response to their concerns.

European springs remain socio-ecologically exceptionally important points in the landscape, where reverence for divine qualities is coupled with exploitation for potable supplies, recreation, and balneological purposes. Such sites include: the cave spring at Delphi (Broad 2007); most of the spring-supplied Roman aqueducts; La Fontaine de Vauclose in southeastern France; the King's, Hetling, and Cross Bath geothermal springs complex in Somerset, England; the sulphurous Saturnia springs near Siena, Italy; the Corinthian Peirene Fountains (Robinson 2011); and many others, as reported among the case studies in Kresik and Stevanovic (2009) and in many of the following synopses. The remarkable individual histories of European springs integrate secular and spiritual aspects of the region's many, diverse, changing, and future cultures.

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United Kingdom

United Kingdom Overview

by Allan Pentecost

England, Northern Ireland, Scotland and Wales, comprising the United Kingdom are underlain by rocks ranging in age from Archaean to Recent (Figure 3-2). Lithologies range from massive granites and gneisses, mainly in the northwest to porous sandstones, clays and limestones in the midlands and southeast. This contrast in geology is matched with high levels of annual precipitation in the west, often exceeding 2000 mm/a to <500 mm/a in the east. Significant aquifers among the sedimentary rocks are sandstones ranging from Devonian to Eocene and the Cretaceous chalk. Glacial and periglacial deposits are also important in some areas. The UK has just one hot-spring at Bath Spa, Avon (45ºC) with a handful of thermal springs, some of which are artesian. Chemical composition varies widely with ionic strengths ranging close to unpolluted rain water to highly saline. Among the mineral springs, chalybeate springs are widespread. There are fewer sulfur springs with most in northern England associated with pyrite-rich sediments. Travertine-depositing springs, usually originating from perched water tables are widespread in some of the limestone districts while saline springs are rare and mainly confined to areas underlain by evaporites. A few hyperalkaline springs associated with historic lime-burning are also known. The majority of UK springs are rheocrenes, but limnocrenes and helocrenes are fairly common, particularly in the north.

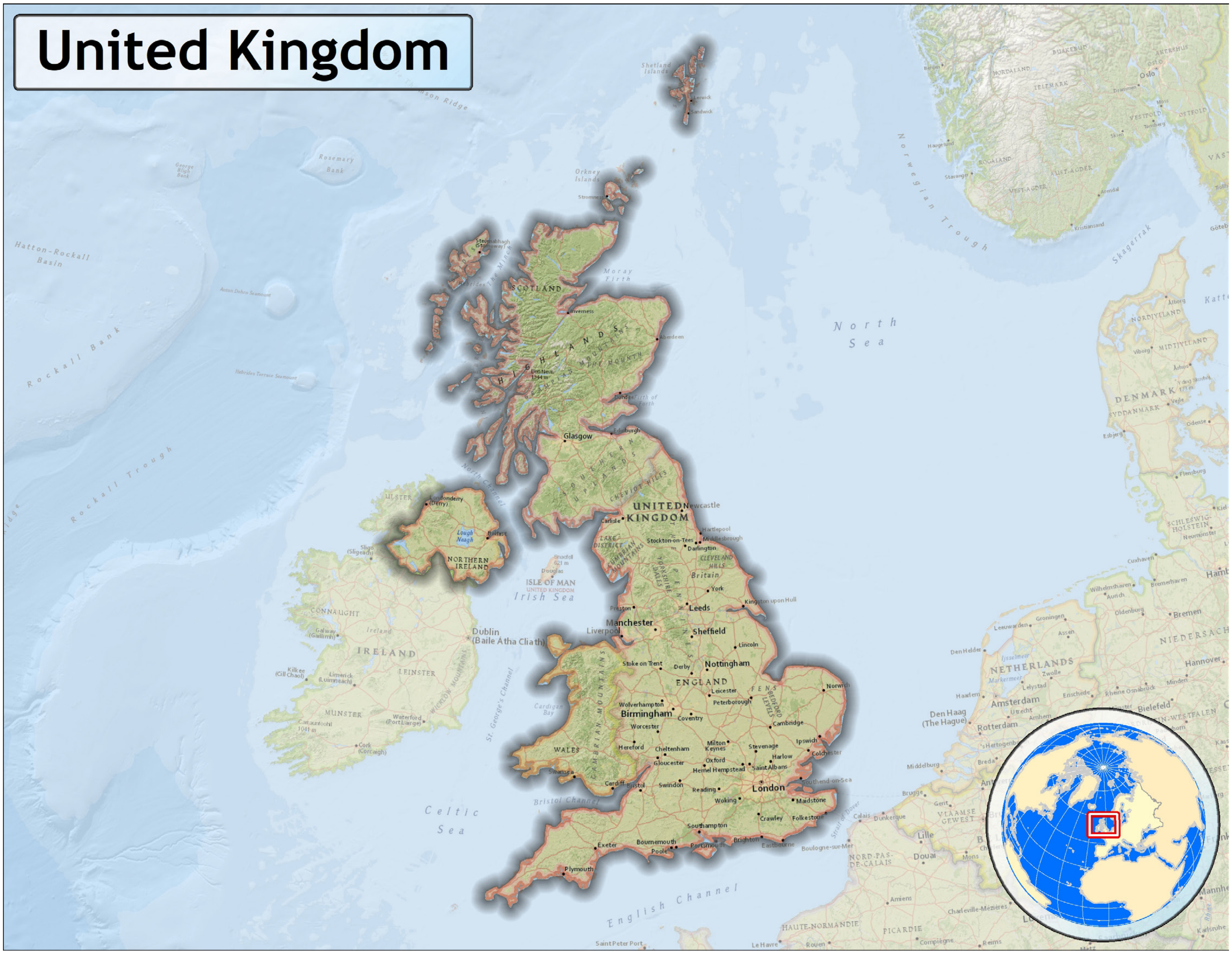

Figure 3-2. Map of the United Kingdom.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 49.96°, 2nd Standard Parallel = 60.84°.

Estimates of spring density for five contrasting but representative areas of the UK vary (Table 3-2). These data suggest that, before urbanization of the UK, total spring numbers were on the order of half a million. This excludes most intermittent springs.

Human association with springs in the UK has a long history. At Blick Meade, a chalk spring close to Stonehenge, Wiltshire, Mesolithic peoples were present from 7-10 Ka BP. The spring contained flints colonized by the red alga Hildenbrandia, which may have given the site special status with the bright red stones possibly collected as talismans. Considerably later, the Romans developed several springs, notably Bath and Buxton spas, which remain in use today. In the early Medieval period, many further springs were developed as Holy Wells, often associated with saints (e.g., St. Akmund's Well in Derby which dates to c. 800 CE). Research suggests that holy wells tended to be more common in areas of the older impervious formations which make poorer aquifers with fewer useful sources of water. During the Reformation (c. 1540-90) patronage of holy wells was discouraged but by 1600 they enjoyed a rebirth along with the development of spas, popularized by the nobility. Spas and holy wells sprung up all over the land and were not confined to the towns (e.g., Figure 3-3). Many became popular places of entertainment in the late 17th and 18th centuries, but most fell out of favor by 1800. Subsequently, almost all declined and few survive to the present day. The population of the UK reached 20 million in the 1860's leading to the rapid growth of towns. Land use also increased and today, 72% of the UK's land area is classified as agricultural with a further 7.1% urbanized. Almost all springs in these areas have been modified to allow more efficient use of the land. Woodland currently covers about 13% of the UK and most of this has been felled at some time in the past, and the associated springs have probably been affected. The greatest impact will have been in the southern and eastern parts of the country where rainfall and spring density

Table 3-2. Variation in estimated spring density in five contrasting but representative areas of the UK.

Location	**Main aquifers**	**Annual precipitation (mm)**	**Spring density/km^2**
Tonbridge, Kent	Cretaceous sandstones	740	1.83
Cambridge	Cretaceous chalk	570	0.51
Kingsbridge, Devon	Devonian sandstones	960	2.20
Rhosneigr. Anglesey	Pleistocene/Holocene drift over chrystalline basement	150	2.41
Broadford, Skye	Jurassic sandstone, Carboniferous limestones, drift	2200	3.53
Average	**All**	**920**	**2.1**

Figure 3-3. Example of a holy well in the United Kingdom.

is lower. Overall, it appears likely that up to 80% of UK springs have been disturbed to some extent by human activities. There are few data relating to the general health of springs in the UK but with the current house-building boom, more springs are likely to be lost or modified. Most UK ground waters are unpolluted but often contain elevated levels of nitrate-nitrogen and orthophosphate, resulting from air pollution and agriculture.

The UK climate is predicted to become warmer, wetter and with more prolonged and severe droughts. The chalk winterbournes – a series of intermittent springs in south-east England – are particularly at risk. Recent studies suggest that most of the indigenous algae and invertebrates recover rapidly but rare and vulnerable species can be affected. Excessive poaching of springs by horses and cattle has also been reported and is unlikely to decline in the near future.

Nine Wells Springs near Cambridge have supplied the city with clean water for 400 years. Rising from the Cretaceous chalk, the springs have been impacted by excessive groundwater abstraction and in the severe drought of 1976 its Site of Special Scientific Interest (SSSI) status was removed when its rare invertebrate fauna was lost. The site is currently protected as a Local Geology Site and the UK Environment Agency has recently driven injection boreholes above the springs to augment their flow with water pumped from the chalk aquifer. Some chalk streams, including their springs, are also designated as a Biodiversity Action Plan (BAP) priority habitat, but few UK springs enjoy specific conservation status. Nevertheless, they may be included in SSSI wetland areas of ecological/geological or archaeological interest. Travertine-depositing springs receive particular notice owing to their sensitivity to water pollution and hydrological disturbance. Several are included in Special Areas of Conservations and SSSI's.

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Petrifying Springs in Ireland

by Melinda D. Lyons

Petrifying springs (also known as tufa-forming or limestone-precipitating springs) are widely distributed throughout much of Ireland as small, local features of ecological importance (Figure 3-4). They are most common across the central part of Ireland, which is underlain by Carboniferous limestone, but are also found in regions where lime-rich glacial till overlies other, less calcareous bedrock types (Lyons 2015). Non-calcareous neutral and acid springs are also widespread in Ireland but are less well documented.

Petrifying springs are specialised habitats with ecologically distinctive plant communities, often dominated by bryophytes (Lyons and Kelly 2017). The large weft-forming pleurocarpous moss *Palustriella commutata* is characteristic. On steeply sloping sites, it is often accompanied by the smaller acrocarpous mosses *Eucladium verticillatum* and *Didymodon tophaceus*, and the thallose liverwort *Pellia endiviifolia* (Figure 3-5). Springs on cliffs in the Benbulbin Range in north-west Ireland (altitude c. 350 m) are of especially high nature conservation value (Figure 3-6). They contain species-rich communities of international importance with Yellow Saxifrage (*Saxifraga aizoides*) and the rare mosses *Seligeria oelandica*, *S. patula*, *Hymenostylium recurvirostrum* var. *insigne* and *Orthothecium rufescens*. Elsewhere, on level or gently sloping sites, petrifying springs are often found in asso-

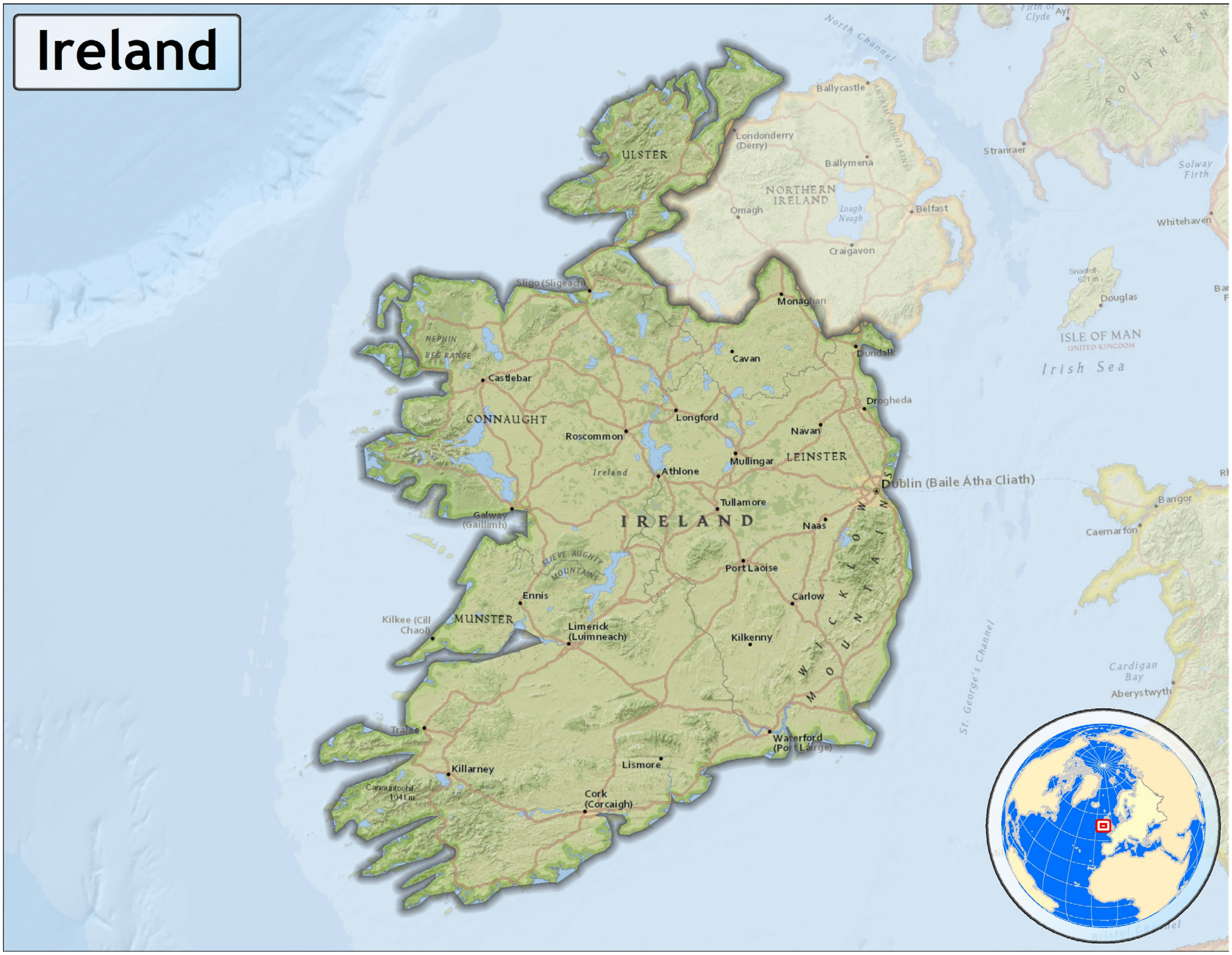

Figure 3-4. Map of Ireland.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 51.45°, 2nd Standard Parallel = 55.38°.

Figure 3-5. Coastal petrifying spring with mosses *Palustriella commutata* (golden, at top of spring) and *Eucladium verticillatum* (green, on vertical tufa surface), near Balbriggan, Co. Dublin. March 2010.

Figure 3-6. *Saxifraga aizoides* (Yellow Saxifrage) and *Orthothecium rufescens* (reddish-pink moss) on Benbulbin, Co. Sligo. The spring water has very low levels of nitrates and phosphates and supports several rare moss species. July 2013.

Figure 3-7. Tufa-forming spring associated with alkaline fen, with *Palustriella commutata* and Black Bog-rush (*Schoenus nigricans*), Co. Sligo. September 2012.

Figure 3-8. Damage to spring flora and fauna due to regrading and clearance of land for agriculture, Co. Kildare. October 2012.

ciation with alkaline fens; characteristic species include Bog Pimpernel (*Lysimachia tenella*), Long-stalked Yellow-sedge (*Carex lepidocarpa*), Black Bog-rush (*Schoenus nigricans*), the mosses *Bryum pseudotriquetrum*, *Palustriella falcata*, *Campylium stellatum*, *Philonotis calcarea* and *Scorpidium cossonii*, and the thallose liverwort *Aneura pinguis* (Figure 3-7). There is a statistically significant inverse relationship between species diversity and nutrient enrichment by both phosphates and nitrates (Lyons 2015). The mosses *Cratoneuron filicinum*, *Platyhypnidium riparioides* and *Brachythecium rivulare* are more abundant in nutrient-enriched spring waters.

The rapid rate of tufa formation in many springs is of scientific and palaeoenvironmental importance (e.g., Preece and Robinson 1982; Preece et al. 1986). A survey of six Irish petrifying spring sites found that tufa deposits increased in height by 20.5 ± 1.1 mm per year, on average (Lyons and Kelly, 2020), with *Palustriella commutata* in particular associated with rapid deposition. The mean height increment of bare, unvegetated tufa, by comparison, was 16.5 ± 3.0 mm per year.

The importance and vulnerability of these habitats is recognised in their designation as a priority habitat type under the EU Habitats Directive (92/43/EEC). The hydrology and vegetation of remote upland petrifying springs in Ireland are relatively intact. In the lowlands, however, many important sites have been lost due to drainage of lands and most (over 70%) of the remaining springs have been degraded (Lyons 2015). The most common causes of degradation are physical modifications to water flow, especially due to road building and agricultural intensification; a reduction in flow due to lowering of the water table; extraction or diversion of water for agriculture, domestic use or servicing canals; nutrient enrichment, especially from agricultural sources; scrub encroachment following abandonment of grazing; the presence of non-native species; overgrazing; and trampling due to recreational activities. As a result, plant communities of petrifying springs have been impoverished and populations of the more sensitive and nationally rare species have declined.

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Scandinavia

Finland

by Jari Ilmonen

Finland is located in the boreal biome, 60-70° N latitude and covers 338,449 km^2 (Figure 3-9). Most of the country lies <300 m above sea level, with highest peaks up to 1,324 m in the northwest. Finland was completely covered by the Weichselian glaciation until ca. 10,000 years BP. Consequently, the terrain is young and endemic species are rare, but the soil is rich with glaciofluvial and ice-edge terminal formations that comprise the majority of aquifers feeding springs in Finland. Moraine deposit aquifers also are rather common, whereas limestone aquifers are rare. Approximately 33,000 springs have been reported in the Topographic Database of the National Land Survey of Finland, but the total number may exceed 100,000 springs. Forests cover three quarters of the Finnish land area, and forestry is the most common land use apart from far northern parts, where forestry is not feasible. During the 20th century, drainage for forestry was intensive in Finland up to the southern half of the northern boreal ecoregion, affecting at least 90% of springs. Consequently, spring complexes were assessed as Endangered (EN) in Southern Finland (hemiboreal, southern boreal and middle boreal subregions) and Least Concern (LC) in Northern Finland (northern boreal subregion) using modified IUCN criteria (Kontula and

Figure 3-9. Map of Finland.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 59.81°, 2nd Standard Parallel = 70.09°.

Raunio 2018). The heavy drainage network has continued to degrade the ecological integrity of springs for decades, and negatively affects spring specialist species (Ilmonen et al. 2012, Lehosmaa et al. 2017a). In addition, groundwater contamination in more urbanized areas impairs the ecosystem functioning and biodiversity of some springs (Lehosmaa et al. 2018), while global warming poses a threat to the existence of cold-stenothermal spring specialist species (Jyväsjärvi et al. 2015). Studies of hydrological restoration of springs have shown that responses of bryophyte and benthic macroinvertebrate communities to hydrological restoration are usually positive, but recovery takes several years (Ilmonen et al. 2013; Lehosmaa et al. 2017b).

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Iceland

by Agnes-Katharina Kreiling and Ragnhildur Guðmundsdóttir

Iceland is a 103,000 km^2 geologically young volcanic island, located between 63°17'N and 66°33'N on the Mid-Atlantic ridge in the North Atlantic, where the Eurasian and North American continental plates diverge (Figure 3-10). The main bedrock type in Iceland is basalt, and within the volcanically active zone that crosses the island from the southwest to the northeast, the rock formations are young and permeable (Sigurdsson and Stefánsson 2002). Iceland has low air temperatures, high precipitation rates, and low evaporation rates. As a result, Iceland is rich in freshwater springs, emerging most commonly along the edges of the lava fields. Both cold (2 - 14°C) and hot (14 - >100°C) springs are common (Tuxen 1944, Þórðarson 1981, Kreiling et al. 2018). Outside the volcanic zone, springs are a result of surface runoff and can often be found in the unconsolidated strata (Einarsson 1994). Eight of the ten largest springs in the world are found in Iceland (Óskarsdóttir 2011), for example the hot spring Deildartunguhver with a discharge of 180 L/s. Rheocrene, limnocrene, and helocrene springs are the most common types, but solfataras, geysers, and fumaroles are abundant in the many high-temperature geothermal areas (Þórarinsson 1978, Fridleifsson 1979).

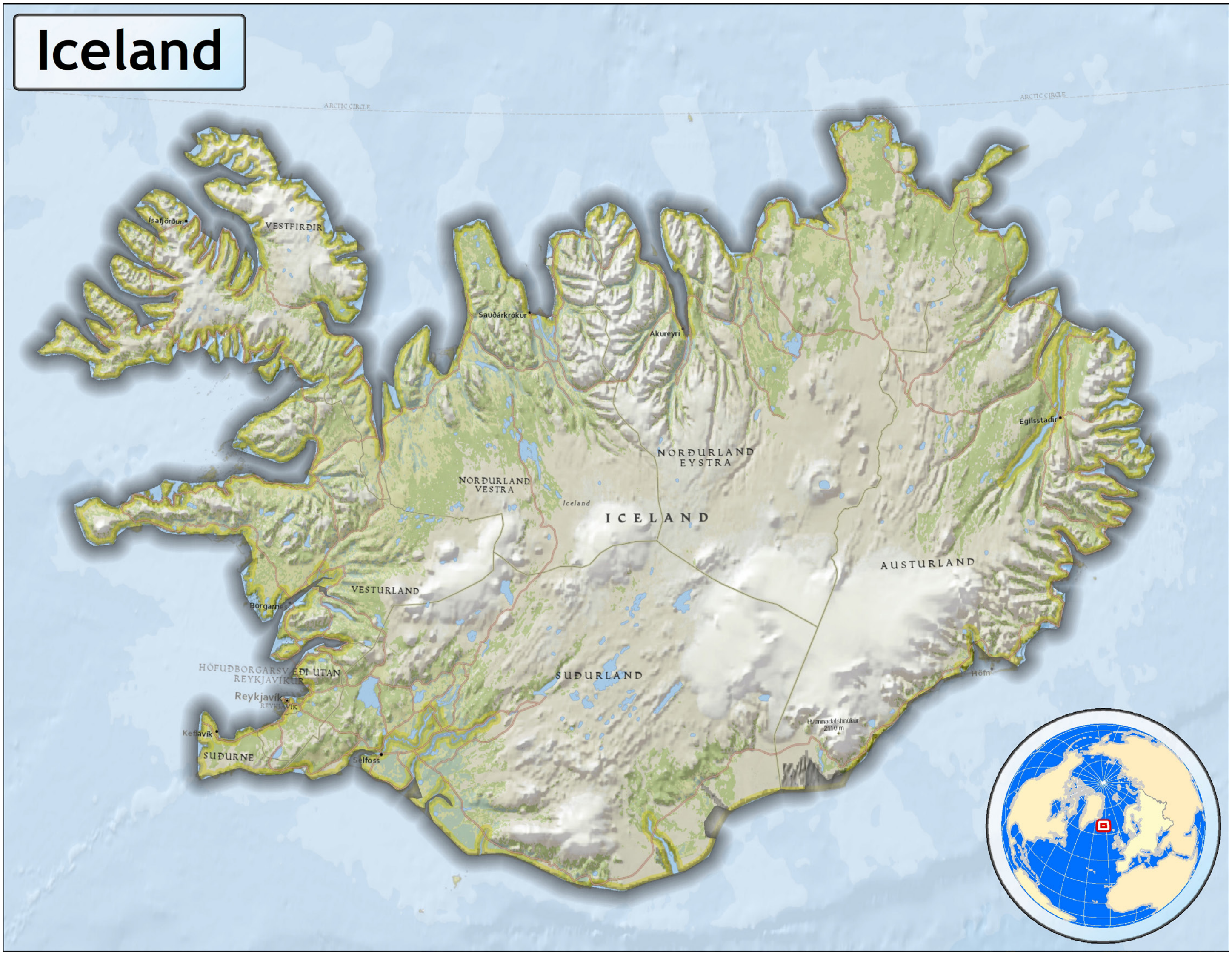

Figure 3-10. Map of Iceland.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 63.39°, 2nd Standard Parallel = 66.54°.

The status of both knowledge and conservation differs between cold and hot springs. Hot springs and geothermal areas are well explored and mapped (Torfason 2003), not least for human resource use. Geothermal heat is used for heating, to provide hot tap water, and to generate electricity and is obtained from boreholes which in turn lead to the drying-out of hot springs. In addition, natural geothermal pools are a big tourist attraction, causing many sensitive hot spring areas to be threatened with severe disturbance due to trampling of the surrounding vegetation, excessive nutrient load, and litter pollution. All hot springs and their immediate surroundings are protected by Icelandic law (Law on Nature Protection Section X, paragraph 57).

As there are no reliable estimates on the number of cold springs, it is challenging to estimate the percentage of springs affected by human activities. However, it is safe to assume that most springs in the peripheral lowland areas (< 200 m asl, 24 % of landmass) of the country are directly or indirectly influenced by humans, as settlements and farmland are almost confined to these areas. Cold springs serve as a source for drinking water as well as water for industrial purpose. Pristine springs remain in National Parks and in remote areas such as the Central Highlands. Although a few cold springs have recently been put on a conservation list (Náttúruminjaskrá 2020), practical actions to protect cold springs have been lacking so far.

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Norway

by Jutta Kapfer, Kamilla Skaalsveen, and Kristian Hassel

Springs are common in Norway (Figure 3-11). High annual precipitation (1971-2000 ca. 1,600 mm on average for the Norwegian mainland) and moderate evaporation cause a surplus of freshwater contributing to a relatively large surface runoff and infiltration into the ground. Although 90% of the drinking water comes from surface waters, springs are of significant importance for water supply, contributing the remaining 10% to approximately 550,000 Norwegian citizens (Skjærstad 2013).

Despite being common and occurring spread all over the 385,207 km² Norwegian mainland, information on the frequency and regional distribution of springs is limited, likely because they usually are too small to be identified on aerial imagery that commonly is used in vegetation or nature type mapping. However, geographical locations of springs mapped are available from different databases (e.g., GRANADA - National Groundwater Database, Geological Survey of Norway 2020; NiN – Nature Types in Norway classification system, Halvorsen et al. 2020) and thematic literature, such as biological, hydrological or geochemical studies (e.g., Moen 1970; Reigstad et al. 2011; Miller et al. 2020).

Most springs in Norway are cold (3-7 °C) and permanent (eustatic; Figure 3-12, Figure 3-13, Figure 3-14, Figure 3-15). Astatic springs occur more often in the

Figure 3-11. Map of Norway.

Map boundaries were extracted from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 57.99°, 2nd Standard Parallel = 71.15°.

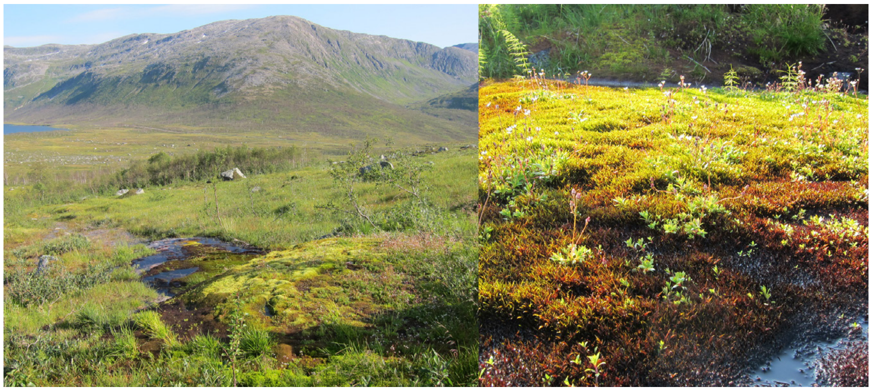

Figure 3-12. Example of a bryophyte dominated, poor springs ('fattigkilde' sensu Fremstad 1997, pH 5-6), *Philonotis* subtype, with *Sarmentypnum procerum*, *Philonotis seriata, Scapania uliginosa*, dominating and scattered occurrence of *Saxifraga stellaris*, *Deschampsia caespitosa* and *Equisetum arvense*. Photo: JK.

Figure 3-13. Example of a bryophyte dominated, poor springs ('fattigkilde' sensu Fremstad 1997, pH 5-6), Philonotis subtype, with *Sarmentypnum procerum, Philonotis seriata, Scapania uliginosa*, dominating and scattered occurrence of *Saxifraga stellaris*, *Deschampsia caespitosa* and *Equisetum arvense*. Photo: JK.

mountains. Only a few warm (thermal, 10-25 °C) springs are known from the Svalbard Archipelago in the Norwegian High Arctic. Aquifers in unconsolidated deposits consist of permeable sand/gravel and in mountains also of areas with fractured rock. Springs emerge at the interception of fluvial deposits with till or marine clay. Hence, they typically occur on slopes, usually below the turning point at leeside where the terrain flattens out and most often in areas with a high relative relief up to and in the mountains. In forests, springs occur frequently in the forest-mire transition zone and at the foot of hills. Springs are generally categorized into rich (calcareous groundwater, pH 7-8) and poor springs (groundwater poor in calcium, pH 5-6(7); Fremstad 1997).

The biodiversity of springs in Norway is little studied, especially in the lowlands. With the exception of a few articles in the mid-1900s (e.g., Nordhagen 1943; Dahl 1957), scientific investigation of springs is relatively recent (Økland et al. 1985; Lindegaard, 1995; Miller et al. 2020). Plant species composition is determined by nutrient gradients, permanence of water flow, and the gradients from springs source to the edges (e.g., transition to mire, snowbed, streams).

Little is known of how different kinds of human activity in the catchment area of springs may impact spring waters and biodiversity. The majority of springs, especially those in mountain areas, are generally assumed to be pristine and undisturbed, with good water quality. At lower altitudes, below the Late-Postglacial sea level stage, incorporation of fossil sea salts can result brackish spring waters (Englund et al. 1980). Human-related impacts on spring aquifers are likely to become more relevant locally and in lowlands with increasing population density and human activity. Groundwater pollution related to diffuse or local discharges by agricultural activity, buildings, industry, traffic and landfills may result from infiltration into aquifers. Examples include faecal bacteria from humans and animals (sewage), mineral and synthetic oils, pesticides, fertilizers and industrial chemicals. Changing nutrient loading in the catchment area (e.g., wet deposition, nutrient input of outfield grazing by domestic animals such as sheep and cattle) can be another important factor influencing spring water quality and biodiversity. Furthermore, habitat loss by, for example, mechanical disturbance (e.g., drainage, water well construction) and climate change (warmer and wetter) might change the occurrence of suitable spring habitats. The latter is expected to be a threat

Figure 3-14. Moss rich seepage at Kvannfjellet Mountain, Troms and Finnmark, Balsfuord. Photo: JK, 2015.

for the future distribution of spring species tracking climate change, especially at high altitudes (Miller et al. 2020).

Springs have been used as freshwater supplies for thousands of years. In the Younger Iron Age in Scandinavia, they also played an important role in funeral rites. In Sweden, for instance, burial sites from the Viking Age were located close to mountains and springs. Ethnographic sources mention that in Sami culture, springs were associated with faith and traditions associated with holy places (Sommerseth 2018). Sacred springs that have been celebrated since pre-Christian ages are found across Norway, although only some still remain (Werner 1998). Two examples are Olavsolla and Olavsbekk, situated in Bø in Telemark, along with most of the sacred springs in Norway, likely dedicated to St. Olav who brought Christianity to Norway (Bø 1965), and at who's grave a spring with miraculous healing powers appeared. The water quality of those two springs were threatened by landfill contamination, but are expected to recover with time (Klempe 2015). Olavsolla has a large storage aquifer (securing constant water provision) and is situated in close proximity to several monuments of pre-historic age and Iron Age burial mounds, underpinning its importance as a sacred spring (Klempe 2015). Springs also were important for settlements and boat traffic as year-round supplies of clean and cold running freshwater (Sommerseth 2018). Locally, until the middle of the past century, fresh water for cooking and washing, and drinking water for both human and domestic animals was collected daily from springs in local surroundings.

Today, springs remain important drinking water sources for use in (mountain) cabins frequently visited at holidays. Some people also use them for short-term conservation of food (e.g., freshly caught fish). In all, Norway is privileged regarding the quality and potability of its groundwater and springs, both for daily usage (average daily per capita water usage is 526 L/day; Myrstad et al. 2007) and as a predominatnly free and safe drinking water resource in the outdoor environment.

Figure 3-15. Spring water discharge at Hjerttinden Mountain, Troms and Finnmark, Sørreisa, JK, 2015.

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Western Europe:

France – Massif Central

by Aude Beauger and Olivier Voldoire

The French Massif Central (FMC) is the largest massif (>85,000 km^2) in the nation, and occupies the central region of the southern part of France (Figure 3-16). Its mountainous reliefs are linked to the Hercynian orogeny during the Paleozoic Era, with plateaus, plains and quiescent volcanoes due to the appearance of young mountain ranges, such as the Alps during the Paleogene. The uplift of these mountain ranges has led to the dislocation of the basement (Mottet, 1999). The highest point is the volcanic summit of Puy de Sancy at 1,885 m. The aquifers of this region include crystalline (granite or metamorphic rocks), volcanic and sedimentary rocks (limestone and marl).

The geologic layers and the many faults occurring in the FMC allow the circulation of water into the rocks and the emergence of water sometimes after a more or less long travel through the earth's crust). Rheocrene, limnocrene and helocrene springs are typical in the FMC, but few caves (mainly in the southern part of the FMC) or geysers exist. No catalogue of FMC springs has been prepared except for its mineral springs (Figure 3-17), but

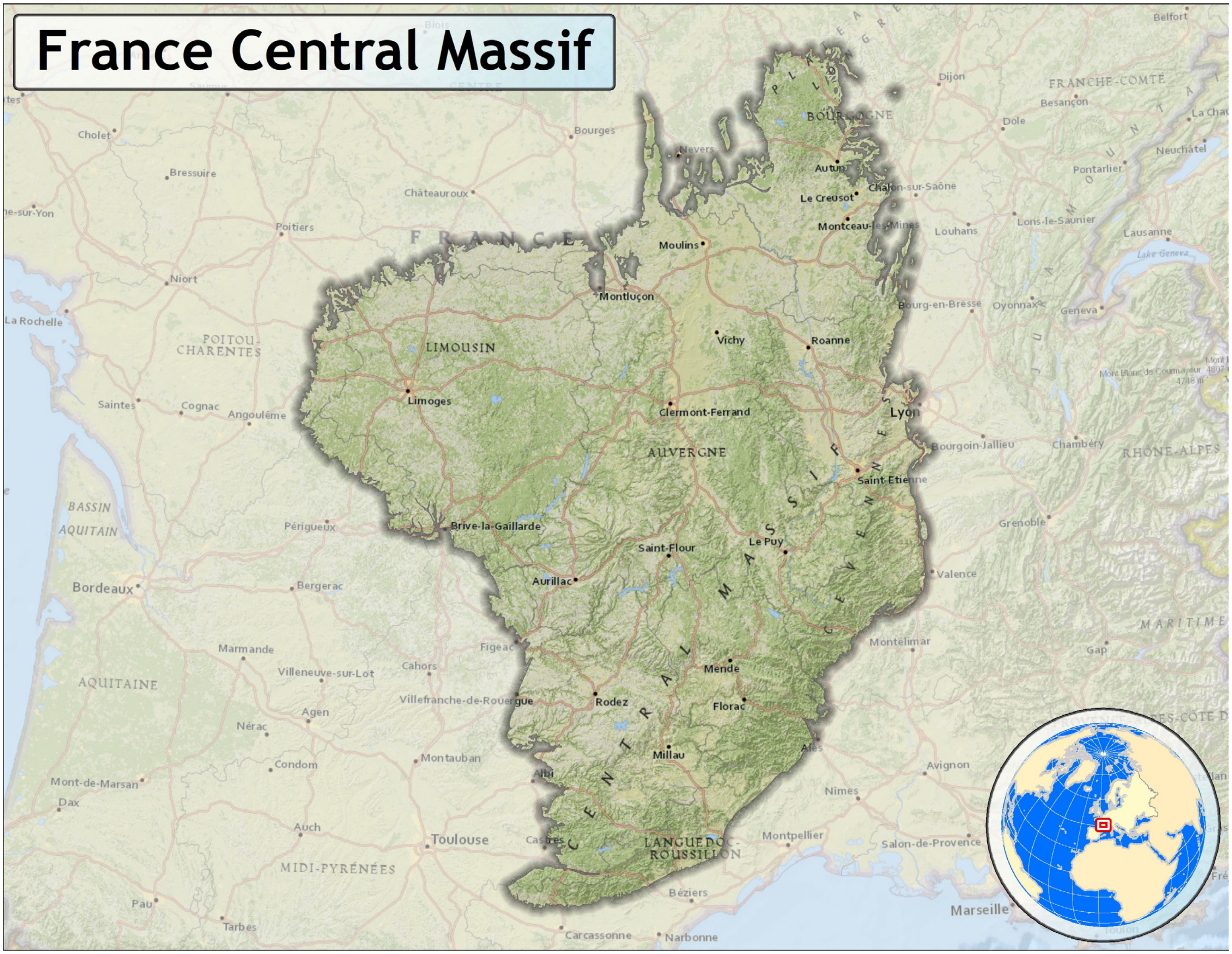

Figure 3-16. Map of the Central Massif Region, France.

Map boundary data were derived from Formations_géologiques ArcGIS Feature Server [https://services.arcgis.com/V6ZHFr6zdgNZuVG0/ArcGIS/rest/services/Formations_g%c3%a9ologiques/FeatureServer, accessed Dec. 27, 2022]. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 43.31°, 2nd Standard Parallel = 47.52°.

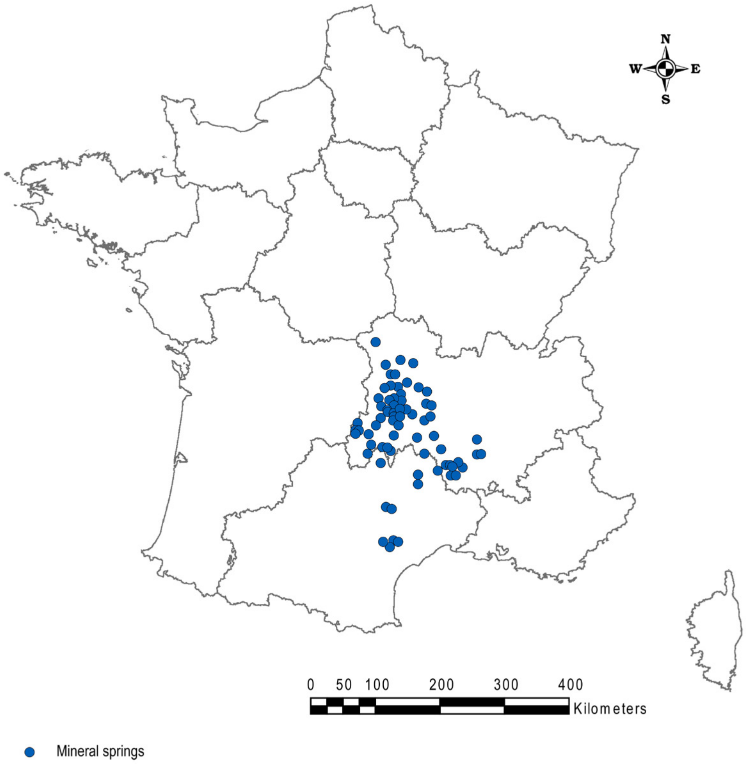

Figure 3-17. Map of the mineral springs of the French Massif Central (prepared by Olivier Voldoire).

Figure 3-18. Font Salado, an iron, saline spring in the French Massif Central.

Figure 3-19. Source Matarets, an iron-depositing spring in the French Massif Central.

different springs have been used since the Gallo-Roman period for therapeutic purposes and bottling. In 1864, Lecoq recorded 466 mineral springs, such as Par, the hottest spring of Europe (80°C) and La Montagne, the most radioactive spring in France (Figure 3-21). Many of them are still used today for balneology or the bottled water industry (e.g., Volvic, St, Yorre). Thus, few mineral springs remain in their natural condition (Figure 3-18, Figure 3-19, Figure 3-20). However, many of them have been either destroyed due to human activity or to their abandonment, ultimately leading to their disappearance. Pristine springs are situated in the different National Nature Reserves of the MC, whereas those in poor condition are situated in the plains where agricultural activities are important.

Climate change in the FMC may result in reduced winter snowpack in the mountains and increased evapotranspiration in the plains, which would reduce water infiltration and spring discharge and ultimately result in the drying up of the springs.

At the present day, some abandoned mineral springs are managed by the Auvergne Conservatory of Natural Areas that protects and restores them. This is the case for Ceix spring (the City of Gimeaux), where the removal of a pipe capturing the spring water at the emergence for former artis-

Figure 3-20. Source Matarets, an iron-depositing spring in the French Massif Central.

Figure 3-21. Source Par, the hottest spring in the French Massif Central.

anal activities, has led to restoring it to its natural situation. In relation with such conservation efforts, several studies have been undertaken to better understand the biodiversity and the potential negative effects on local human, animal and plant populations, considering the natural radioactivity known to occur in this particular ecosystem (Beauger et al., 2020; Millan et al. 2020).

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Germany

by Dirk Hinterlang

An ideal combination of topography, temperature, and precipitation creates perfect conditions for numerous and ecologically manifold spring habitats in Germany (Figure 3-22). From the limestone Alps to the tidal mud coasts and lagoons of the North and Baltic Seas, the total area of Germany comprises 357,386 km². Half of Germany rises to more than 200 m a.s.l., with an average relief energy of 300-400 m. For Central Europe (sub-Atlantic to sub-continental), the mean ambient air temperature is 9°C, with a winter average 0°C and a summer average of 17°C; mean precipitation averages 790 L/m², evenly distributed with a slight maximum in the summer months. These climate conditions allow for excellent overall infiltration and aquifer support for spring habitats.

No wonder the total number of German spring habitats is significantly high. The federal topographical mapping agency counted some 67,279 spring features in their cadaster (ATKIS 2021). However, more detailed studies show that this total estimate is a gross underestimation that may reflect only half of the actual number at best. A closer look at each of the hydro-geographically determined spring plots reveals that on a large scale one finds three or more distinct spring habitats in their vicinity. The total number of spring habitats in Germany may thus be well over 350,000.

Figure 3-22. Map of Germany.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 47.27°, 2nd Standard Parallel = 55.06°.

Calcareous bedrock makes up approximately 15% of the mountain ranges in Germany, mostly of alpine Devonian or Cretaceous origin. In the larger parts of Germany, however, slate, greywacke or sandstone formations of the Caledonian Folding influence the aquifers, specifically the chemical composition of the spring water. The distinction between calcareous and non-calcareous, moderately acidic spring water is extremely relevant for both spring vegetation and its benthic fauna (Crunoecia 1996).

Vegetation surrounding spring habitats is another notable ecological trait: springs within near-natural (beech) woodland differ significantly from springs in forests of planted coniferous trees; and forest spring habitats are completely different from springs situated in open, mostly (pastured) grassland.

Natural conditions given, beech (Fagus sylvatica) forests would cover 66% of Germany and would be especially prevalent in the medium-range mountain areas where most spring habitats are found (Figure 3-23). However, nowadays, near-natural beech forests only occupy 7.6% (16,801 km^2) of its natural area. The rest is artificial plantation, mostly of spruce trees (*Picea abies*). Therefore near-natural spring types are now restricted to a very small area.

Spleenwort (*Chrysosplenium oppositifolium*, *Chrysosplenium alternifolium*), bitter cress (*Cardamine flexuosa, Cardamine amara*) and the sedge (*Carex re-*

Figure 3-23. *Chrysosplenietum oppositifolii, n*ear-natural spring vegetation in a beech forest.

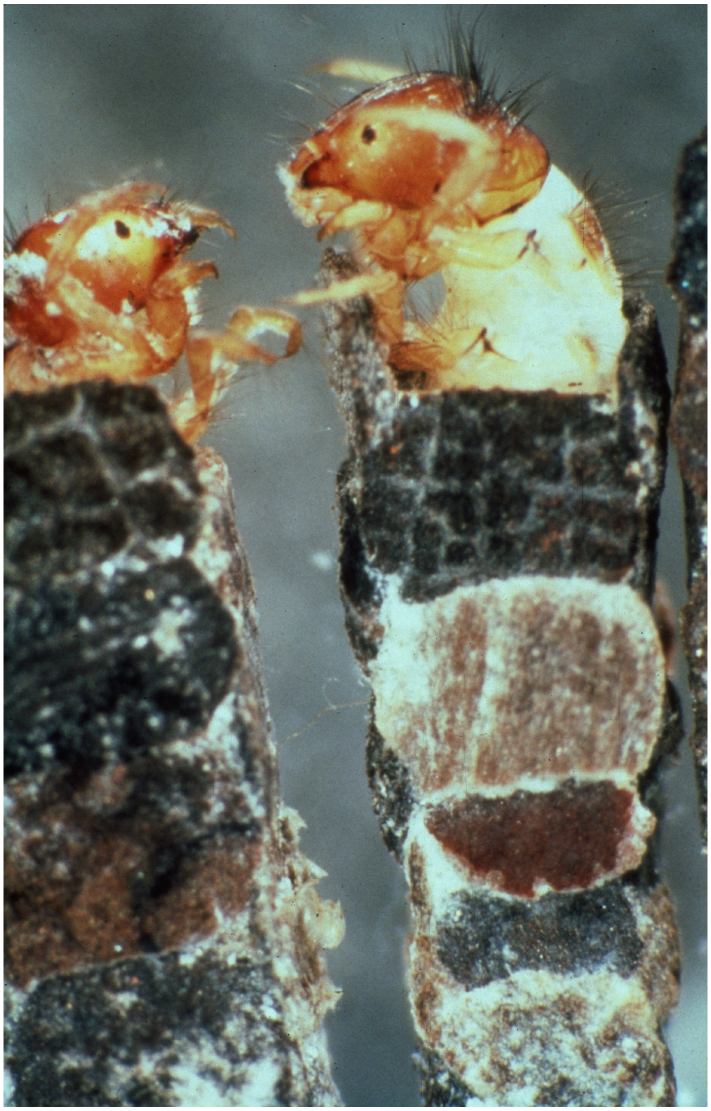

Figure 3-24. *Crunoecia irrorata,* a typical caddisfly of beech forest spring habitats. Its scientific name explains its habitat characteristics: Crun=crenon=spring, oecia=oikos=-house, irrorata=irrorare= drizzle, sprinkle.

mota) dominate the near-natural plant communities of springs in beech forests. Hinterlang (1992, 2017) established a vegetation order named after those species: *Cardamino-Chrysosplenietalia*. Under these ecological conditions, one also finds most of the typical benthic fauna of natural spring habitats, like *Cordulegaster bidentata* (a large spiketail dragonfly), *Bythinella dunkeri* (a tiny snail), *Crunoecia irrorata* (a caddisfly; Figure 3-24), *Crenobia alpina* and *Polycelis felina* (flatworms), and *Salamandra salamandra* (the fire salamander).

Spring habitats in spruce forests show a dramatic difference in vegetation due to acidic needle litter: peat-accumulating *Sphagnum*-moss cushions replace the natural bitter cress and spleenwort communities, and only a few ecological generalists make up the benthic fauna.

Spring habitats in open land (excluding intensely pastured grassland) include vegetation types closely related to arctic or alpine spring vegetation, with typical vascular plants (*Montia fontana* aggr., *Stellaria alsine*) or spring mosses (*Philonotis* ssp., *Bryum pseudotriquetrum*, *Anisothecium palustre, Palustriella commutata*). Among the benthic fauna, one still finds spring specialists like *Pedicia rivosa, Gammarus pulex, Pisidium personatum,* and some of the species mentioned above. Due to land use changes towards more intensive care, on one hand, and abandonment of use on the other hand, these spring habitats and their typical biodiversity are in danger of extinction.

The Federal Agency for Nature Conservation in the Red List of Habitat Types in Germany (Finck et al. 2017) assessed the threats to spring habitats in general as endangered, ranging from IUCN criteria “Vulnerable” to “Endangered” to “Critically Endangered”. Spring habitats in the northern lowlands of Germany are “Critically Endangered”, considered to be facing an extremely high risk of extinction in the wild, because of their small numbers and the increasing intensity of land use. Grassland spring habitats in the mountainous regions are “Endangered”, facing a high risk of extinction due to increasing land use intensity, afforestation or abandonment. Beech forest spring habitats in the mountainous regions are “Vulnerable” because of their restricted distribution. Especially the alpine spring habitats are assessed as “only” vulnerable, because of their remote locations. However, global warming strongly affects the Alps, with major ecological changes and challenges for spring habitats.

Figure 3-25. Example of a memorial stone set up at the headwaters of many rivers.

Figure 3-26. Typical facility for drinking water extraction from springs; in maps one often finds “Wbh.” (Wasserbehälter) as its topographical signature.

In Germany, all natural or near-natural spring habitats and creeks are protected under the Federal Nature Conservation Act. Thus, any use or change of spring habitats requires a prior environmental impact assessment. Since spring habitats are not compensable, plans and projects usually have to ensure their preservation.

In the 19th and early 20th century, there was a German tradition of setting up memorial stones at the headwaters of rivers and creeks. Depending on the extent of these structures, natural spring vegetation may be found in the surrounding areas (Figure 3-25) inducing statutory conservation. However, many spring habitats have no standard appearance, not to mention any typical species, and thus do not meet the criteria of the Federal Nature Conservation Act. In former times, it was common to use springs for drinking water; however, Rathshygienic restrictions no longer allow this type of usage, but in most places, one can still find those facilities (Figure 3-26). Although it might seem surprising, pollution of spring water, in general, does not play an important role in Germany.

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Switzerland

by Pierre Marle and Vojsava Gjoni

Thanks to its mountainous terrain and the associated high-rainfall catchments, Switzerland is often called the "water tower of Europe" (Figure 3-27). Indeed, Switzerland provides 45% of the total discharge of the Rhine River when it reaches the Netherlands. In addition, a large part of Switzerland's precipitation falls as snow and 2.5 % of the total area of the country is covered by glaciers (Maisch 1999). Switzerland is also rich in spring ecosystems (Zollhöfer 1999). According to Zollhöfer (1999) the springs of Switzerland belong to distinct types, four are associated with mountainous regions: (i) karst rheocrenes, (ii) lime-sinter rheocrenes, (iii) unsintered rheocrenes, and (iv) linear springs. Two other types (v) alluvial rheocrenes and (vi) limnocrenes are found at lower elevations in association with alluvial rivers and streams of the Swiss plateau. The same study also revealed that unsintered and alluvial rheocrenes exhibit the highest invertebrate richness, containing ubiquitous, alpine, boreal, phreatophilous and rheophilous macroinvertebrate taxa. However, this diversity is considerably lower in altered than in natural springs, which act as refugia for different organisms (i.e., sensitive and endangered species, including diatoms; Taxböck et al. 2017; Fumetti 2006). These characteristics lead to regarding springs as playing crucial roles in the maintenance of Swiss biodiversity.

Figure 3-27. Map of Switzerland.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 45.83°, 2nd Standard Parallel = 47.81°.

Despite their high ecological values, springs have received only limited attention in Switzerland. There appears to be no specific legal framework for dealing with their management and protection. At present, despite "EN" or a "CR" status on the Swiss Red List of habitats, springs remain under-considered in Swiss environmental management procedures ("interest level 1"; Delarze et al. 2016). Springs in Switzerland often are subject to various types of alteration, including trampling, ringing, drainage, contamination with nutrients, lowering of the groundwater table, and removal of wetland and riparian vegetation. These impacts likely have reduced the number of springs over the past century. Currently, the remaining pristine spring ecosystems with perennial flow regimes are extremely rare, with most of them found at higher elevations. On the Swiss Plateau (400-700 m AMSL), the loss of springs has been so severe that only 1.2% of the endorheic springs and 4.8% of the free-flowing springsbrooks present in 1884 were still considered in the work of Zollhöfer (1999). This low proportion is mainly concentrated in forest areas with limited direct impacts of agriculture (e.g., fertilization and drainage). The karstic Jura Mountains are less densely populated than is the Swiss Plateau, and supports highly productive springs that are still in a near-natural condition. In this area, precipitation events result in strongly increased springs discharge due to rapid infiltration and circulation (Spreafico and Weingartner 2005). This hydrological dynamism makes springs highly vulnerable to pollution (Schürch et al. 2006), in contrast to mountainous areas, in which geomorphological impairment (e.g., livestock trampling) are probably stronger impacts than is pollution. Whereas some high-yielding springs occur in karst regions, these areas are not the most unique spring areas in Switzerland. Indeed, quaternary moraines, crystalline rocks, and flysch cover about 78% of the Swiss land surface in which locally significant springs occur; however, aquifers in such settings are typically of low production (Schürch et al. 2006). In those regions, the influence of meteorological events has a less dynamic impact on springs discharge, except during prolonged precipitation events that result in significant recharge (e.g., during autumnal rainfall events).

Delarze et al. (2016) considered the conservation status of springs without vegetation and seeps to be critically endangered (CE) and the status of alluvial springs and resurgences to be endangered (EN). Overall, the general conservation status of Swiss springs is endangered (EN).

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Southern Europe

Greece

by Angeliki Mentzafou, Ioannis Karaouzas, and Vojsava Gjoni

Greece is a uniquely complex landscape, and has undergone a diverse and tumultuous geological history across its 132,000 km^2 area, influenced significantly by geodynamic processes, which are expressed through volcanic activity, orogeny and active tectonism (Figure 3-28). The Greek peninsula is characterized by a complex geological structure composed of mostly Palaeozoic crystalline and metamorphic rocks in the Aegean area and northern Greece, and of primarily Mesozoic limestones flanked by Tertiary flysch and other sediments at the Central, Western and Southern Greece (Koukis and Koytsoyiannis 1997). These surroundings create favorable hydrogeological conditions for the emergence of seepage, fracture, karst, or even geothermal springs, which discharge from porous, fissured or karst aquifers, as well as springs emerging from unconsolidated or semi-consolidated granular aquifers (e.g., Kallioras et al. 2016). Overall, more than 3,600 springs have been reported, of which 28% are karst (IGME 2010; MEE 2020). Karst springs located mainly in western and southern Greece and on the island of Crete (e.g., Almyros Springs discharge >50 m^3/s; Lazarou 2006), occur at areas struc-

Figure 3-28. Map of Greece.
Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 34.93°, 2nd Standard Parallel = 41.75°.

tured by calcareous aquifers, and are either mountainous/semi-mountainous, coastal, or submarine, and therefore are vulnerable to marine intrusion. Due to the geology of the country, numerous terrestrial springs occur, characterized by the mixing of deep thermal reservoir water with meteoric water, while coastal springs also are characterized by mixing geothermal, marine water, and/or freshwater, and thus losing their heat. The geothermal springs of Greece related to mainly low-temperature geothermal fields, are estimated at around 833 (IGME 2020), and the most important are located on the islands of the active Aegean volcanic arc, on the North Aegean islands with Miocene volcanism, and the main sedimentary basins of northern Greece (Mendrinos et al. 2010).

Over 50% of Greek springs provide local domestic water demands, while 20% meet irrigation needs and 13% are used for combined purposes (IGME 2010). As such, springs are considered to be a valuable water source. Overexploitation of water resources leading to quantitative and eventually qualitative degradation of aquifers is the main threat of springs (Kazakis et al. 2018). Furthermore, climate warming will undoubtedly affect the quantity and the quality of the available spring water resources. In recent years, the decline of springs discharge, as well as drought in parts of Greece have served as indicators of global climate change (Korner et al., 2005; Maramathas and Gialamas 2011). Based on spatial variation in the intensity of groundwater use, and the poorly understood effects of long-term anthropogenic use on springs-dependent species, the vast majority of spring ecosystems in Greece are regarded as being in endangered (EN) to critically endangered (CE) conservation status.

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Iberian Peninsula

by Roger Pascual i Garsaball, Jaume Solé i Herce, Guillermo García Pérez, and José Barquín

The Iberian Peninsula occupies approximately 600,000 km^2 in southwestern Europe and is well-known for its high levels of ecological and biological diversity (Figure 3-29). That diversity results from the transition from a temperate oceanic climate at its northern and northwestern edges to the thermo-Mediterranean climate at the southern and southeastern territories, in addition to areas of alpine climate among its mountain ranges. Iberian geology is similarly varied, including Paleozoic and Mesozoic lithostratigraphy of its mountain and Cenozoic sedimentary basins that dominate the central plateau and the Ebro and Guadalquivir valleys. There are three main types of Iberian groundwater systems: detrital aquifers in valleys and plateaus; karst aquifers in the northern, eastern and southeastern limestone mountains; and small, confined aquifers in igneous substrates dominating in the western reliefs

Portugal does not have a systematic catalog of its spring ecosystem. In the case of Spain, the only attempt to map natural springs on a national scale progresses very slowly, unevenly in different geographical areas, and without coordination with the other main inventories, including inventories on a regional scale and those conducted at river basins scales. The regional cartographies have been initiated independently in four of the 17 au-

Figure 3-29. Map of the Iberian Peninsula.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 36.01°, 2nd Standard Parallel = 43.76°.

Table 3-3. Variation in estimated spring density in five contrasting but representative areas of the UK.

Study Site	Approx. Area (km^2)	No. Inventoried Springs	Spring Density (km^2)	Reference
Montblanc municipality	90	350	3.89	Pallisé, J. (2019). Las fuentes naturales frente a Escila y Caribdis. In: SICEF'19 1st Iberian Symposium on the Conservation of Spring Ecosystems. Barcelona, 10-12 June 2019. https://fuentes-naturales.org/sicef19
Collserola range	100	332	3.32	Les fonts de Collserola. Associació Fes Fonts Fent Fonting. URL: https://fontscollserola.com/. [Accessed 04/09/2020]
Montsant range	175	398	2.27	MN Consultors en Ciències de la Conservació (2012). Determinació de les característiques fisicoquímiques i de l'estat sanitari de les fonts naturals de la serra de Montsant. Fase 1:Localització i inventariat de les fonts i proposta d'estudi sanitari. Parc Natural de Montsant, Generalitat de Catalunya.
Montseny range	500	850	1.7	Farrerons-Vidal, O. (2019). Una visión multidimensional etnográfica, cultural, histórica y patrimonial de las fuentes de la reserva de la biosfera del Montseny. In: SICEF'19 1st Iberian Symposium on the Conservation of Spring Ecosystems. Barcelona, 10-12 June 2019. URL: https://fuentes-naturales.org/sicef19
Tramuntana range*	1000	1157	1.17	Morell, A. (2020). Fonts de Mallorca. URL: https://sites.google.com/a/fontsdetramuntana.com/fontsapps/home. [Accessed 04/09/2020]
Comarca de la Sierra de Albarracín	1414	1200	0.85	Ibáñez, R. (2019). Albaqua. Un proyecto integral para el conocimiento de las fuentes de la sierra de albarracín. In: SICEF'19 1st Iberian Symposium on the Conservation of Spring Ecosystems. Barcelona, 10-12 June 2019. https://fuentes-naturales.org/sicef19
La Rioja	5054	1357	0.27	Inventario de Fuentes y Manantiales de La Rioja (2020). Gobierno de la Rioja. URL: https://www.larioja.org/medio-ambiente/es/agua/inventario-fuentes-manantiales-rioja. [Accessed 04/09/2020]
Catalonia	31,895	9846	0.31	García, G. (2019). Las fuentes naturales ibéricas: comprender y conservar un "ecosistema difuso". In: SICEF'19 1st Iberian Symposium on the Conservation of Spring Ecosystems. Barcelona, 10-12 June 2019. https://fuentes-naturales.org/sicef19
Andalucía	87,268	12,384	0.14	Conoce tus Fuentes. Manantiales y Fuentes de Andalucía (2020). Instituto Universitario de Investigación del Agua de la Universidad de Granada. URL: http://www.conocetusfuentes.com/home.php. [Accessed 04/09/2020]
Peninsular Spain & Balearic Islands	499,003	26,060	0.05	García, G. (2019). Las fuentes naturales ibéricas: comprender y conservar un "ecosistema difuso". In: SICEF'19 1st Iberian Symposium on the Conservation of Spring Ecosystems. Barcelona, 10-12 June 2019. https://fuentes-naturales.org/sicef19

tonomous communities by the hand of regional governments (Andalusia, Catalonia, La Rioja), and private initiative (Balearic Islands), while an inventory of the main springs in some catchments has been initiated by its river basin management administrations (e.g., in Ebro, Segura or Guadalquivir basins; García et al. 2019). None of these inventories provide significant ecological information on the springs, which are usually cataloged as a mere point of water resource. Finally, there are some inventories on a local scale, of which some are much more exhaustive. In short, survey efforts have not been consistent over the whole territory, being the deficiency in the mapping of the Iberian crenic ecosystem well reflected in the range of spring densities reported by the different inventories (from 0.05 to 3.89 springs/km^2) clearly related to their spatial scale (local/regional/national; Table 3-3; Figure 3-30, Figure 3-31, Figure 3-32).

Figure 3-30. Karstic regions of the Iberian Peninsula.

All throughout the Iberian Peninsula springs have been the primary source of water for many rural and urban communities. Thus, most of the major springs have been transformed to ensure water supplies for towns, while the smaller ones have also been capped for agricultural and livestock activities (e.g., López 2019). So far, there has been no consistent estimate of the ecological integrity of Iberian springs. Small springs (< 1 l/s) in pristine conditions might be abundant in some mountain areas; however, large springs (> 1 m^3/s) in good conservation status are almost non-existent, apart from few exceptions, as for example rheocrene springs known in the Cares

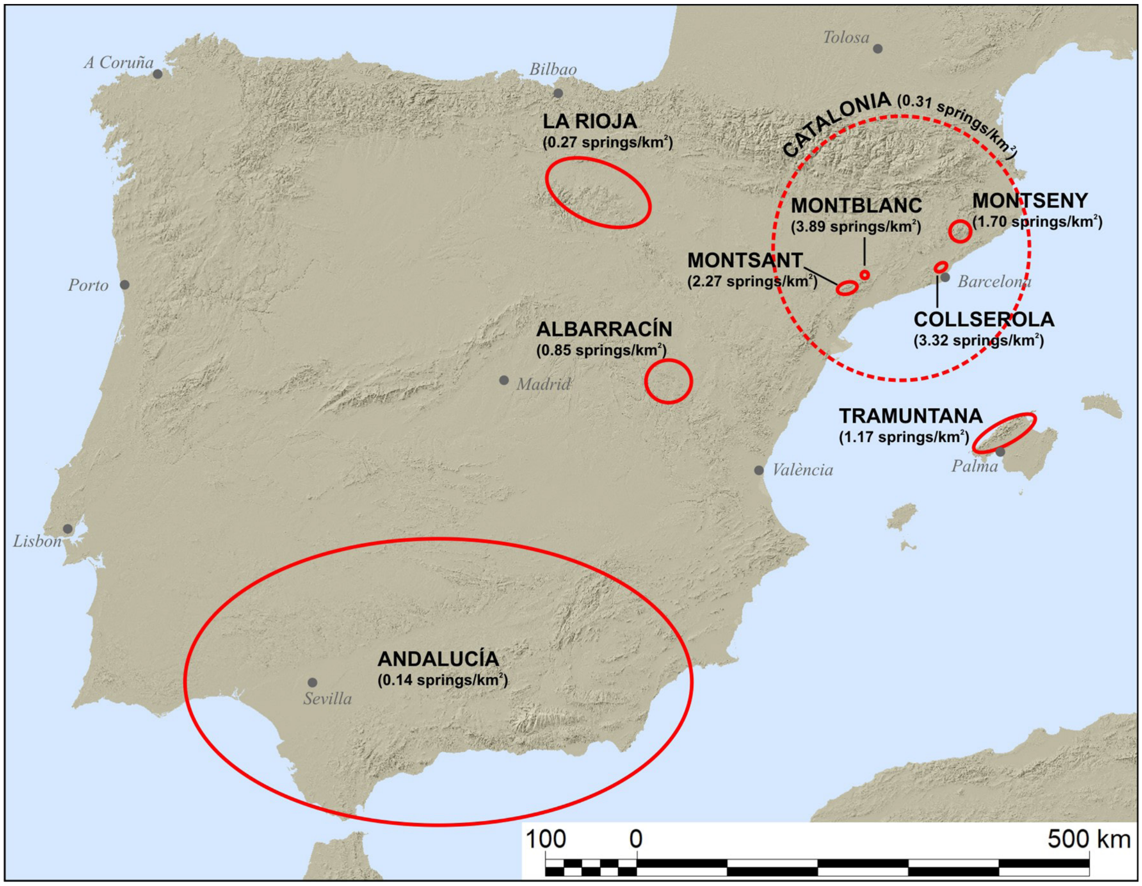

Figure 3-31. Location of the study sites of several local/regional spring inventories in the Iberian Peninsula.

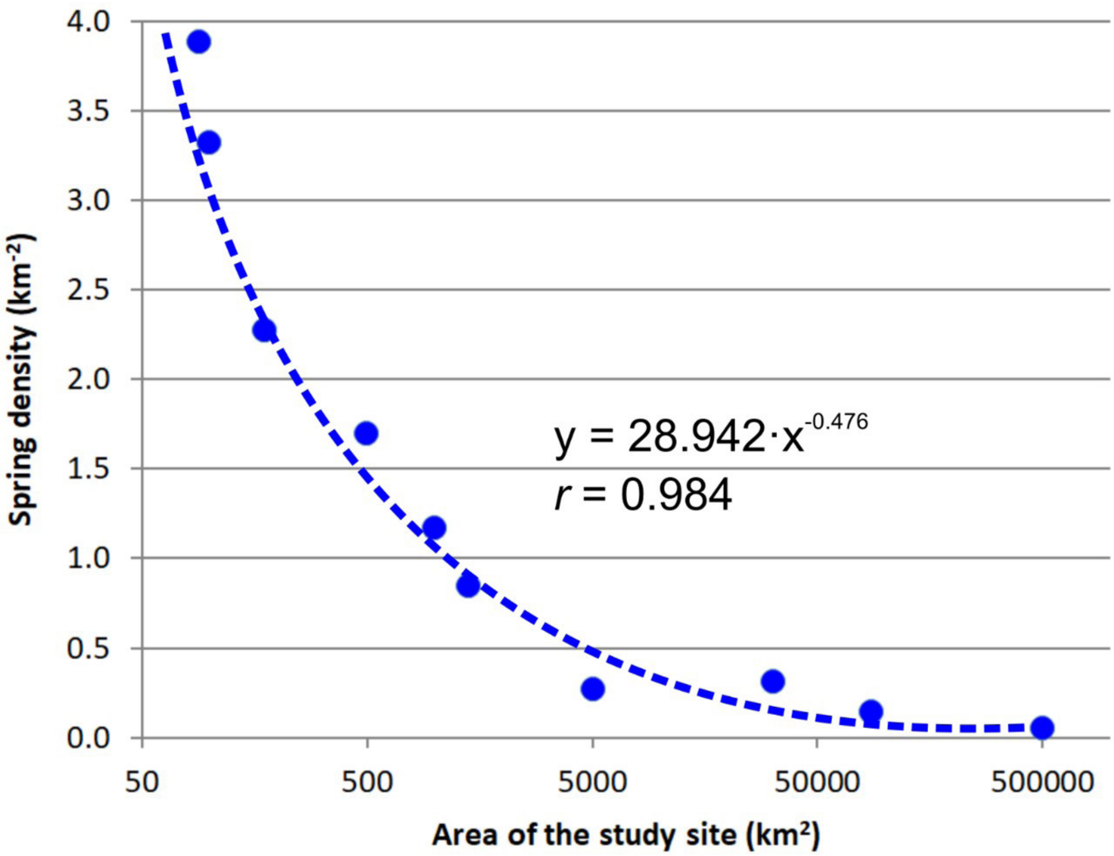

Figure 3-32. Correlation between springs density and area of the study site.

River gorge, in Picos de Europa National Park, some with a base discharge greater than 5 m^3/s.

Iberian springs can be subject to multiple co-occurring stresses and impacts, depending on the region. Aquifer overexploitation for agricultural use or urban supply may affect entire crenic systems, leading to the desiccation of many springs, as has occurred in the Júcar and Cabriel basins (López, 2019). Water pollution with nitrates from livestock manure and other intensive agricultural practices has affected many aquifers, rendering the springs they support useless for human consumption (Prat et al. 2019). Climate change is expected to result in a decrease of aquifer discharge of 13-24% from 2070-2100 (Martín-Vide 2019). In addition, as elements of cultural heritage, small springs are being lost due to reforestation related to the ongoing abandonment of the rural environment and the advance of urbanization.

The role of springs as biodiversity refugia is widely accepted today in the scientific community. However, studies documenting total biotic richness even for conspicuous taxonomic groups are scarce. In fact, the works broadening the scope in this direction have only appeared in the last two decades (Cantonati and Ortler 1998; Pascual et al. 2020). A richness ranging 50-150 taxa in few square meters has been found in these studies for alpine and Mediterranean springs respectively. Moreover, high levels of species turnover occurs among springs, suggesting the distinctiveness of every individual spring (Cantonati et al. 2020; Pascual et al. 2020) and contributing to high levels of regional (γ) diversity, much higher than in other natural habitats.

Studies on biological assemblages in the northern part of the Iberian Peninsula have shown a higher density of macroinvertebrates in spring habitats in comparison to runoff-fed rivers, what has been suggested as a consequence of buffered hydrological variability and more abundant food resources in spring habitats (Barquín and Death 2004). Moreover, the general pattern of greater insect dominance in higher versus lower altitude spring-fed systems (Barquín & Death 2006) also appears to occur on the Iberian Peninsula (Barquín and Death 2009).

Despite these research efforts and some recent regional contributions (e.g., Delgado et al. 2013; Meijide-Failde et al. 2017; among others), more systematic and deeper knowledge on Iberian spring ecosystems is needed. Such research should include typification and basic inventories of springs, as well as studies of aquifers dynamics, hidroecology, biotic communities and diagnosis of conservation aspects. The production of this knowledge is essential for designing efficient programs aimed to preserve spring biodiversity and the ecological and cultural services provided by Iberian springs.

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Italy

by Marco Cantonati and Stefano Segadelli

Hydrogeology

The characteristics of the Italian hydrogeological complexes are highly variable with often-significant socio-economic repercussions, especially for mountain areas where groundwater (GW) is the main or only source of water (Figure 3-33). The distribution of the related GW resources in Italy can be summarized as follows (Civita 2005).

Alps: The landscape is mainly composed of a very-permeable carbonate series due to fracturing and karst, with springs having discharge between 0.02 and 2 m^3 s-1, and GW reserves on the order of 1.4 Gm^3 y-1. The central sector of the mountain chain is characterized by crystalline and metamorphic rocks that are scarcely permeable for GW infiltration, with ca. 350 Mm^3 y-1.

Alluvial deposits (Po Valley, Tyrrhenian coastal plains and the Adriatic side, the alluvial plains of Marche, Abruzzo, Campania, and Basilicata): This region contains an aquifer system of great socio-economic importance. They occur in highly permeable alluvial fans that are generated by the rivers that feed them, with dispersion into their apices, while in the middle course the waters are partly returned to the river and partly come into the "fontanili line". Fontanili (plain springs) are semi-natural springs found in the Po river flood plain.

Figure 3-33. Map of Italy.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 36.65°, 2nd Standard Parallel = 47.09°.

Apennines: The long ridge that is developed along the entire peninsula, includes: a) the northern Apennines, in which the only important springs are those of the Apuan Alps (GW recharge rate of 66 Mm^3 y-1), the carbonate aquifers of the Calvana Mountains and of some parts of the metalliferous hills and the volcanic aquifer of Mt Amiata (57 Mm^3 y-1). Scarce GW resources are allocated in medium-permeable aquifers such as ophiolites and turbidite sedimentary sequence. b) The central and southern Apennines, formed by important carbonate series that feed some of the largest springs in the Mediterranean, such as the Peschiera spring in Val Velino (Lazio region) with a mean discharge of 18m3 s-1. There are also the volcanic areas of Lazio and Campania for a total of GW recharge rate of 2.1 Gm^3 y-1.

Large islands: Sicily has discrete aquifers in the eastern part (Etna volcanites and carbonate complexes); aquifers of local importance in the Madonie and in the mountains of Palermo. In the central areas of these islands, GW resources are scarce due to the low permeability of the rocks. Sardinia has a scarcity of important aquifers, with the exception of some small areas along the east coast and in the southwest, where carbonate aquifers feed some springs discharging small amounts of waters that are sometimes of poor quality due to contact with sulphide deposits.

Main Conservation Problems

Waste, misuse, increase in the frequency and duration of recurrent droughts and heat waves, pollution, over-exploitation and marine intrusion are the causes that generate critical situations. At present, 48.6% of the total water resources available in Italy come from wells, 37.9% (a gross underestimate) from springs, 8% from artificial basins, 4.8% from watercourses, 0.4% from lakes and 0.3% from surface brackish waters. The derivation of the resource for more than 86% from GW should suggest the need for careful protection and conservation policies, but these often are neglected in favor of other economic opportunities. The losses of the aqueducts are unfortunately conspicuous (27% of the collected discharge as a national average, with peaks of 46% in Campania) whose networks have an average age of 32 y. The main impacts affecting springs in the main GW domains in Italy are listed below by region.

Alps: The main impacts are due to spring tapping and water diversion. A well-documented example (Zollhöfer 1997) refers to the Swiss Alpine Foreland, but is applicable to many other parts of the (Italian) Alps. Hydrological maps revealed that by 1880 more than 75% of the springs were affected by water extraction and habitat destruction, which further increased to 95% by 1990.

Alluvial deposits: The still existing fontanili are among the last remnants of a spring system that until a few decades ago characterized the alluvial fans of the main watercourses. Today, this system has almost disappeared due to the irrigation diversions that have caused a drastic lowering of the water table. Overall, the water balance is highly deficient due to intense over-exploitation, resulting in water crises that are exacerbated by droughts and increasingly prolonged and frequent heat waves. Agro-zootechnical levies are primarily responsible for the present deficit. From a qualitative point of view, the alluvial fans in the central belt are characterized by waters with poor basic quality (ammonium, arsenic of natural origin, iron, manganese), while GW in the foothill/distal areas is polluted by nitrates, chlorinated hydrocarbons, and pesticides because of widespread societal pressures.

Apennines: In the case of ophiolites, the waters captured for aqueduct use may be affected by natural chromium VI pollution (Boschetti & Toscani 2008). Another significant threat to these important GW resources and their related biota is forced drainage induced by tunneling for transport infrastructures and/or water abstraction purposes (e.g., Cantonati et al. 2020a). The drilling of the High Speed Railway connection between Bologna and Florence (Gargini et al. 2008, Vincenzi et al. 2014) caused permanent loss of natural environmental flows during the dry season (summer) and the complete desiccation of major springs.

Large islands: Sicily's mountain aquifers are heavily exploited in the Trapani area, and so is the aquifer of the alluvial plain of Palermo. Sardinia has serious problems with water supplies. In the southwest, in the lowland areas there are alluvial aquifers which are sometimes contaminated by anthropogenic sources.

Stewardship

Ecological research on springs in Italy has mainly focused on floristics and faunal studies, and was sporadic before the beginning of the 1990s when it gained new momentum. Currently, the geographic areas where biodiversity end ecology research on springs in Italy is most developed are: the south-eastern Alps, particularly in Trentino (e.g., CRENODAT Project and Adamello-Brenta Nature Park, Cantonati et al. 2012) and the Dolomiti Bellunesi National Park (Cantonati & Spitale 2009); in the Emilia-Romagna Region (e.g., EBERs and LPS Projects Cantonati et al. 2016a, 2020b), particularly the Northern Apennines (e.g. Bottazzi et al. 2011); the Pre-Alps in the surroundings of Verona (Cantonati et al. 2016b); the south-western Alps (Mogna et al. 2015); the fontanili of the Po plain (e.g., Abdelahad et al. 2015); the

Abruzzo Region (Fattorini et al. 2018); the Friuli Venezia Giulia Region (e.g., Lai et al. 2019a, Brancelj et al. 2020); and the Sardinia Region (e.g., Lai et al. 2019b). Important studies on the water mites of springs in Sicily have been conducted by Gerecke (1991).

Italy, as a whole, would be quite rich in GW resources were management improved. Their protection should be based on a careful territorial planning policy, which favors conservation and rational use. At a national level, captured springs are surveyed by the Regions using information systems, but the same cannot be said for unexploited springs (those not captured for aqueduct use), which have been mapped in detail only in some protected areas (e.g., Cantonati et al. 2007). Such springs often fall within the Natura 2000 network (the primary EU nature protection framework). The absence of adequate national legislation capable of safeguarding and promoting springs protection has serious consequences. The various regional water protection plans do not pay adequate attention to unexploited springs. Sometimes "sources of environmental-naturalistic interest" are mentioned, but without specifying an adequate definition or attention to their recognition, mapping, and study. Even at the level of the EU, the only widespread type of sources that are protected are limestone precipitating springs (Cantonati et al. 2016).

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East-Central Europe

Central Europe - Poland to Carpathian Ukraine

by Michal Hájek

Geography

East-Central Europe, as defined in this chapter, comprises Czech Republic, Austria, Slovakia, Poland, Romania, Hungary and the Carpathian part of Ukraine (Figure 3-34). The Carpathian Mts connect these countries, but the majority of Czech, Polish, Austrian and Hungarian territory belongs to other geological units such as Bohemian Massif (Czech Republic, Poland, Austria), Eastern Alps (Austria), Pannonian Plain (Hungary, Austria, Czech Republic) and Polish Plain (Poland). Slovakian and Romanian territory belongs largely to the Carpathian Mts, but contain the Pannonian Plain as well.

Hydrogeology

East-Central Europe is geomorphologically diverse, from lowlands to high mountains, and varying in terms of spring persistence over geologic time. Consequently, the groundwaters of Central Europe exhibit a wide range of pH and calcium richness (Hájek et al. 2020), from extremely acidic and calcium-poor groundwater in granitic portions of the Bohemian Massif, to strongly calcareous, mineral-rich travertine springs in Slovakia (Figure 3-35), and even saline springs in Romania.

Figure 3-34. Map of East-Central Europe.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 36.39°, 2nd Standard Parallel = 56.45°.

Figure 3-35. This well-known Bešeňová travertine mound Sivá brada ("grey chin") is a relictual wetland on a partially active travertine mound.

Figure 3-36. Alpine springs and fens in close to the Ştiol Lake in the Rodnei Mts, Eastern Carpathians (Romania). Fens in this area are characterised by deep layer of old peat, unlike most other alpine springs. Disjunct populations of some glacial-relict, boreo-continental species such as *Carex chordorrhiza* and *Calliergon trifarium* occur here as a consequence.

Human Use History

Central Europe has a lengthy history of interactions between human and springs. Since Middle Paleolithic times, especially hot or at least moderately warm springs have attracted humans, as evidenced by the presence of a Neanderthal cranium in a travertine mound close to the village of Gánovce in Slovakia. Hot springs might have facilitated human survival during colder Pleistocene times, now becoming popular as recreational spots. In prehistoric and medieval times, anthropogenic deforestation of mountains frequently increased infiltration and resulted in springs emergence, not only in the deforested mountain but also in basins beneath them. The largest Carpathian calcareous groundwater-dependent ecosystem (GDE) is the fen, Belanské lúky, which arose from a bog and alder carr after such an event (Hájková et al. 2012). Similar events have been documented in Polish lowlands (Lamentowicz et al. 2007).

In recent history, springs have played important roles not only as critical water sources, but also as important cultural landscape features. Even small springs close to villages or within managed grasslands have been revered and protected by local people. Crosses and calvaries were built around them, they are subject of many folk songs, and they served as meeting points and refreshment points during heavy field work. Local people have long used them to cool beverages and to moisten scythe sharpeners, as evidenced by the discovery of an ancient sharpener in a spring deposit in the Czech Republic's White Carpathian Mountains (Hájková et al. 2018). Carbonate-rich springs water has been used by local people for raising dough and for medicinal purposes. Long-lasting belief in the health benefits and even miraculous medicinal effects of mineral springs in East-Central Europe had led to development of many world-famous spa resorts, such as Carlsbad (Czech Republic), Piešťany (Slovakia), Baile Tuşnad (Romania; Figure 3-36), Bad Ischl (Austria), and Luhačovice (Czech Republic). The latter resort became additionally famous because the world-renowned composer Leoš Janáček collected folk songs in surrounding villages, often meeting native people near local springs. In present times, these resorts still play important roles in national culture and politics.

Mountains springs often serve as a source of drinking water for hundreds of small communities, some medium-sized towns, such as Ružomberok or Martin in Slovakia, and even for large cities, such as the Austrian capital Vienna. However, such water abstraction often leads to groundwater depletion, decreasing the discharge of groundwater-dependent ecosystems (GDEs), such as fens and petrifying springs, and consequently leading to biodiversity losses.

Springs Classification and Persistence

Classification of springs in Central Europe reflects a long tradition in hydrobiological research, emphasing geomorphological attributes (helocrene, hypocrene, rheocrene, limnocrene) and in vegetation classification through botanical composition. The latter classification forms the basis of national habitat classification schemes, which are compatible with international habitat classifications (Habitat Directive, EUNIS; Chytrý et al. 2020). In that classification system, individual springs are classified

Figure 3-37. Petryfing springs with tufa formation close to the village of Omšenie, Western Slovakia. Small-scale and sometimes developmentally young petrifying springs frequently occur in traditionally managed (scythed, grazed) landscapes, where they harbour both spring and calcareous-fen species. In wooded landscapes they are composed of few calcicole spring bryophytes and accidentally occurring woodland species. Contrary to deep-water travertines they usually do not contain relict species, but despite this they act as important refugia of endangered species in modern landscapes.

based on insolation and elevation (e.g., shaded springs in woodlands, exposed springs in the woodland vegetation belt or in alpine habitats above treeline), and classification is further refined by considering mineral richness, which distinguishes petrifying springs (Figure 3-37) from other types. Insolation affects species composition by filtering light-demanding species, and also changes the isotopic signal in spring deposits (Dabkowski et al. 2019).

Floodplain and upland helocrenes, hillslope springs, and many other geomorphological springs types occur in Central Europe, including the following.

Fens, particularly floodplain helocrenes (percolation fens) are more common in lowland areas of Poland than in other countries. Mound organic springs occur both in lowlands, called "cupola spring fens" in Poland, and in mountains (Figure 3-36, Figure 3-38) where they rise above the surrounding terrain at hillslope springs. The latter are lens- shaped and are known as "sihly" ("sihla" is singular) in the border region between Slovakia, Poland, and the Czech Republic.

Rheocrenic springbrooks arise from some spring fens, providing important habitat for aquatic invertebrates. The temperature regime in and around these streams buffers changes in air temperature and provides environmental stability for springs biotic communities and resistance to climate change, including ongoing warming (Horsák et al. 2018).

Some anthropogenic sources are exposed as a result of former gravel mining, and serve as sources of drinking water in southeastern Czech Republic and elsewhere. Contrary to the impacts of groundwater abstraction, these sources of drinking water do not endanger biodiversity.

Artesian springs previously occurred in Hungarian, Czech or Polish lowlands and supported lowland fens, but now have largely been captured and no longer flow.

Cave springs occur in karstic areas, including the Moravian Karst near Brno in the Czech Republic, the Slovak Karst at the border between Slovakia and Hungary, and in the limestone-rich mountains of Transsilvania (Romania).

Geysers naturally occur in the westernmost part of the Czech Republic (Soos National Nature Reserve) or in Transsilvania (Romania) as a product of past volcanic activity. They are sometimes associated with iron-rich mineral waters and iron fens. Although anthropogenic drill hole, the Herľany Geyser in Eastern Slovakia has become a touristic attraction.

Mud volcanoes are a specific type of springs at the southeastern margin of the Carpathians in Romania (Vulcanii Noroioși close to the village of Pâclele in the Buzau region) while only fragmentarily in other locations (Figure 3-39). The wet salty mud, enriched by oil and methane, migrates at the surface throughout faulted flanks of the anticline, from Middle Miocene deposits at a depth of around 3,000 m (Brustur et al. 2015). The springs form distinct mud volcanoes of various sizes and shape and harbor rare halophytic plants Nitraria schoberi and Obione verucifera in their surroundings.

Figure 3-38. Stankovany travertines (Močiar Nature Reserve) is one of the last ca 10 travertine spring fens still harbouring characteristic biota, although had been repeatedly damaged by modern anthropogenic disturbances and hydrological interventions. On the other hand, just at this site Hájková et al. (2020) have demonstrated that the positive effect of medieval land use for preserving populations of glacial-relict species to the present times (Postalm, Austria).

Figure 3-39. Mud volcano springs in Romania.

Long-term persistence is another important habitat characteristic, but is not sufficiently thoroughly addressed in habitat classification. GDE fens that provided stable conditions during Quaternary climate oscillations (endangering warmth-demanding species) or during Holocene expansion of woodlands (endangering shade-intolerant species) are richer in habitat specialists and relictual species (Hájek et al. 2011, Horsák et al. 2012, Horsáková et al. 2018). Spring fens that arose during late Holocene anthropogenic deforestation of mountains are usually poorer in specialised species than those that initiated during late glacial times. Hot springs illustrate additional evidence of paleorefugial effects, providing glacial refugia for warmth-demanding species, such as *Cladium mariscus* in the hot springs of Slovakia (Hájková et al. 2013) or possibly *Nymphaea lotus* in hot springs near Oradea in Romania.

Habitats and Species Conservation

According to the national vegetation surveys of individual countries in the region and the list of diagnostic species presented in the European vegetation survey of Mucina et al. (2016), I estimate that approximately 50 species of vascular plants and 50 species of bryophytes are tightly associated with springs and spring fens of East-Central Europe, with approximately half characterising non-fen springs. In the Czech Republic overall, Sádlo et al. (2007) report 117 vasular plant species occupy hard-water springs with tufa formation, 273 species occupy lowland and montane soft-water springs, and 174 species occupy alpine and subalpine soft-water springs.

Mineral-rich travertine mound springs and associated fens are outstanding habitat types in East-Central Europe. Contrary to petrifying springs associated with shallow groundwater circulation and of more recent origin (Hájek et al. 2002, Onete et al. 2014), the travertine mounds in inter-Carpathian basins in Slovakia's Western Carpathians range in age from former Pleistocene interglacials perhaps back into Tertiary time. Sourcing on deep Tertiary faults, these springs allow deep groundwater to reach the surface. As a result, travertine springs often are more stable and less influenced by climate than are other springs, and support populations of relict species. Some travertine paleosprings that eroded during Quaternary time, forming a specific relief called "rock towns", such as Dreveník Nature Reserve. These features provide building materials for many towns in Slovakia. A few dozen active travertine mounds have persisted into recent time and host unique relict biota. Unfortunately, due to direct destruction and groundwater abstraction, only around 10 of travertine springs continue to support characteristic biota (Hájková et al. 2020). The fens associated with these travertine springs support unique assemblages of fen and halophytic plant species, resembling wetland assemblages in the Altai Mountains of Siberia under a glacial-like climate. These travertine fens recently have been acknowledged as a separate habitat in the EUNIS habitat classification system (Chytrý et al. 2020). The fens around travertine mounds in Slovakia represent a world-recognised phenomenon and deserve priority protection.

Although still harbouring a suite of relict species, some of these features increased in areal extent after reduction of woody species and reeds during medieval times (Hájková et al. 2020). Their findings indicate that these habitats require active conservation management. The initiation of fens around travertine mound springs may have coincided with emergence of additional springs in the surrounding discharge area. Šolcová et al. (2020) report that isotope signals in drilled profiles throughout the deposits around the Santovka-Budzgov Travertine Mound in southern Slovakia varied substantially, from those resembling other deep-water travertine mounds (Gradziński et al. 2018), to those resembling petrifying springs appearing on shallow-circulation groundwater (Dabkowski et al. 2019).

The Natura 2000 Habitats Directive classifies Petrifying spring and associated tufa cascades, small streams, and flushes (7220) and Alkaline-fen ecosystems (7230) as endangered ecosystems in the EU. Each has its own conservation measures, which differ from each other and from those of Calcareous-spring-mires. Petrifying-springs. However, recent research on co-occurrence of these two spring types in Poland indicates that restoration measures should take account of their habitat differences to ensure appropriate management (Grootjans et al. 2021).

The Red List of Czech Republic habitats (Chytrý et al. 2019) presents estimates of current and past ecosystem area changes and biological qualities. The IUCN RLE criteria indicates that the most endangered (EN) biotic community occurs at exposed springs below treeline. Threats there involve surface water abstraction, afforestation, eutrophication, heavy disturbance by cattle, and accelerated natural succession. GDE fens, especially calcareous and mineral rich fens, are even more strongly threatened, falling into the CE category.

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Bulgaria

by Michal Hájek and Iva Apostolova

Geography and Hydrogeology

Bulgaria is a part of Balkan Peninsula, including the Danube Lowland at the north, western Black Sea Coast at the east, the Maritsa lowland to the southeast, and the geomorphologically and geologically diverse Balkan Mountains to the southwest (Figure 3-40). The Balkan Range (the Stara Planina Mountains) lies across the central part of the country. Groundwater chemistry is variable (Hájek et al. 2020, Benderev et al. 2016) and provides conditions for different types of spring and fen habitats (Hájková et al. 2006, Michev & Stonyeva 2007, Hájek et al. 2008). Bulgaria harbours most of the spring types that occur in the Balkan Peninsula, with fissured aquifers of karstified rocks being less abundant than in the western Balkans (Croatia, Bosnia and Herzegovina). On the other hand, non-aquiferous crystalline rocks are more common, especially in the highest mountains (the Rila, Pirin, Rhodopes, Stara Planina mountains; Figure 3-41, Figure 3-42). Contrary to other Balkan countries, Bulgaria's sandy sea coast supports the development of dune slacks. Bulgaria is a territory rich in thermal springs, with temperatures ranging from 25˚C to 100˚C among >250 hydrothermal fields. About 70% of these waters are slightly mineralised (<1g/L) and are suitable for drinking

Figure 3-40. Map of Bulgaria.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 41.24°, 2nd Standard Parallel = 44.22°.

Figure 3-41. Cliff face seepage close to Yasenovo village, Stara Planina Mountains.

Figure 3-42. Travertine waterfall in the Devetashko plato karst, close to the city of Lovetch, Northern Bulgaria. Contrary to Western-Balkan countries, karstic and travertine springs are less common in Bulgaria.

(Benderev et al. 2016). Most of those localities occur in the southwestern part of the country (Biserkov 2015).

Human Use History

Bulgaria has a lengthy history of interactions between humans and springs. Springs served as important sources of drinking water, and humans have long been attracted to hot and mineral-water springs. Many Neolithic and Paleolithic settlement developed around hot springs (e.g., the towns of Sofia, Kyustendil, and Stara Zagora). For example, the springs in Sofia attracted many Roman emperors, especially Constantine the Great. Currently, the thermal waters are used for balneological purposes as spas, and public mineral baths are used to treat many diseases following scientific programs. Hot springs also are widely used for recreational swimming pools, space heating (greenhouses), and by the bottled water industry for potable water and soft drink production. Micro-algae open mass cultivation occurs in Roupi field (SW Bulgaria; Bojadgieva et al. 2007). Cold springs emerging in warm sub-Mediterranean areas attract citizens who concentrate there during hot summer days, taking rest and cooling wine and beer. Montane springs serve as drinking water sources for local settlements, small and even large cities. Much of the potable water supplies for the capital Sofia are captured from Rila Mountain, which provides rich spring waters. Additional water abstraction for Sofia also is derived from the largely non-aquiferous crystalline rocks of the Vitosha Mountains, but decreasing water tables there may threaten mountain fens with the associated loss of some endangered relictual species (Hájek et al. 2010; Figure 3-43).

Springs Classification

Most Bulgarian springs are classified as limnocrenes or helocrenes (Michev and Stonyeva 2007). Most of Bulgaria's springs are exposed, occurring either in deforested lowlands and middle elevations, or in naturally treeless habitats above the treeline. Forest-shaded springs are less abundant than elsewhere in Central Europe. Bulgarian fens, particularly floodplain helocrenes in lowlands, and hillslope spring fens in mountains (Figure 3-44) are quite common (unlike in most of southern Europe), and serve as important refugia for endangered species (Hájek et al. 2019). Rheocrenic springbrooks arise from some spring fens, especially in high-mountain valleys such as those in the Rila Mountains. Artesian springs occur in lowlands, sometimes supporting lowland fens, such as Dunavtsi and other fens in the foothills of the Stara Planina Mountains (Hájek et al. 2009), often as warm or hot springs (Stoyneva 2003). Karstic areas support some rare, biologically distinctive cave springs (Pulido-Bosch et al. 2015), as well as upland helocrenes in karstic depressions and sinkholes (e.g., the fen near the village of Tzraklevtsi; Hájek et al. 2009). Saline springs also occur in Bulgaria, especially in the eastern part of the country near the Black Sea coast.

Habitats and Species Conservation

Bulgaria harbours most of spring and spring fen habitats defined by habitat classification schemes in Europe, including travertine mounds (a priority habitat "Petrify-

Figure 3-43. Endemic primroses of Bulgarian alpine fens and springs, *Primula deorum* and *Primula farinosa* subsp. *exigua* in an alpine fen in the Rila Mts. Black ground is formed of the arctic-alpine moss species *Sarmentypnum sarmentosum*.

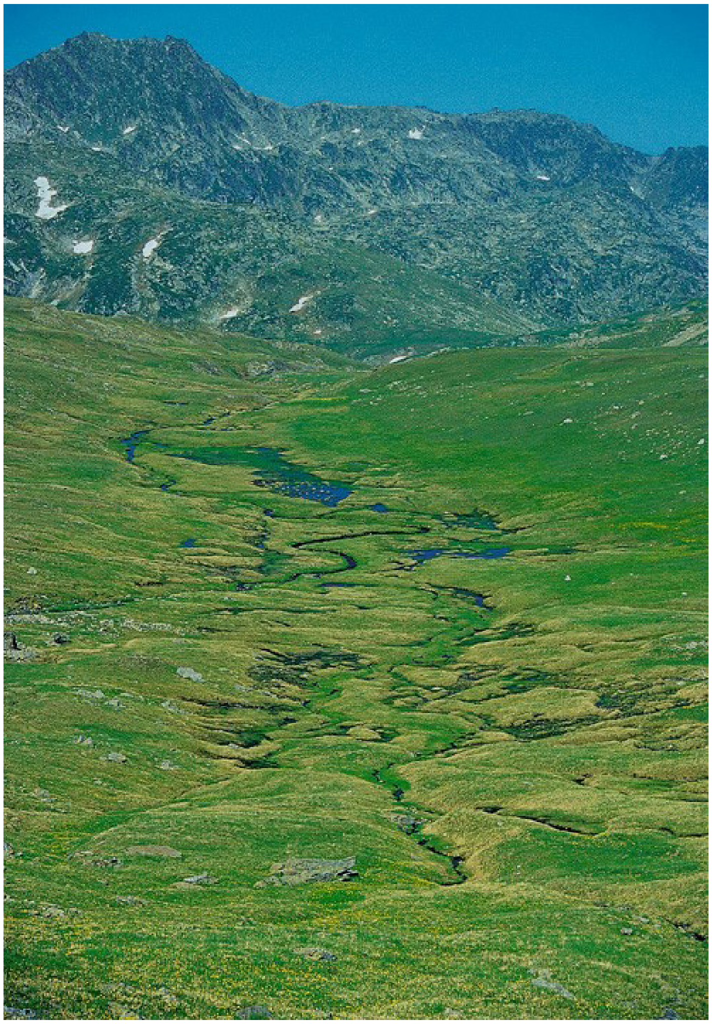

Figure 3-44. Alpine spring in the Rila Mountains.

ing springs with tufa formations" of the European Union Habitat Directive, Evans 2006) and other karst springs, relictual fens in lowlands and at middle elevations (Hájek et al. 2008, 2009) and a specific habitat rich in endemic species and local ecotypes, belonging to the unit "Relict mire of Mediterranean mountains" in the EUNIS habitat classification scheme (Chytrý et al. 2020). According to the IUCN criteria, all of these above-mentioned habitats match the EN category of endangerment across Bulgaria (Biserkov 2015). Lowland spring fens with *Cladium mariscus*, such as Dunavtsi fen, have been classified in the Red Data Book of Bulgaria (Biserkov 2015) as a separate habitat with the CR category (critically endangered).

Hájková et al. (2006) focused on patterns in botanical species composition (bryophytes and vascular plants) in Bulgarian springs including spring fens. They found that elevation was the most important factor influencing species composition. Among springs occurring above timberline (i.e., above ca 1700 m a.s.l.), organic matter production was the principal gradient separating the two major vegetation and habitat types, springs and fens. Water geochemistry further diversified springs vegetation, while succession due to peat accumulation diversified fen vegetation. The correlation between species richness and pH was significant only when arctic-alpine and European high-mountain species were considered separately, while richness of boreal species was independent of pH. Some species shifted habitat optima to more acidic fens as compared to studies in Central Europe or to regions below the timberline (Hájková et al. 2008). Sekulová et al. (2012) compared plant diversity patterns in European high-mountain springs, demonstrating that Bulgaria had the highest alpha-diversity of vascular plants in the middle part of the mineral richness gradient, but the lowest total species pool. Although harbouring many relictual species with distributions in boreal, boreo-continental, or arctic areas of Eurasia (Hájek et al. 2009), Bulgarian springs plant gamma-diversity and individual species relative representation in local communities are smaller as compared to more northerly areas in Europe (Horsáková et al. 2018). Unfortunately, the last remnants of relictual fens are highly endangered, especially those below the treeline. Some of the most important fens have been severely damaged by recent development activities, coincident with the great economic progress at the beginning of this millennium but shortly before their legal protection was adopted (Hájek et al. 2010). The State and municipalities are both owners of Bulgarian water sources, according to the Water Law (2015). The Ministry of Environment and Waters designates the legal protection of all water reservoirs, including the springfed fen habitats described in the Natura 2000. The Ministry of Health monitors the geochemistry and mineral composition of thermal springs and the general state of water sources in the country.

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Chapter Image Credit

The map is the property of J. Jenness, Jenness Enterprises, Flagstaff, Arizona, USA, and is derived from Senex, J., and J. Harris. 1721. A New Mapp of Rome Shewing its Antient and Present Scituation, Most humbly Inscribd To His Grace The Duke of Queensbury and Dover. Hand Colored, London.

Chapter 4

Africa

Overview

Africa, like Europe, the Middle East, and Eurasia, supports a great diversity of springs, at least the larger of which probably have sustained substantial pre-human and contemporary human populations and impacts over post-Miocene time (e.g., Cuthbert and Ashley 2014). Recent habitat mapping has been conducted across the continent, including in Madagasgar (e.g., Thieme et al. 2005; MacDonald 2012). Many Saharan oases are highly endangered by groundwater pumping, and some are on the verge of collapse. Groundwater exploitation has increased recently with the discovery of late Neogene aquifers (Powell and Fensham 2016, and below). Sahel wetlands throughout Sub-Saharan Africa, and the continent's wetlands, springs, and springs-dependent species in general, are critically important for the human subsistence and the survival of many wildland biota. (Mitchell 2013), including taxa that are poorly many poorly known SDT, including endemic and unique hydrobiid springsnails and fish (e.g., Garcia et al. 2010). Primary threats to Africa's springs and aquifers include national and international conflict, Human population growth, and ever-intensifying land use, as well as climate-related increased variability and overall reduction in rainfall. Nearly two hundred Ramsar Convention-designated wetlands occupy nearly 800,000 km^2 in Sub-Saharan Africa, however, most basic data on use, threats, and biodiversity are outstanding, and aquifer, springs, SDT, and adjacent landscape management are often limited or relegated to secondary consideration due to cultural and socio-economic problems.

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North Africa

by Abdullah A. Saber, Roderick Fensham, Stefano Segadelli, and Marco Cantonati

Groundwater (GW) Resources

North Africa is characterized by two main transboundary non-renewable aquifers (Vos and Soliman 2014, Nijsten et al. 2018): 1) The North-Western Sahara Aquifer System (NWSAS), an important underground resource characterized by high fluorine level, the availability of which is shared among three nations: Algeria, Libya, and Tunisia. It extends in the desert for about one million km^2 (Figure 4-45). The total volume stored in the NWSAS is estimated to be around 30 trillion m^3. The NWSAS designates the superposition of two main deep aquifer layers: the Continental Intercalary (CI) and the Complex Terminal (CT). The first (CI) is deeper and more extended, whilst the second (CT) is closer to surface. CI has a thickness of many hundreds of meters, and is found in depths ranging from ca. 400 m down to 2,000 m below ground. The CI contains a set of layers with very differing lithology, comprising mainly continental sandstone in alternation with marine limestone and clay formations. CT consists of a homogeneous shallow carbonated formations of the Upper Cretaceous and detritus episodes of the Tertiary and, mainly, the Miocene (Al-Gamal 2011). 2) Nubian Sandstone Aquifer System (NSAS), the world's largest fossil water resource. It is located in the eastern Sahara Desert, ca. 1,600 km wide in both north–south and east–west directions. It extends

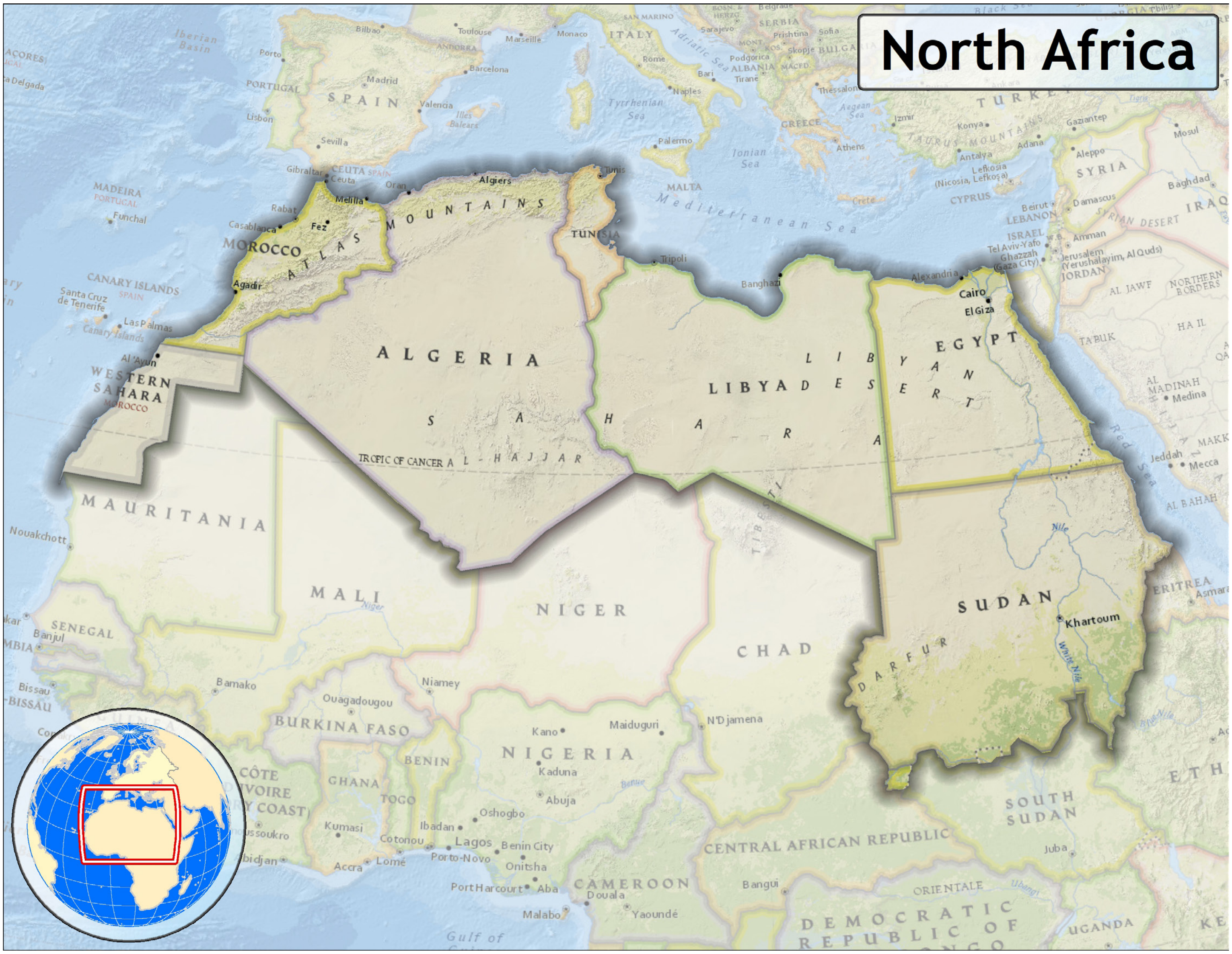

Figure 4-45. Map of North Africa.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 8.68°, 2nd Standard Parallel = 37.34°.

for just over 2.6 Mkm^2 between the north-western sector of Sudan, north-east of Chad, south-east of Libya, and most of Egypt, and thickness of its permeable water-saturated sediments varies from hundreds of meters at its southern peripheries to several kilometers in its center and in the north. This aquifer is comprised of a wedge-shaped sandstone deposit spanning early Paleozoic to Cretaceous age with the thin edge of the wedge outcropping to the south in the highlands of Sudan and Chad. Within Libya and Egypt the aquifer is 1–2 km deep and confined beneath impermeable upper Cretaceous-Eocene beds (Dabous and Osmond 2001). Much of NSAS contains a large amount of high-quality groundwater, recharged during previous pluvial periods thousands to millions of years ago, with almost no current recharge (Vos and Soliman 2014, Powell and Fensham 2016). The groundwater resources in the Eastern Desert of Egypt are different and represented by four main geologic units: the NSAS, the fractured crystalline Pre-Cambrian aquifer, the fractured limestone and sandstone aquifer, and the Quaternary aquifer. The latter and NSAS are the most productive aquifers while the fractured limestone and sandstone (Miocene) are only productive along the eastern part of the desert (Abdel Moneim 2005). In Morocco, groundwater is present within unconsolidated material (e.g., gravel, sand, or silt), fractured rocks (e.g., granite, schist), weathered rocks, karst, and other geological formations. Six major hydrogeological domains can be identified: Saharan, South Atlas Mountains including the Anti-Atlas, Atlas Mountains including the High and Middle Atlas, Eastern in the northeast (Eastern Meseta), Atlantic in the Western Meseta along the Atlantic coast, and Rif in the north. Within each of these domains, there are similarities in geology and climate, but groundwater exists in different geological environments (Hssaisoune et al. 2020).

Main Conservation Problems

Until the 1980s, the North African aquifers remained in substantial balance. Then pressure kept augmenting due to (Aly 2015, Alfarrah et al. 2017, Hssaisoune et al. 2020): population increases; human draining; intensive agricultural expansion; seawater intrusion; nitrate pollution (fertilizers, sewage and manure); natural salinity changes linked to global climate changes (evaporation and dissolution); reduced availability of water from other sources and because of the low cost of access and use of the resources; subsequent water-table drawdown and those planned are compromising some of the main characteristics, first of all the artesian behavior. The over-use of the Nubian aquifer system (NSAS), as the world's largest aquifer, has already resulted in the abandonment of oases settlements, where natural springs have been dewatered, and this subsequently will lead to oases loss and severe environmental impacts (Powell and Fensham 2016). A clear relationship between the ever- increasing number of wells and the dramatic decrease of active flowing springs has been observed (e.g., in oases of the Western Desert of Egypt) and is predicted to exacerbate due to the lack / non-compliancy with sustainable exploitation plans (Voss and Soliman 2014; Hamed et al. 2018). Beyond the main threats of increased groundwater overexploitation and global climate changes, other human pressures, such as land-use, pollution, infiltration, use of pool-springs for recreation and cattle-watering etc., frequently undermine the ecological integrity of inhabited oases. This is particularly evident in the assemblage composition of human pressure-sensitive cyanobacterial and algal communities, which are found to be dominated by indicators of nutrient-enriched conditions (Cantonati et al. 2020). Moreover, introduction of non-native and invasive algal species have also been documented (e.g., Saber et al. 2018c). There is a clear need to identify the location of near-natural springs that may still host a specialized biota as is well known from these habitats in other continents.

Stewardship

Ecological research on springs in North Africa was mainly floristic-faunistic and sporadic before the beginning of the 1990s when it gained new impulse. Research on the biodiversity, hydrogeochemistry and ecology of springs in North Africa is limited, for example from: the Western Desert of Egypt (e.g., Saber 2016, Yehia et al. 2017, Saber et al. 2018b, c); coastal aquifer at North-west Libya (Alfarrah et al. 2017); thermal springs in the Guelma region of Algeria (Foued et al. 2017); and Atlas Mountain springs (Hssaisoune et al. 2020). Freshwater organisms in desert springs often show striking behavioural, biochemical, physiological, reproductive, morphological, and distributional adaptive traits (e.g., Saber et al. 2018a, b; Cantonati et al. 2020). Better understanding of desert oases ecological dynamics and maintenance of springs integrity will greatly help to conserve their unique biodiversity. The strategic importance of NWSAS and NSAS lies in their substantial extension under desert and semi-desert areas and in their artesian nature. This resource guarantees the water supply of the numerous natural oases and wells along the main communication routes, but also the partial supply of the surface strata that guarantee the life of the spontaneous vegetation, which represents the main natural defense against progressing desertification. Drawing water without a clear understanding of the cross-border implications and potential damage to biodiversity can accelerate the degradation of the entire territory and of the hydrogeological complexes. For these reasons, adequate international legislation, monitoring of withdrawals and cooperation interventions between the nations concerned, would seem to worthy of consideration, together with increased public awareness to prevent a possible collapse of these systems (Hamed et al. 2018).

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Egypt Case Study: Siwa Oasis

by Anwar A. Aly

Siwa Oasis is considered the most important oasis in the western desert of Egypt (Figure 4-46). In addition to the existing cultivated area, there are more than 17,000 feddans (a unit of land equal to 0.42 ha; 71.4 km^2) that were determined to be suitable for agricultural development. The area under cultivation has been gradually increasing in recent years as the population of the oasis is on the rise. New land reclamation development projects aimed at the exploitation of water resources have been in progress. Siwa is a fragile low-land oasis ecosystem, highly vulnerable to environmentally induced land and water resources degradation. The ecosystem resource degradation problems in Siwa are exacerbated by poor natural resource management and practices. The groundwater quality in Siwa is deteriorating due to increased salinity. Groundwater is the only source of drinking and irrigation water in Siwa Oasis. Old artesian wells originating from the top shallow aquifer are the traditional source of irrigation water in the Oasis; the numbers of these wells are well over 220. As the need for more land arise, the upper limestone aquifer has been tapped by boreholes as a new source of irrigation water. The number of these artesian wells had exceeded 900 wells. Recently, the deep sandstone aquifer has been tapped at depths of 1200 m of the aquifer. The water salinity of shallow wells ranges between 1,600 and 8,000 ppm in some places, while the salinity of deep artesian wells range between 300 and

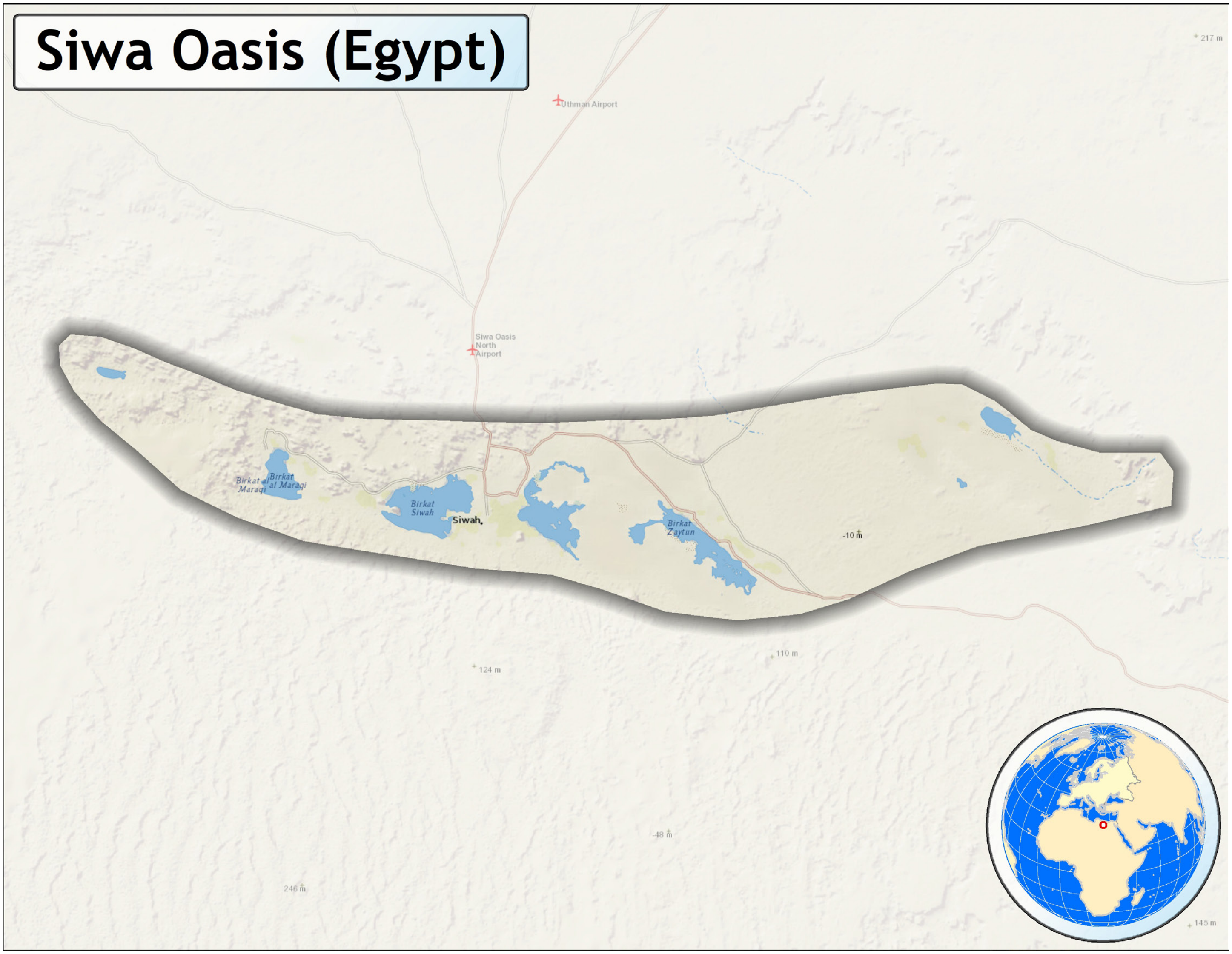

Figure 4-46. Map of the Siwa Oasis, Egypt.

Map boundarie were drawn manually around region of Siwa Oasis The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 29.12°, 2nd Standard Parallel = 29.36°.

400 ppm. Due to the continuous agricultural expansion and urban development in the oasis and the increased demands on water supplies, more water abstraction is currently taking place raising the dangers of overexploitation and deterioration of water quality. Thus, with regards to the IUCN RLE categorization criteria, Siwa Oasis in a Critically Endangered condition.

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Morocco

by Lhoussaine Bouchaou

The majority of Moroccan springs emerge from Atlas Mountains aquifers (Figure 4-47). The country's prominent springs have long been used for ecological goods and services, and emerge primarily in karstic terrain along faults or at contacts with impermeable formations (Bouchaou et al. 2002, Ait Brahim et al. 2019). Springs are most important in the piedmont regions of the Mountains (e.g., Atlas of Beni Mellal). The average discharge of Moroccan springs varies from minor flow to more than 1 m^3/s. The springs play an important role in many areas for drinking water and irrigation and, for geothermal springs, for recreation and health resorts (Bouchaou et al. 2017). Ain Asserdoune Springs in the Beni Mellal region, and is an excellent example of the high level of interest in, and intense use of spring waters for multiple purposes. These springs provide the baseflow of rivers flowing from the Atlas Mountains, with infiltration derived from the higher levels of rainfall and snowmelt that occur there. Several other kinds of springs (e.g., oases, other wet areas) are recognized as groundwater-dependent ecosystems in southern Morocco as well.

During the past several decades, all Moroccan springs have been affected by climate change and many have been affected by intensifying anthropogenic pressures. Several springs clearly demonstrate depletion of discharge, and others in the arid zones have completely

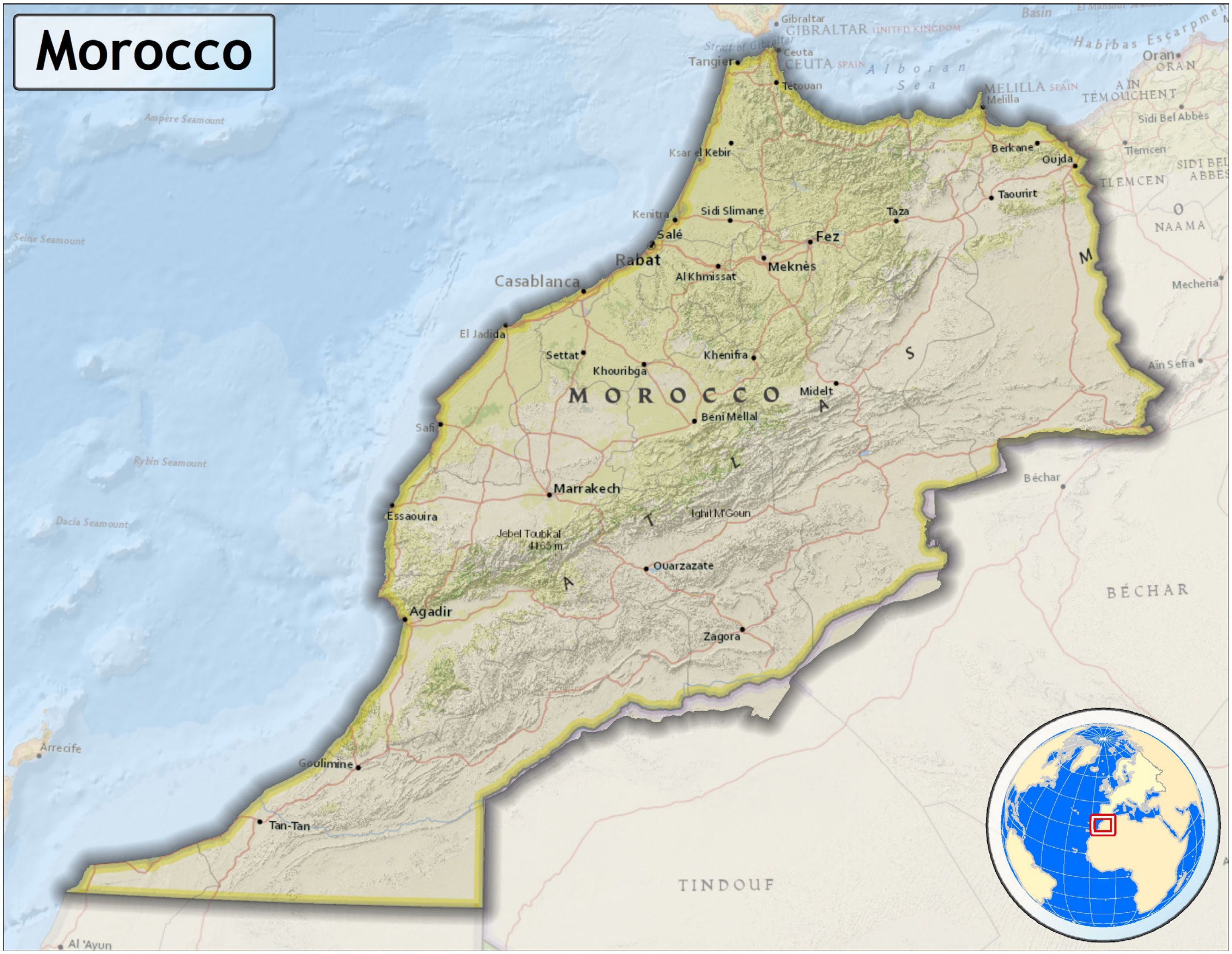

Figure 4-47. Map of Morocco.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 27.67°, 2nd Standard Parallel = 35.92°.

dried. All sources emerging from watersheds subject to increasing intensity of land use through urbanization, agriculture, and other factors show signs of pollution from human impacts (Heiß et al. 2020 a, b). These various forms of development and alteration have accentuated the problem of turbidity, of particular concern for larger, more well-known sources (Bouchaou et al. 2002). Water scarcity and demographic development in this generally arid region have generated much conflict over springs, which traditionally had been considered as resources to be shared. Source-dependent ecosystems have sustained very advanced degradation or even total disappearance (e.g., oases in southern Morocco). In several cases in recent decades, local populations have gone to great effort to safeguard aridland springs because water there is a scarce and highly valued commodity (Ettayfi et al. 2013, Heiß et al. 2018). Participatory management of springs water and ecosystems in rural areas has been the only conservation means that has enhanced springs preservation and sustainability, despite the enormous concern over decreasing flow. Overall, Moroccan springs conservation status varies from VU to EN, and many spring ecosystems have collapsed in the past few decades, particularly in southern Morocco. Ain Asserdoune, a heavily used and widely recognized spring ecosystem, is highly vulnerable to dewatering and groundwater pollution.

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Subsaharan Africa: South Africa

by Memory Tekere and Ernest Azwindini Tshibalo

South Africa is a semi-arid country with an average of 550 mm/yr of rainfall (Figure 4-48). The hydrological environment is complicated, but rich in ground water resources. The geological setting of the country shows that 90% of its groundwater occurs in hard rock, with only secondary openings (Wu 2008). Springs water is available in many parts of the country, and communities have been using springs for decades without monitoring water quality. To date, not much research has been conducted on the actual quantities of spring water used, especially in rural communities (Nkuna et al. 2014).

The ecological integrity of some springs in Limpopo Province were described, including six springs at in the vicinity of Vondo between latitudes of S 22.91^0 and S 22.93^0, and longitudes of E 30.35^0 and E 30.38^0, and six springs near Meidingen between latitudes of S 23.63^0 and 23.64^0, and longitudes of E 30.24^0 and 30.25^0. Both communities rely on springs for daily water needs. Stock grazing takes place in both communities, causing negative impacts on the ecological integrity of springs. The pH of those springs ranges from 5.1 to 6.2 at Vondo, and 5.9 to 7.2 at Meidingen. Microbiological bacteria monitoring showed indicator E. coli, total coliforms, and heterotrophic plate counts. Fecal matter and high level of nitrate + nitrite (N), iron and aluminum concentrations

Figure 4-48. Map of South Africa.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -34.82°, 2nd Standard Parallel = -22.14°.

were measured (Nkuna et al. 2014) contaminate these springs, making them unfit for human consumption, according to the South African Drinking Water Standards (Holmes 1996).

Pearson (2003) studied 40 South Africa springs in KwaZulu Natal and the Eastern Cape Province. The springs there are described as follows: 1) Bergville area (KZN) – springs, moderate to poor yielding. 2) Hill flats, (Jollvet area) – springs generally low yielding. 3) Transkei (Eastern Cape) – springs generally moderate to poor yielding. Water quality was monitored and did not meet the targeted water quality limits. Land uses including livestock watering and small-scale crop farming had negative impacts on the ecological integrity of those springs. In contrast, Wu (2008) studied eight springs at Table Mountain in Cape Town, a relatively affluent area, including springs at: 1) Kirstenbosch, 2) Albion, 3) Newlands, 4) Palmboom, 5) Main springs, 6) Table Mountain, 7) Kommetjie, and 8) Waterhof springs. Those springs currently are used for recreation (casual walkers, picnickers), and companies (brewers), as well as local community gardening and cleaning. Physical characteristics of those spring waters were: pH ranging from 4.7-6.2, temperature from 15.4 – 22.1 °C, EC from 7.29-36.00 (mS/m), TDS from 32.6-176.8 mg/L, and hardness ranging from 6.7-39.7 mg/L. In general, water quality of those springs met South Africa Domestic Water Use Guidelines. In conclusion, springs in poorer communities are generally polluted and unsuitable for human consumption, as compared to springs in affluent communities, such as Cape Town.

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Namibia—a Broad Overview

by Braam van Wyk

Introduction

Namibia is a relatively large country comprising a surface area exceeding some 800,000 km^2 (Figure 4-49). The central, north, and northeastern parts receive generally good rainfall in some years, where the average annual rainfall is in the order of 400-450 mm/yr (Figure 4-50). The southern and western parts are drier and the west, in particular where the Namib Desert is located. The Namib Desert, its presence due to the cold Benguela current, stretches along the whole coastline and continues into Angola. The Kalahari Desert is located towards the southeast of the country. All the rivers in her interior, as large as it is, occur as dry riverbeds. Run-off only occurs for short periods in some seasons after good summer rainfall. The only permanent flowing rivers define her borders and so are shared with her neighbors.

These permanent rivers are the Okavango, Zambezi, Kunene, and Orange Rivers. Before the arrival of drilling technology for making boreholes, humans settling in Namibia's water sparse landscapes were often reliant on fountains. Still today, a locality often bears the name of the fountain. A database of the springs of Namibia is kept at the Department of Water Affairs in Windhoek and presently contains 700-800 documented sources.

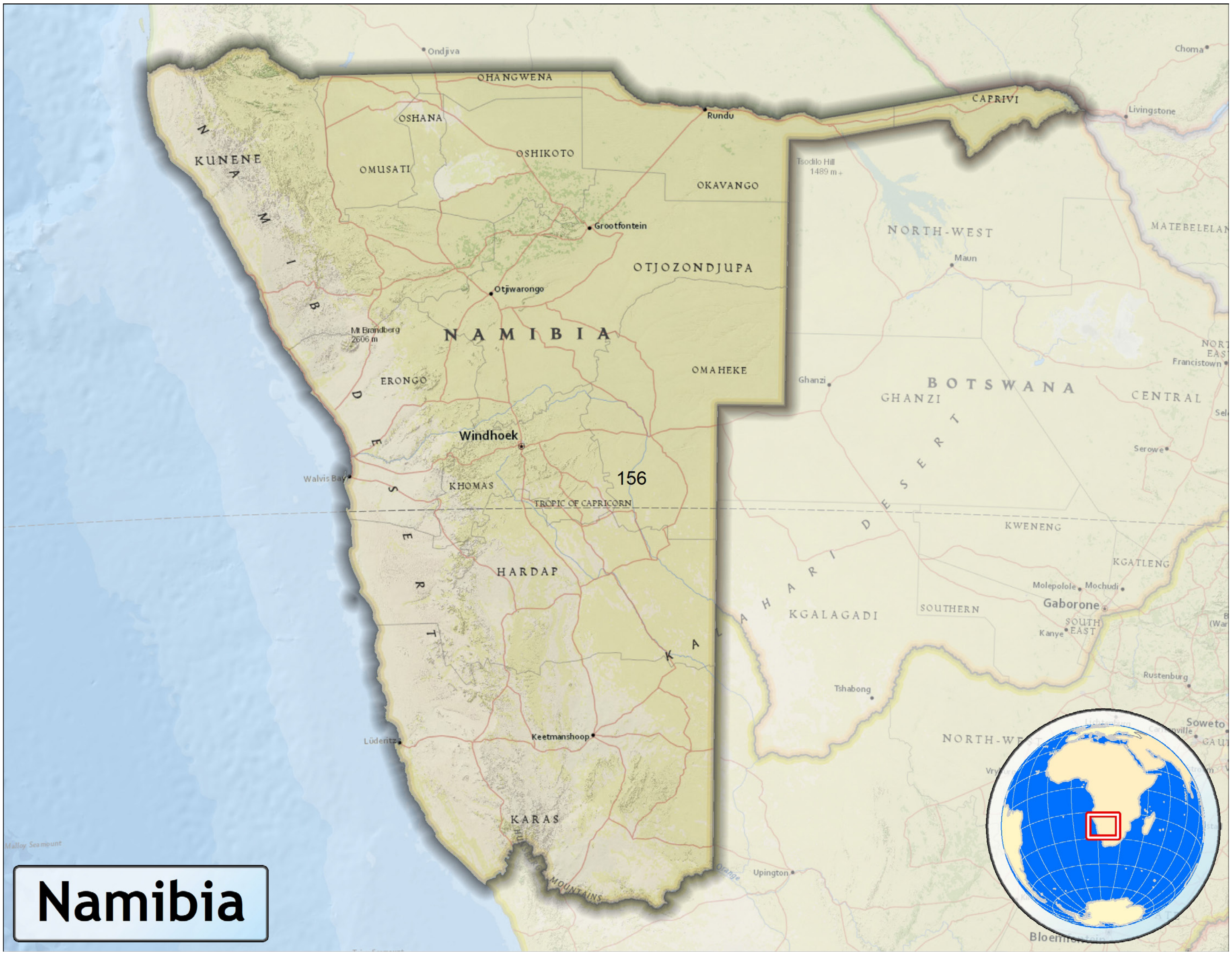

Figure 4-49. Map of Namibia.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -28.97°, 2nd Standard Parallel = -16.96°.

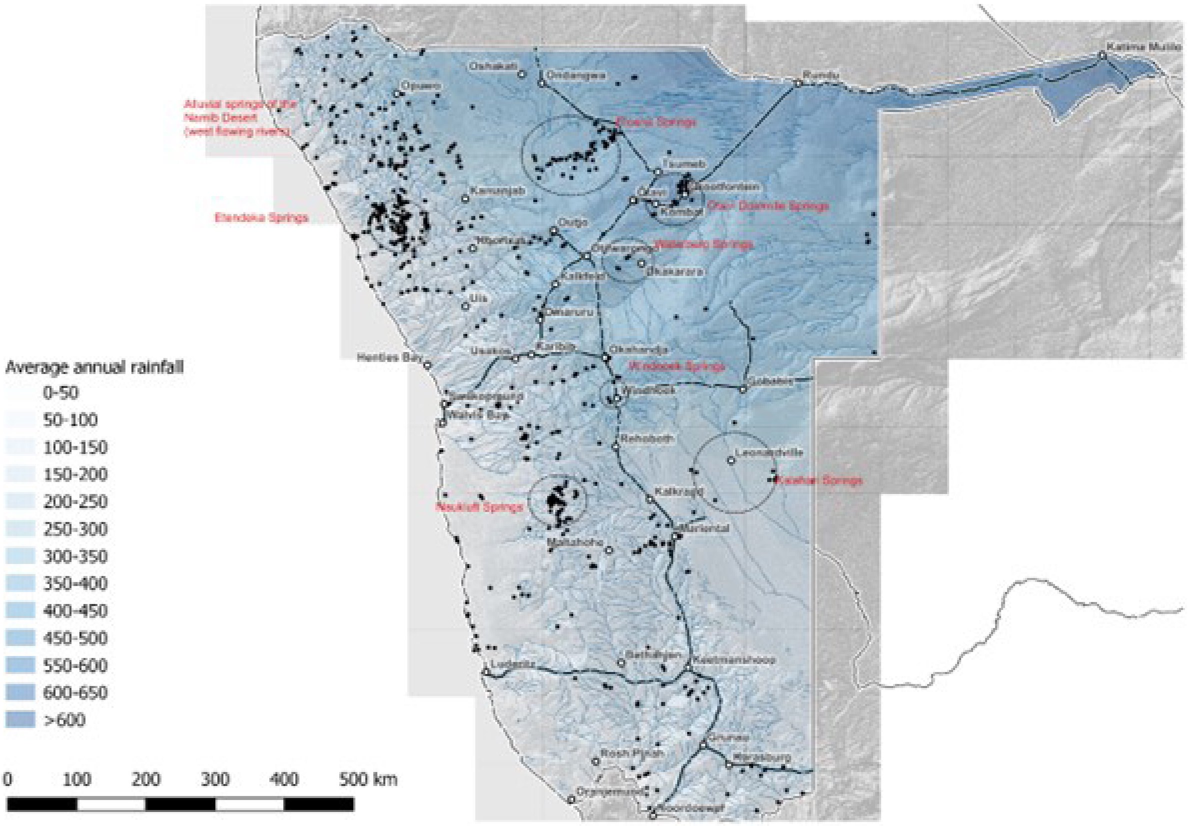

Figure 4-50. Distribution of Namibia`s springs and average rainfall

The Relevance of Springs

Springs, due to their existence over thousands of years, have been the point of settlement of stone age hunter-gatherer communities or early pastoralists. Well-known localities include Twyfelfontein and the rock springs of the Brandberg. Lesser-known are the stone circles of Kuidas Spring of the Huab River. At such localities, anthropologists study the life of the early occupants, and what they hunted and used for protein thousands of years ago (Badenhorst, Veldman and Lombard 2016).

Springs are historically relevant. At the Omuhiva village, close to Opuwo in the Koakoland, the spring of Nanganga is located. It is the site of the story of Nanganga, who lived there and was raided by a group of Okavena. They set fire to Nanganga`s house, robbed her cattle and murdered her. When Tjireka, her son found out he decided to avenge his mother`s death. The fight took place at the water source and Tjireka left the scattered corpses for the hyenas (Kavari and Bleckmann 2009). There are additional interesting historical stories and anecdotes. For example, the account of how Twyfelfontein (Afrikaans for "Doubtful Fountain") got its name in the early 1940s is certainly entertaining to read. It tells the story of David Levin, an early farmer who was perennially doubtful whether the spring would last to the next rainy season and hence got the nickname David "Twyfelfontein" (Gondwana Collection Namibia, 2012). The story of how Windhoek, Namibia's capital, got its name relates to the settlement of the Jan Jonker Afrikaner at the hot water springs, who named the area after the Winterhoek Mountains of the Cape Colony.

Biologists are attracted to springs to study present and past life forms. A study of fossils found in tufa deposits, a freshwater carbonate often associated with springs reveals information on paleoecology. Such is the case Ongongo Springs close to Sesfontein, which contains a rich collection of macroscopic fossil plant leaves, roots and trunks (Mocke 2013). A tufa deposit of a spring near Outjo revealed a calcified honeycomb, estimated to be a million years old. Calcified freshwater crabs are found in fossil tufas of the Naukluft Mountains. During a study of dragonfly assemblages, surveys had been conducted at 70 spring points across the country. Dragonflies are indicators of threatened freshwater wetlands. The authors of this study expressed concern about the state of degradation of Namibia's springs and freshwater wetlands (Suhling et al. 2006).

Haloalkaline environments are considered to have the highest abundance and diversity of viruses of all types of environments. The Namib Desert salt playas, salt pans and hyper-saline springs had attracted the attention of microbiologists. Such a site where virome data have been well-studied is Eisfeld Spring, 20 km northeast of Swakopmund (Olonade et al. 2021).

Geochemists have studied the biochemical sulfur cycle of several of Namibia`s desert springs as part of a study understanding the occurrence of gypsum deposits in the central Namib Desert (Eckardt and Spiro 1999). These include Rossing Mountain Spring, Eichfeld, Piet`s Spring, Khan Gorge, Husab Spring and Gai-Ais, among others.

Geothermal springs have been the subject of tectonic studies. Namibia`s geothermal springs, such as Ai-Ais, Omapyu, and Gross Barmen en Rehoboth are super-saturated in fluoride, similar to the geothermal groundwaters of the Ethiopian Rift Valley (Sracek et al. 2015). The examples provided above should convince the reader that springs are culturally rich and relevant to the interests of a wide range of scientific disciplines.

Namibia's Most Prominent Spring Systems

Springs of the Etendeka System

Although located in a desert to semi-desert environment, spanning an area with average annual rainfall ranging from 50 to 150 mm, the Etendeka of Namibia are abundant with springs with 140 sources reported thus far (Figure 4-51). Named after the so-called Etendeka Geology, they are located 450 km northwest of Windhoek. The Etendeka Formation consists of interbedded basalt units approximately 120 Myr in age (Milner 1986). Erosion there has left behind a topography best described as flat-topped table mountains.

The Etendeka Comnplex include Anabeb, Awaxas, Crowtersquelle, Fonteine, Gomakukous, Juriesdraai, Koabes, Karkappiefontein, Khoraxa-ams, Leeufontein, Naodai, Nuwas Ugams, Palmwag, Tweepalms, Ugibputs and Wereldsend springs. The occurrence of so many springs in an area with such low rainfal probably is related to the basalt units. The upper and main zones that build the table mountains and mesas are weathered and/or massively jointed, so recharge likely takes place with relative ease when rainfall occurs. Lower lying valleys probably comprise of the basal zones that are perhaps less weathered and less permeable to groundwater infiltration, hence groundwater flows out onto the surfaces of the foothills and valleys.

River Alluvium Springs

These refer to spring sources associated with Namibia's dry, alluvial riverbeds, most of which are flowing in a westerly direction through the Namib Desert to the Atlantic Coast (Figure 4-52). Although these rivers are dry most of the time, run-off occurs occasionally with good summer rainy seasons. These springs are particularly prominent in northwestern Namibia, an area extending from the Omaruru River in the south to the Kunene River in the north and bordering Angola. Prominent riverbeds with these springs include the Hoarisib, Hanib, Huab, Ugab and Omaruru rivers. These ephemeral riverbeds often are referred to as Namibia's ephemeral oases, due to the livelihoods and ecology that the ephemeral floods and the groundwater within their alluvial beds support in these otherwise desertic environments. Spring flow occurs where the groundwater in the alluvium resurfaces as a consequence of topography or geology. There are about 120 such emergences documented nationwide. Where these river systems meet the Atlantic Ocean, groundwater often appears on the surface as "desert outflows" There are about 15 such emergences.

Springs of Etosha National Park

The Etosha Springs are water sources for wildlife in Etosha National Park, Namibia's best-known national park (Figure 4-53). The park is located approximately 400 km north of Windhoek and contains about 56 springs. These generally occur as waterholes or spring mounds located on the southern rim of the Etosha Pan, a large deflation feature situated in sediments of the early Cretaceous Kalahari Group strata. The pan floor comprises the Etosha Pan Clay member (Andoni Formation), which can be up to 50 m thick. Of interest is the Etosha Calcrete Formation, a "gigantic groundwater calcrete 80 km wide and up to 120 m thick". The calcrete covers an area between the Otavi Mountainlands and the southern rim of the Etosha Pan where the springs are located. The calcrete, covering underlying sedimentary units, is associated with groundwater flows from the Otavi Mountainland Dolomite (Miller 2008). Although these springs are mostly underlain by aquifers associated with sediments of the Kalahari Group, the probable groundwater pathways are associated with groundwater flows from the dolomite and calcretes of the Otavi Group towards the south and west. Visitors to Etosha can encounter Agab, Aroe, Batia, Groot Okeve, Kapupuhedi, Klein Namutoni, Klein Okeve, Okaukuejo, Ombika, Otjovasandu, Salvadora, Twee Palms and Wolfsnes springs, among many others.

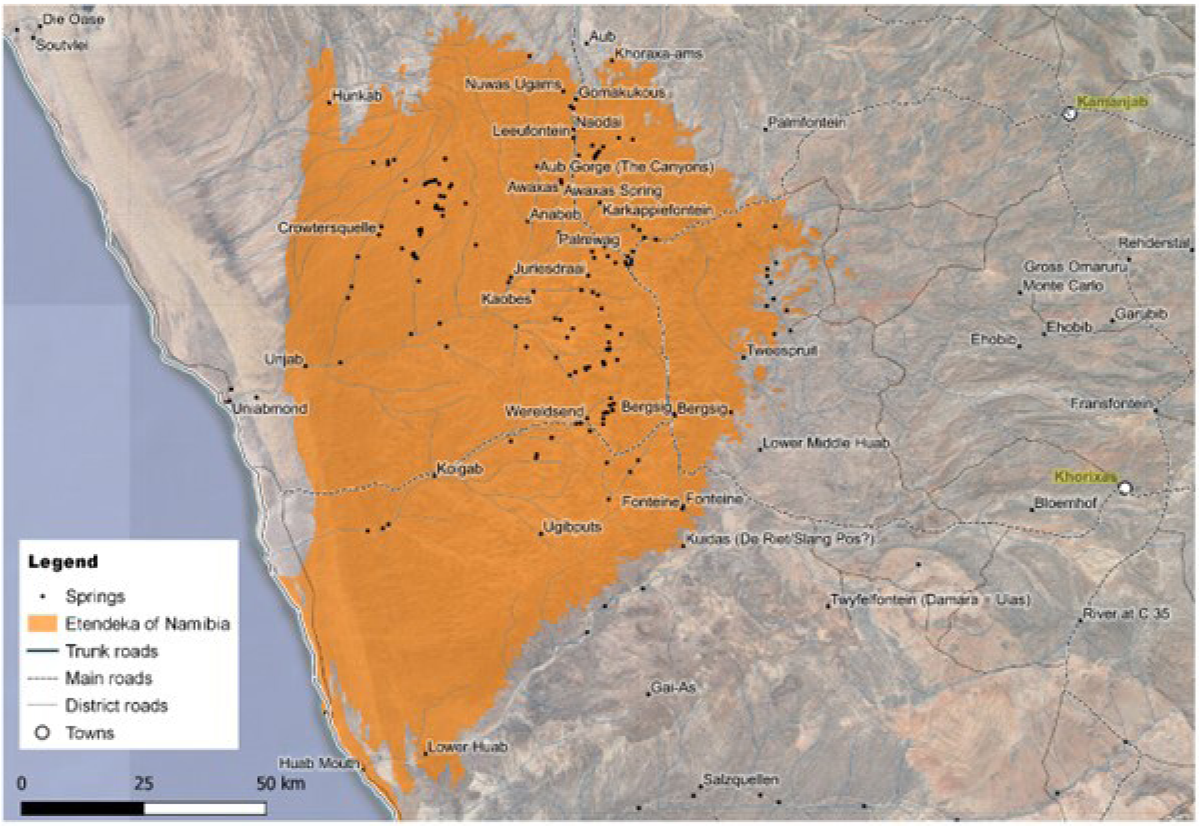

Figure 4-51. Distribution of springs in the Etendeka System.

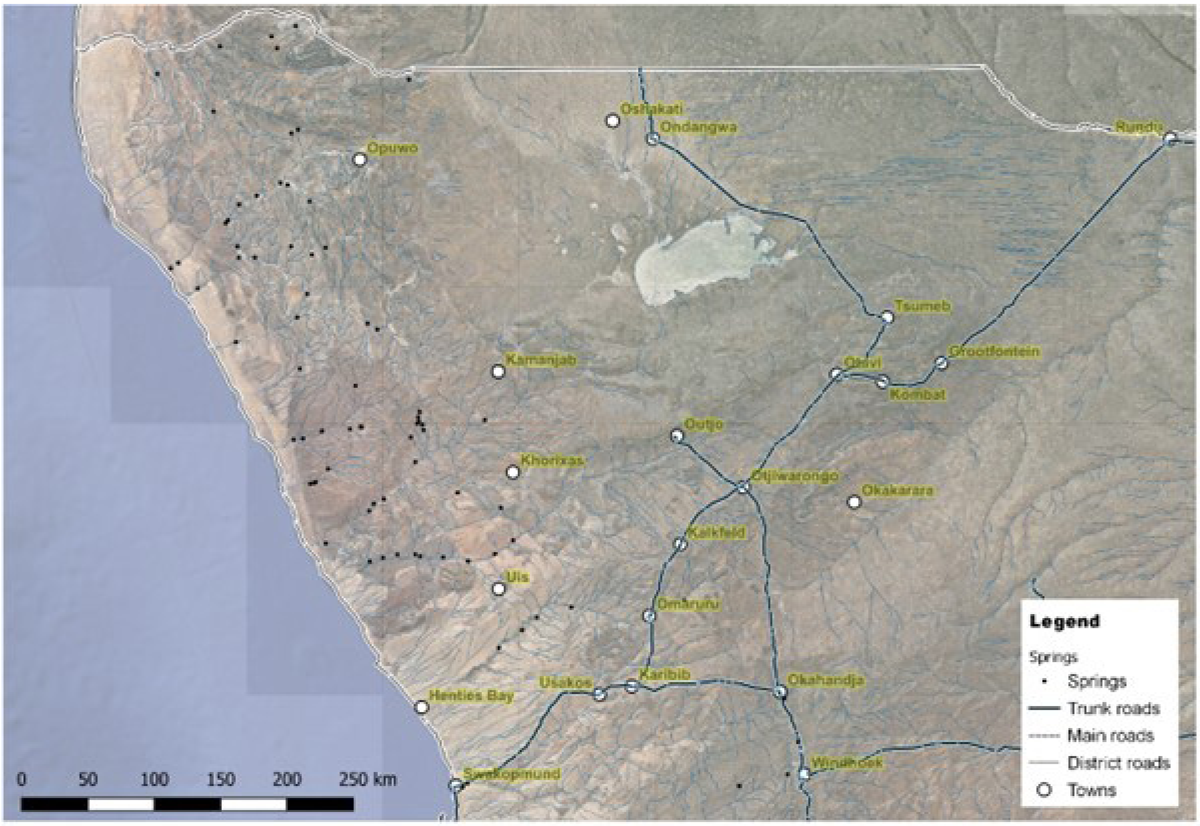

Figure 4-52. Distribution of river alluvium and desert outflow springs.

Figure 4-53. Springs of Etosha National Park.

Carbonate Springs of Northern Namibia (Otavi Mountainlands)

Like the springs of the Etosha National Park, these springs are also associated with the carbonate rocks of Otavi Group Dolomites, in particular, the Abenab, Tsumeb and Otavi Formations (Figure 4-54). Some 50 well-known sources are documented. The most prominent of those emerge from the Otavi Mountainlands "Karst Area", located 350 km north of Windhoek in central-north Namibia in the surroundings of Otavi, Grootfontein and Tsumeb. From the Otavi Mountainlands onwards, one arm of the dolomites extends along the rim of the Cuvelai Etosha Basin in the direction of Opuwo in the far northwest. Another second arm extends southwesterly in the direction of Khorixas. These dolomite strata are well known as aquifers and karst landforms. They source several prominent springs with high discharge, often where dolomitic rock units overlie each other or other impervious geological rock units. Well known springs include Abenab, Berg Aukas, Jägersquell , Khusib Springs, Maria Brunn, Olifantsfontein, Otavifontein, Rietfontein, Tigerquelle, Gasenairob, Ombombo, Tsuwandes, Fransfontein springs, and many others. A discharge of 300 m^3/hr was once recorded for Rietfontein, but this value is subject to change due to variation in the depth to groundwater.

Carbonate Springs of Southern Namibia (Naukluft)

The Naukluft Mountains are located 200 km southwest of Windhoek in southwestern Namibia at the edge of the Namib "Sandsee", and not far from Sossusvlei and Sesriem further to the west (Figure 4-55). It is a nappe complex, the result of a basal thrust fault, and comprises predominantly sedimentary units of dolomite, limestone, quartzite, and shale. Despite the semi-arid to desert climate with an average rainfall of about 100-150 mm/yr, the Naukluft Nappe Complex sources a relatively large number of springs in this dry region. There are about 50 known springs associated with limestones and dolomites of the Naukluft Karst Aquifer, which are highly fractured and well karstified (Kambinda and Mapani 2017). Despite the low rainfall, recharge occurs readily due to the porous nature of the karstified carbonate rock units. High groundwater discharge likely occurs towards the west into the Namib Desert. Spring discharge varies greatly between wet and dry periods as a consequence of groundwater table fluctuations. There are many unnamed springs in this region, but perhaps the best known are the

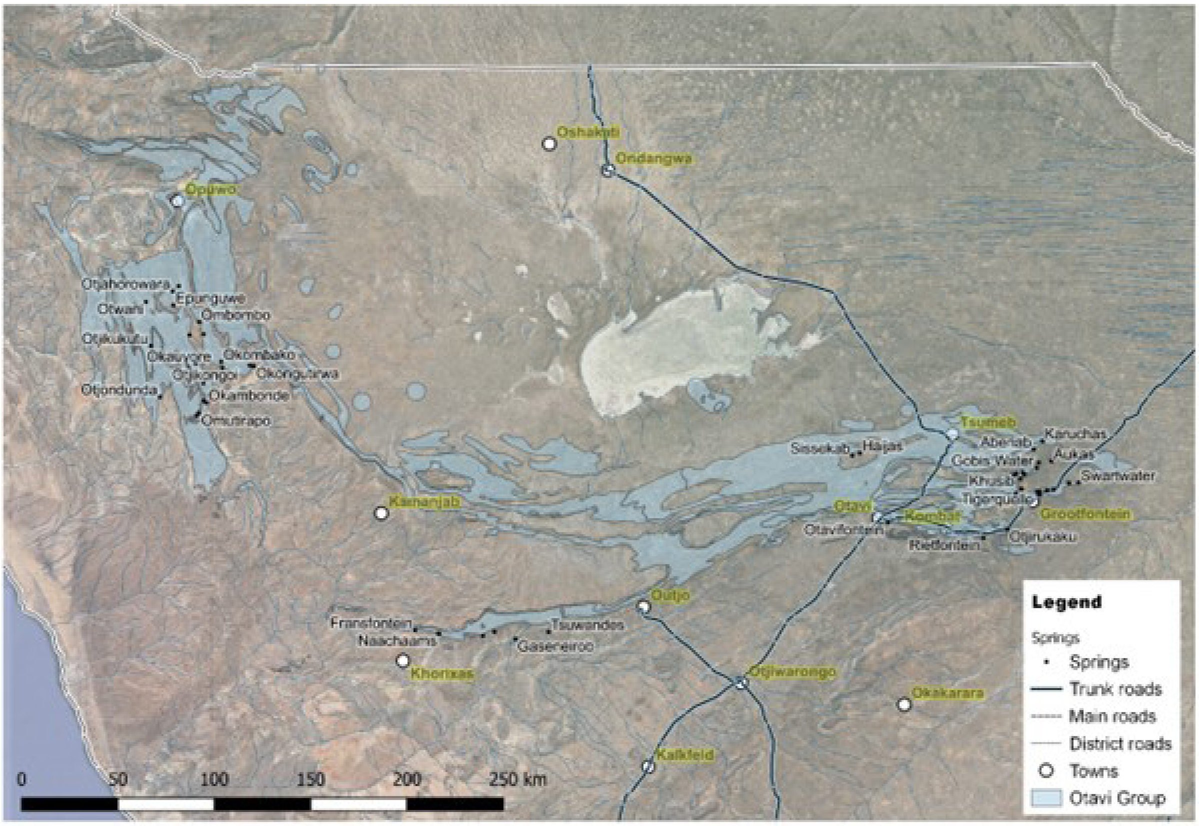

Figure 4-54. Carbonate Springs of Northern Namibia (Otavi Mountainlands).

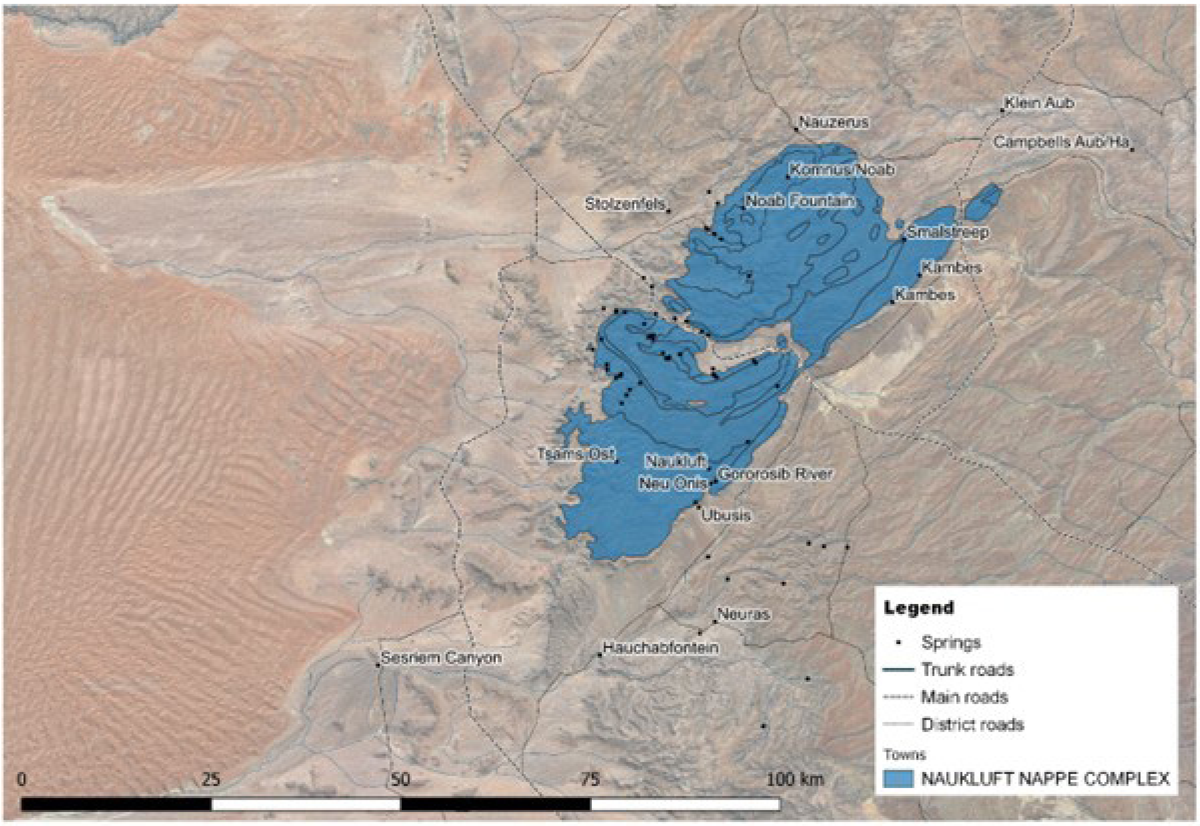

Figure 4-55. Carbonate Springs of Southern Namibia (Naukluft).

Naukluft Springs located 1 km upstream from the present Namibia Wildlife Resort.

Springs of the Waterberg

The Waterberg Plateau is located in central-north Namibia located 250 km north of Windhoek and 50 km east of Otjiwarongo (Figure 4-56). It is a prominent landmark in Namibia due to the scenic cliffs of the Etjo Sandstone Formation that shapes the plateau and that overlie shales, and the Omnigonde Formation mudstones. About eight major springs are found here. Relative high volume spring discharge occurs close to the base of the mountains, near the contact of the Etjo Sandstone (mostly permeable) with the underlying Omnigonde silts and clays (mostly non-permeable). These springs are described as “mesa” or “contact overflow” springs. The most well-known of these springs are located in Waterberg National Park, near the main campsite where groundwater seeps and flows from the sandstone cliffs above. Other prominent springs include Schneider Waterberg, Okawaka, Otjosongombe, Okamumbonde, Onjoka, Okamiparara and Hohensee springs.

Windhoek Springs

The hot springs of Namibia’s capital, Windhoek, are a veritable landmark in the history and development of the region (Gevers 1932; Figure 4-57). Eight major spring sources previously existed here. In historic times the land was occupied by the Nama people who called it Ai=//gams (Ais = fire // gams = water) and the Herero people, who referred to it as Otjomuise (the place of smoke), on account of the visible cloud of water vapour on moist days that hang over the largest and hottest springs. In 1842 a Remish Mission was built that later became Catholic Mission Garden, perhaps near where St. Paul`s College is located today. At that time Jan Jonker Afrikaner, a leader of the Nama tribes, had settled there. The name Windhoek arose and replaced all other names. In 1890 Curt von Francois selected Windhoek as the headquarters for German colonial troops. The swamps of the hot springs were gradually developed to become the first water supply source for Windhoek. In the 1920s the Municipality of Windhoek commenced drilling of the first boreholes to keep up with increasing water demands. As a consequence, all of the Windhoek Springs ceased flowing.

These springs can be divided into the “Greater Windhoek Springs” and the “Klein Windhoek Springs”. The former originally included six springs aligned on what Gevers (1932) described as a well-marked spring fissure (today called the Pahl fault). In the centre, nearby the present-day Windhoek High School was Pahl Spring, the

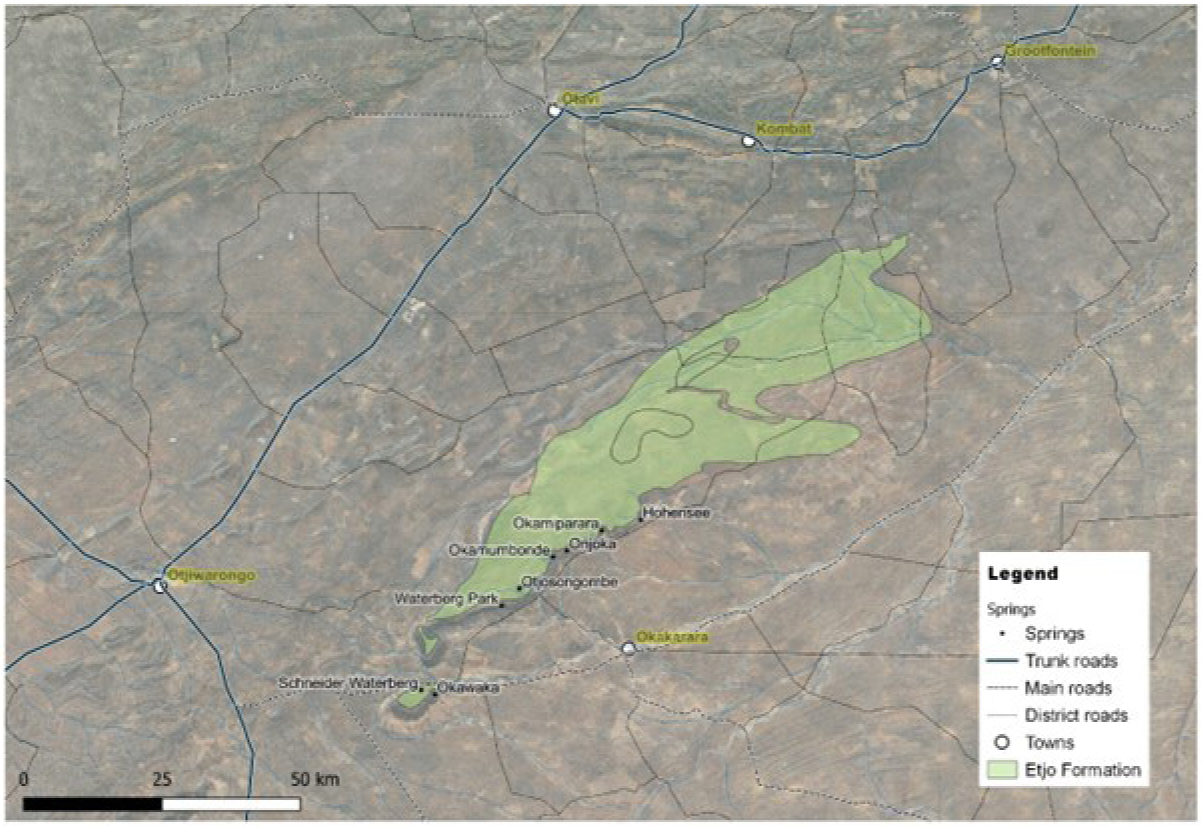

Figure 4-56. The springs of Waterburg

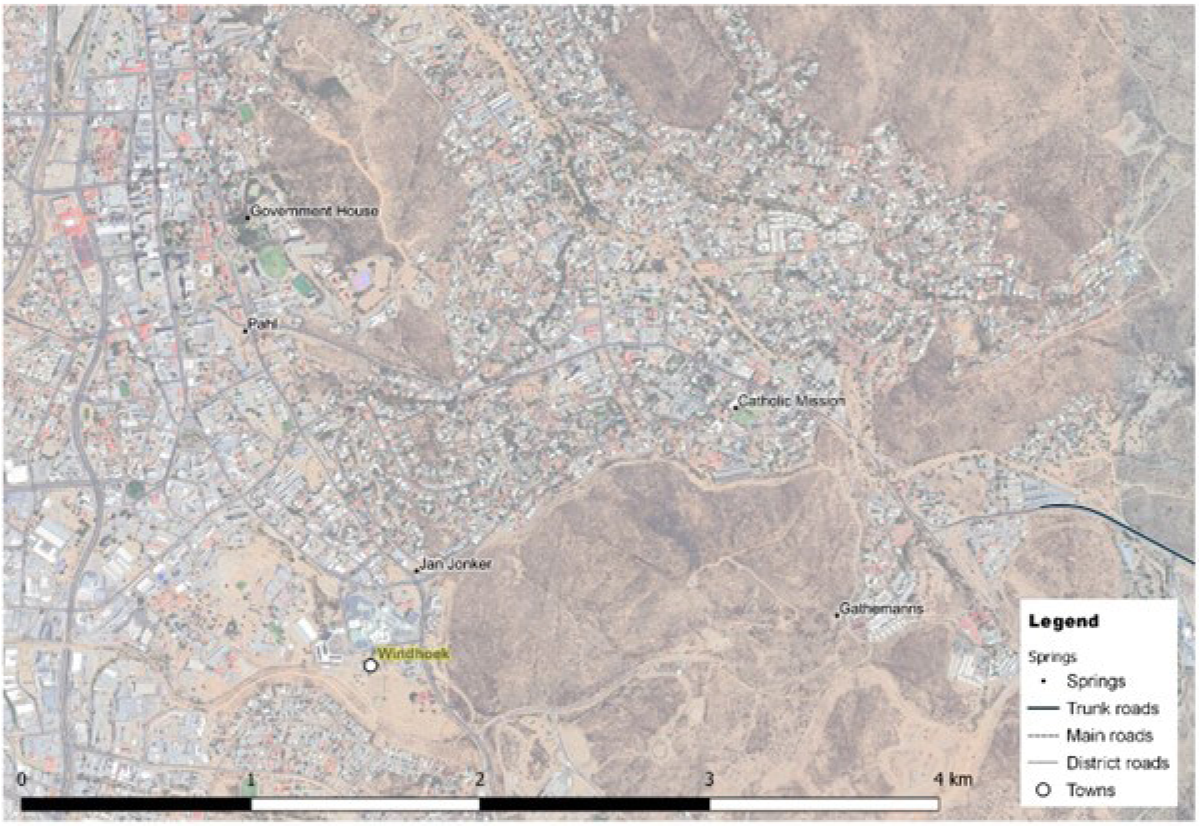

Figure 4-57. Springs of Windhoek.

hottest and most prominent source. Pahl Spring had a maximum yield of 15 m^3/hr recorded in 1923, with temperatures ranging from 70-80 °C. North, in the garden of the present-day Parliament and the Zoo Park, was Junker (Jonker) spring of the Government House and South, near the crossing of present-day Jan Jonker and Robert Mugabe Streets.

East, across the escarpment formed by the Eros Mountains that divide Windhoek and Klein Windhoek, are the Klein Windhoek Springs. In contrast to the Greater Windhoek Springs that arise from the well-marked fissure, the Klein Windhoek Springs are more complicated, being associated with the occurrence of fissures in with breccia dykes. The most prominent of these springs were those in the garden of the Catholic Mission on the northern slope of the Wasserberg, and on "Gathemann`s property" on the southeastern slope. Reported temperatures among them ranged from 36 °C for Gatheman Spring to 54 °C in Catholic Mission Spring, as measured from a nearby borehole.

With a population of more than 400,000, the present-day water requirements of Windhoek amounts to several millions m^3/yr. Water for domestic and industrial purposes is sourced from a much greater and integrated water supply system located in central Namibia, comprising well fields, surface water supply dams and a water reclamation plant..

Springs of the Kalahari Desert

Kalahari Desert springs are situated in aeolian and alluvial sediments of in southeastern Namibia (Figure 4-58). Stressors influencing springs ecological integrity among 52 studies in 77 regions or nations on all continents except Antarctica. Red dots indicate study areas reported in the synopses presented in chapters 2-10.. There are few Kalahari springs, most of which are found in a radius of 70-80 km around Leonardville, a village 200 km southeast of Windhoek. Not much is documented about these springs, but they appear to be associated with the occurrence of hardpan calcrete. They may be related to the Stampriet Artesian Basin (SAB), an artesian basin that comprises one of Namibia`s most important groundwater resources, and also is a transboundary aquifer extending into Botswana and South Africa.

The groundwater discharge mechanisms of these springs has apparently not yet been studied in great detail. Some of them, such as the Aminius Springs, may be related to the upper groundwater recharge zones of the SAB, while springs such as Lidfontein and Klein Swartmodder springs are connected to the artesian groundwater units themselves. Further studies will provide interesting insights into their relationships to aquifers.

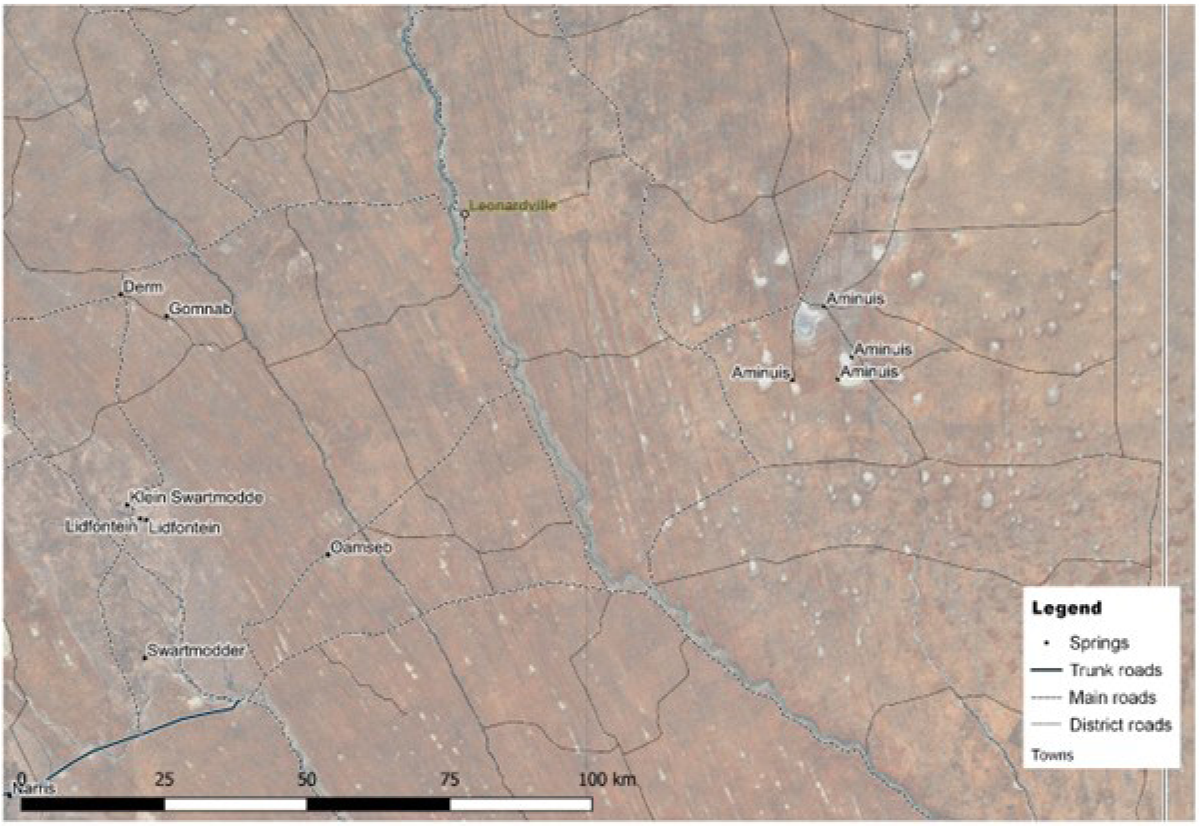

Figure 4-58. Springs of the Kalahari Desert.

Thermal Springs

Namibia has 10-15 thermal or warm water springs, also including the Windhoek springs that stopped flowing in the early 20th Century (Figure 4-59). The hottest springs measured were the Windhoek Springs (up to 80 °C), followed by Rehoboth and Ais-Ais (up to 65 °C). Temperatures in the 1940s were reported for Gonanigobes (45 °C), Gross Barmen (40 °C) and Omapyu (47 °C) springs. Currently, we are unsure of the recorded temperatures for Warm Quelle, Warmbad, Ondongantje and Sneyrivier springs. As far could be determined, little has been published on the warm/thermal springs of Namibia and their fluoride content (Sracek et al. 2015) or the springs of Windhoek (Gevers 1932).

Other Springs

A large number, perhaps 200 (25%) of Namibia's springs are scattered across the country, often appearing on maps as "waterholes", "an-eye" or "rock springs", but these cannot be clearly classified according well known geological or hydrogeological systems.

Conservation

In Namibia`s arid and semi-arid landscapes, springs are refuges on which ecosystem ecology and human livelihoods are reliant. These springs vary from tiny trickles below a rock in the desert that provide water for small animals, to oases with flourishing wildlife. Striking examples of lush ecosystems that support life and human livelihoods are the alluvial springs of Namibia's westward flowing ephemeral rivers. Others include the springs of the arid Etendeka landscapes, which support human communities and wildlife. Springs are essential, life-supporting ecosystems in Namibia, and deserve better recognition and greater awareness. About 350 springs are identified that are potentially used by game and wildlife, 170 springs are used for livestock watering, and, about 120 sources are used for gardening and horticulture by rural communities. Springs are relevant to many scientific studies in a great diversity of scientific fields, as described above, and springs reveal information about aquifer mechanics and recharge of some the country's great aquifers and groundwater resources. Yet at present, relatively little is known about springs as ecosystems. In 2006 a group of biologists raised alarm concerning the threats to Namibia's springs and wetland systems as part of a dragonfly study (Suhling et al. 2006). There is, therefore, a call for custodianship, public and governmental awareness, fund raising, protection and more scientific research for many of these essential ecosystems.

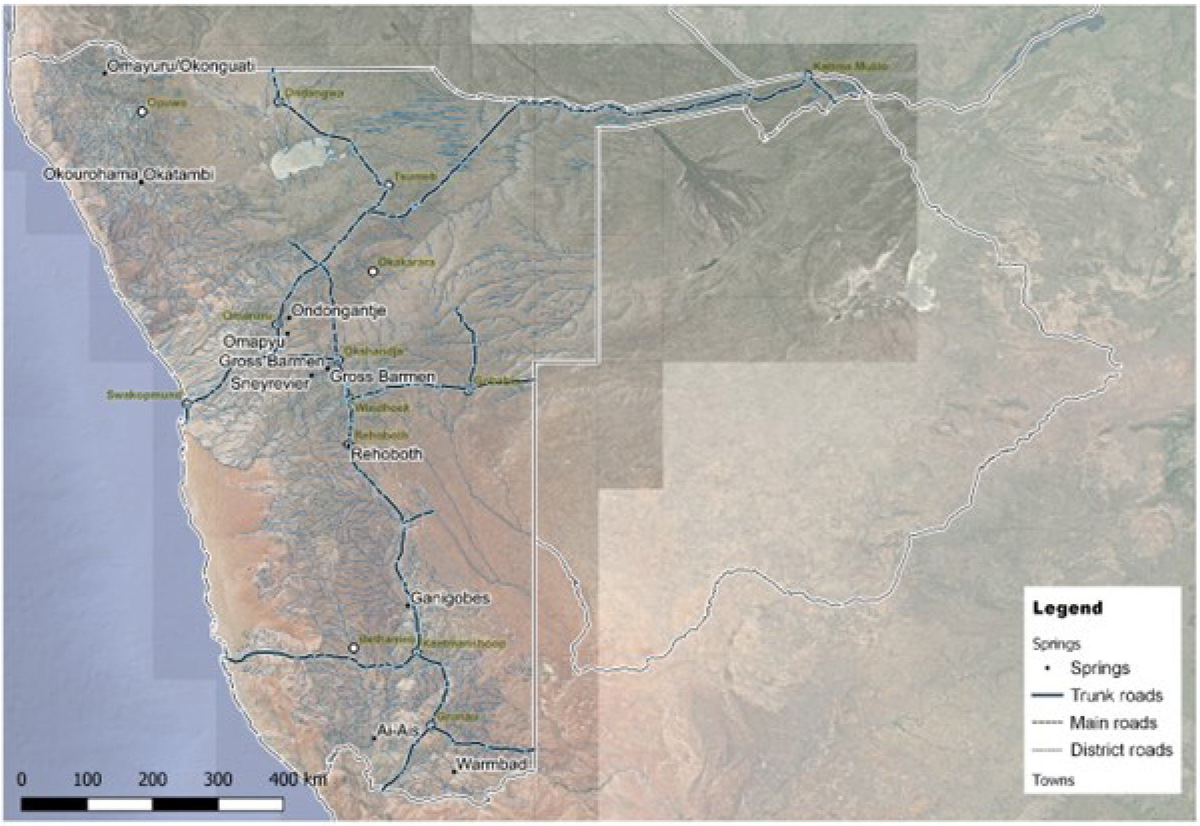

Figure 4-59. Thermal springs.

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Tanzania: Ngorongoro Volcanic Highlands

by Gail M. Ashley and Monica K. Norton

Ngorongoro Volcanic Highlands, a complex of nine shield volcanoes, is located at 3°S within the bifurcation of the East Africa Rift System in northern Tanzania (Figure 4-60, Figure 4-61). It is within the boundary of the Ngorongoro Conservation Authority (NCA), a UNESCO-designated World Heritage Site that contains Ngorongoro Crater (a wildlife preserve) and two archaeological sites (Olduvai Gorge and Laetoli Footprint Site). The NCA is home to approximately 70,000 Maasi people, a few million animals (both domesticated and wild), and is visited by over 600,000 tourists annually. Moist air from the Indian Ocean carried by easterly trade winds condenses as it rises over the massif. The highland is about 6000 km^2 in area, reaches 3300 m in elevation, and receives approximately 1000 mm/yr of rainfall. High elevations support a rich, diverse rainforest. However, the highlands cast a rain shadow so that lowlands to the west are arid (about 300 mm/yr of rainfall) and are typified by acacia-dotted grasslands. Some of the rainfall is lost to evapotranspiration, some infiltrates into subsurface directly, and the rest moves downslope on the surface in losing streams that continually add water to the groundwater system (Ashley 2017).

Springs persist year-round (Figure 4-61) despite the moisture-limited environment. The 13 springs in our study were chosen because they appeared to be of high

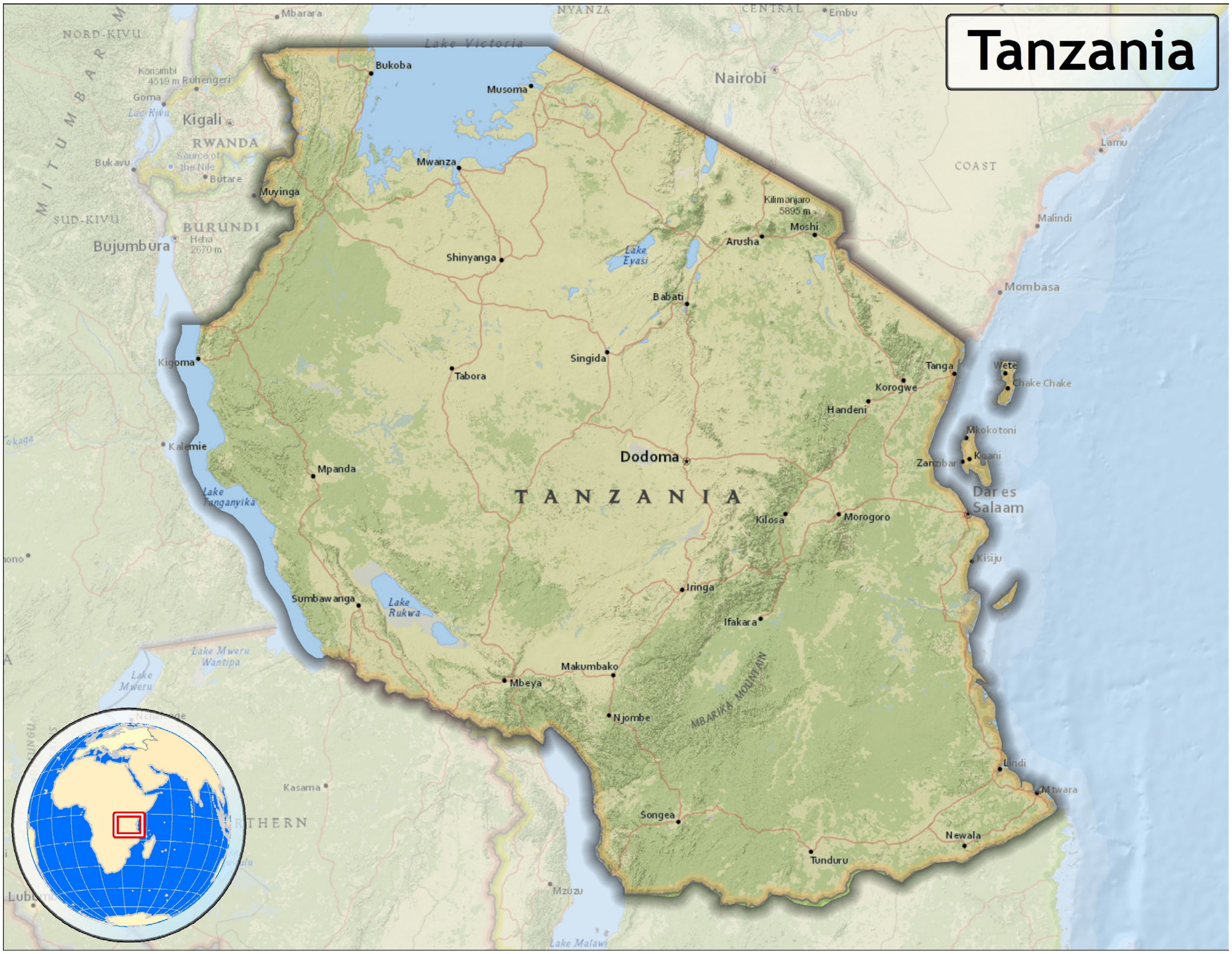

Figure 4-60. Map of Tanzania.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -11.74°, 2nd Standard Parallel = -1.00°.

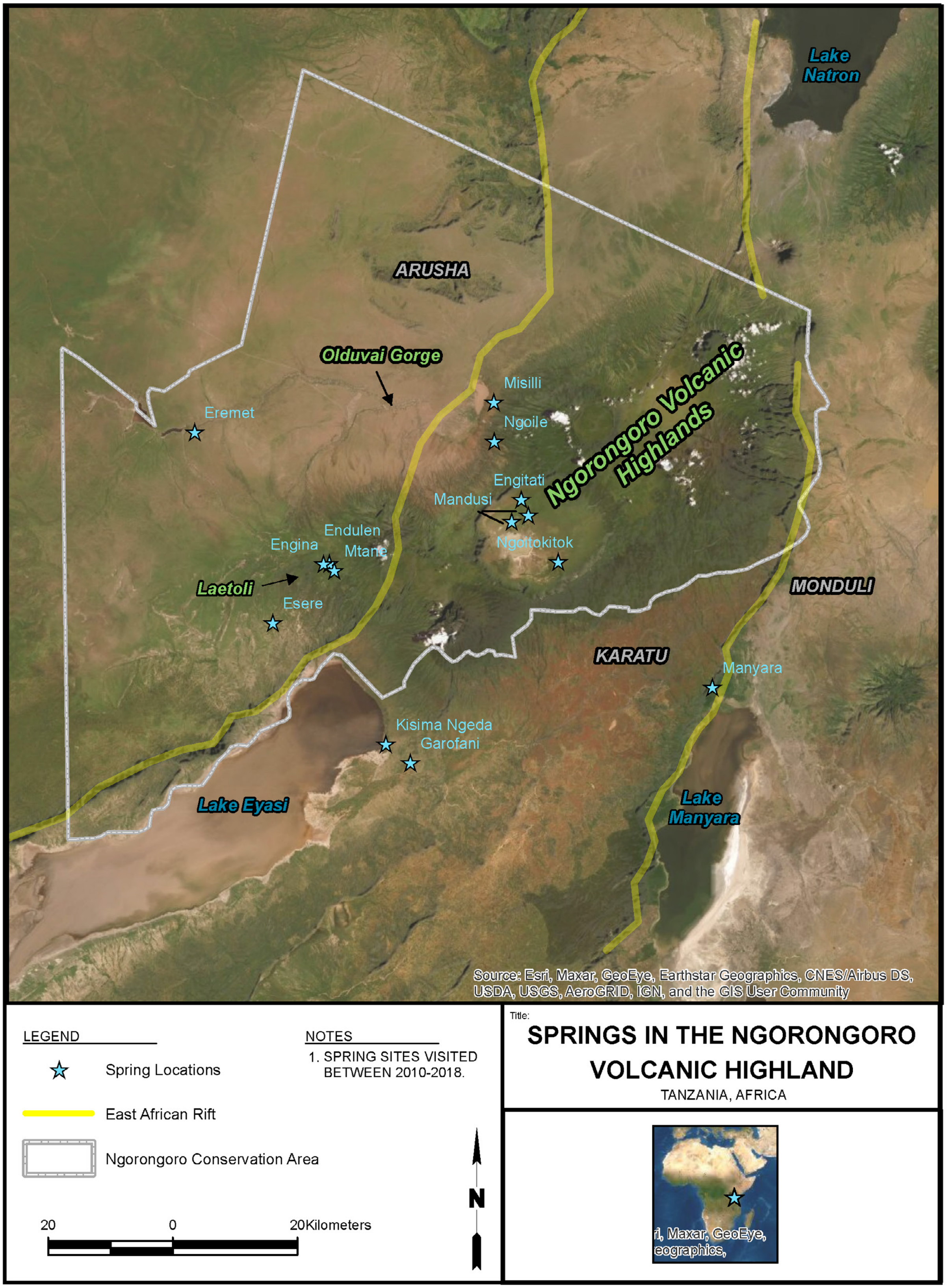

Figure 4-61. Springs of the Ngorongoro Volcanic Highlands study area described in this research.

Table 4-4. Distribution and water quality of springs described in the Tanzania study area.

Site Name	Coordinates (decimal degrees)	pH	Temperature (°C)	Conductivity (uS)
Endulen	S 3.215556, E 35.26903	7.86	19.9	397
Engina	S 3.216528, E 35.26069	7.26	20.7	407
Mtane	S 3.226389, E 35.27583	7.19	22.2	702
Misilli	S 2.983467, E 35.50659	7.64	25.4	246
Ngoile	S 3.039689, E 35.48337	7.78	23.9	211
Kisima Ngeda	S 3.475778, E 35.35028	7.79	20.7	1398
Garofani	S 3.502333, E 35.38586	7.77	21.1	259
Esere	S 3.301389, E 35.18728	8.62	29.0	892
Eremet	S 3.026389, E 35.07492	8.10	26.8	464000
Manyara	S 3.39425, E 35.82070	8.04	23.9	379
Engitati	S 3.159128, E 35.550571	7.44	24	700
Mandusi	S 3.159128, E 35.550571	7.34	18	540
Ngoitokitok	S 3.004078, E 35.600644	8.00	26	550

quality (Table 4-4). The dense concentration of people and animals within the NCA has produced serious conflicts over water and, until recently, access to groundwater was very poorly managed. Hotels and farmers drilled private wells but provided no records of usage. In the last decade the government has begun to build infrastructure and hire professional hydrogeologists. To our knowledge there are no published case studies of spring distribution, nor studies of sustainable spring management. Even more challenging is the uncertainty that will arise as the global climate changes and impacts the already poorly understood/managed groundwater system.

The petrology and chronology of the Highlands are well documented, but little is known of structure and stratigraphy, therefore the understanding of the hydrogeology is rudimentary. Preliminary field work indicates that the volcanoes are layered mafics and pyroclastics, with a cover of colluvium/soil that thickens toward the base of slope. The groundwater system appears to be two-tiered (Norton 2019). 1) A deep aquifer exists, mainly in porous pyroclastic deposits, although water also moves along fractures and bedding planes in the mafic rocks. Modeling suggests that recharge of this deep aquifer occurred thousands of years ago (i.e., Milankovitch precession time scale) (Cuthbert and Ashley 2014). 2) A shallow aquifer exists in the colluvium that has a much shorter residence time, on the order of decades to centuries (Shilling 2012). Springs emerging from it are widely dispersed and occur in clusters determined by local geologic structure (faults, aquicludes, local base lev-

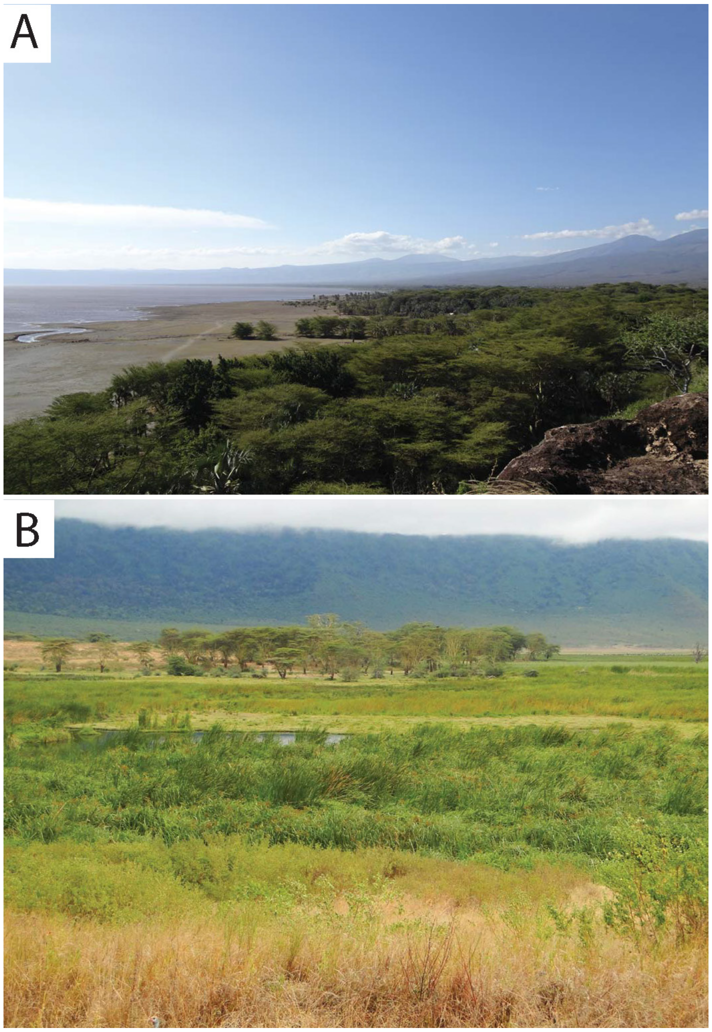

Figure 4-62. A, B) Examples of spring emergence environments in Tanzania.

Figure 4-63. A-D) Springs of the Ngorongoro Volcanic Highlands are imperiled by tourism, human intrusions and disturbance by grazing, agriculture, and water supply management.

els) (Figure 4-62). However, those springs are imperiled by tourism/human intrusions and disturbance, animal grazing, agriculture, water management and usage. The springs are currently controlled locally to ensure that potable water for people and animals is dependable and occurs in sustainable amounts (Figure 4-63). The techniques used to manage water supplies include 1) well installation and pumping water to storage tanks for controlled disbursement; and 2) construction of cement dams to create reservoirs, from which water is piped to a disbursement site.

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Chapter 5

Middle East

Overview

While our review of the diverse springs of the Middle East is far from complete, human use of springs and oases there extends back many thousands of years (Solomon 2010), and references to goat, sheep, and other livestock watering are common throughout the ancient literature, and many springs in the region are well known. Prominent, historically and both agriculturally and recreationally important springs in Israel include Banias, Baruch, Dan, the Gedi complex, Homa, Maimon, Sataf, Shokek, and Yizrael springs. A list of 148 prominent recreational and balneological springs in Iran is provided at https:// https://www.itto.org/iran/attractions/category/57-Springs/. Some of the largest terrestrial springs in the world are Middle Eastern, including Ra-El-Ain Spring in Syria (mean discharge 3.63 *104 L/s) and Dumanli Spring in Turkey (mean discharge 5.03*104 L/s; Karanjac and Günay 1980, Alfaro and Wallace 1994). The Greek city Hierapolis was constructed on the travertine deposits of Pamukkale Springs complex near Denizli in southwestern Turkey, which is now a UNESCO World Heritage Site. But many of the thousands of less well-known Middle Eastern springs have long been subjected to human uses. The practice of developing springs for delivery to dwellings and settlements is widespread and historic, with the construction of channels and qanats (excavated horizontal bores and tunnels to focus flow delivery). A classic example of such development is the Gihon Tunnel in Jerusalem (e.g., Guil 2017). In addition, pisciculture is widely and intensively practiced at springs across the region (Job, no date).

As everywhere in arid regions, human uses of springs are intensive and diverse, including domestic use for potable water supplies, livestock watering, irrigation, recreation, and rural and urban development. Turkey has long been regarded among the most water-rich regions of the Middle East, but its population increased 2.5-fold in the latter third of the 20th Century, reducing fresh water availability from approximately 4000 m^3 person-1 yr-1 to 1650 m^3 person-1 yr-1 in 2000, and to <1350 m^3 person-1 yr-1 in 2020, as reported by Reuters (2021). (https://www.reuters.com/article/turkey-water-climate-change/feature-climate-shifts-and-rising-demand-leave-turkey-battling-growing-water-stress-idUSL8N2MC1UM). With nearly 75% of Turkey's water supply used for irrigation, less than 11% is available for industry and 15% for potable supplies. This likely has already placed great pressure on the sustainability of Turkey's groundwater supplies, and therefore its springs.

Recent attention to geochemistry has clarified the origins and appropriate uses of Middle Eastern springs. For example, the hottest geothermal springs in Jordan emerge closest to faults, where groundwater emergence can be controlled by gas lift pressure (Schäffer and Sass 2013). Although not detectably influencing discharge, groundwater exploitation there has resulted in changes to isotopic composition. The two largest oasis complexes on the Arabian Peninsula are Al-Hasa in eastern Saudi Arabia and Al-Buraimi (including Al-Ain) in the United Arab Emirates and Oman. Geochemical analyses among the 280 springs in the Al-Hasa Oasis revealed elevated salinity and concentrations of chloride and nitrate that exceeded drinking water standards (Al-Naeem 2008). In western Iraq, a similar study of 11 sulfurous springs along the Euphrates River between Haqlaniya and Hit in the Al-Anbar governorate indicated that springs there that emit hydrogen sulfide gas were unfit for drinking or aquaculture, but had limited value for irrigation (Awadh and Al-Ghani 2014).

Geochemical studies are important to maximize water availability in this arid region; however, relatively few ecosystem-level studies have been conducted in the Middle East. A survey of the River Dan headwaters revealed the lowest density but the greatest species richness of aquatic macroinvertebrates at spring sources, and suggested that invertebrate drift may be an important assemblage-structuring mechanism (Degani et al. 1992). Such ecosystem studies are important for integrating ecosystem integrity into water supplies management, particularly in the face of increasing anthropogenic pressures and climate change. Although Middle Eastern springs are historically and presently highly valued and intensively used, few have been studied as ecosystems and many springs there exist in a state of elevated endangerment.

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Israel

by Nataly Levine

Israel is situated in an arid to semi-arid region and is characterized by high variability in annual precipitation (Ben-Gai et al. 1998; Figure 5-64). Drought is a common phenomenon, making perennial water sources unique and rare in the natural landscape. The 6,203 km^2 western mountain basin on the western slopes of Jerusalem ranges in elevation from 900 m in the eastern slopes and 600 m at the western slopes. For thousands of years this area has served as an important agricultural and cultural center (Olsvig-Whittaker et al. 2015). However, water scarcity and the lack of perennial streams have made human activity reliant on spring water sources. The steep landscape forced the construction of complex development systems for capturing and transporting surface water flow.

The aquifers in this region consist of three units. The top consists mainly of limestone strata and is characterized by high hydraulic conductivity. The middle unit is dominated by marlstone and is characterized by medium to low hydraulic conductivity. The lower unit is dominated by dolomite and is characterized by medium to very high hydraulic conductivity. Springs in the region are co-dominated by hillslope, cave and rheocrene types (Yavin et al. 2014). Estimates of ecological impairment exceeds 65% in the western mountain basin of Jerusalem

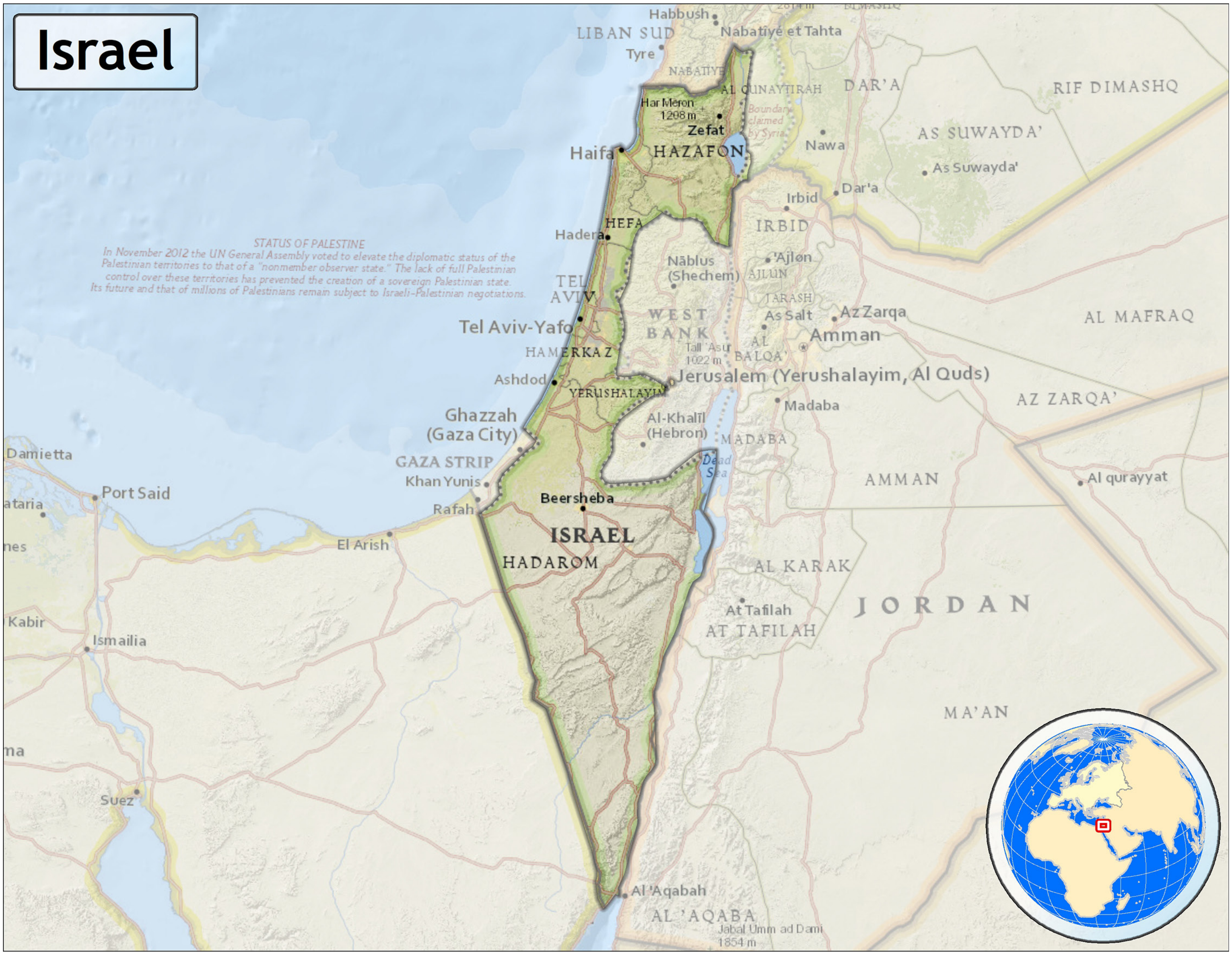

Figure 5-64. Map of Israel.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 29.49°, 2nd Standard Parallel = 33.27°.

and 45% at the southern Jordan River basin. Most springs are captured for agriculture or are heavily used for recreation (Elron and Rotchild 2012).

In recent years several hydro-biological surveys in different regions of Israel have reported significant increases in the phenomenon of remodeling (development of) springs, in areas adjacent to the big cities, estimates of remodeling exceed 50%, while in peripheral areas estimates range between 20-30% of the springs. In some cases, the area in and around the springs have been remodeled aggressively to satisfy recreation needs, including clearing natural vegetation, introducing invasive fish species, and construction of physical barriers preventing access by terrestrial wildlife (Elron and Cohen 2020). There are no present restrictions in protected areas, and pristine springs are now rare in the landscape.

The ecosystem ecology of springs remains understudied in Israel. While the Israel Nature Parks Authority commonly conducts local biodiversity surveys, it does not normally publish those results. A study of the Kishon drainage basin adjacent to springs revealed amphibians, including *Ommatotriton vittatus*, *Hyla savignyi*, and *Pelophylax bedriagae*, and invertebrates including: *Melanopsis buccinoidea*, Ostracoda sp., *Theodoxus michoni* snails, *Gammarus syriacus* amphipods, *Cloeon dipterum* mayflies, *Crocothemis erythrea* dragonflies, *Notonecta* sp. backswimmers, and Dytiscidae predaceous diving beetles. Springs in such arid regions have a strong positive impact on species richness: a newly discovered hydroptilid caddisfly in the genus *Stactobia* was recently discovered at a small spring in wadi-Tzin, although discharge was extremely low (Elron and Rotchild 2012). Moreover, chemical analyses by the water authority reported high concentrations of nitrate, chloride, and carbamazepine, which indicate anthropogenic pollution (Yaniv et al 2014).

Climate change is predicted to increase extreme rain events leading to increased runoff and alter flood frequency, which may reduce overall infiltration and result in a decline in groundwater recharge and springs discharge (Sternberg et al. 2015).

Adoption of the 1959 water law in Israel diminished private ownership of water resources. The Water Council was instituted subordinate to the government to assure appropriate management of water resources (Petre et al. 2012). In 2013 the government defined nature as an equally important water consumer, permitting evaluation of natural water sources needs and allocating water resources to restore and maintain wetted ecosystems (Tahahl Group and Aviv Amcg 2013).

Imperilment of springs by free-roaming cattle is common in northern Israel. A recent study suggested that fencing water sources, as well as aggregation of shading, trough and supplementary provision of grain resources at a distance of 50 m to 500 m from the springs resulted in an estimated decrease of 61%-100% in the number of cattle visiting the springs (Dolev et al. 2013).

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Chapter 6

Russian Federation

Overview

The Russian Federation occupies 17.13 million km^2, 12.5% of the terrestrial world land area, and contains nearly one quarter of the world's fresh water supplies (Centre for Climate Adaptation 2019; Figure 6-65). The Federation surface waters include 200,000 km^2 among >1.5 million lakes and ponds, 100,000 km^2 of reservoirs, and many large rivers (e.g., the Don, Dnieper, Dvina, Lena, Mezen, Onega, Pechora, Volga, and multiple Siberian rivers). However, the federation's water supplies are highly unevenly distributed, with the developed west and south having only 8% of its fresh water supplies. While discharge from northern rivers and that in reservoirs is anticipated to increase in coming decades due to rising temperatures and ice melt, the flows in southern rivers, such as the Dnieper and Don rivers are expected to decrease. The Centre for Climate Adaptation (2019) predicts up to 15% reduction in water availability in heavily populated southern areas and those subject to high-intensity agriculture, a reduction that is coupled with up to 25% increase in demand.

Russia has long engaged in rigorous federal water quality monitoring and assessment that reveal sometimes severe anthropogenic impacts to its surface water bodies (e.g., Ovaskainen et al. 2019). Basin-wide monitoring of rivers in the agriculturally heavily-developed North Caucasus Region of Russia since 1963 revealed increasing fluvial discharge coupled with reduced interannual flow variability, suspended sediment transport, and fluvial erosion intensity (Gusarov et al. 2021). Causes for these changes were attributed to reduction in land disturbance by agricultural machinery and livestock, flow augmentation from adjacent rivers, and climate change-related reduction in the depth of soil freezing during winter. Reduction in fluvial flow variability has occurred due to reduced snowpack and consequent reduction of snowmelt flooding intensity. Although groundwater contributions were not the focus of this study, reduced soil freezing depth are expected to result in more continuous and less variable groundwater discharge from springs, which may contribute to increased fluvial baseflow consistency.

The Russian Federation contains millions of springs, many of which have long been used as water supplies and for other anthropogenic purposes. Approximately 30% of Russian freshwater use is derived from groundwater. Among the Federation's many springs, Great Springs is protected as a monument in Ulyanovsk Oblast in the Volga River basin in southwestern Russia. More than 400 springs are being monitored for water quality in the St. Petersburg area (Real Russia 2019). Many hot springs exist and have been developed for recreation, including geothermal resorts or recreational destination sites in Arshan, Aushiger, Guamka, Paratunskiye, Sosnoviy Bor, and Vodnaya Rivyera. Russia also is renown for its geysers: the Valley of Geysers on the Kamchatka Peninsula is the second largest geyser field in the world, with hundreds of geothermal geysers and springs. Also, Smirnovsky Geyser at Zheleznovodsk in Stavropol Krai is a recreational destination. While geothermal springs have long been recognized and in many cases used for recreation and balneological purposes, and springs hydrogeology have been the focus of much attention, the distribution, ecological functioning, and conservation status of the majority of Russian springs are not widely known and require more study.

The Baltic Sea is regarded as the most significant transnational boundary in Europe. An intensive investigation of climate change threats to the water sources on the Russian side of the Baltic Sea basin focused on surface water inflow among thousands of rivers and streams (Georgievsky and Mamaeva 2020). While their study considered groundwater contributions to some of those rivers, the hydrogeology of the springs that provide the baseflow for most or all of those streams were not reported.

Many climate change-related factors threaten the integrity and safety of Russian society; however, analyses of groundwater sustainability and the ecological integrity of springs appear to be under-represented. For example, the Centre for Climate Adaptation (2019) provided a bibliography of nearly 120 Russia-related climate change studies, of which only one (Taylor et al. 2012) included groundwater as a focal topic. A vast literature on groundwater and the hydrogeology of springs undoubtedly exists within Russia; however, increased focus on springs ecosystem ecology is needed to help improve long-term water supplies sustainability and natural heritage conservation planning.

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Figure 6-65. Map of the Russian Federation.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the WGS 1984 North Pole LAEA Russia coordinate system; Central Meridian = 100.00°, Latitude of Origin = 60.00°.

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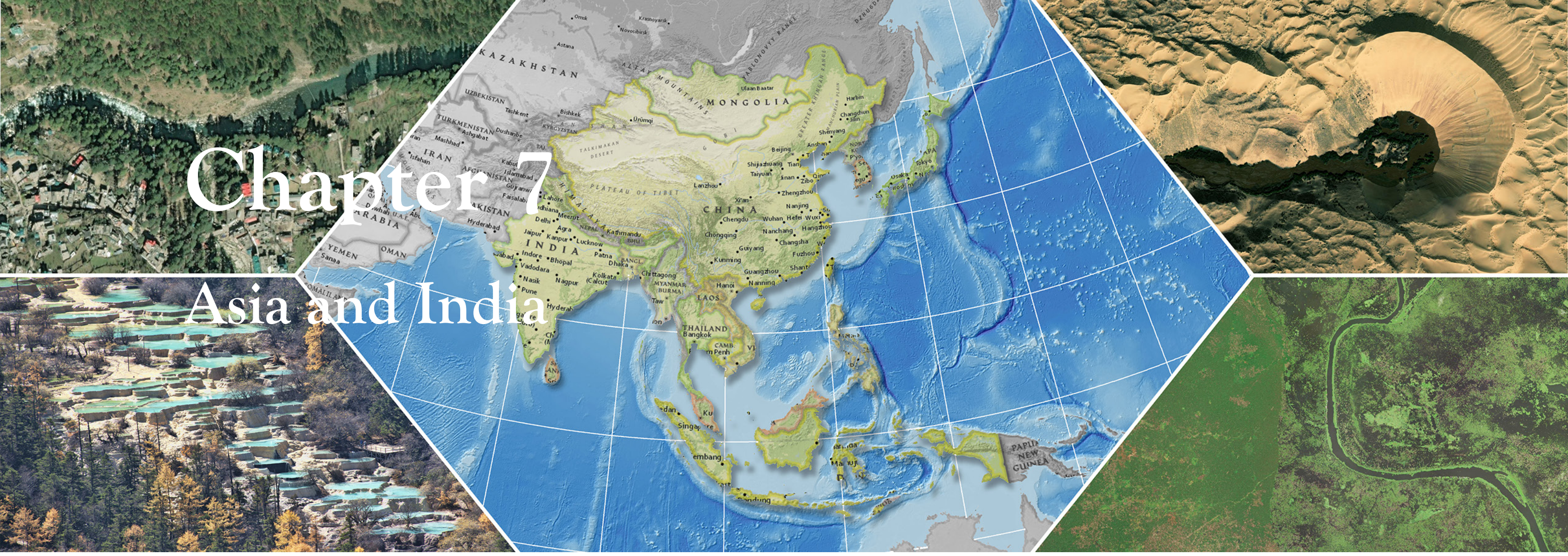

Chapter 7

Asia and India

Overview

The springs of Asia are diverse in water quality, geomorphology, springs-dependent species, and socio-cultural significance, and have been both revered and intensively used for potable and irrigation water supplies for millennia. Among the many springs of China, the most renowned are the "72 Famous Springs of Jinan" in Shandong Province. Baotu Spring has been heavily developed as a recreational site, and was declared the "Number One Spring Under Heaven" by Emperor Qianlong in the 17th Century. Renowned for its jetting emergence and unithermal water temperature (18°C), the spring's discharge from its karstic aquifer has been heavily compromised by regional groundwater pumping over the past half century (Fang et al. 1988; Wu and Xu 2005).

Lying between Russia and China, Mongolia occupies a high plateau with arid to semi-arid desert and steppe habitat to the south and east (lowest elevation 524 m), and it is flanked by mountains to the north and west (highest elevation 4,316 m). With an area of 1.57 million km^2, it is the largest land-locked country on Earth. Due to its dry, continental climate, the sustainability of its water supplies is of increasing concern in developed areas (Batsaikhan et al. 2011). While surveys of its springs are few, studies of its water supplies and groundwater sustainability are increasing. Dandar (2017) evaluated climate change impacts on the Upper Tuul River that flows through Ulaanbaatar, the capital. Rapid population growth in that river basin is driving increasing aquifer exploitation. He developed a two-compartment water and energy balance groundwater assessment model that accounted for freezing and melting. The river freezes over in winter, but flows under the ice due to groundwater influx. However, groundwater depletion in the middle reaches causes the river there to freeze entirely and may go dry in late winter due to sublimation and infiltration of melted water. While studies of groundwater hydrology are important for water supplies management, additional research is needed on springs ecosystem ecology there.

With its long history of springs use, the rapidly growing population of India is increasingly relying on groundwater for potable supplies, but also exerts many other anthropogenic impacts on its water supplies. As Bhat and Glazier describe below, much of northern India's rural population relies on springs for domestic and agricultural water supplies. The nation has begun to integrate grassroots, state, and federal concerns for sustainable groundwater supplies with the ecological and cultural integrity of its springs.

Japan contains a great number of springs, particularly geothermal springs, the larger of which have long been regarded as places of importance. "Onsens" are recreationally used, mineralized warm or geothermal springs with temperatures >25°C. Among the most renowned is Kusatsu in Gunma Prefecture, with a discharge of nearly 540 L/s and a pH of 2. However, information on the distribution, ecology, and use status of non-geotherrmal springs in Japan is not readily available. This is unfortunate because springs often support rare and sometimes endemic species, and Japan is facing a major national biodiversity crisis, with many recent extinctions and few improvements to native species populations (Government of Japan 2014).

Chiu et al. (2023) examined the water quality and aquatic fauna of 65 springs in Taiwan from 2012 to 2017. Their river pollution index (RPI) analyses revealed that 26 (40%) of the springs were non- or very mildly-polluted, 23 (35%) were slightly polluted, nine (14%) were moderately polluted, and seven (11%) had been dewatered or sealed. The authors cautioned that the use of dissolved oxygen concentration, which often may be naturally low in springs, artificially inflates RPI scores and suggested that coliform concentration may provide a better metric of contamination. They reported that springs fauna made up 27 to 35% of the aquatic taxa of the island, and documented 14 crab species in 18 springs, 16 shrimp species in 34 springs, 20 Mollusca species in 46 springs, and 48 fish species in 44 springs. Taiwan's springs deliver important social, cultural, and economic goods and services, protect climate refugia, and provide abundant research opportunities, and although the island's springs are biodiversity hotspots, six (11%) aquatic macroinvertebrate species and 31 (65%) fish species detected were exotic. In addition, threats to Taiwan's springs include depletion or degradation of groundwater for development and urbanization, potable water extraction, agricultural and industrial pollution, and under-informed management. Improving the sustainable stewardship of Taiwanese springs will require increased societal awareness and revision of springs management strategies and practices.

From the above examples, we can see that groundwater use intensity is likely greater in arid areas that are subject to intensive agriculture and urbanization. Use intensity also can be high in mesic areas. For example, geochemical monitoring of Ngerong Spring, the largest source of irrigation water in the Rengel Karst region of Tuban in East Java, revealed it to be a calcium bicarbonate water source, of good to excellent quality for irrigation (Tjahyo et al. 2020). However, concern for long-term sustainability of the ecosystem services of Asian springs is growing, particularly in regions and countries where water shortages are emerging as national challenges, such as India, China, and the eastern Himalayan nations. Climate change threatens high elevation snowmelt sources of major rivers in those countries. However, adequate information and research on spring ecosystem integrity is generally rare and the geographic and ecological studies are few.

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India

by Sami Ullah Bhat and Douglas S. Glazier

Springs are unique, geographically diverse biotopes. In the absence of comprehensive and detailed inventory, approximately 3 million springs are conservatively estimated to occur in the Indian Himalayan Region (IHR), a landscape that covers nearly 15% of the geographical area of India (~600,000 km^2; Gupta and Kulkarni 2017; Figure 7-66). These IHR springs provide various ecosystem services, including drinking water (Bhat and Pandit 2009; Bhat et al. 2020; Bhat and Pandit 2020), and sustain the livelihoods (Tambe et al. 2009, 2011a; Bhat and Pandit 2018) of numerous mountain communities totaling 50 million people. For example, about 65,000 (nearly 80%) of Sikkim's rural households depend on springs for drinking water and irrigation (Sikkim Department of Rural Management and Development 2015). Despite the increasing, well- documented reports of discharge reduction or drying of springs, with many perennial springs becoming seasonal (ephemeral) throughout the Himalayan region (Valdiya and Bartarya1989; Tiwari 2000; Jeelani et al. 2014; Bhat and Pandit 2018; Bhat and Pandit 2020), little has been done to conserve these important biotopes. Exceptions include recent initiatives by the National Mission on Himalayan Studies and the Ministry of Environment and Forests & Climate Change

Figure 7-66. Map of the Indo-Himalayan Region, India.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 21.54°, 2nd Standard Parallel = 35.50°.

(NMHS-MoEFCC) to fund research for the rejuvenation and revival of springs, and policy initiatives of the Dhara Vikas (Springshed Development) Programme by the Sikkim Department of Rural Management and Development, and the National Institution for Transforming India (NITI Aayog) of the Government of India.

Since few IHR springs have been studied scientifically (Singh and Rawat, 1985; Singh and Pande, 1989; Valdiya and Bartarya 1991; Negi and Joshi, 1996, Bhat and Pandit, 2010; Bhat et al. 2010; Tambe et at. 2011a), and only at the local or regional levels, no comprehensive spring database on evidence-based policy and planning initiatives is yet available at the national level. Despite their uniqueness and great value, springs remain rarely mentioned in major policy and legislative initiatives, including the National Water Policy of 2012. The major research foci on IHR springs have been on hydrogeology (Valdiya and Bartarya 1991; Negi and Joshi, 1996, Jeelani et al. 2010; ACWADAM, 2011) and water quality (Jeelani, 2005, 2007). Only a few spring ecosystem studies have been carried out (Bhat and Pandit 2018; Lone et al. 2020; Bhat et al. 2020), including those focused on ecosystem ecology, crenic biodiversity (Bhat and Yousuf, 2002; Bhat and Pandit, 2009; Lone and Bhat, 2020; Poddar and Das, 2017; Mehetre et al. 2018; Kumar et al. 2020), threats to springs (Lone and Bhat, 2020; Lone et al. 2020), conservation, and management (Bhat et al. 2020).

Interestingly, shifts in focus from watershed to springshed, and from spring ecohydrology to rejuvenation and revival have gained momentum, as demonstrated by recent studies and discussions of policy initiatives on springs (Tambe et al. 2011b, c; Gupta and Kulkarni, 2017; https://nmhs.org.in/Springshed_Management.php). In particular, 116 springs have been subjected to rehabilitation, out of a total of 3,560 springs that have been georeferenced among 18 watersheds in the Indo-Himalayan states of Jammu and Kashmir, Himachai Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland.

Although the success of such concepts and approaches has not been independently and sufficiently replicated at regional and national scales, efforts by various individual education and research institutions, communities, non-governmental organizations, and a few government departments are beginning to advance the cause of spring research across the IHR, especially in the states of Jammu and Kashmir, Sikkim, and Uttarakhand. However, such efforts typically lack information on spring biodiversity because of the lack of investigators with appropriate expertise. Overall, and despite their importance, Indian springs remain far less intensively studied than other aquatic ecosystems, and national efforts in this direction are therefore urgently needed.

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Southeast Asia

by Joseph H. Holway

Little has been reported on springs in the 4.3 million km^2 of mainland Southeast Asia, including Myanmar, Thailand, Lao PDR, Cambodia, Viet Nam, and peninsular Malaysia (Brancelj et al. 2013; Figure 7-67). Ranging in elevation from sea level to over 5,000 m in northern Myanmar, the region is one of the most geologically complex and largest karst environments in the world (Day and Urich, 2000). While Southeast Asia has significant sedimentary aquifer capacity, particularly in alluvial deposits adjacent to large rivers of the region (Lee et al. 2018), groundwater use has dramatically increased, particularly in the rich agricultural lands of the Mekong Delta. Groundwater extraction has resulted in rapid declines of aquifer levels in some regions (Erban et al. 2014). If trends continue without intervention, and couple with climate change, land use land cover change (Samek et al. 2012), and continued hydroelectric development (particularly in the upper basin of the Mekong; Grumbine and Xu 2011), groundwater resources will certainly become increasingly depleted. Although few to no data exist on the distribution and ecological integrity of springs in Southeast Asia, groundwater trends indicate high levels of impairment and on-going degradation without appropriate, sustainable monitoring and management.

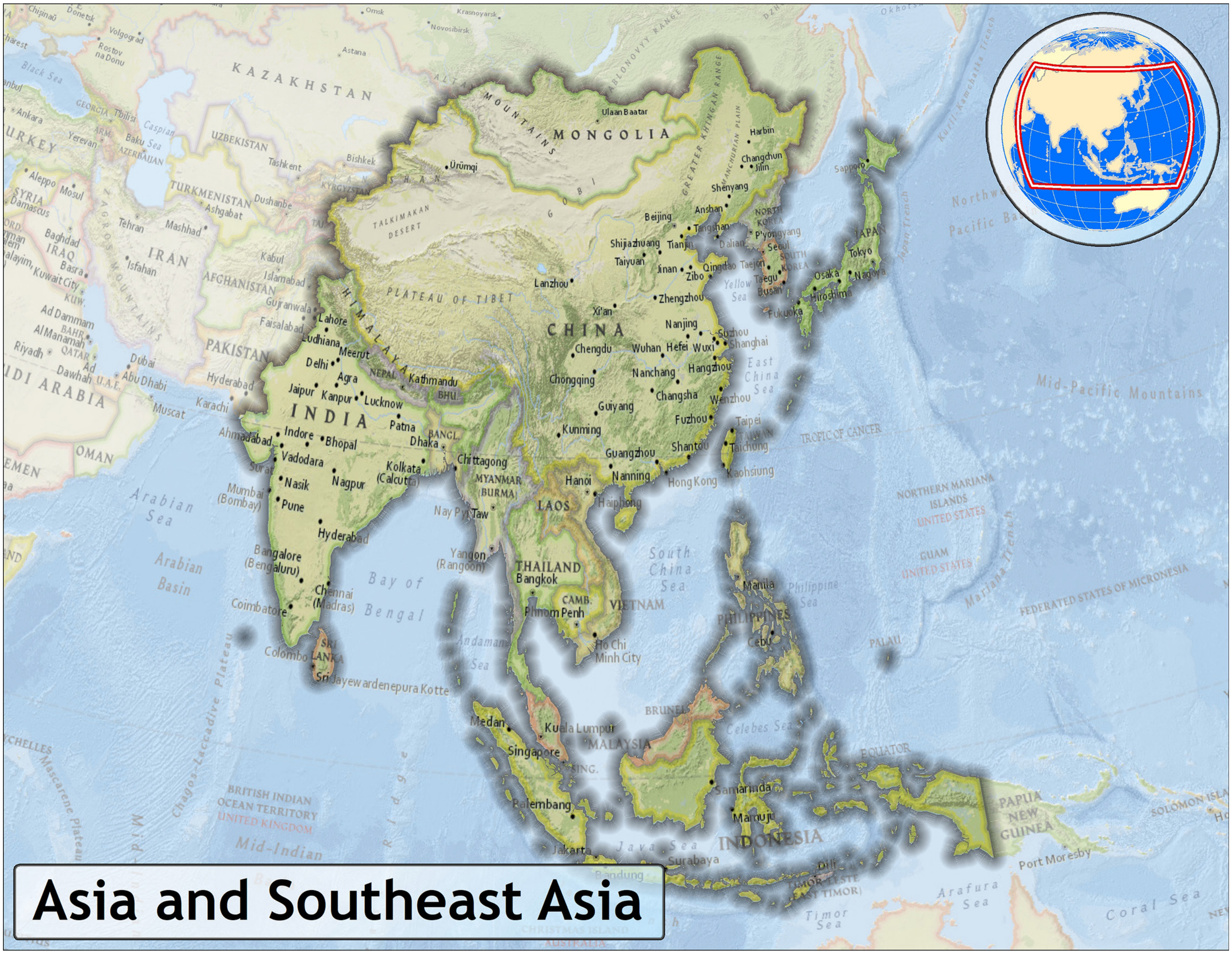

Figure 7-67. Map of Southeast Asia.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -10.93°, 2nd Standard Parallel = 28.55°.

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Spring ecosystems in Japan: Knowledge and perspectives

by Masaru Sakai , Risa S. Naito , and David Bauman

The Japanese archipelago is located in the northwestern Pacific Ring of Fire, extending approximately 3,000 km from north to south along the eastern coast of Eurasia, across multiple tectonic plates (Figure 7-68). Volcanic activity has formed mountains with numerous hot springs, and the moist climate has led to the further development of widespread springs. These springs have historically been used by humans as water sources for daily life and agriculture. The Ministry of the Environment has recorded over 16,000 springs in Japan (Ministry of Environment 2021) and designated 100 notable water spots (meisui), including clear springs sustained by continual conservation practices on the part of local people (Figure 7-69). Permanent springs in small valleys, particularly in terraced regions, were used for traditional agriculture in East Asia, including Japan (Ikegami et al. 2011). These springs form habitats for endangered wetland species; however, they are now shrinking due to urbanization in some areas (Kim et al. 2020). Although humans have long used springs as water resources, our understanding of the unique habitat characteristics associated with spring ecosystems remains limited. Here, we introduce the functions of Japanese spring ecosystems in

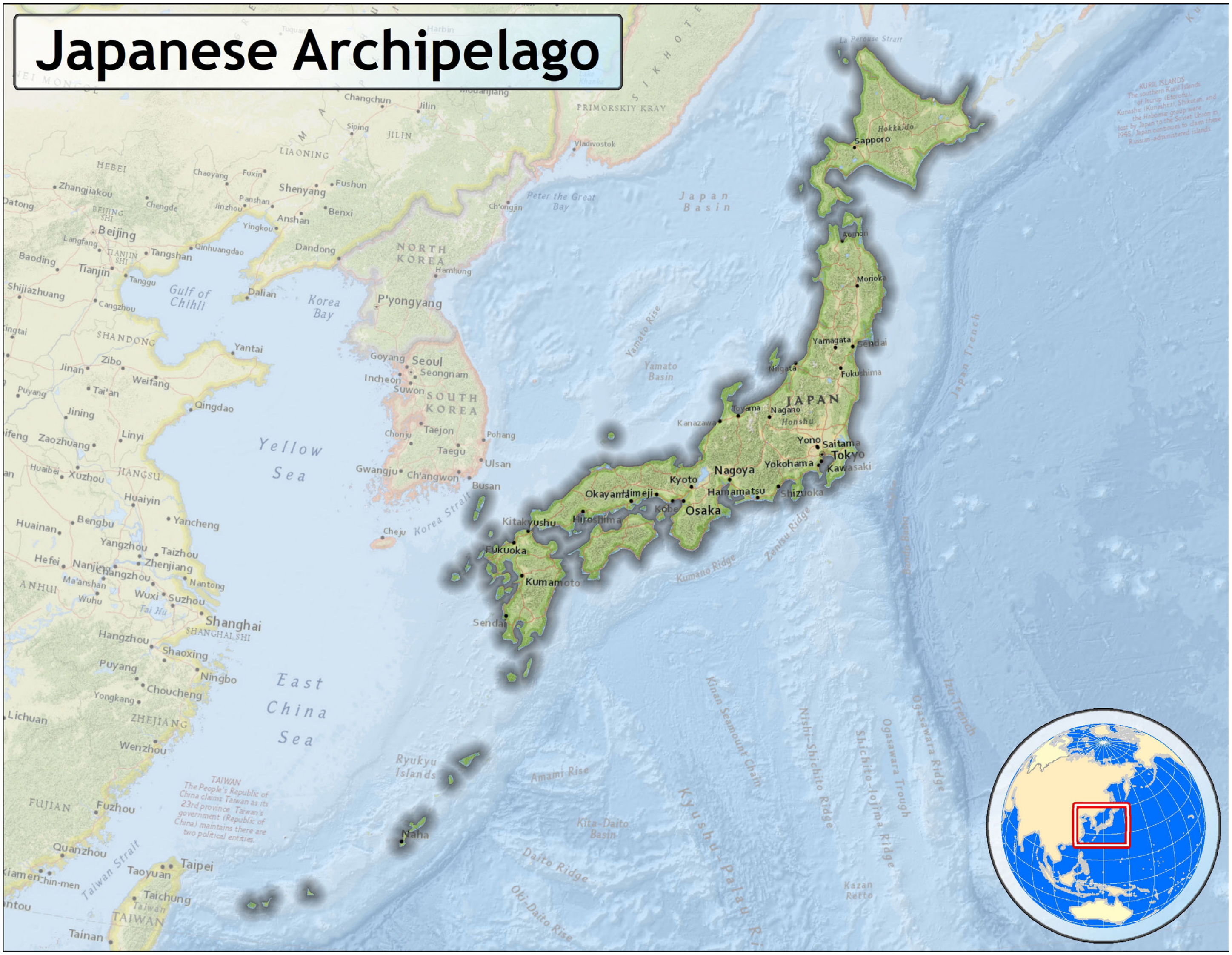

Figure 7-68. Map of Japan.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 24.25°, 2nd Standard Parallel = 45.49°.

Figure 7-69. Yatsugatake southern highland springs in Yamanashi Prefecture, a designated notable water spot (meisui). This spring discharges 8,500 m^3/day and is managed and used for agricultural water. (Photo by M. Sakai)

Figure 7-70. Yatsugatake southern highland springs in Yamanashi Prefecture, a designated notable water spot (meisui). This spring discharges 8,500 m^3/day and is managed and used for agricultural water. (Photo by M. Sakai)

structuring freshwater communities, focusing in particular on stable flow and temperature regimes. We also discuss perspectives and priorities for freshwater biodiversity research and conservation of spring ecosystems.

Groundwater flow generated in geologies with less macropores (e.g., clastic geology) is rarely affected by rapid fluctuations following rainfall, snowmelt, or seasonal or diurnal changes in air temperature, such that spring ecosystems generally have stable water flow and water temperature regimes (Sakai et al. 2021a). Due to this stability, stream substrates tend to be dominated by fine sediments, giving rise to an animal community comprised mainly of detritivorous burrower macroinvertebrates (Sakai et al. 2021b). This unique relationship between habitat formation and animal communities has been reported in a lowland spring-fed stream; however, other spring-fed streams draining mountainous regions on volcanic and karst geologies may not show such fine sedimentation due to steep gradients, as reported from other countries (Wigger et al. 2015, von Fumetti and Blatter 2017). The degree to which stream substrates of Japanese spring-fed streams vary spatially across regions and geologies remains poorly understood. The stable flow regime of spring-fed streams has been suggested as providing a refuge for fish during floods or droughts (cf. Koizumi et al. 2013), although this remains to be investigated. Because the stable flow regime of spring-fed streams allows safe animal sample collection during rainfall (Sakai et al. 2021a), it should be easy to test this refuge hypothesis (Figure 7-70).

The stable water temperatures of spring-fed streams also provide a refuge from thermal stress during both hot and cold seasons. For example, Inoue and Ishigaki (1968) reported that juvenile masu salmon (*Oncorhynchus masou*) accumulate in a spring-fed stream in winter, when neighboring non-spring-fed tributaries and mainstems are significantly colder. Nakagawa et al. (2015) observed that the herbivorous fish *Plecoglossus altivelis altivelis*, which is endemic to East Asia, aggregates in upwelling spots during summer, probably to avoid hot water stress. These findings suggest that the stable water temperatures of springs, which remain warm in winter and cool in summer, provide thermal buffers, in which aquatic animals can escape physiologically constraining thermal environments. This ecosystem function may be particularly crucial in the present context of rapid climate change, as more frequent and intense temperature anomalies interact with increasing temperature baselines (Harris et al. 2018). Although mobile animals such as fish use springs as a thermal refuge, some less mobile invertebrates tend to inhabit springs continuously. Most of these are considered to be stenothermal (Sun et al. 2020), such as *Allomyia* species (Trichoptera: Apataniidae), which are often found in spring habitats in Japan (Nishimoto and Kuhara 2001, Sakai et al. 2021b). Such groundwater-dependent taxa (crenobiont and/or crenophilous) are vulnerable to the loss and deterioration of spring habitats, and are critically threatened by anthropogenic impacts on springs due to their immobility.

The unique habitat characteristics of springs can further induce peculiar interspecific interactions. The chum salmon *O. keta*, which is an anadromous fish, often preferentially forms redds in springs (Kobayashi 1968) by running upstream during floods (Banks 1969). Because the eggs deposited by this species are nutritious and are actively consumed by freshwater animals, the location and timing of *O. keta* spawning events affect the spatiotemporal accumulation of mobile consumers. Sakai et al. (2021a) reported that preferential migration of *O. keta* into a spring-fed tributary for spawning induces subsequent aggregation of juvenile *O. masou masou*, with increasing *O. keta* egg consumption after a rainfall event. Watz et al. (2019) found that Dolly Varden charr (*Salvelinus malma*) may be excluded to cold spring-fed tributaries in summer as a result of competition from white-spotted charr (*S. leucomaenis*). The leech *Taimenobdella amurensis*, which primarily parasitizes *S. malma*, exclusively inhabits spring-fed tributaries and headwaters, and may form metapopulations via dispersion with its host (Katahira et al. 2017). Although such interspecific interactions within and around springs require further study, they may contribute an unexpected enhancement of the gamma diversity of river networks.

Due to its moist climate and tectonically uplifted mountainous landscapes, the Japanese archipelago possesses plentiful and persistent groundwater, which provides spring habitats in various regions of Japan. Nevertheless, a variety of anthropogenic impacts such as urbanization, water exploitation, and flood control management are damaging these unique habitats. To understand and conserve these ecosystems, further research is urgently needed to advance our floral, faunal, and functional understanding of springs. Further, it is worth noting that groundwater provides habitats not only in springs but also underground. For example, species of the endemic water beetle genus *Phreatodytes* (Coleoptera: Noteridae), lacking eyes, pigmentation, and the ability to fly or swim, have developed a permanent underwater life cycle within Japanese groundwater (Kato et al. 2010). Therefore, groundwater resource management strategies must consider the integrity of water flow (precipitation, infiltration, and discharge) to maintain a sustainable water supply and successful biodiversity conservation across spring ecosystems. Understanding flow and temperature regime stability in groundwater and the associated adaptations and acclimations of the communities of living organisms in these unique habitats is vital to supporting conservation efforts.

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Chapter 8

Oceania and Australasia

Overview

The distribution, ecology, and conservation status of springs in most of Oceania remains poorly understood (Figure 8-71). However, those in New Zealand and the desert regions of Australia have received intensive research. As everywhere, use intensity is often extreme, and likely more so on islands where freshwater supplies are rare and highly valued. The study of spring ecosystems in Australia and New Zealand provided important habitat stewardship insights. In particular, studies of springs in the Great Artesian Basin in east-central Australia have related hydrogeology, springs and SDT distribution and geomorphology, and anthropogenic uses (Rossini et al. 2018; Fensham, below). Additional attention to the many upland and montane springs throughout Oceania are warranted, as springs generate the baseflows for most of the region's streams and rivers, except in the ice-dominated landscapes in New Zealand. New Zealand protects both its coldwater and geothermal springs in the conservation estate, which covers nearly one third of the nation. Such protection has conferred good to high ecological integrity on those protected springs (Death, below). However, springs in the rest of New Zealand are subject to impacts from rapidly developing dairy farm operations. Springs and seeps are also affected by abstraction for various purposes, including urbanization, agriculture, and water bottling operations, and intensive recreational use of the nation's hot springs is common, as are impacts from extraction of hot waters for steam and power production. Spring distribution and uses have yet to be extensively explored in the more tropical portions of Oceania.

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Rossini RA, Fensham RJ, Stewart-Koster B, Gotch T, Kennard MJ. 2018. Biogeographical patterns of endemic diversity and its conservation in Australia's artesian desert springs. Diversity and Distributions 24(9):1199-1216. https://doi.org/10.1111/ddi.12757.

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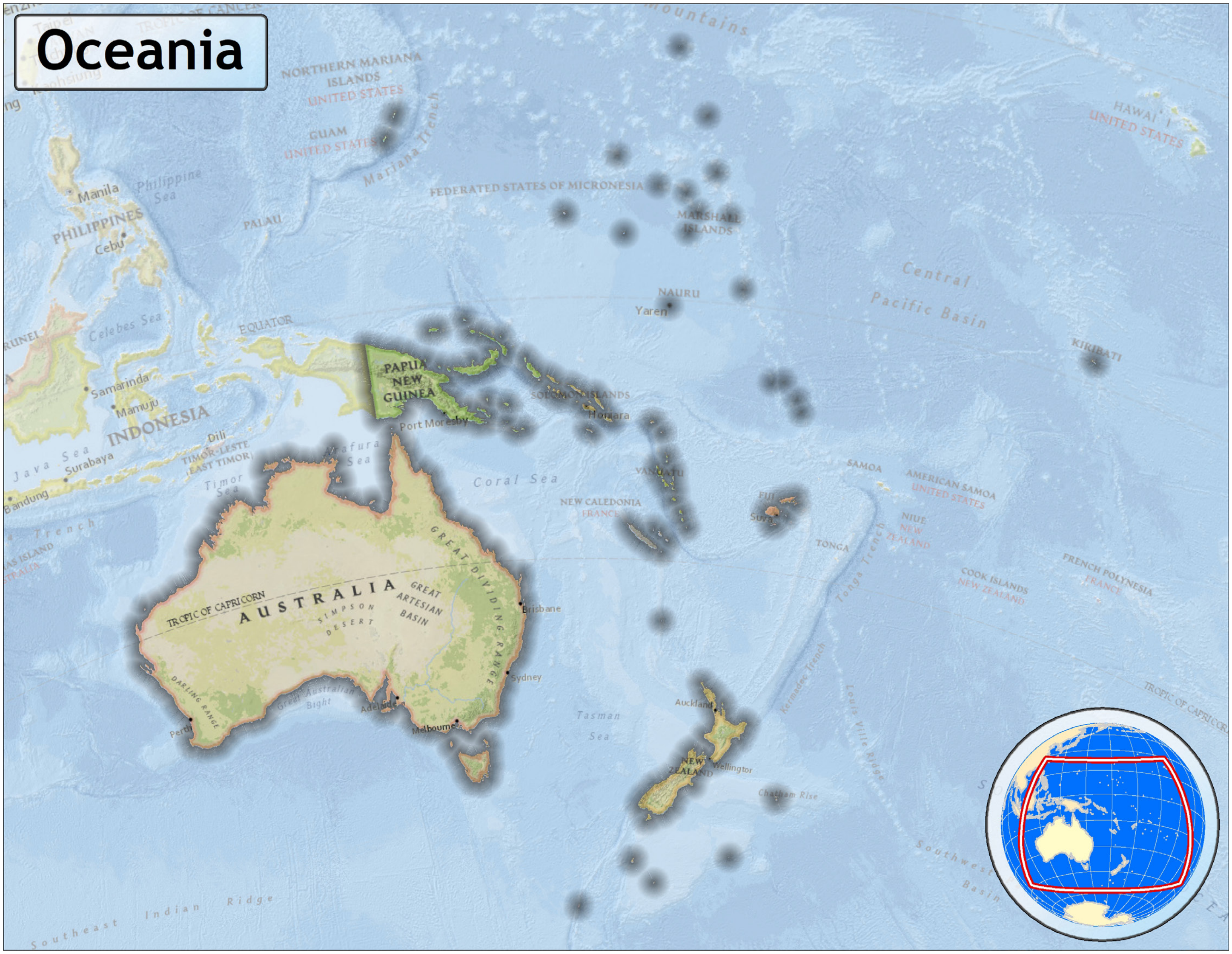

Figure 8-71. Oceania map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -18.00°, 2nd Standard Parallel = -36.00°.

Australia - Great Artesian Basin

by Roderick J. Fensham

Springs occur throughout the Australian continent but have the greatest cultural and biological significance in arid environments. The most substantial aquifer is the Great Artesian Basin (GAB) which spans one fifth of the continent (Figure 8-72). The GAB is a sedimentary basin that is recharged in areas that receive high rainfall. These areas feed local 'outcrop springs,' some of which provide the base flow for major streams. In tropical areas outcrop springs support specialized evergreen rainforest communities including many specialized plants (Russell-Smith, 1991). However, it is the artesian springs of the Great Artesian Basin that have received the most conservation attention. These springs are supported by ancient groundwater, occur in the driest part of the Australian continent and provide habitat for many specialized endemic species across a range of lifeforms (Rossini et al., 2018). These springs not only have high conservation values, but are also imperiled, with about half having been dewatered as a result of pressure decline in the aquifer (Fensham et al., 2016). The aquifer was exploited by thousands of crude bores that released groundwater into open drains

Figure 8-72. Map of the Australian Great Artesian Basin.

Map boundary data were derived from Ransley TR and Smerdon BD (eds). 2012. Hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -18.00°, 2nd Standard Parallel = -36.00°.

to provide drinking water for livestock. An ambitious and largely successful scheme has rehabilitated many of the bores and direct water into polythene pipes. However, there are renewed pressures on the aquifer with the water requirements of the mining industry.

The highest concentration of endemic species is found at Byarri which was purchased by a private conservation organization. The springs have been subject to intensive management, particularly in relation to rescue and recovery for Australia's most imperiled freshwater fish the red-finned blue-eye (Scaturiginichthys vermeilipinnis). This species is being extirpated by non-native gambusia (Gambusia holbrooki), which has dispersed from old bore drains during flood events. Recovery actions include fish fencing to limit the spread of gambusia, translocation of populations to 'safe' springs high in the landscape, and establishment of bore-fed 'artificial springs' (Kerezsy and Fensham 2013).

The largely artesian GAB desert springs are considered to be in Vulnerable condition under IUCN RLE categories C3 and D3. Those springs do not qualify under category A because they have not noticeably declined in the past 50 yr, and under present policy conditions should be secure for the next half century. They also do not qualify as endangered under category B because of EOO is substantial and due to their distribution do not qualify under B2 or B3. However, these springs have lost >50% of their area since 1750, with losses most severe in terms of abiotic properties (in some cases >90% decreases in long-term groundwater discharge) as well as biotic factors (i.e., aquatic and wetland species extirpation).

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Australia - Non-Great Artesian Basin Spring Wetlands in Queensland

by Jonathan Marshall, Peter Negus, Katharine Glanville, Mike Ronan, and Harald Hofmann

Introduction

This chapter presents hydrogeological, ecological and socio-cultural overviews of representative examples of Queensland's non-GAB springs, which reflect the broader range and extent of these features throughout Queensland (Figure 8-73). While many individual springs are not well studied, the selected examples and broader hydrogeological settings illustrate their diversity across Queensland.

Australia is the driest continent on earth (Blewett 2012) with the exception of Antarctica. Almost three-quarters of the continent is arid or semi-arid, receiving less than 500 mm of rain/yr, and over a third is classified as desert (Blewett 2012). The vastness of the continent spans many climate zones from equatorial and tropical in northern Australia to temperate in the south (Bureau of Meteorology 2020).

Queensland is the second largest state of Australia, with a land area of over 1.73 million km^2 located in the northeast of the continent (Figure 8-74). The east coast of Queensland receives average rainfall totals of 1000 mm/yr or more, but this is highly variable. Precipitation in some areas, like the Wet Tropics region, exceeds 3000 mm/yr, and the summit of Mount Bellenden Ker receives

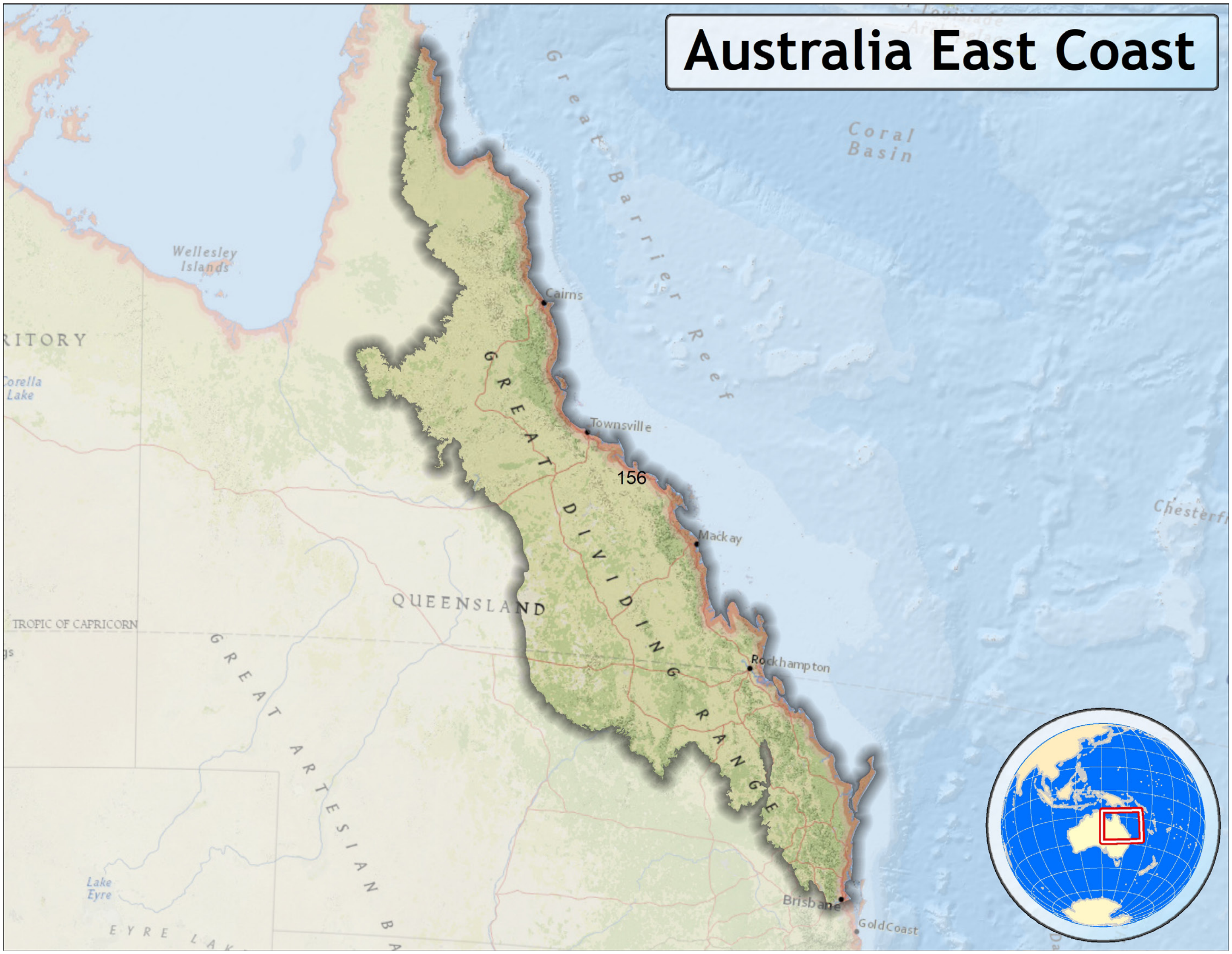
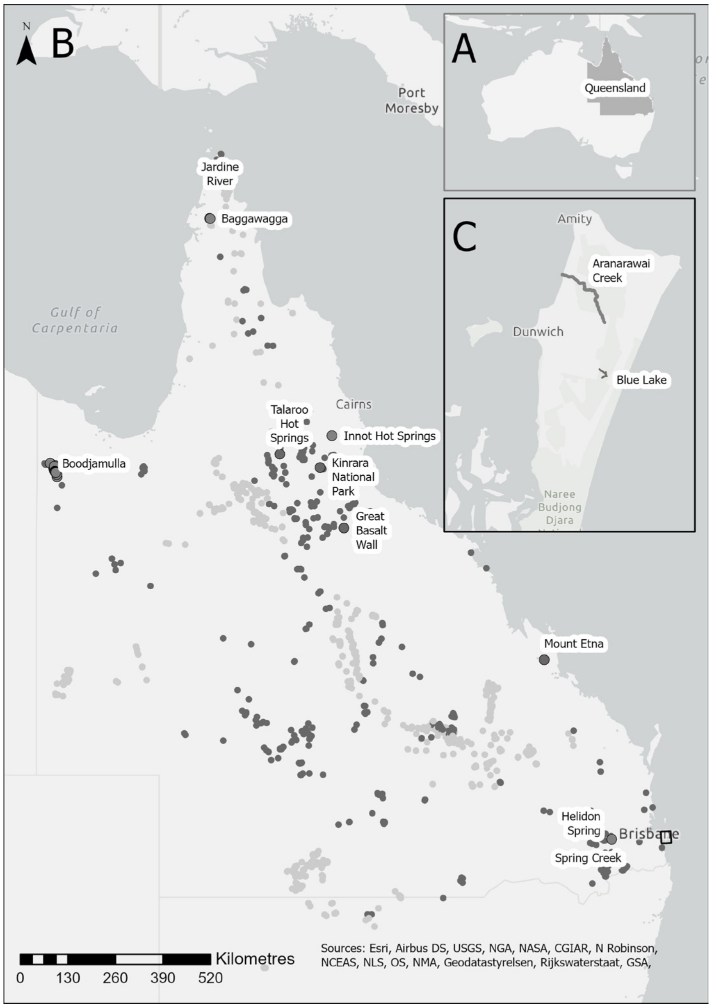


Figure 8-73. Map of hte Australian East Coast between the eastern edge of the Great Artesian Basin and the northeastern coastline.

The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -18.00°, 2nd Standard Parallel = -36.00°.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA,

Figure 8-74. A) Location of Queensland within Australia. B) Map of Queensland indicating spring locations and naming those discussed. Light coloured circles indicate Great Artesian Basin springs and dark coloured circles indicate non-Great Artesian Basin springs, which are the subject of this chapter. The rectangle in southeast Queensland indicates the location of expanded map C) of North Stradbroke Island.

>8000 mm/yr (Bureau of Meteorology 2020). In contrast, the south-western corner of Queensland is arid, receiving only between 100 and 200 mm/yr (Bureau of Meteorology 2020). Queensland is also subject to significant inter-seasonal and interannual climate variability.

Queensland has a large diversity of landscapes resulting from the interactions between climate and its diverse geology (Willmott et al. 2009), with rocks of varying ages, and differing tectonic associations (Jell and Geological Survey of Queensland 2013). The level of geological diversity is a result of the interrelationship between older, stable bedrock elements common in western Queensland, the orogenic belt, where the upward movement of continental plates has formed mountains of the Great Dividing Range fringing the eastern coastline, and coastal and aeolian processes (Blewett 2012; Jell and Geological Survey of Queensland 2013). Furthermore, more than three quarters of Australia, including large parts of Queensland is covered in unconsolidated sediment (Blewett 2012).

Geology, landscape and climate dictate the nature and extent of Australia's groundwater supply, which accounts for around 20% of the continent's freshwater (Blewett 2012). Groundwater occurs in many consolidated and unconsolidated sediments with its hydraulic characteristics dependent on the origins, extent, volume, porosity and permeability of the parent materials (Jell and Geological Survey of Queensland 2013).

Fractured rock aquifer systems generally form in older igneous, metamorphic, and sedimentary cratonic rocks (i.e., bedrock). They tend to be unconfined, discontinuous localised and low-yielding (Blewett 2012; Jell and Geological Survey of Queensland 2013). Along the Great Dividing Range, some volcanic and sedimentary landscapes also produce fractured rock and tertiary porous aquifers and these (particularly certain basalt flows) produce higher yields of water from springs that feed rivers that flow both east and west (Blewett 2012). Aquifers with inter-granular (primary) and fracture (secondary) flow are extensive and form confined, high-yielding, regional aquifer systems (Blewett 2012; Jell and Geological Survey of Queensland 2013). Australia's large Mesozoic basins, such as the Great Artesian Basin (GAB) and the Perth Basin, are prominent examples of this type. These aquifers can reach great depth (~2500 m below the surface) and often produce artesian or sub-artesian discharges close to the surface that manifest as springs. Unconsolidated sediments, including Cenozoic to Quaternary alluvial sediments and aeolian or coastal dune sands, generally support unconfined aquifers (Blewett 2012; Jell and Geological Survey of Queensland 2013). However, semi-consolidated and consolidated aquitards can form throughout these sediments and result in point discharges of groundwater to the surface as springs. Some coastal and aeolian sand deposits contain significant groundwater resources, such as the sand masses along the coast of southeast Queensland (e.g. the Pleistocene North Stradbroke Island sand dune system), which provide flow to significantly important groundwater-dependent ecosystems (GDEs; Leach 2011).

In this chapter a 'spring' is considered to be surface expression of groundwater via a recognisable hydrogeological feature which supports a riverine, palustrine or lacustrine wetland ecosysem. Groundwater may also be expressed at the surface of the land but may not be considered a spring if it does not express through a recognisable hydrogeological feature. In such cases the surface features may be considered to be a GDE, but not a spring-fed ecosystem.

Many springs have been identified and surveyed across Queensland, with additional surveys occurring each year. Due to their more distinct formation and appearance (many are located in arid and semi-arid landscapes) there has been more survey effort devoted to active springs associated with permanent groundwater discharge from the GAB (Fensham et al., this volume). It is estimated that > 70% of permanently flowing GAB springs have been surveyed, with a survey comprehensiveness as high as 98% for three GAB spring supergroups. Much less research effort has been extended to the non-GAB springs within Queensland as many are not as visible as distinct features, are located in wetter landscapes, and many may not be permanent and are not artesian (discharge in the aquifer may fluctuate with climatic variability).

This chapter examines Queensland's non-GAB springs primarily based on the lithology of the parent aquifer water source, and summarises current understanding of the ecology, biodiversity and hydrogeochemistry of selected examples. The form and nature of springs is directly related to the underlying geology, in terms of water chemistry, water porosity and volume. This approach also allows for a systematic consideration of non-GAB springs, as understanding the aquifer source allows for understanding of many features of the springs. Here, we describe springs derived from metamorphic, igneous, and sedimentary rocks, followed by those emerging from unconsolidated sediments.

Springs in Igneous Rock Aquifers

The east coast of Australia is characterised by multiple mountain ranges that formed during two major phases of geologic activity. In the first phase tectonic uplift resulted in compression of rocks to form metamorphic rocks, while the second phase started during the Cenozoic era as heat anomalies in the upper mantle resulted in uplifting. The latter were associated with hot spot volcanism that is characterised by broad shields of mafic lavas interspersed with more fractionated plugs and flows. This pattern of vulcanism is present from the top of Cape York to southeast Queensland. Of particular importance for the expression of springs are the numerous basalt flows throughout the Great Dividing Range, many of which are associated with extensive aquifers. While springs can also be associated with intrusive granites, these are not as common because granites are usually less porous unless they are weathered or fractured. However, several important springs associated with granite rocks are described below.

Remnants of this volcanism are preserved in prominent landscape features, such as volcanic plugs that form distinctive mountains (e.g., the Glasshouse Mountains in southeast Queensland) (Ball et al. 2021). Many of the basalt flows have all three types of porosity; primary (usually associated with vesicular basalt), secondary (fractured basalt) and tertiary (usually boulders). The basalts of the Atherton Tablelands of the Wet Tropics support numerous springs and GDEs, and spring-fed rainforest streams provide permanent flow crucial for agriculture production. Smaller basalt flows, with associated springs, exist in various areas of Cape York, including at Hopevale in the Endeavour River catchment, and at Lakeland in the Normanby River catchment.

The volcanics of the Upper Burdekin River catchment are extensive and include the McBride and Nulla Basalt Provinces. The former is approximately circular and groundwater flows radially from its centre. It provides baseflow to the Burdekin River, which is perennial near its headwaters. Water from the McBride basalt also feeds numerous palustrine and lacustrine wetlands in the Valley of Lagoons. In the elongated Nulla Basalt Provence (often referred to as the Great Basalt Wall; Figure 8-75) water generally flows in an easterly direction and supplies spring fed permanent rivers to its northern and southern boundaries and numerous palustrine and lacustrine wetlands (Dixon-Jain et al. 2020; Cook and Ransley 2021).

Several basalt flows in the Lower Fitzroy River Basin support springs, and those sources in the basalts provide permeant baseflow to Headlow Creek, and several permanent waterholes and wetlands, which would otherwise dry out in the dry tropical environment. The extensive

Figure 8-75. Great Basalt Wall spring of the Nulla Basalt Provence (photo by Mike Ronan).

basalts of the mountain ranges of southeast Queensland provide spring-fed base flows to numerous rivers and creeks running to the east and west and support the World Heritage listed Gondwana Rainforest.

Innot Hot Springs and Dhalaru Gogo (Talaroo Hot Springs): Springs Associated with Intrusive Granites.

The potential for development of geothermal energy in Queensland is mainly limited to regions with high heat producing granitic geology, which is found in several areas, including in the Etheridge Geological Province in North Queensland (Draper and D'Arcy 2006). This region encompasses the Georgetown Inlier, which contains middle Carboniferous to lower Permian volcanic and intrusive formations (Branch 1966) where Innot Hot Springs and Talaroo Hot Springs are situated. Hot springs associated with these granites are a rare occurrence in Queensland. However fossil evidence from the Drummond Basin in central Queensland indicates that similar hot spring ecosystems existed in Queensland as long ago as the late Devonian period, approximately 360 million years ago (Mya; Cunneen and Sillitoe 1989), with fossil structures remarkably similar to those that can be seen forming today at Talaroo Hot Springs (Negus et al. 2021).

Innot Hot Springs is situated about 95 km west of the tropical north coast in the easterly draining Herbert River catchment. The water discharges from the ground at temperatures up to 71°C into a small creek where it mixes with surface water and cools as it flows away from the spring vents (Lottermoser and Clevererley 2007; McGregor and Rasmussen 2008). Hydrochemistry and analysis of stable isotopes of water from Innot Hot Springs indicates that its source waters fell as rainfall and percolated into the ground where it interacted with the deep granite geology to become heated (Lottermoser and Clevererley 2007). The water is also high in fluoride (1-16 mg/L), with a pH of 8 - 8.7 and electrical conductivity of ~1000 µS/cm (Lottermoser and Clevererley 2007; McGregor and Rasmussen 2008). Mixing with creek water after discharging gradually dilutes the spring water, causing it to more closely resemble the geochemistry typical of the area (Lottermoser and Clevererley 2007; McGregor and Rasmussen 2008).

The first survey of microbial mats at an Australian thermal spring was undertaken at Innot Hot Springs (McGregor and Rasmussen 2008). This survey found a complex of eight genera and 10 species of cyanobacteria, including the family Pseudanabaenaceae, *Leptolyngbya* spp., *Geitlerinema* sp., and *Oscillatoria amphigranulata*. While the latter species also are found in hot springs in New Zealand, the other species are considered unique to Innot Hot Springs (McGregor and Rasmussen 2008). This cyanobacterial taxon richness is lower than reported internationally from other granitic hot springs, a condition attributed to disturbance through seasonal flow variation in the small creek, and possibly by losses of species sensitive to human disturbance (McGregor and Rasmussen 2008).

Figure 8-76. The hot water emanating from the vents at Talaroo Hot Springs creates steam across the top of the mound, which contributes to Aboriginal mythology of the mound (photo by Peter Negus).

Talaroo Hot Springs (Dhalaru Gogo in the local Aboriginal language) is situated adjacent to the Einasleigh River, 80 km east of Georgetown in the Gulf of Carpentaria, far north Queensland. An elevated spring mound has several active discharge vents where water at temperatures up to ~65°C flows across the mound into surrounding wetlands and small streams, eventually flowing into the Einasleigh River (Negus et al. 2020b; Figure 8-76). The hydrochemistry of the water, including high fluoride concentrations, indicates similar and potentially the same heated granitic origins as Innot Hot Springs, 200 km to the east (Negus et al. 2021).

The spring mound is 5 to 10 m higher than the surrounding landscape and formed through biomineralization of its CO_2-rich water into travertine (calcium carbonate; (Negus et al. 2021). The mound is unique to Australian springs by not only discharging hot water but also by the physical terracing of flowing water. These terraces are created by microbial colonies, including cyanobacteria and sulphur-metabolizing bacteria, which facilitate deposition of travertine stomatolites. These form the terrace lips, and conspicuous yellow and green biofilms that line shallow flowing and pooling sections (McGregor and Sendall 2017; Negus et al. 2021; Figure 8-77). Similar

Figure 8-77. Travertine terracing formed by dark coloured cyanobacteria and conspicuous yellow sulphur bacteria at Talaroo Hot Springs (photo by Jonathan Marshall).

Figure 8-78. At Talaroo Hot Springs dragonflies try to oviposit in the hot water and die. Then they mineralise before they decompose, making travertine dragonfly fossils and many other animal fossils (photo by Jonathan Marshall).

biomineralization processes rapidly encrust all organic materials that fall into the stream, including many insects and other animals that become fossilised by travertine (FFigure 8-78).

The temperature of Talaroo Hot Spring water decreases gradually as it flows away from the spring mound, reaching ambient conditions by the time the streams join the adjacent river. This thermal gradient structures the biological communities along the streams (Negus et al. 2020b). In addition to these unique microbial communities, the spring mound and surrounding wetlands that receive spring waters support numerous rare and endangered species including the Salt Pipewort (*Eriocaulon carsonii*), which is otherwise restricted to springs of the GAB, and thermophilic extremophiles, such as a carnivorous ostracod (Negus et al. 2020b).

Both Innot Hot Springs and Talaroo Hot Springs have been recognised as unique ecosystems, and both were used as health retreats and spas following their discovery by European explorers and early colonial settlers in the late 1800's (Griggs 2013; Negus 2021). Currently, access to the Innot Hot Springs area is unrestricted, resulting in ongoing human disturbance (McGregor and Rasmussen 2008).

Talaroo Hot Springs was associated with multiple pastoral properties throughout the 20th Century, and later adjacent camping facilities were built and the spring mound was used as a tourist attraction until the property was destocked and returned to the Traditional Owners (Negus 2021). Currently, access to the springs is managed by its Traditional Owners (represented by the Ewamian Aboriginal Corporation) as a tourist attraction, with discharge waters used as a hydrotherapy retreat. However, the mound is conserved as an Indigenous Protected Area and human disturbance to this unique Australian spring wetland has been reduced (Ewamian Aboriginal Corporation 2017).

Spring Creek, Killarney – Springs associated with Basalt Flows

The Condamine River in southern Queensland is the northeast most tributary of Australia's largest river system, the Murray-Darling. The headwaters of the Condamine River are bounded to the east by deeply eroded volcanic uplands with elevations up to 1300 m above sea level near the township of Killarney (Huxley 1982). These uplands consist of the Main Range Volcanics which are aligned northwest to southeast, with an outcrop approximately 25 km wide and 60 km long (DNR&M 2016). The Main Range Volcanics were formed during a single lengthy period of epeirogenic uplift, with sub-aerial extrusion of basalts in the Oligocene-Miocene epochs. The formation consists of alkaline, olivine basalt, most of which appears to have erupted from fissures along the line of the present-day Main Range (DNR&M 2016). Near Killarney it contains weathered, fractured and vesicular zones that support unconfined aquifers (Hansen et al. 2008).

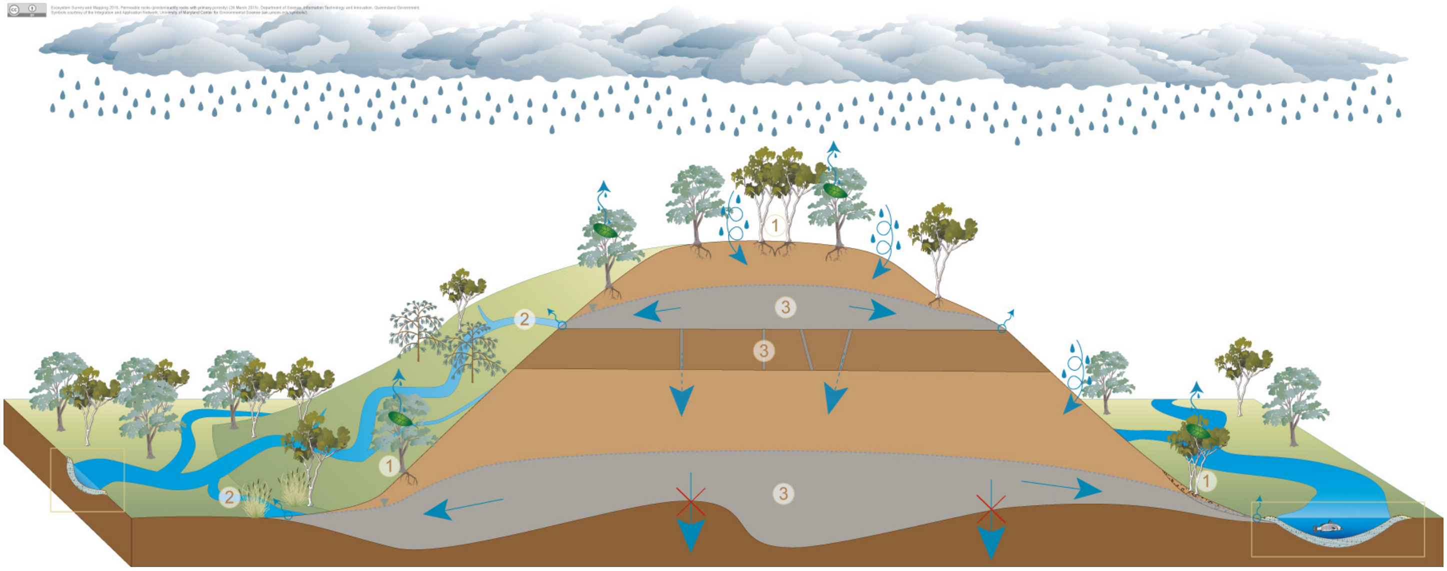

Ecosystem Survey and Mapping 2015. Permeable rocks (predominantly rocks with primary porosity) (26 March 2015). Department of Science, Information Technology and Innovation, Queensland Government. Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Figure 8-79. In the upper Condamine River valley, springs form near the contact between groundwater within the Main Range Volcanics and the less permeable, underlying, fine grained sedimentary rocks, and these springs typically provide baseflow to the streams (Department of Environment and Science). (1), (2), and (3) in the diagram are indicative of areas where terrestrial, surface, and subterranean groundwater dependent ecosystems may exist respectively.

Test bores (RN 42231663) have revealed significant aquifers in shallow layers of fractured basalt 9 to 13 m below the ground surface (Hansen et al. 2008). This region sustains an elevated mean annual rainfall of 1300 mm (Department of Natural Resources 1999), and groundwater in the fractured basalt is readily recharged from rainfall through well-drained porous soils (Condamine Alliance 2008). Groundwater this aquifer has a yield of approximately 6.98 L/s (Huxley 1982; Hansen et al. 2008).

Figure 8-80. South Spring Creek near Killarney in southern Queensland has perennial, cold baseflow supported by springs fed by unconfined aquifers within weathered, fractured, and vesicular zones of basalt in the Main Range Volcanics (photo by Jonathan Marshall).

The volcanics are characterised by very steep sided valleys carved by the Condamine River and its tributaries (Huxley 1982). Springs form near the contact between the Main Range Volcanics and the less permeable, underlying, sedimentary rocks such as the Walloon Coal Measures, and these springs typically provide stream baseflow (Huxley 198; Figure 8-79).

Combined discharge has been estimated to yield an average 100 m^{3}d-1 with no noted depletion in groundwater storage (McNeil et al. 1991). This contributes to perennial baseflow in some streams, including Spring Creek near Killarney (Figure 8-80). A combination of hydrological and geochemical methods have been applied to estimate that approximately 27% of the total streamflow of Spring Creek is derived from deeper groundwaters, most likely Main Range Volcanic basaltic aquifers, and an additional 25% of long-term streamflow is likely derived from a combination of shallower subsurface flows from soil water, and bank return flow and/or interflow. This indicates a system capable of supporting the stream over short, intermediate, and long time frames, and Main Range Volcanic basaltic aquifers are the dominant source of baseflow during dry climate phases (Hatlow 2022).

The springs that feed these perennial streams are recognised as having cultural and spiritual, aesthetic and aquatic ecosystem environmental values (Condamine Alliance 2017), including cultural significance to local First Nation peoples (Southern Queensland Landscapes 2019b). Of note is the specialist, cold-stenotherm fauna supported by these spring-fed perennial streams (Figure

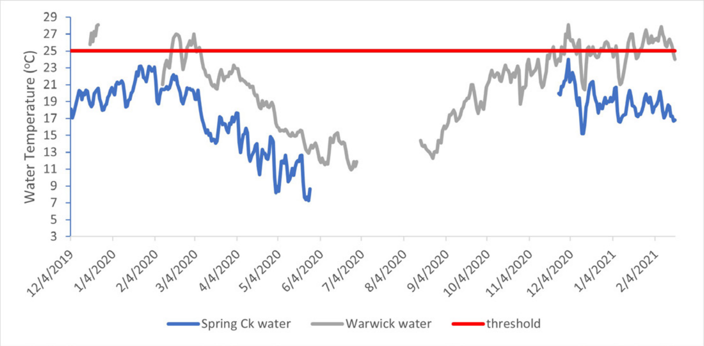


Figure 8-81. Plot of average daily water temperature in groundwater-fed South Spring Creek and in a more typical upper Condamine River site at nearby Warwick (Queensland Government stream gauge 422310C). Even during the extreme heatwave conditions of late 2019 Spring Creek water temperature remained below the thermal threshold of 25°C required to sustain its specialist cold water species, whereas water in the general region exceeded that limit (Queensland Government, unpublished data).

8-83). These include the river blackfish *Gadopsis marmoratus* (Percichthyidae), the mountain galaxias *Galaxias olidus* (Galaxiidae), and the spiny mountain crayfish, *Euastacus sulcatus* (Parastacidae).

The permanent spring discharge of cold groundwater keeps stream water temperature well below the ca. 25-27°C lethal limit for these species (Marshall 1989; Bone et al. 2014; Turschwell et al. 2017; Turschwell et al. 2020; Ebner et al. 2020). Such conditions provide these once broadly distributed species with long-term thermal refugia required for long-term persistence here since ancient, cooler times (Figure 8-811).

Not only are these populations isolated by lethal downstream temperature regimes, they are also poor dispersers, with river blackfish in particular having little adult movement (Khan et al. 2004). A genetics study revealed that local populations mix little at even fine spatial scales (Huey et al. 2017). Waterfalls at discontinuities in the Main Range Volcanics (Figure 8-80) characterize these streams, further constraining the potential for fish dispersal. If this population were to die out, there is little to no chance of natural recolonization from distant populations in southern Australia.

Nonetheless, these cold water species in southern Queensland are threatened by warming, both as a result of riparian vegetation clearing (Hutchinson 2014; Turschwell et al. 2018) and from climate change, particularly extreme events (Ebner et al. 2020). In the Killarney region, 2019 was both the hottest and the lowest rainfall year on record, and streams supporting these species approached their lethal thermal limits (Figure 8-82). Springs that feed those tributaries all but ceased flowing, so they very nearly dried out. This prompted a rescue operation to bring representative individuals into captive holding in case reintroductions became necessary (Ebner et al. 2020). Fortunately, those extreme climate conditions relaxed before the local populations were lost. However, this episode highlights the vulnerability of this special spring-fed ecosystem to future climate change, with forecasts for greater extremes and frequencies of both drought and heatwave conditions for the region (Kirono et al. 2020; Marshall et al. 2021). In addition,

Figure 8-82. Browns Falls on South Spring Creek near Killarney showing columnar basalt of the Main Range Volcanics (photo by Jonathan Marshall). Waterfall, columnar basalt.

Figure 8-83. Cold groundwater maintains a thermal refuge for specialist cold water aquatic species, such as the spiny mountain crayfish *Euastacus sulcatus* (photo by Jonathan Marshall).

groundwater extraction from the Main Range Volcanics can rapidly reduce yields when rainfall recharge declines (McEniery 1973), such as during drought. This suggests that spring-fed baseflow may be vulnerable to increased groundwater take under climate change. In response to these threats, activities are underway to protect, restore and raise community awareness of the unique spring-fed stream ecosystems around Killarney (Turschwell et al. 2018; Southern Queensland Landscapes 2019a). Such outreach includes engaging local school students to write and perform a song about the plight of river blackfish (https://www.youtube.com/watch?v=MbzcmQUESl4).

Springs in Sedimentary Rock Aquifers

There are large areas of sedimentary rocks through Queensland in a range of topographic settings, from elevated mountain ranges to coastal and inland plains. The degree of spring formation associated with these rocks depends on a number of factors, including the primary porosity of the parent materials, the degree of fracturing of the rocks, and the origin of the parent material (terrigenous or biogenic). Generally, fine grained sedimentary rocks do not contain much groundwater and are rarely associated with springs. However, when fine grained sedimentary rocks are located close to more porous rocks and sediments, springs often emerge at the interface. Thus, coarser grained sedimentary rocks can contain significant groundwater resources and often have significant spring development.

Many sedimentary rocks have quite variable composition and are a combination of conglomerates, fine and coarse grained sediments, and limestones. Many of these mixed sedimentary rocks occur along the coastal fringe of Queensland. While not large in area or extent, there are karst deposits in Queensland associated with important spring formations and caves. Karst landscapes are predominantly composed of carbonate-based biogenic rocks, such as limestone. The geochemical properties of carbonate rocks make them more susceptible to mechanical and chemical weathering. Karst landscapes are often characterised by primary, secondary and tertiary porosity (e.g., voids, caves, sinkholes, and/or springs). Important areas of limestone springs are found around Boojamulla (Lawn Hill) in northwestern Queensland, which provide a permanent water supply to the rivers and streams in this area. The following provide examples of the range of sedimentary rock springs in Queensland.

Sandstones of the Clarence-Moreton Groundwater Basin

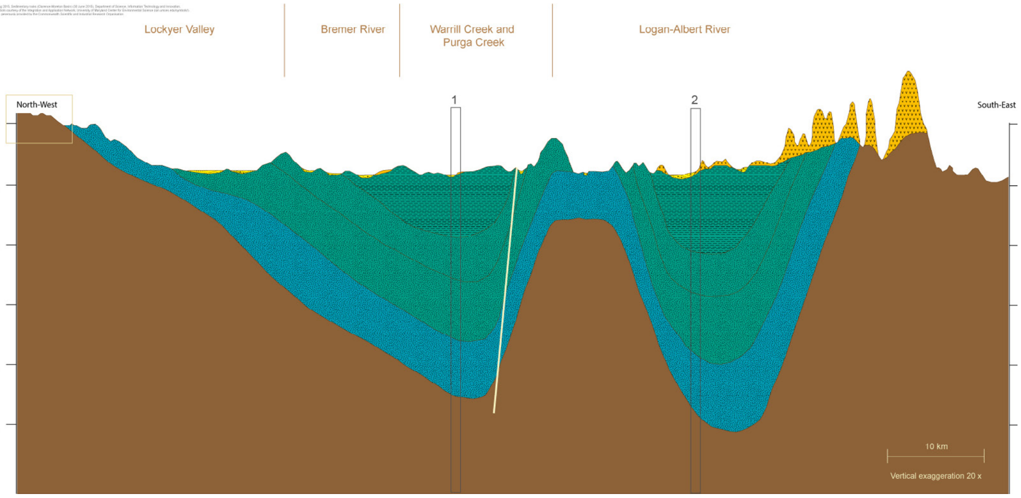
The Clarence-Moreton Groundwater Basin, extending over 10,000 km^2 in southeastern Queensland, is underlain by Triassic to Jurassic sedimentary rocks (Jell and Geological Survey of Queensland 2013; Rassam et al. 2014; Willmott 2014; Figure 8-84). The basin is defined by three depocentres: the Logan Sub-basin; the Laidley Sub-basin; and the Cecil Plains Sub-basin (Jell and Geological Survey of Queensland 2013). The older sequences of the Clarence-Moreton Basin include the fine- to coarse-grained Woogaroo Subgroup and the Myrtle Creek Sandstone (Willmott 2014). The younger sequences are generally fine-grained sandstones, siltstones and mudstones of the Marburg Subgroup (including Gatton Sandstone and Koukandowie Formation) and the Landsborough Formation (Willmott 2014). These sedimentary bedrock strata form landscapes of undulating hills to ranges.

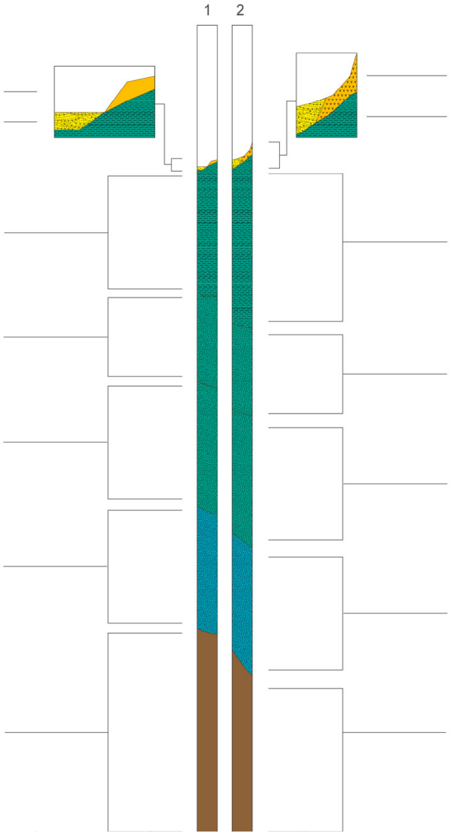
The coarser grained sedimentary rocks of the Woogaroo Subgroup are relatively permeable. Groundwater tends to discharge from these sedimentary aquifers along foot slopes and drainage lines. The presence of small undercut caves in these landscapes may result from erosion due to groundwater percolation through the sedimentary rocks (Willmott 2014). Other groundwater-bearing sandstones of the Clarence-Moreton Basin are the Gatton Sandstone, Koukandowie Formation, and the Walloon Coal Measures (Rassam et al. 2014). Some of this groundwater is under artesian or sub-artesian pressure and may locally recharge the overlying shallow Cenozoic and more recent alluvial sequences (Rassam et al. 2014). The Walloon Coal Measures and Gatton Sandstone have highly saline groundwater, affecting the composition of spring-dependent vegetation.

Surface water-groundwater interactions occur across the Clarence-Moreton Basin, with many streams receiving baseflow from underlying aquifers and/or contributing to aquifer recharge (Rassam et al. 2014). Generally, there are strong geochemical similarities among the waters in streams, in the alluvium, and in the underlying sedimentary rocks (Rassam et al. 2014). In the northwest, creek systems of the Lockyer Valley have highly variable conductivity (190 – 14,000 µS/cm), which relates to their underlying geologies (Rassam et al. 2014). Creeks overlying sedimentary rocks of the Woogaroo Subgroup

Figure 8-84. Conceptual model of the (top) geological and (middle) hydrogeological setting of springs associated with the Clarence-Moreton Basin, south-east Queensland, Australia (Department of Environment and Science). (1) and (2) in all three diagrams indicate areas where terrestrial and surface groundwater dependent ecosystems may exist respectively.

Ecosystem Survey and Mapping 2015, Sedimentary rocks (Clarence-Moreton Basin) (30 June 2015), Department of Science, Information Technology and Innovation, Queensland Government. Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). Based on hydrogeological data generously provided by the Commonwealth Scientific and Industrial Research Organisation.





Undifferentiated Neogene and Paleogene sediments (orange)

Quaternary alluvium (yellow)

Walloon Coal Measures
Claystone, shale, siltstone, coal seams, and minor limestone.
Contains saline groundwater.

Koukandowie Formation
Sandstone, conglomerate, shale, siltstone, and minor coal.

Gatton Sandstone
Sandstone, clay, conglomerate and fossil wood fragments.
Contains saline groundwater.

Woogaroo Subgroup
Sandstone, conglomerate, siltstone, claystone and coal.

Basement of Clarence-Moreton Basin

Lamington Volcanics
Basalt, rhyolite, agglomerate, conglomerate and andesite.

Quaternary alluvium (yellow)

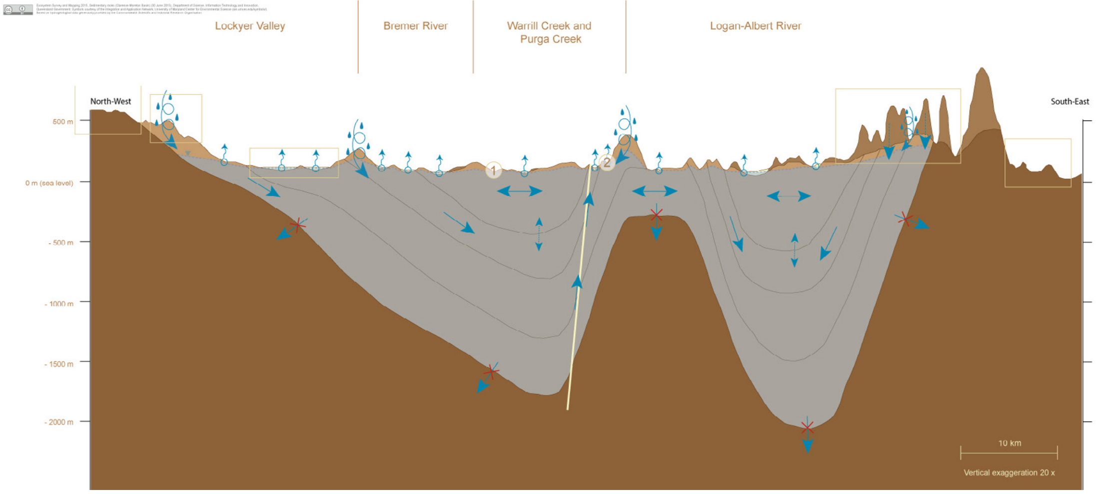
Walloon Coal Measures
Claystone, shale, siltstone, coal seams, and minor limestone.
Contains saline groundwater.

Koukandowie Formation
Sandstone, conglomerate, shale, siltstone, and minor coal.

Gatton Sandstone
Sandstone, clay, conglomerate and fossil wood fragments.
Contains saline groundwater.

Woogaroo Subgroup
Sandstone, conglomerate, siltstone, claystone and coal.

Basement of Clarence-Moreton Basin



have fresh water, while those directly overlying Gatton Sandstone, Koukandowie Formation, or the Walloon Coal Measures have saline water (Rassam et al. 2014). Similarly, Purga Creek and its alluvium has a similar hydrochemistry to the underlying Walloon Coal Measures, indicating that these streams receive significant baseflow from that groundwater (Rassam et al. 2014).

Sandstone Spring-fed Headwaters of the Jardine River

The spring-fed Jardine River is located at the northern-most part of mainland Australia, at the tip of Cape York Peninsula in tropical, far north Queensland. It is Queensland's largest perennial river (DES 2018). Aquifer sourcing of springs on Cape York is not well understood, and the region includes outcroppings of sandstone rock units considered to be associated with recharge zones of the GAB (Marshall et al. 2014). Consequently, our interpretation here of the source of perennial flow in the Jardine River deriving from non-GAB springs is not entirely certain.

Perennial flow is the result of many springs discharging from the Helby Sandstone, a part of the Carpentaria Basin that formed during the Jurassic and Cretaceous periods (Willmott 2009). The springs also provide flow to palustrine wetlands adjacent to the river (Cook et al. 2011). This hydrology is specific to the Jardine River and is considered rare elsewhere in northern tropical Australia (Cook et al. 2011). In downstream reaches the sandstone is covered by a thick weathered laterite with a cap of ferricrete that becomes richer in aluminium oxides and bauxite near the coast (Willmott 2009).

Figure 8-85. Fruitbat Falls on Elliot Creek in the Jardine River catchment (photo by Jonathan Marshall).

The Jardine River headwaters contain rare rainforests (refugial vine forests) situated on sandy soils that line the riparian zones (Abrahams et al. 1995; Willmott 2009; Figure 8-85). This relict vegetation type likely has persisted as a result of perennial springs from the underlying sedimentary rocks. The uniqueness of the Jardine River as a springfed catchment is illustrated by its distinct aquatic biota (Marshall et al. 2006b; Cook et al. 2011). This includes the highest species richness of freshwater fish in Queensland and across northern Australia, with affinities to rivers from Papua New Guinea (Allen and Hoese 1980; Cook et al. 2011). Aquatic species endemic to the river include the Jardine River painted turtle (*Emydura subglobosa subglobosa*), one of the rarest freshwater turtles in Australia (Freeman and Ebner 2020). The riparian zones and adjacent swamps also contain high species richness of carnivorous plants, including the Queensland pitcher plants *Nepenthes rowaniae, Nepenthes tenax, and Nepenthes parvula*, sometimes occurring as hybrids, and with the latter two species endemic to the Jardine catchment (Clarke and Kruger 2006; Wilson and Venter 2016).

Boodjamulla (Lawn Hill)

North Australian karst landscapes, like the Lawn Hill region in northwest Queensland, are generally flat-lying limestone and/or dolomite terrains with low primary porosity (Grimes 1999; Figure 8-86).

The Barkly Tableland, west of Lawn Hill (Boodjamulla in the local Aboriginal language), is a Cambrian carbonate plateau (Van der Ley et al. 2014). Groundwater chemistry from these carbonate groundwater systems indicates a freshwater aquifer with fast recharge. The influence of chemical weathering processes are also evident in the groundwater geochemistry producing a karst-specific calcium bicarbonate type water. Recharge is largely a result of local rainfall (Grimes 1999) and, in combination with short groundwater residence times, suggests that these karstic aquifers may be vulnerable to anthropogenic extraction activities (Van der Ley et al. 2014).

The Lawn Hill region has a semi-arid monsoonal climate (Grimes 1988; Grimes 1999; Van der Ley et al. 2014) with pronounced wet and dry seasons. In this region, riverine systems typically have seasonal flow regimes as they progressively dry out in drier months. However, there are several major perennial stream and river systems (Van der Ley et al. 2014; Waanyi People and Queensland Parks and Wildlife Service 2022). The permanence of these streams is due to the contributions of baseflow from permanent springs along the northern margin of the karst Camooweal Dolostone and Thorntonia Limestone aquifers (Grimes 1988; CSIRO 2009).

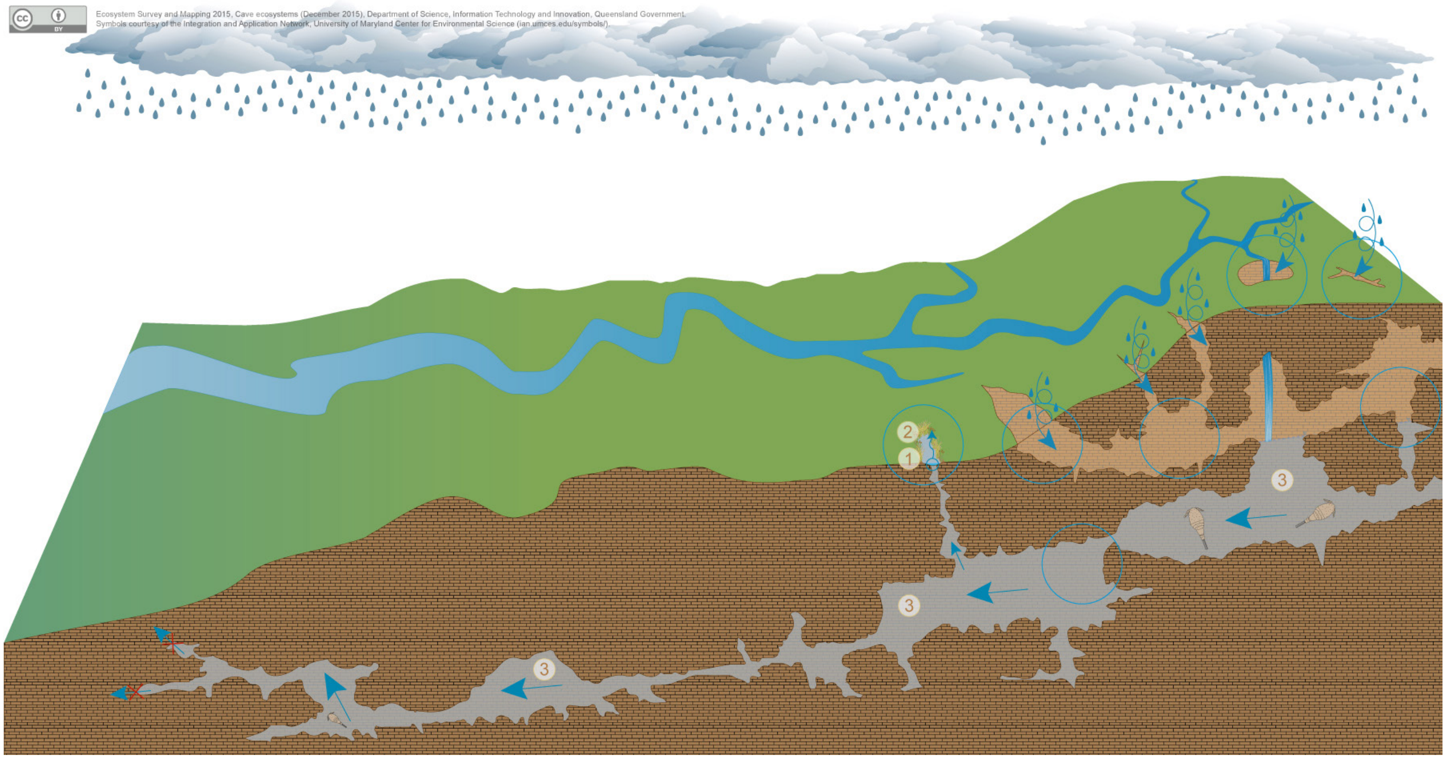


Figure 8-86. In karst landscapes, springs form along the margins and, with sufficient groundwater discharge, support permanent river systems (Department of Environment and Science). (1), (2), and (3) in the diagram are indicative of areas where terrestrial, surface, and subterranean groundwater dependent ecosystems may exist respectively.

The extensive Camooweal Dolomite is also thought to recharge a groundwater system in the underlying Thorntonia Limestone (CSIRO 2009).

The groundwater discharging into perennial creeks and rivers in the Lawn Hill region are rich in CO_2, which is chemically and biologically precipitated as travertine or tufa (a calcium carbonate) when dissolved CO_2 degasses into the atmosphere (Drysdale and Gillieson 1997; Carthew et al. 2003; Figure 8-87). This travertine or tufa forms the base of the wetted substrates. The rate of deposition at any location is variable and dependent on flow velocity, seasonality and biological activity, as well as the presence of nucleation sites (e.g., caddisfly nets), but is a geomorphic feature that is important to the development of the hydrological and landscape features of the region (Drysdale and Gillieson 1997; Carthew et al. 2003).

Figure 8-87. Travertine encrusted tree trunk, Lawn Hill Creek (photo by Peter Negus).

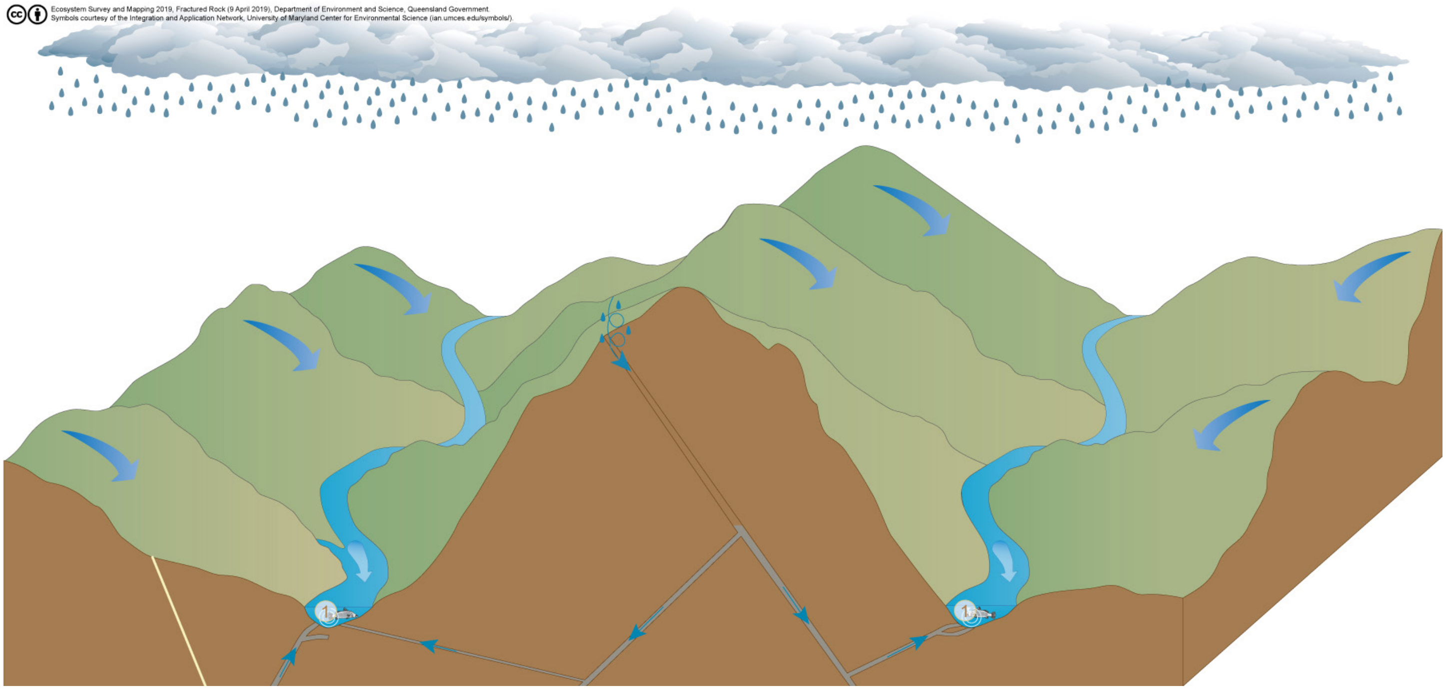
Figure 8-88. Lawn Hill (photo by Jonathan Marshall).

Figure 8-89. Springfed ecosystems at Lawn Hill support a diverse aquatic fauna (photo by Jaye Lobegeiger).

These springs and the perennial rivers they support form the nationally important Thorntonia Wetland Aggregation (Waanyi People and Queensland Parks and Wildlife Service 2022; Figure 8-88, Figure 8-89). The relative stability of these perennial river systems over time provides a critical refuge for flora and fauna, especially in arid and semi-arid climates. Permanent water supports the presence of significant vegetation communities in the region and flora that use the permanent water include algae, ferns, mosses, palms, and rainforest species (Australian Government n.d.). These springs and the riverine systems they support provide habitat for several species of conservation significance, including the purple-crowned fairy wren (Malurus coronatus) and the Gulf snapping turtle (*Elseya oneiros*) (Waanyi People and Queensland Parks and Wildlife Service 2022). They also support the presence of a diverse faunal assemblage, including: amphibians (11 species); birds (139 species including bittern, brolga, cormorants, egrets, herons, pelicans, storks, waterfowl); crustacea (3 species); fish (23 species); mammals (3 species including the rock ringtail possum, *Petropseudes dahli*); molluscs (5 species); and reptiles (33 species including geckos, goannas, lizards, skinks, snakes, and turtles).

Springs in Metamorphic Aquifers

Geological compression and deformation towards the end of the Carboniferous period converted the early Palaeozoic era marine sand and clay sediments and volcanics into metamorphic rocks (Willmott 2014; Figure 8-90). These metamorphic rocks were subsequently uplifted and combined with intrusive and extrusive volcanics to form mountain ranges, including the D'Aguilar Range in southeast Queensland that extends over



Ecosystem Survey and Mapping 2019, Fractured Rock (9 April 2019), Department of Environment and Science, Queensland Government.
Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Figure 8-90. Conceptual model of the hydrogeological setting of springs associated with fractured metamorphic rock aquifers. These are typically localised groundwater systems with ephemeral baseflow contributions to streams overlying fracture or bedding planes (Department of Environment and Science). (1) in the diagram is indicative of areas where surface groundwater dependent ecosystems may exist.

700 km from Rockhampton to the border of Queensland and New South Wales (Willmott 2014). In southeastern Queensland, examples of these metamorphic rocks include: Bunya Phyllite (composed of phyllite and quartzite); Jimna Phyllite (composed of slate and phyllite); the Naranleigh-Fernvale beds (composed of argillite, greywacke, quartzite and greenstone); the Pinecliffe Formation (composed of chert and silicified mudstone) and the Sugarloaf Metamorphics (composed of sandstone, black slates and contorted phyllites; Willmott 2014; Department of Environment and Heritage 2015). In addition to southeast Queensland, a combination of metamorphic and volcanic rocks is found throughout the Great Dividing Range to the top of the Cape York and the North West Highlands near Mount Isa in the Gulf of Carpentaria region.

Metamorphic rocks have generally very low primary porosity and groundwater only occurs in joints and fractures, which can be infilled with fine-grained deposits. This reduces their water-holding capacity and permeability. While fracturing can be common in metamorphic rocks, large fractures are often localised and the presence of water in fractures is temporally variable. Many fractured metamorphic rock springs are well defined features and flow only as long as the aquifer contains water, decreasing in discharge as the weather dries. Fractured metamorphic rock aquifers typically contribute some baseflow to streams where larger, open fractures intersect the stream bed or bedding planes (Department of Environment and Heritage 2015).

Runoff from metamorphic rock mountains contributes flow to some major rivers (Willmott 2014), but this is mainly surface runoff. The fracture flow spring contributions to baseflow in higher order and lower elevation streams becomes more important where open, localised fractures are present. In some cases, such springs are associated with the presence of mesic vegetation communities, including vine forests (Department of Environment and Heritage 2015). Groundwater discharge into these streams is likely to be ephemeral due to the low capacity and yield of the groundwater flow systems found in fractured metamorphic rocks (Department of Environment and Heritage 2015). There is limited information available on these springs due to their intermittent flow regimes and localised aquifers.

Springs in Unconsolidated aquifers

Springs associated with unconsolidated sediments are quite variable and occur at either the interface between the unconsolidated sediment and underlying bedrock or where aquitards may develop in the unconsolidated sedimentary strata due to chemical precipitation of metals, formation of organic layers, or a combination of both. Unconsolidated sediments can vary in permeability; some clays are nearly impermeable, while other sediments, such as gravels and sands, can be highly permeable.

As unconsolidated sedimentary strata are widespread throughout Queensland, springs arising from these landscapes are common and difficult to accurately map, particularly in alluvial areas. They are probably the most diverse non-GAB springs, varying in size, permeance of water, and location (unconsolidated sediments can be moved by major weather or seismic events). Many floodplains in Queensland contain extensive paleochannels through which groundwater preferentially flows and many of these areas can have surface expressions, resulting in the presence of springs. Virtually all unconsolidated sediment systems can have associated springs, including alluvium, coastal sand masses, fluvial inland sand ridges, aeolian inland sand ridges, and sand and clay plains.

Bauxite Springs, Steve Irwin Reserve

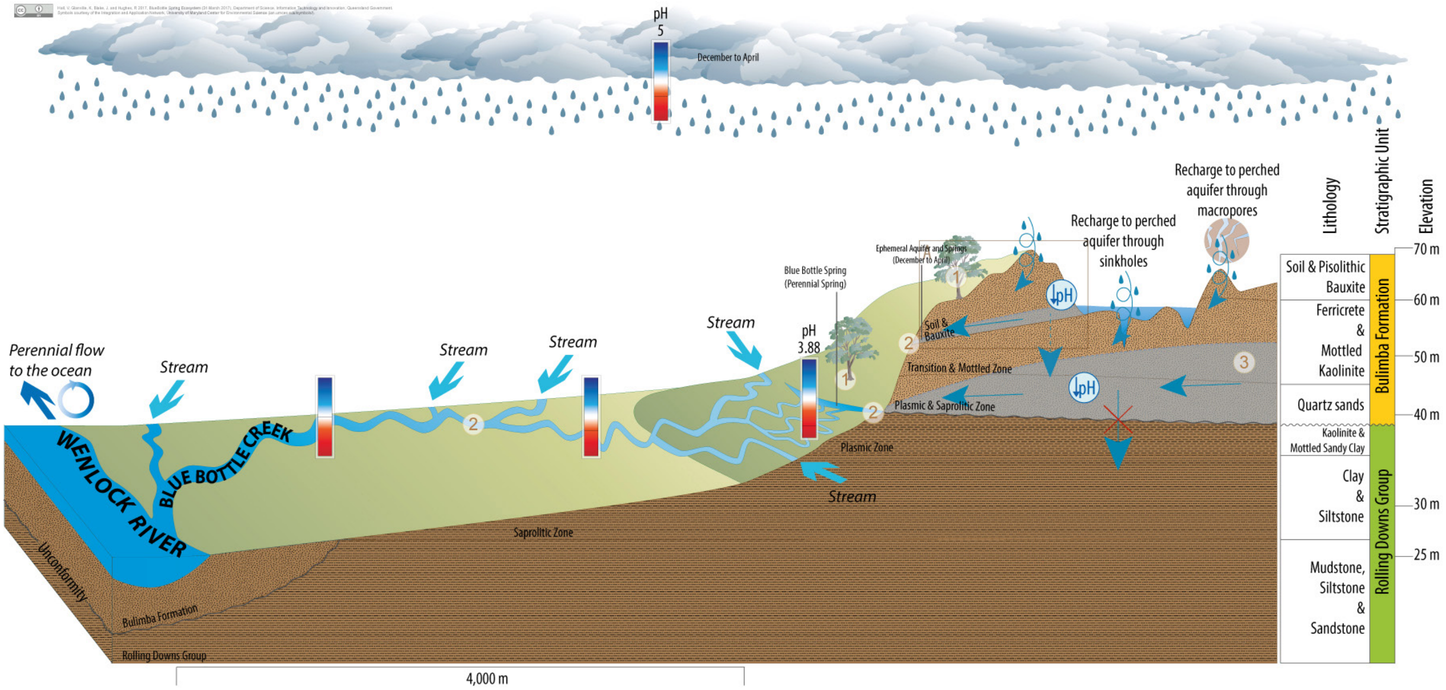
The Weipa Plateau is a remnant of the Cretaceous Rolling Downs Group and Bulimba Formation (Willmott et al. 2009; Jell and Geological Survey of Queensland 2013). It extends 350 kilometres along the western side of Cape York Peninsula and covers 11,000 km^2 (Taylor et al. 2008). This low-elevation plateau rises to 80 m towards the east (Jell and Geological Survey of Queensland 2013) and contains gentle rolling hills with discontinuous fluvial systems. The tropical monsoonal climate resulted in significant in-situ weathering during the late Eocene to early Oligocene (Taylor et al. 2008; Jell and Geological Survey of Queensland 2013). That weathering formed lateritic profiles up to 20 m deep (Willmott et al. 2009) that contain the world's largest bauxite deposit (Taylor et al. 2008). A generalised lateritic profile in this area comprises: kandosols with bauxite pisoliths and minor hydrosols; pisolithic bauxite; ferricrete; mottled zone; pallid zone; and non-weathered parent material (Taylor et al. 2008; Willmott et al. 2009). The Weipa Plateau is actively eroding at the margins and in-situ weathering continues to further develop ferricrete surfaces (Taylor et al. 2008; Willmott et al. 2009)

Perched springs can be found along the scarp of the Weipa Plateau at an elevation consistent with the interface between the low permeability pallid zone and overlying permeable layers. The compacted kaolin clay of the pallid zone impedes vertical movement of groundwater resulting in the formation of a perched groundwater system. Sufficient rainfall promotes the accumulation of groundwater above the pallid zone, which subsequently flows laterally to the plateau margins, emerging as springs along the scarp. The weathering of the mottled and pallid zones destabilises parts of the plateau causing the collapse and formation of 'melon holes' up to 4 km in diameter (Taylor et al. 2008; Willmott et al. 2009). During the wet season, these melon holes contain water (Willmott et al. 2009) and may support groundwater recharge.

The geochemistry in these perched aquifers varies greatly among springs (Leblanc et al. 2015); however, they are generally acidic, have low concentrations of total dissolved solids, and are derived from meteoric origins (Leblanc et al. 2015). The acidity of discharged groundwater decreases with distance from the spring vent (Lyon et al. 2010c). A groundwater flow pathway was identified from the bauxite surface through discontinuities in the ferricrete layer to the aquifer, and shown to have a groundwater residence time of < 1 to 30 yr (Leblanc et al. 2015).

BlueBottle and Oasis Springs, for example, are located along the exposed interface of the permeable mottled zone and the underlying less permeable pallid zone on the scarp. Oasis Spring (Figure 8-91) forms a 240 m arc at 40 m elevation on the scarp just above the pallid zone. A gully incises the spring head, forming a spring wetland, and permanently saturated soils are found on the adjacent eastern spring flank. This permanent spring maintains the perennial flow of the wetland up to 800 m downstream. Similarly, BlueBottle Spring forms a continuous 650 m arc at 50 m elevation. Groundwater discharged from BlueBottle Spring coalesces into several streams that form BlueBottle Creek at their confluence 400 m downhill. BlueBottle Spring is permanently flowing; however, flow rates are observed to slowly reduce throughout the dry season, indicating a local groundwater flow system.

The presence of springs supports pockets of forests in a landscape otherwise dominated by savannah (Leblanc et al. 2015). These spring forests are floristically distinctive (Lyon et al. 2010a) and have significant conservation importance (Lyon 2010). Perched springs (including BlueBottle and Oasis Springs) support closed notophyll vine forests "often dominated by Syzygium angophoroides, Melicope elleryana, *Xanthostemon crenulatus*, *Horsfieldia australiana*, *Buchanania arborescens* and *Lophostemon suaveolens*" (Queensland Herbarium 2021). These spring forests contain plant species of national, state, and regional significance. For example, several terrestrial and epiphytic orchids of conservation significance are found near these springs including *Bromheadia pulchra*, *Chiloschista phylloriza*, *Dockrillia rigida*, and *Spathoglottis plicata* (Roberts and Covacevich 2010). Additionally, a significant population of *Calophyllum bicolor*, a vulner-



Hall, V, Glanville, K, Blake, J. and Hughes, R 2017, BlueBottle Spring Ecosystem (31 March 2017), Department of Science, Information Technology and Innovation, Queensland Government. Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Figure 8-91. Conceptual model of the geological and hydrological setting of BlueBottle Spring, Cape York Peninsula, Australia (Department of Environment and Science). (1), (2), and (3) in the diagram are indicative of areas where terrestrial, surface, and subterranean groundwater dependent ecosystems may exist respectively.

Figure 8-92. Oasis Spring in Cape York Peninsula, Australia (Department of Environment and Science).

able tree of national conservation significance, was also recorded at some of these perched springs (Leblanc et al. 2015; Figure 8-92).

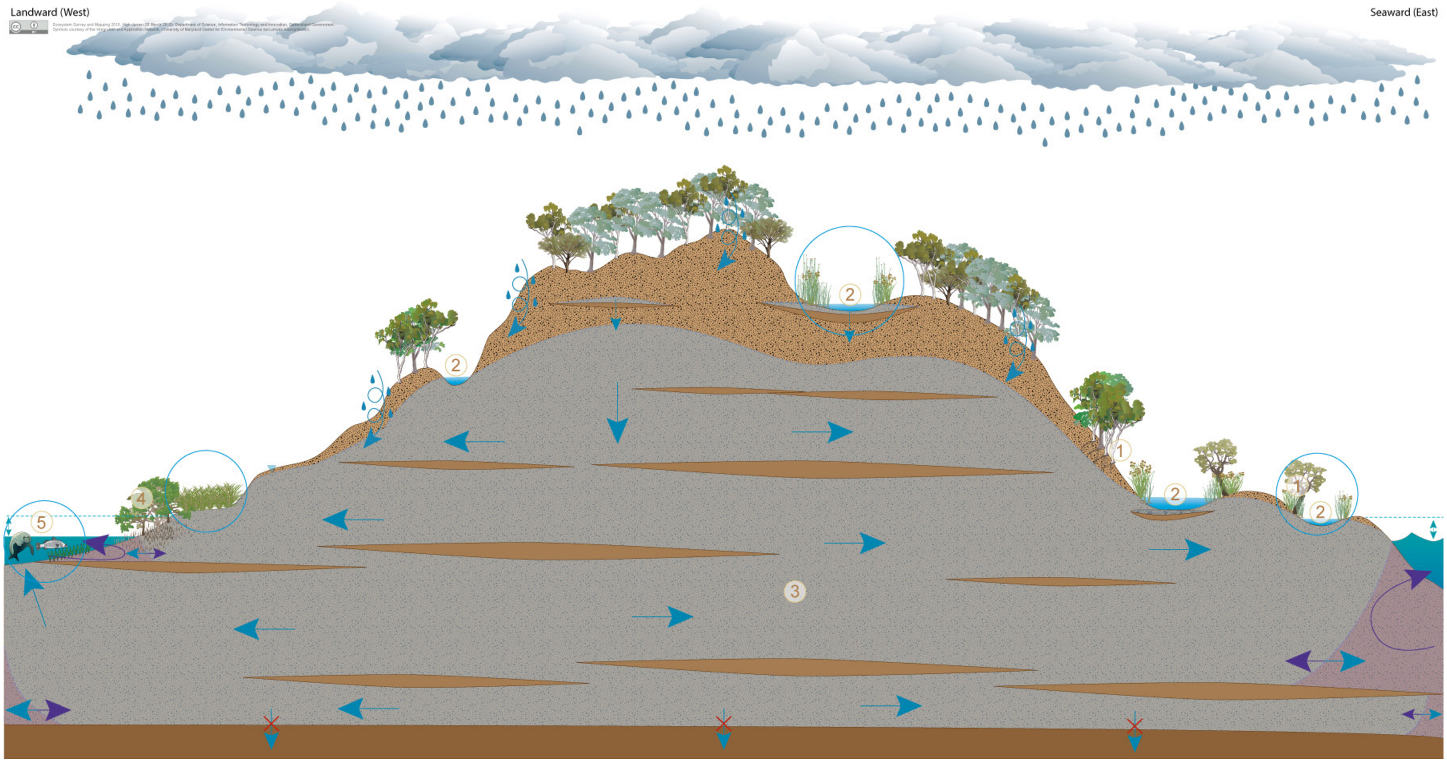
Spring forests support a wide variety of wildlife species including several of conservation significance. The red goshawk (E*rythrotriorchis radiatus*), an endangered bird, has been sighted on multiple occasions adjacent to perched springs (Lyon and Lyon 2010). In addition, several rainforest obligate bird species including the trumpet manucode (*Manuokodia keraudreni*i) and the yellow-billed kingfisher (*Symo torotoro*) rely on these spring forests (Lyon and Lyon 2010). The palm cockatoo (*Probosciger aterrimus*) (Figure 8-93) uses the habitat for nesting, and forages in adjacent woodlands (Lyon and Lyon 2010). These spring forests also provide habitat for numerous mammals, including the red-legged pandemelon (*Thylogale stigmatica*), northern brown bandicoot (*Isodon macrourus*), giant white-tailed rat (*Uromys caudimaculatus*), and the spotted cuscus (*Spilocuscus maculata*; Lyon et al. 2010b).

A wide diversity of species of frogs and reptiles is also associated with these spring forests (Lyon et al. 2010a). More than half of regional frog species use spring forests in addition to riparian rainforests and permanent wetlands (Lyon et al. 2010a). The small springfed watercourses and associated wetlands are oligotrophic, as indicated by the presence of endemic carnivorous plants (e.g. *Nepenthes* sp.). As a result there is a low diversity of aquatic invertebrates, freshwater fish and diatoms (Negus et al. 2017). However, the spring water feeds the main Wenlock River, where these biological groups have some of the highest richness across the Cape York region and Australia (Abrahams et al. 1995; Negus et al. 2017) and the river flows are considered important for providing dry season habitats for restricted estuarine species that also use freshwater reaches, such as speartooth sharks, sawfish and freshwater whiprays (Campbell et al. 2012; Department of Environment 2014). Overall, these springs provide refugial habitat that enables high ecological diversity and supports the persistence of numerous taxa of conservation significance and those with restricted distributions.

Figure 8-93. The spectacular palm cockatoo (*Probosciger aterrimus*) is associated with bauxite springs on Cape York Peninsula (photo by Jonathan Marshall).

Kaboora (Blue Lake)

The southeast Queensland coastline has multiple areas of deep, siliceous, weathered sand in dune systems that were formed by coastal sand movement from the large rivers along the southern east Australian coast and further aeolian reworking during Pleistocene and Holocene low sea-level stands. Examples are the Cooloola sand mass on the mainland and offshore sand islands including K'gari (Fraser Island), Moreton Island (Mulgumpin) and North Stradbroke Island (Minjerribah). They have



Ecosystem Survey and Mapping 2015. High dunes (25 March 2015). Department of Science, Information Technology and Innovation, Queensland Government. Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Figure 8-94. Sandmass regional aquifers are groundwater mounds that form in unconfined sand masses of coastal dune systems. These are higher in the centre and discharge towards the margins, reflecting the general surface topography, particularly on sand islands. Numerous, smaller, perched groundwater systems overlay the regional aquifers, supported to various extents by indurated sands that formed as a product of pedogenesis in dune systems. Infiltrating rain and organic acids from decomposing vegetation percolate through the quartz sand, which is characterised by little buffering capacity, producing low pH conditions and leaching accessory minerals down the soil profile. pH progressively increases as water percolates through the soil profile. This changes metal solubility and leads to precipitation of iron and manganese oxides and hydroxides in pore spaces between the quartz grains in the B-horizon, consequently binding the sands and reducing further permeability. The indurated sand layer can be up to tens of metres below the surface in old dune systems (Tyler et al. 2022). (1), (2), and (3) in the diagram are indicative of areas where terrestrial, surface, and subterranean groundwater dependent ecosystems may exist respectively.

Figure 8-95. Blue Lake is a springfed lake emerging from the regional aquifer within the sand mass of North Stradbroke Island in southeast Queensland, Australia (photo by Jonathan Marshall).

the largest and highest sand dunes of this island type in the world (Leach 2011). Regional and perched aquifers (on aquitards in the sand formed through a variety of processes) form in these dune systems, supporting numerous GDEs, with some springs discharging groundwater directly into lakes and wetlands (Figure 8-94).

Blue Lake (Kaboora in the local Aboriginal language) on Minjerribah is a comparatively well-studied example of a spring-dependent ecosystem that is fed by a sand mass regional aquifer (Marshall et al. 2006a; Marshall et al. 2011; Marshall and McGregor 2011; Page et al. 2012; Barr et al. 2013; Barr et al. 2015; Tibby et al. 2017; Maxson et al. 2021; FFigure 8-95). Located within the Naree Budjong Djara National Park, Blue Lake is of environmental and cultural significance, particularly to First Nations people of the island. It has an area of 10.3 ha, volume of 500,000 m^3, and a maximum depth of 11 m (Barr et al. 2013). It is thought to have been formed by sand deposition across former drainage lines (Lee-Manwar and Arthington 1980) and occupies a V-shaped interdunal depression at a point where the water table of the regional aquifer intersects with the ground surface (Barr et al. 2013). Spring discharge is evident as multiple, approximately circular patches of white sand in the otherwise organic-dominated sediment along the upslope side of the lakebed. This indicates that there may be an underlying aquitard present. Groundwater input is the dominant water source for the lake, with runoff inflows only during large rainfall events (Barr et al. 2013). Average lake-water residence time is 36 days and due to the continual and rapid throughflow of groundwater, Blue Lake does not stratify (Barr et al. 2013). Groundwater model simulations over 117 yrs indicate very little fluctuation in groundwater level at the lake (McGregor and Marshall 2013). Multiple lines of evidence indicate continual groundwater discharge has occurred from these springs for at least 7,500 yrs (Barr et al. 2013; Maxson et al. 2021). Groundwater discharges through outflow into a swamp, which acts as a natural weir and maintains a constant lake depth (Figure 8-96). Therefore, the Blue Lake ecosystem is recognised as an important climate refuge with exceptionally stable environmental conditions in a regional context (Tibby et al. 2017).

The properties of the regional aquifer water are fundamental to the ecology of Blue Lake. The groundwater entering Blue Lake has a mean residence time in the regional aquifer of approximately 100-150 yr (Hofmann et al. 2019). The water is very clear and the entire 11 m deep lake is euphotic, with benthic primary producers dispersed throughout (Barr et al. 2013). Autotrophs are dominated by cyanobacteria (Maxson et al. 2021), some prominent species of which grow colonially in gelatinous polysaccharide rich masses that initially encrust hard substrates such as fallen trees or the stems of emergent reeds. Some fall to the floor of the lake and form fist-sized, 'jelly ball' sphereoids that eventually roll downslope into the deepest part of the lake. There they accumulate creating a surprising and remarkable sight. The lake also supports a species of colonial cyanobacteria *Symphyonema kaboorum* that has been found nowhere else and appears to be endemic to Blue Lake (McGregor 2018). It forms expanded, cushion-shaped growths on the upper surface of large, submerged logs. Blue Lake is home to a submerged macrophyte *Eleocharis diformis* (Cyperaceae), which grows throughout the lake and is also presumed to be endemic to the lake. The flowers of this species are emergent around the lake margins, but in deeper water in addition to vegetive propagation by rhizomes, it has been observed flowering under water, with cased leptocerid trichopterans feeding on the flowers. This association suggests the possibility of underwater pollination by insects. The margins of the lake are dominated by the robust, emergent sedge *Lepironia articulata* (Cyperaceae), which grows in water up to 5 m deep (Marshall and McGregor 2011). The water is also very low in nutrients and the lake is oligotrophic (Barr et al. 2013). Many of the dominant lake cyanobacteria are able to fix atmospheric nitrogen (Maxson et al. 2021) and carnivorous macrophytes *Utricularia* spp. (Lentibulariaceae) harvest nitrogen from the bodies of planktonic animals.

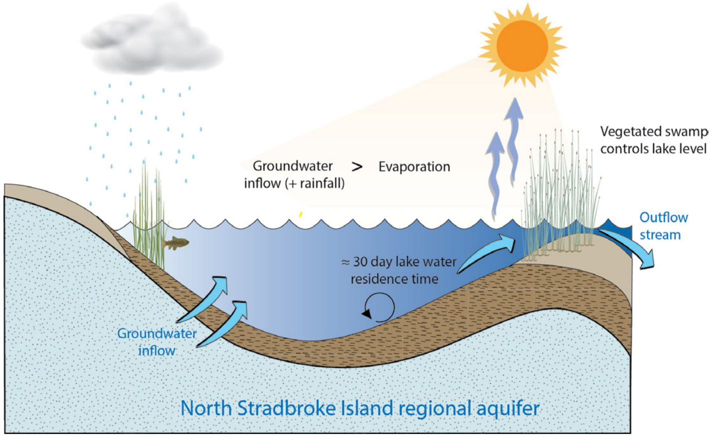


Figure 8-96. A conceptual model of Blue Lake hydrology with groundwater inflow via springs in the lake bed representing the major source of lake water. Lake depth is governed by a vegetated discharge swamp that actis as a natural weir. Groundwater discharge and throughflow results in a mean water residence time in the lake of just over 30 d (Barr et al. 2015). The margins of the lake are dominated by the robust, emergent sedge, *Lepironia articulata.*

Water residence time is an important driver of nutrient availability to other plants. Recent research suggests that longer residence times, as a result of reductions in the rate of spring discharge into the lake during dry climate phases, allow more nutrient remobilisation from the bed sediments, thereby resulting in higher lake productivity (Maxson et al. 2021). The weathered nature of the constituent sands also results in groundwater that is lacking in both dissolved ions and buffering capacity, so its dependent wetlands have characteristically soft and acidic water. These conditions are unsuitable for many regional aquatic species, resulting in many sand mass wetlands supporting specialised faunae (Marshall et al. 2011). Blue Lake and its outflow stream system support an evolutionarily unique population of the threatened oxleyan pygmy perch *Nannoperca oxleyana* (Nannopercidae; Marshall et al. 2011) and other specialist species, such as the ornate

Figure 8-97. The dune glider dragonfly *Tramea eurybia* (Libellulidae) is found at Blue Lake and other acid, coastal lakes in eastern Australia (photo by Jonathan Marshall).

rainbowfish *Rhadinocentrus ornatus* (Melanotaeniidae; Marshall et al. 2011), the so called 'wallum dragonflies' (Marshall et al. 2011), and threatened species of 'acid frogs' *Litoria cooloolensis, L. freycineti* (Hylidae), and *Crinia tinnula* (Myobatrachidae; McGregor and Marshall 2013; Figure 8-97).

Aranarawai Creek

Springs associated with perched aquifers in the coastal sand masses of southeast Queensland are less well known. Many perched aquifers do not discharge directly to the surface at all so have no associated springs, but there are some exceptions. Aranarawai Creek on Minjerribah is a small perennial stream that flows west into Amity Swamp (Figure 8-98). It discharges 0.04-0.08 m^3/s based on limited measurements (Leach 2011). It is the only known location on the island for the one-gilled swamp eel *Ophisternon* sp. (Synbranchidae), and is one of the few known habitats of an undescribed freshwater shrimp *Caridina* sp. *C1* (Atyidae), which is endemic to Minjerribah and Mulgumpin (Page et al. 2007; Marshall et al. 2011). The wet heath vegetation that lines its banks provides habitat for threatened acid frog species. At the location of the creek, the regional aquifer varies between approximately 3 and 14 m below the surface, based on a 117 yr groundwater model simulation, suggesting that the stream is fed by a perched aquifer and not the island's regional aquifer (Leach 2011; McGregor and Marshall 2013), although its aquifer source has not been definitively confirmed. A groundwater monitoring bore located immediately adjacent to the creek has a positive head above ground level, indicating positive flux of groundwater into the stream. The lower reaches of Aranarawai Creek may also intersect the regional water table near the coastal margins. Yet, as with many perched aquifer systems, investigations into the dynamics of discharge into the stream have not been undertaken and the locations of defined springs have not been mapped.

Figure 8-98. Aranarawai Creek on Minjerribah is a small perennial stream fed by a perched aquifer (photo by Jonathan Marshall).

History of Spring Use

Australia's climate is dominated by drylands (~78%), with smaller regions of temperate (~14%) and tropical conditions (~8%) (Peel et al. 2007), which contribute to the spatial and temporal variability of runoff and river flows across the nation (Kennard et al. 2010). However, this great variability in climate and landform makes it difficult to consistently access water (Silcock et al. 2016), with the exception of small waterbodies like rain-filled rockholes (gnammas; (Bird et al. 2016), riverine waterholes (Silcock 2009), and both GAB and non-GAB springs (Fensham et al. 2011).

Generally, springfed wetlands and other points of access to groundwater (e.g., wells where spring soaks were excavated and covered by First Nations people to prevent evaporation) are sites of reliable water that allowed Aboriginal peoples to survive and travel in an otherwise hostile dry environment (Powell et al. 2015; Moggridge 2020). Spring oases are proposed as mechanisms facilitating the initial dispersal of humans across the landscape (Bird et al. 2016). The long-term importance of springs for providing water to First Nations people is highlighted by the frequent association of springs with important archaeological sites (Neal and Stock 1986; Bird et al. 2016). Knowledge of spring locations was passed down through generations of First Nations people using stories and artwork, including rock paintings and carvings in wooden equipment (e.g., spear throwers; Moggridge 2020). Stories in the cultural Dreamtime of many Aboriginal groups include the Rainbow Serpent. The Rainbow Serpent relates to different aspects of Aboriginal life depending on the individual cultural group, but for many it includes a connection with groundwater and the formation of water features, including springs. Springs were considered the doorways for the Rainbow Serpent to travel through groundwater (see Moggridge, 2020 for more information).

Similarly, springs have provided an avenue for the colonial exploration and exploitation of Queensland (Harris 2002; Powell et al. 2015). The location of GAB springs guided early pastoralists and geologists to the presence of artesian groundwater, which began the widespread development of bores providing water for livestock production (Fairfax and Fensham 2003; Powell et al. 2015). Some springs became the sites of Cobb and Co transportation stations as rest stops for horses, bullock and cart freight, and travellers (Silcock et al. 2016). The early colonial fervour for obtaining water in arid areas also lead to many non-GAB springs being dynamited in the quest to increase available water supply (Silcock 2009). Other forms of physical damage to spring habitats also are common (e.g., grooved channels to alter flow paths in travertine at Talaroo Hot Springs; Negus et al. 2021; Figure 8-99).

Figure 8-99. Physical damage in the form of grooving of the lip of the spring vent to guide the direction of water flow around the travertine mound at Talaroo Hot Springs (photo by Peter Negus).

Mineral springs, especially those that discharge hot water, such as Innot and Talaroo Hot Springs (Figure 8-100) in north Queensland and Helidon Springs in southeast Queensland (Figure 8-74), have long attracted visitors for their health benefits; a practice called ‘taking the waters’ (Griggs 2013). ‘Taking the waters’ is the ancient practice of using the properties of spring water, such as heat (hydrotherapy) and mineral content for balneology, to heal ailments such as gout, rheumatism and skin problems (Griggs 2013). However, while interest in therapeutic bathing at Innot Hot Springs continues today, the use of many mineral springs in Queensland waned in the early 20th century. For example, the use of Talaroo Hot Springs as a health resort lasted for only a few years (Griggs 2013). This fading interest has mainly been due to the difficulty in travelling and accessing these remote locations, but also is related to concerns about radioactivity and bacterial contamination, as well as the rapid advancement of new, more effective medical treatments (Griggs 2013). Today, many springs and their associated watercourse discharges that are not located in conservation areas are still utilised as water sources for stock and recreational purposes.

Spring Biota: Endemics (Crenobionts) and Threatening Processes

Springfed wetlands are typically ecotones between different types of ecosystems (e.g., groundwater and surface water). They also often are refugial habitats, especially in arid areas, and are renowned as biodiversity hotspots (Cantonati et al. 2020). Despite their rarity in arid landscapes, isolation, and small habitat area, they present a wide array of habitat conditions and support many endemic species. Crenobiology in Australia is a relatively new field with few scientific papers published prior to 1980 and most since then focused on biological surveys and identification of newly described species from GAB springs. This rapid increase in newly described species has resulted in a proliferation of spring ecosystem studies on gene flow and the role of dispersal/isolation in structuring their biodiversity (e.g., Worthington Wilmer et al., 2008; Murphy, Guzik and Wilmer, 2010; Guzik et al., 2012; Mossop et al., 2015, 2017).

Non-GAB springs have received far less attention than their GAB counterparts, with the possible exception of those described in this chapter. As is the case with GAB spring wetlands (Bertrand et al. 2012; Boulton 2014), presence of water, hydroperiod and isolation are likely the key determinants of biological diversity and endemicity in non-GAB springs (Davis et al. 2013). Groundwater use and other impacts, such as physical damage from excavation, impoundments, grazing and feral animals, and establishment of exotic species (e.g., the invasive fish *Gambusia hoolbrooki* and toad *Rhinella marina*; Negus and Blessing 2022) have extirpated and threatened populations of endemic biota in GAB springs (Powell et al. 2015). Unfortunately, little is known about the extent to which this is the case in Queensland's non-GAB spring wetlands.

Many non-GAB springs include endemic, isolated and threatened plant species and therefore these spring wetlands merit conservation efforts and protection (Fensham et al. 2004). Examples of these species are illustrated in this chapter, including several that overlap in range with GAB springs (e.g., *Eriocaulon carsonii*; Figure 8-100), and they are also affected by the same types of threatening processes. Yet they do not generally receive protection under similar conservation frameworks (Negus et al. 2021; see below). Examples of biota indicative of the non-GAB spring ecosystems of Queensland include pitcher plants (*Nepenthes* spp.) from Cape York Peninsula (Wilson and Venter 2016; Figure 8-101), small aquatic snails, such as those of the Tateidae (previously Hydrobiidae; also common in GAB springs) and some Bithyniidae and Planorbidae (Ponder and Walker 2003; Ponder et al. 2019; Negus et al. 2020b) and, in hot springs, diverse microbial mats that include cyanobacteria and other algae and bacterial groups, some of which form stromatolite structures at Talaroo Hot Springs (McGregor and Rasmussen 2008; McGregor and Sendall 2017).

Figure 8-100. The endangered wetland plant, *Eriocaulon carsonii* is an example of a species that occurs in both GAB and non-GAB spring wetlands (photo by Glenn McGregor).

While non-GAB spring wetlands across Queensland support many endemic species and continue to generate scientific interest, most lack biological inventories and anthropogenic threats and damages are ongoing.

Conservation and Management of Non-GAB Springs

No single mechanism exists for protection of spring ecosystems in Queensland. The Queensland Government shares responsibility for the management of wetlands, including those fed by springs, with the Australian Government, local governments, landholders and the wider community. These responsibilities are formalised in laws passed by the Queensland and Commonwealth governments, through international obligations, agreements,

Figure 8-101. Carnivorous pitcher plants (*Nepenthes* spp.) on Cape York Peninsular are an example of Queensland biota dependent upon non-GAB springfed wetlands (photo by Jonathan Marshall).

and under a suite of policies and programs. Various aspects of spring ecosystems may be protected to varying degrees under one or more different instruments, including various national, state and local laws that regulate activities that impact springs (Department of Environment and Science 2022). In many situations these mechanisms of protection do not apply to a specific spring wetland, or are limited in managing threats (Lewis and Harris 2020). This issue is particularly relevant for many non-GAB springs, whose ecological and cultural values are still poorly characterised (McGregor and Rasmussen 2008).

At a national level, the Australian Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) regulates activities that may impact on Matters of National Environmental Significance. Matters of National Environmental Significance may include spring ecosystems as threatened ecological communities (e.g., karst springs and associated alkaline fens of the Naracoorte Coastal Plain Bioregion), spring ecosystems as habitat for threatened species, or spring ecosystems as a component of a broader matter (e.g., wetland of international importance, National Heritage area, World Heritage area, or water resources; Pointon and Rossini 2020).

State laws also regulate activities that may affect spring ecosystems. The Queensland Vegetation Management Act 1999 for example, regulates the clearing of native vegetation, particularly activities that may impact endangered or at-risk vegetation communities, and including springs where they support such communities. The Queensland Water Act 2000 and associated catchment Water Plans provide for the sustainable planning and management of water resources and regulate activities that affect water resources (e.g., groundwater extraction). The development of Water Plans includes consideration of the environmental needs of dependent ecosystems, such as those associated with rivers, lakes, and springs. Where threatened by groundwater extraction, springfed ecosystems are considered as environmental assets for Water Plans, and risks to their water needs are considered in the balance of decisions about water allocations (e.g., DES 2022). The Queensland Nature Conservation Act 1992 regulates activities that may interfere with native animals and threatened species, including those in springfed wetlands, as discussed in the non-GAB spring examples in this chapter. It provides the framework to create and manage protected areas on both public and private land.

As described above, the Boodjamulla (Lawn Hill) National Park and adjacent resource reserves contain a complex of springs from karstic rock aquifers, including Jirringirri Spring, an important meeting ground for Waanyi People (Waanyi People and Queensland Parks and Wildlife Service 2022). This national park and its springfed ecosystems are managed under a cooperative management arrangement between the Waanyi People, the Traditional Owners of Boodjamulla (Lawn Hill) National Park, and the Queensland Parks and Wildlife Service (Waanyi People and Queensland Parks and Wildlife Service 2022). Private nature refuges, also declared under the Nature Conservation Act 1992 (Qld), are another type of protected area that are managed to conserve cultural and natural resources while providing for the controlled use of those resources. The establishment of nature refuges gives priority consideration to areas with springs among other factors. The Steve Irwin Wildlife Reserve Nature Refuge, also discussed above, is an example of such a nature refuge that contains perched bauxite springs supporting biodiverse forests that provide habitat for threatened species and species with restricted distributions (Lyon 2010; Lyon et al. 2010a; Leblanc et al. 2015).

The range of threats affecting aquatic ecosystems, including springfed wetlands, includes pollution, modification of hydrology, disturbance (or removal) of habitat and biota, and introduction of exotic species (Marshall and Negus 2019; Negus et al. 2020a). Strategies for good stewardship of spring wetlands include the on-the-ground management of threats that are likely to compromise the spring's economic, ecological and social values. Ecological risk assessment provides a means of assessing and prioritising these threats using a range of data sources and can subsequently be used to guide management (Marshall and Negus 2019). For example, threats to the ecological values at Talaroo Hot Springs were assessed and identified as modification of hydrology, and the presence of ntroduced species such as cane toads (*Rhinella marina*) and feral pigs (*Sus scrofa*; Negus et al. 2021). The feral pigs root for food in the wetland sediments surrounding the mound, affecting the wetland vegetation including the endangered *Eriocaulon carsonii*, which is known to be impacted in this way (Fensham et al. 2011). Erection of an exclusion fence surrounding the greater area of the mound complex, including the adjacent wetlands and outflowing watercourses, now prevents feral pig access (Negus et al. 2021).

Finally, spring ecosystems may also be protected simply by geography, with many springs located in remote areas with limited accessibility. For example, some spring ecosystems on Cape York Peninsula are located at a significant distance from large population centres in terrain with limited access via roads.

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New Zealand

by Russell Death

New Zealand supports a diversity and abundance of both coldwater and geothermal springs that are distributed throughout most of the country (Death et al. 2004; Barquín and Scarsbrook 2008; Figure 8-102). The fauna of coldwater springs in New Zealand differs from most global springs in being typically dominated by insects and by having a higher diversity of macroinvertebrates than similar rhithral streams (Death and Winterbourn 1995; Barquín and Death 2006; Death and Barquín 2012). Crenobionts also seem to be less common, although this probably reflects a lack of study, as more recent work has found many new taxa, including those with restricted distributions (Collier and Smith 2006; Haase 2008). The geothermal springs, with temperatures often well above 45°, are characterized by a unique microbiotic assemblage of protozoa, algae, fungi, cyanobacteria and archaebacteria (Brock and Brook 1971; Brock 1978; Vincent and Forsyth 1987), although several Diptera and Coleoptera also can occur in these hot springs (Winterbourn 1968; Boothroyd 2009).

Many coldwater and geothermal springs retain good ecological integrity if they are protected in the conservation estate, which covers 30% of New Zealand. However, much of the remainder of New Zealand has sustained

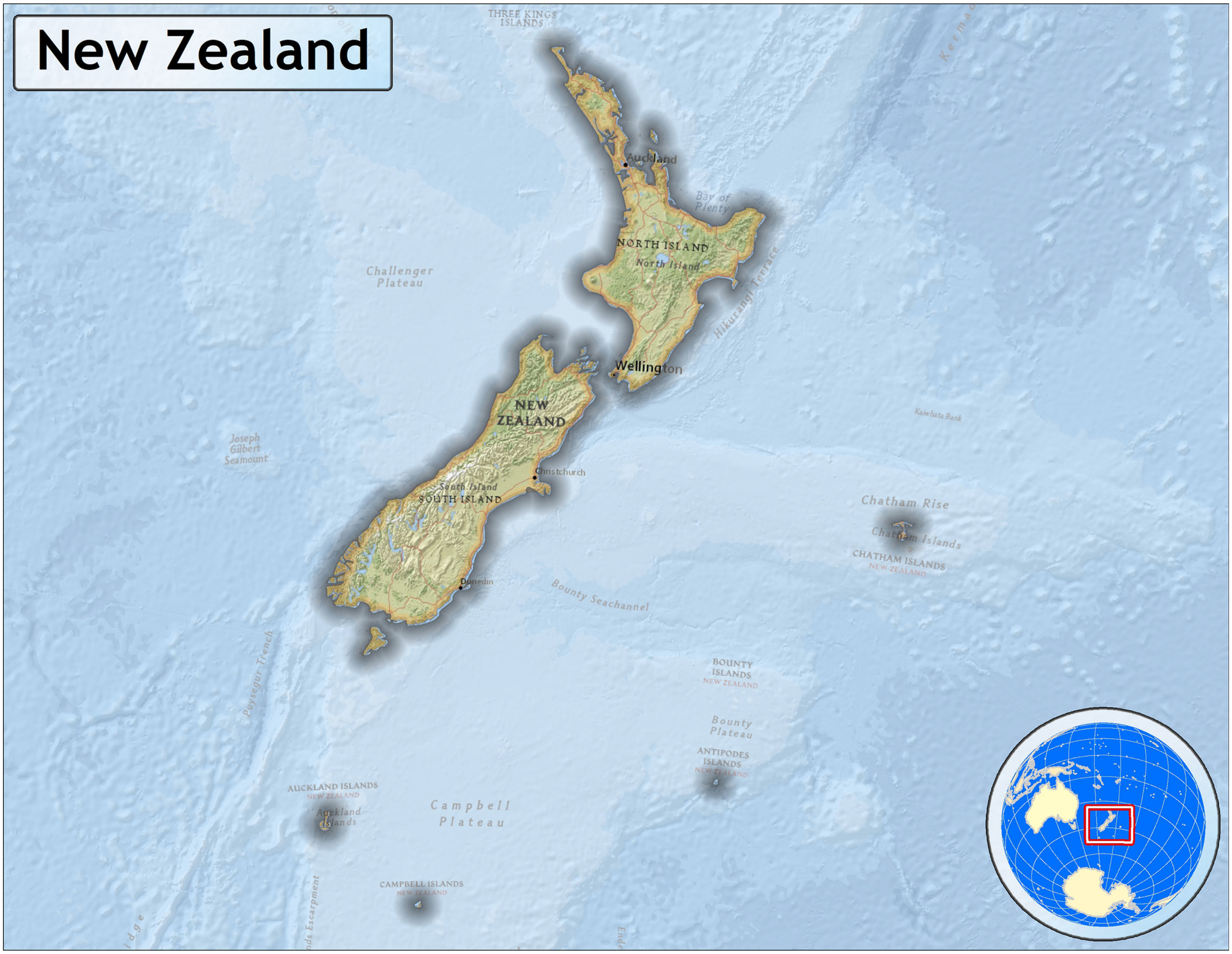

Figure 8-102. Map of New Zealand.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -41.00°, 2nd Standard Parallel = -48.00°.

rapidly intensifying dairy farming over the past two decades, with concomitant declines in surface water quality and the ecological health of many New Zealand waterways (Foote et al. 2015; Julian et al. 2017; Joy et al. 2018). Te Waikoropupū springs is the largest freshwater spring in the southern hemisphere. It is situated in a conservation estate, is sacred to local Māori culture, and is purported to have the highest water clarity in the world (73 m), but it is threatened by eutrophication of groundwater from adjoining dairy farms (Owen et al. 2020). Smaller springs on farmland often are poorly managed and have low ecological health (Scarsbrook and Haase 2003; Scarsbrook et al. 2007), although recent changes in legislation hopefully will result in exclusion of livestock from larger springs. Many smaller springs and seeps in farmlands also are heavily impacted by water abstraction for agriculture, town drinking water supplies and, increasingly, by water bottling for export. Geothermal springs are threatened by steam and hot water extraction for thermal baths and power generation.

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Chapter 9

Latin America and the Caribbean Region

Overview

While the timing of human colonization of South and Central America has been hotly debated (Figure 9-103), New World paleolithic hunter-gatherer cultures were related to those that had crossed the Bering land bridge. They reached the American landscape in the late Pleistocene, perhaps before 33,400 ya (Somerville et al. 2021), and colonization was likely nearly extensive by about 14,000 yr ago (Gruhn 2020). Although occupation of the landscape was much more recent than that in the Old World, springs throughout these continental areas have been intensively used for the same purposes as across the globe, and many have been altered, particularly in arid and semi-arid regions. However, springs likely play important but little-recognized roles in mesic landscapes as well. Unfortunately, knowledge of the springs ecosystem distribution and status in these regions is generally restricted to specific regions, and is less well understood at national and more coarse spatial scales. The synopses presented here include vastly different landscapes. The springs of the Río Lola in northern Chile (the "longest river in the driest desert in the world", De los Ríos-Escalante 2012), where mining is affecting river discharge and water quality (Lameli, below). Springs in southern Brazil are subject to significant impacts of deforestation, urbanization, and agricultural uses (Felippe, this chapter). Many large springs and innumerable small springs in Mexico have been intensively used for potable and agricultural water sources, sometimes with elaborate water delivery systems, as well as for irrigation, and livestock management, as documented by Fensham and Rodriguez Guzman and by Quadri Barba (this chapter). However, many Mexican SDT are at risk of extinction and warrant conservation attention (Lozano-Vilano et al. 2020). Springs also are relatively abundant in the Caribbean region, some contributing to high levels of productivity in coastal areas. However, as everywhere, many springs have been altered by intensive uses of potable supplies extraction and agriculture (Heartsill-Scalley, below). The geothermal and springfed Río Shanay-timpishka, a "boiling river," was recently described emerging in the Amazonian lowlands, 700 km from the tectonic uplift of the Andes (Ruzo 2016). Such basic discoveries and the complex socio-economic and cultural relationships around springs reflected in the synopses below, demonstrate that much more research on the springs of South and Central America and the Caribbean region is warranted.

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Figure 9-103. Map of Latin America, including Central and South America and the Caribbean region.

The map image was developed from National boundaries extracted from the Database of Global Administrative Areas [GADM], version 2.8 (see https://gadm.org/index.html). The background reference map developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). This map was projected into the Lambert Conformal Conic coordinate system; Central Meridian = -67.84°, 1st Standard Parallel = 27.27°, 2nd Standard Parallel = -36.0°.

South America

Brazil

by Miguel Fernandes Felippe

Brazil has a wide variety of landscapes and some of the largest rivers in the world (Figure 9-104). However, we barely know its springs. Brazilian territory is located in a Precambrian cratonic basement that formed Neoproterozoic orogenic systems which were covered by large Paleozoic sag basins (Alkmin 2015). The altitude ranges from the sea level to 2,995 m. Besides the important continental aquifers of Guarani and Alter do Chão, deep and developed soils cover most of the territory and have considerable relevance to springs discharge. Despite this scenario, springs from some regions (e.g., the Atlantic Tropical region) are far better known than those from others (e.g., Amazonia or the Semi-arid Northeast).

The calculated density of springs in Brazil varies from 1.9 springs per km^2 in the semi-humid karstic depression to more than 28 springs/km^2 in the Atlantic highlands. Most Brazilian springs are small helocrenes and rheocrenes, fed by local underground flows (Felippe and Magalhães 2014, Carvalho et al. 2015), but their perennity varies spatially. Modern spring water is predominant, with groundwater residence times normally varying from 12 yr to more than 60 yr, indicating the importance of rainfall regime (Felippe 2013). The Brazilian Forest Act mandates a 50 m-radius of preservation area around

Figure 9-104. Map of Brazil.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -33.74°, 2nd Standard Parallel = 5.27°.

springs throughout the country; however, the reality is far from the paper. Reports about integrity of springs show disturbing results. In rural zones, more than 70% of studied springs are rated as being of moderate quality or worse (Gonzalez and Schiavinato 2019, Rezende and Luca 2017). An example of imperilment of springs is in Belo Horizonte (6th largest Brazilian city), where even urban parks report that 35% of springs are in moderate or poor ecological integrity, and 24% exhibit *Salmonella* sp. contamination (Felippe and Magalhães 2012). The main pressures on Brazilian springs and other freshwater ecosystems are due to urban expansion, livestock and agriculture use, mining, and deforestation (e.g., Azevedo-Santos et al. 2016). The greatest challenge regarding the protection of springs in Brazil is increasing awareness of their diversity, functioning and importance.

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Northern Chile

by Christian Herrera Lameli

Chile is a long and extensive country with a great diversity of climates (Figure 9-105). In northern Chile, the Atacama Desert is renowned as the driest desert in the world, where average annual rainfall in some areas does not exceed 1 mm/yr. However, a more temperate climate prevails in central and southern Chile, with more rainy conditions and the presence of numerous springs. Numerous hot springs are recognized throughout all of Chile and are linked to the extensive volcanic chain of the Central Andes (Cortecci et al. 2005).

It is in the north of Chile where important mineral resources of copper and lithium are concentrated, which are intensively exploited. Large volumes of water are required for the development of mining activity, which has produced significant negative effects on the different surface ecosystems (Ríos et al. 2010). The management of groundwater resources in arid and hyper-arid areas is always challenging, as the low water availability in these zones conflicts with high potential demand for different needs (Wheater et al. 2010). Many springs and rivers born from the emergence of spring waters have significantly reduced flows, and there are many cases where these have dried up due to the overexploitation of aquifers.

Along the coastline of northern Chile, an extensive mountain range called Cordillera de la Costa (Coastal

Figure 9-105. Map of northern Chile.

Map boundaries extracted from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the GDA 1994 Geoscience Australia Lambert coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = -33.97°, 2nd Standard Parallel = -17.51°.

Figure 9-106. The springfed Río Loa north of the city of Calama.

Range) exists. One of the driest regions of the Atacama Desert, it encompasses many areas with an average annual precipitation of less than 1 mm/yr. This means there are long periods of extreme aridity and rare rainfall events widely separated in time (Herrera and Custodio 2014). On the western slope of the Cordillera de la Costa, some low discharge springs are recognized. Spring waters there are of the sodium-chloride type, with sulfate as the second anion in importance. Groundwater composition has some similarity to seawater due to atmospheric deposition being dominated by marine aerosols and intense concentration by evapotranspiration (evapoconcentration) of precipitation. The radiocarbon content of the coastal spring waters indicates increased recharge between 5,000 and 3,000 ya, but a mixture of groundwater recharged at a small rate along millennia is also a possible explanation (Custodio et al. 2018). Wetter conditions between 5,000 and 3,000 ya, when recharge to coastal aquifer occurred, can be explained by the incursion of warmer atmospheric currents from the coast of Ecuador to northern Chile associated with a southward displacement of El Niño-Southern Oscillation.

Figure 9-107. An unnamed spring that feeds the flow of the Río Loa in the vicinity of the city of Calama.

One notable example of the consequences of intensive aquifer exploitation on a surface water course is the Río Loa (Loa River), which is the longest river in Chile (Herrera et al., 2020; Figure 9-106, Figure 9-107). The Río Loa supports a truly green corridor that flows across the hyper-arid core of the Atacama Desert. The Río Loa is born from numerous springs located in the western volcanic chain on the flanks of the Miño and Aucalquincha volcanoes. Its main tributaries are the Río San Pedro and Río Salado, which also originate in the high Andes, and the Río San Salvador, which joins the Río Loa downstream of the city of Calama (Aravena and Suzuki 1990). The Río Loa has a small flow that varies between 4000 L/s in its upper course to 300 L/s at the mouth of the river where it discharges into the Pacific Ocean (CORFO 1977). The small flows of the Río Loa have progressively decreased over the past decades as a result of the intensive exploitation of the aquifers adjacent to the Loa River. This affects the indigenous communities living since pre-Hispanic times on the river banks, and has produced a significant deterioration of typical flora and fauna associated to the wetlands along the Río Loa (Yañez and Molina 2008), which are in danger of extinction.

The determination of the residence times of the water of the springs in the volcanic arc of the Andes has been made from 14C of the dissolve inorganic carbon (DIC). However, high CO_2 discharge in geothermal springs suggests that 14C-inactve volcanic CO_2 is an important component of groundwater DIC (Godfrey et al. 2019). The Río Loa catchment basin close to the western slope of the Andes contains groundwater that is often supersaturated with CO_2 (Aravena and Suzuki 1990).

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Central America

Continental Central America

by Roderick J. Fensham and Atzalan Rodriguez Guzman

The springs in central America are generally poorly documented but occur in the karst systems in high rainfall environments (Rosales Lagarde et al. 2014), provide a source for lakes in montane environments (Arriaga and Rodriguez Estrella 1997; Palacio-Núñez et al. 2010; Bogan et al. 2014) and also occur throughout the desert regions of northern Mexico (León de la Luz et al. 1997; Hendrickson et al. 2008; Bogan et al. 2014; Figure 9-108).

More than 500 species of fish occur in Central America (Miller 2005) and springfed systems provide habitat for much of this diversity. One of these species has a rare adaptation for survival in hyper-sulphidic environments (Tobler et al. 2008). Cuatro Ciénagas is a large complex of spring-fed pools and streams in north-central Mexico, and is a renowned biodiversity hotspot. The hydrogeology has been reasonably well studied (see references in Felstead et al. 2015) and biological survey extends back to the 1960s (Hendrickson et al. 2008). There is a plethora of endemic organisms within the wetlands of this single location including at least eight species of fish (Hendrickson et al. 2008) and nine species in five genera of hydro-

Figure 9-108. Map of Central America, excluding Mexico.
Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 7.21°, 2nd Standard Parallel = 18.49°.

biid snails (Hershler 1985). Semi-systematic monitoring suggests many populations are in decline (Hendrickson et al. 2008). There are also six species of endemic reptiles, including two terrestrial species (McCoy 2018). A recent study highlights the diversity and range of bacteria there with affinities to marine environments (Souza et al. 2006).

The springs of Cuatro Ciénagas are beset by the same threats that are impacting desert springs throughout the world. The most pressing is the diminished flows associated with dewatering of their source aquifer, but exotic species are also having a major impact (Hendrickson et al. 2008; Gesundheit and Macías Garcia 2018). The spring-fed 'oases' around the coast of Baja are being degraded by pollution and aquifer drawdown associated with coastal development (Imaz-Lamadrid et al. 2020).

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Mexico

by Paulo Quadri Barba

Spring ecosystems in Mexico remain largely understudied. Information about their distribution has only been reported for some thermal springs by the Federal Commission of Electricity (Prol Ledesma 2020) (Figure 9-109; Figure 9-110). Even without data on their distribution, we know that most spring ecosystems in Mexico are likely to exist on private property, as most of the Mexican territory is owned either as private collective or private individual property, with only about 2 – 4% of public lands (Quadri and Quadri 2016). Importantly, Mexican law stipulates that springs belong to the owner or owners of the land where they occur and only those springs occurring on federal land such as river or watercourses, beaches, or the few public lands that exist – mostly within protected areas – are direct responsibility of the Mexican federal government.

Depending on the region, Mexican springs may face different threats. In the southern and eastern portions of the country, were precipitation can exceed 4,000 mm/yr and where deforestation rates exceed 30,000 ha/yr, in states like Chiapas or Campeche (Global Forest Watch 2014), spring integrity is mostly threatened by soil erosion and pollution. However, north of the Trans-Mexican Volcanic Belt precipitation decreases, to an average of less than 200 mm/yr, in the hearts of the Sonoran and Chihuahuan deserts. Northern Mexico is also characterized

Figure 9-109. Map of Mexico.

Map boundary suggested by Stevens. National boundaries extracted from the Database of Global Administrative Areas [GADM], version 2.8 (see https://gadm.org/index.html). Background reference map developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). Map projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = -102.53°, 1st Standard Parallel = 14.53°, 2nd Standard Parallel = 32.72°

by Calcisols and Leptosols (SEMARNAT 2002), which typically develop at shallow depth that favors water evaporation over infiltration, and lead to slow groundwater recharge times. Thus, springs in northern Mexico are mainly threatened by aquifer over-exploitation caused chiefly by agricultural expansion, mining, and to a lesser extent, urban consumption.

Widespread and systematic assessments of spring ecosystems are almost non-existent or are limited to a few areas where springs have very high ecological, economic, and/or cultural value. Perhaps one of the most studied springs complexes in the nation is Cuatro Cienegas in the northern state of Coahuila. This large springs complex has a level of biological endemism similar to that of the Galapagos Islands, with more than 70 endemic taxa (Unmack and Minckley 2008; Souza et al. 2012). Despite its designation as a protected area, the springs of Cuatro Cienegas are severely threaten by aquifer overexploitation for agricultural and mining activities. Between 1977 and 2000, researchers found spring pool size reductions of up to 80% (Torres-Vera et al. 2012), indicating a critically endangered status.

While data on springs in Mexico is scarce, aquifers across the country are relatively well monitored by the National Commission of Water (CONAGUA 2015). CONAGUA recognizes a total of 653 aquifers in Mexico, of which only 448 are considered available for human uses (CONAGUA 2015). In 2015, 105 of the aquifers were reported as overexploited. Most of the overexploited aquifers are located in central and northern Mexico along corridors of densely populated areas and areas supporting large-scale agricultural activities. For example, Sonora and Chihuahua are two of the states with the most overexploited aquifers. This is problematic because mining operations are projected to intensify in the region over the coming decades, and the desert, forest, and grassland habitats of Sonora and Chihuahua are also home to critical populations of endangered species, such as the Mexican gray wolf (*Canis lupus baileyi*), black bears (*Ursus americanus*), jaguars (*Panthera onca*), and American bison (*Bison bison*).

Under climate change, springs will become increasingly important as climatic refugia or holdouts for many species (Cartwright et al. 2020). Yet, competing uses of water will certainly increase social and political tensions in critical regions, such as northern Mexico, and will potentially displace conservation uses of water. Hence, it is imperative for Mexico to increase its springs mapping and monitoring efforts to more effectively manage its water resources, and to use these data to better equip federal and state level conservation agencies with climate adaptation planning tools.

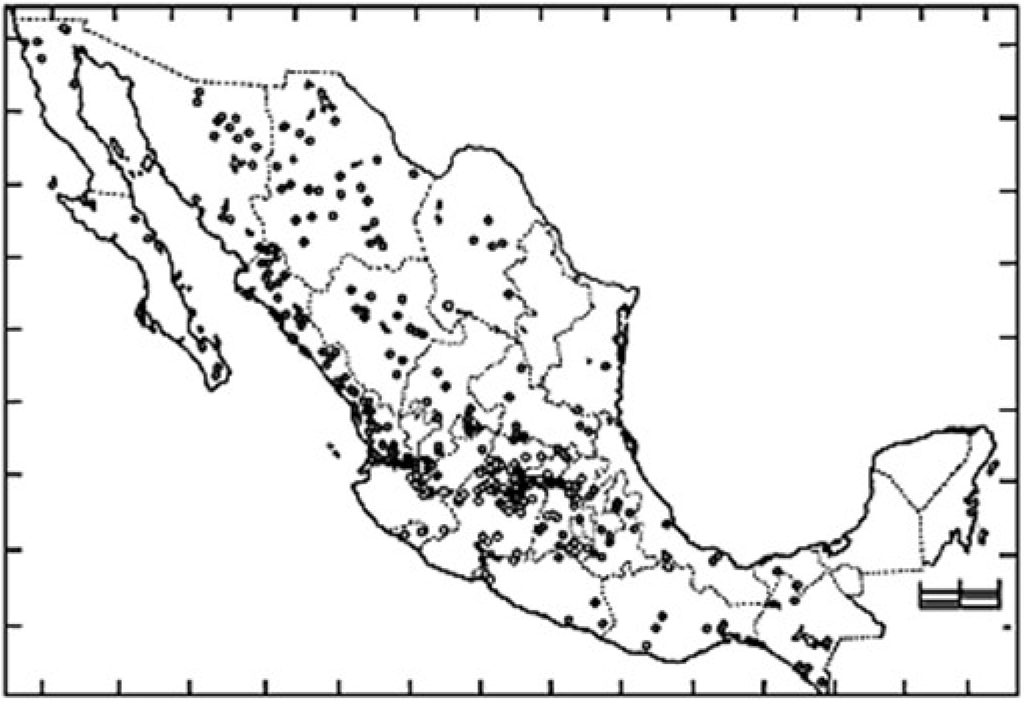

Figure 9-110. Distribution of thermal springs mapped by the Federal Comissión of Electricity of Mexico.

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Caribbean Islands

by Tamara Heartsill-Scalley

Overview

Caribbean springs are sites of early indigenous human presence, legends, and fossils (Beeker et al. 2002, Peros et al. 2006, Cristóbal 2007, Aranda et al. 2017; Figure 9-111). Diffuse, contact, artesian, and solution conduit springs are all known to occur in the region. Thousands of springs have been identified in Cuba, Jamaica, Hispaniola, and Puerto Rico (Giusti 1978, Rodríguez-Martínez 1997, Miller et al. 2001, Troester and Turvey 2004, Lluberes et al. 2013, Gómez-Gómez et al. 2014, Wishart 2015, Gordon-Smith and Greenaway 2019). A quarter of these may be named or identified in maps. There are only a few perennial freshwater springs the British and U.S. Virgin Islands. Local streams known as ghuts or guts, depend on springs within headwater pools to maintain habitat for wetlands, migratory birds, shrimp, fish, and amphibians (Howell and Towle 1976, Nemeth and Platenburg, 2007; Gardner, 2008). Active volcanos and volcanic areas result in broadly distributed hydrothermal springs in Saba, St. Eustatius, St. Kitts and Nevis, Montserrat, Guadeloupe, Dominica, Martinique, St. Lucia, St.Vincent and the Grenadines, and Grenada (Huttrer 2000). These springs have high total dissolved solids and a range in water temperatures due to the combination of infiltrated rainfall from meteoric waters

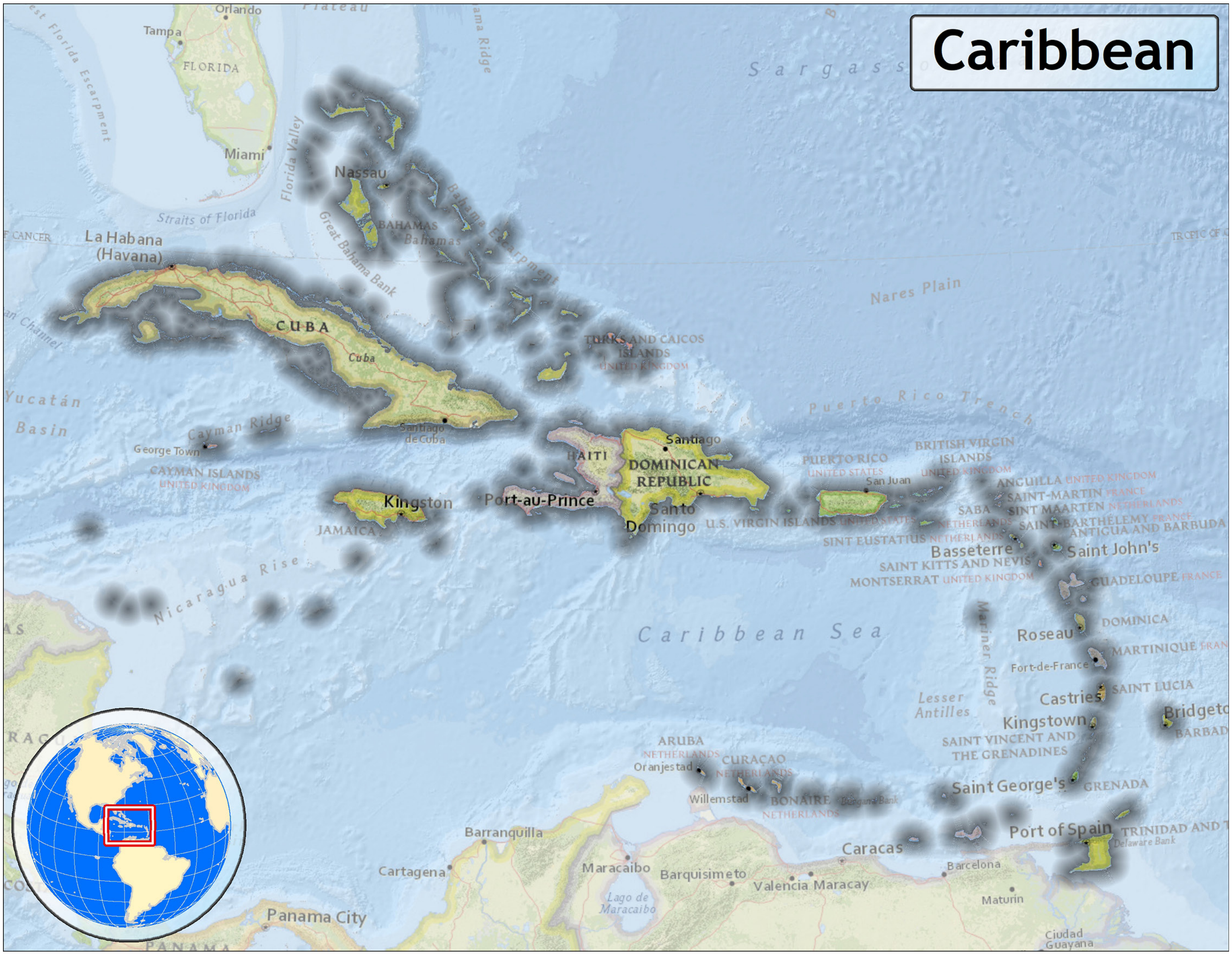

Figure 9-111. Map of the Caribbean region.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 10.04°, 2nd Standard Parallel = 27.27°.

mixed with deeper groundwater and hydrothermal fluids of magma origin (Rad et al. 2013, Hemmings et al. 2015). In Puerto Rico, spring water composition is predominantly calcium-magnesium-bicarbonate in karst aquifers, sodium-chloride-sulfate in thermal springs, and volcanic rock springs are grouped as Ca-Mg-HCO waters. One exception is "Pozo de la Virgen" spring, located in serpentinite substrates, with high silica concentration from hydrated magnesium silicate mineral (Guzmán-Ríos 1988).

Ecology

Although macroinvertebrates and gastropods from freshwater springs have been described for Antigua, Barbados, Barbuda, Puerto Rico, St. Kitts and Nevis, details of sampled sites as being true springs, or streams or wells associated to springflow, or sites named "spring" are not clearly categorized because it was not a main research objective (Bass 2005, Bass 2006, MacKay and Williams 2011, Pérez-Reyes et al. 2013, Boger et al. 2014). Exceptions are the species lists of sulfur-tolerant fauna (with the endemic fish, *Limia sulphurophila*) in the Dominican Republic (Greenway et al. 2014), and the microbial diversity study of Baños de Coamo in Puerto Rico using a metagenomic approach, which yielded genes associated to iron, phosphorous and sulfur biological processing (Padilla-Del Valle et al. 2017).

Coastal submarine fresh and brackish water springs have been documented in various islands (Giusti 1978, Blume et al. 1981, Lugo et al. 2001, Adame et al. 2013, Gordon-Smith and Greenaway 2019). The flow dynamics from those springs alter the near shore wetland forests and seagrass communities via changes in water physical-chemical attributes. Springs are part of ecosystem flows to coastal ecosystems, and sea-level rise will alter the role of springs in many parts of the region (Adame et al. 2013, Lambs et al. 2018). The highest carbon stocks in mangroves have been associated with submarine freshwater springs (Adame et al. 2013). Springs buffer soil salinity and water level height in forested wetlands, marshes and other forest types during drought periods and contribute to balancing freshwater budgets (Lambs et al. 2015). In Puerto Rico, spring-fed marshes create habitat for a recently identified (coqui llanero, *Eleutherodactylus juanariveroi*) riverine frog species (Ríos-López and Thomas, 2007). Less than 5 km from the coast, springs support forested *Pterocarpus officinalis* and *Annona glabra* wetlands, marshes, and quartz-dominated blanket sands bogs with carnivorous bladderworts (*Utricularia*) and sundews (*Drosera*). These communities differ from other coastal sites due to important spring water inputs from underlying karst and alluvium (Medina et al. 2007, Lugo et al. 2001 Feagin et al. 2013).

Contaminants

Discharge from industrial and sewage treatment plants and land cover changes that alter recharge capacity, water flow, and soil surface elevation have been documented to affect spring discharge and ecosystem dynamics (Guzmán-Ríos 1988, Lugo et al. 2001). Atypical algal growths, agricultural pesticide residues, phthalates and chlorinated volatile organic compounds have been identified in springs from Jamaica and Puerto Rico (Guzmán-Ríos 1988, Witter et al. 1999, Torres et al. 2019). Padilla et al. (2011) describe that long-term contamination found in karst aquifers reflects the characteristics that make the aquifer productive, which is the capacity for storing and releasing over long-terms, which also increases potential for contaminant exposure at spring discharge areas. Hydrogeological research on recharge and contamination dynamics suggests that karst springs are complex, combine inter-basin diffuse and conduit, and are affected by seasonal fluctuations of head boundaries in relation to distance from the ocean (Ghasemizadeh et al. 2016).

Information regarding the condition of springs as ecological systems in the insular Caribbean is dispersed and fragmented. Water quality and hydrogeology data are generally available, but descriptions and classifications of springs need to integrate ecological knowledge about springs.

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Chapter 10

North America

Overview

Early scientific investigation and assessment of springs in North America north of Mexico include studies by California (Waring 1915), Meinzer (1923, 1927), Waring (1965), and other US Geological Survey researchers, who documented discharge, geochemistry, hydrogeological processes, and the distribution of larger geothermal and non-thermal springs. Springs distribution has been recorded on US Geological Survey 1:24,000 topographic maps since the 1920s. However, the symbol used to designate springs is a circle with a squiggled line indicating the direction of flow, which precludes ready assessment of springs density (placing an asterisk in the center of the springs symbol would facilitate such analyses). Early studies of springs in Canada were summarized by van Everdingen (1991), and were primarily focused on mineralized and geothermal springs, with more recent interest and concern over permafrost responses to warming climate. Spring ecology and arthropod biodiversity studies in Canada were the focus of an influential book by Williams and Danks (1991), and the special issue in the Journal of the Kansas Entomological Society by Ferrington (1995).

Unfortunately, the early focus on North American springs hydrogeology did not include much consideration of ecosystem ecology. That scientific field arose from the conceptual advances by Lindeman (1942), and was ground-truthed by H.T. Odum (1957) at Silver Springs in Florida. Advances in understanding the taxonomy and ecology of SDT has been gradual and poorly integrated over the past century and a half, with conservation concerns emerging in the latter half of the 20th Century, particularly among fish, and subsequently for SDT invertebrates (e.g., Hendrickson and Minckley 1985; Minckley and Deacon 1991; Shepard 1993; Hershler et al. 2014).

Recognition of the importance of springs, and legal protection for them in North America, has lagged behind that in Europe. Water rights policies in Canada and the United States are generally applied to surface water and are largely relegated to individual states, except in situations where water features (streams, rivers, lakes) cross state boundaries or, in Canada, where indigenous cultures claim priority. However, there is considerable variation in springs distribution (Stevens and Meretsky 2008) among regions, states and provinces. For example, Hawai'i apparently has a low density of springs, but few have been mapped. However, the Waimea River that drains Waimea Canyon, "the Grand Canyon of the Pacific" on Kaua'i has a mean annual discharge of 3.64 m^3/s, and is baseflow fed apparently by unmapped springs emerging from high-level dike aquifers in the Nepali volcanic series and by discharge from the Alakai Swamp (Mink and Lau 1992). In contrast, Nevada, the driest state in the USA, has an estimated springs density of nearly 0.11 springs/km^2, the highest density yet reported for the nation (Stevens unpublished data).

Much variation in jurisdictional status also exists among North American states and provinces, with appropriative water rights in western USA states and Canadian provinces where arid climates prevail, and riparian ownership policies generally applied in more mesic eastern states and provinces. Canada's northern provinces (Northwest Territories, Nunavut, and Yukon) practice public authority management, while Quebec uses civil code to manage its water rights. Exceptions and mixed policies also exist: California and Nova Scotia both use a mixture of appropriative and riparian rights (McGuinness 1951; Christensen and Lintner 2007). Groundwater policies in both countries are far less rigorously defined or enforced and springs, which lie at the contact between the subsurface and surface, often "fall between the cracks" of jurisdictional attention (Nelson 2008).

As across the world, losses of habitat and SDT populations in North America are generally inversely related to elevation, latitude, and proximity to human development, including regions with intensive agriculture. Among USA states with springs inventory and assessment programs or in which springs inventories have been conducted (e.g., Arizona, California, Florida, Missouri, Nevada, Texas, Wisconsin; see synopses on these states and regions, above) springs are generally reported to be in degraded or collapsed ecological condition. Many recent extinctions have been among SDT populations, particularly in arid regions (e.g., Williams and Sada 2020). Groundwater pollution from agricultural and industrial wastes threatens Florida's many limnocrene and other springs (Knight 2015).

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Canada

Alberta

by Abraham E. Springer

Alberta supports a broad array of habitats among a dozen natural regions within its Rocky Mountain, foothills, grasslands, and parklands ecoregions (Natural Regions Committee, 2006; Figure 10-112). There has not been an accounting of all springs in the province. Borneuf (1983) described over 600 springs and the Alberta Geological Survey digitized locations from these maps and published the data as a geographic database (Stewart 2014). Non-thermal springs are abundant across Alberta in areas with significant topographic relief, in montane and foothill zones and in river valleys, while a few geothermal springs are generally restricted to the east slope of the Canadian Rockies (i.e., Cave and Basin springs complex in Banff National Park). Groundwater dependent fens are abundant but poorly mapped on the northern Great Plains and in the adjacent aspen parklands. These fens support high concentrations of rare orchids, other wetland plants, invertebrates, and some amphibians (Moss and Packer, 1983; Clifford, 1991; Russell and Bauer, 2000; Lepitzki, 2002).

The array of provincial spring types is related to topographic diversity, with hillslope, rheocrene, gushet, and, less commonly, geothermal and limnocrene springs emerging in the foothills and along the piedmont of the

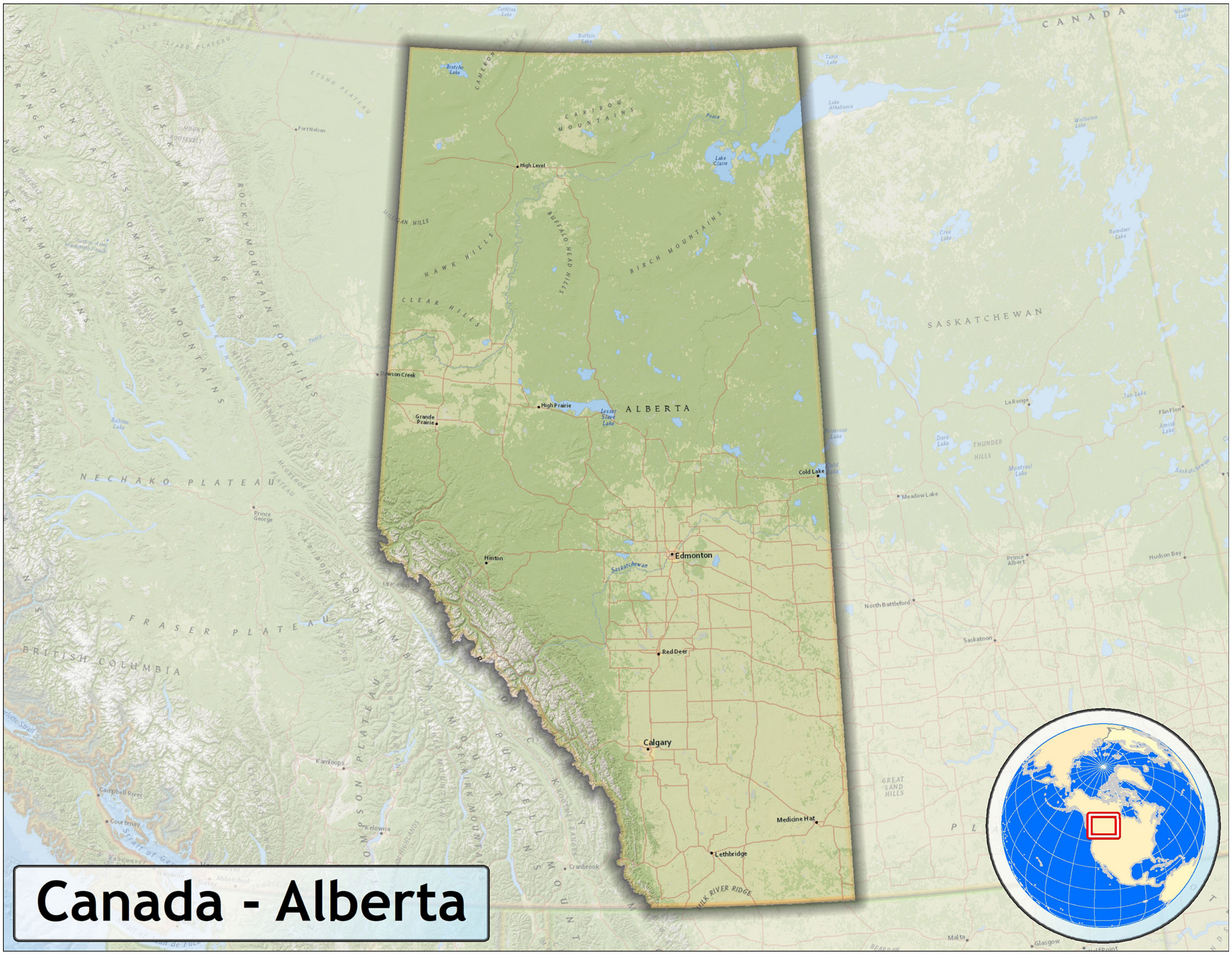

Figure 10-112. Map of Alberta, Canada.

Map boundary data were derived from the Database of Global Administrative Areas [GADM], version 2.8 (https://gadm.org/index.html). The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 49.00°, 2nd Standard Parallel = 60.00°.

Canadian Rocky Mountains. Springer et al (2015) conducted comprehensive inventories at 56 springs across different biomes and identified 526 plants, >25 % of the provincial flora, on less than 4 ha of spring habitat, 12.5% of which were non-native. Across Canada overall, Williams (1983) reported that ecological impacts on springs were primarily related to logging, road building, livestock grazing, water development, wildfire. In Alberta, spring ecosystems with greater human disturbance, from factors such as livestock management, are more vulnerable to invasion by non-native plants, and this reduces plant biodiversity and the ecological services provided by these distinctive, insular ecosystems (Nielsen et al 2019). Because the surface water in the province is overallocated, management strategies to maintain ecosystem flows will be essential to support stewardship of the springs in the province.

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United States

Florida Springs

by Robert L. Knight

The Coastal Plain of the Southeastern USA is underlain by porous carbonate geology that creates the highly productive Floridan Aquifer, extending over an area of about 259,000 km^2 (Figure 10-113). Historic groundwater discharge from this aquifer through springs is estimated as 57 million m^3/day (Bush and Johnston 1988). Although incompletely inventoried, >1,132 Florida springs have been reported (Florida Springs Task Force 2000, Scott et al. 2004), of which >30 have average flows >245,000 m^3/day. Under premodern development conditions, Florida's springs had among the highest known primary and secondary productivity (Odum 1957). This high community metabolism is evidenced by abundant fish and other aquatic wildlife populations, including rare and endangered species. Florida's springs are popular summer recreation destinations, contributing $1 billion/yr to the state's economy (Knight 2015). Florida's springs and associated spring runs have an estimated combined area of <4,050 ha, making them the one of the rarest natural communities in Florida (Florida Springs Institute 2019). Floridan Aquifer artesian springs are highly imperiled due to excessive human groundwater extraction

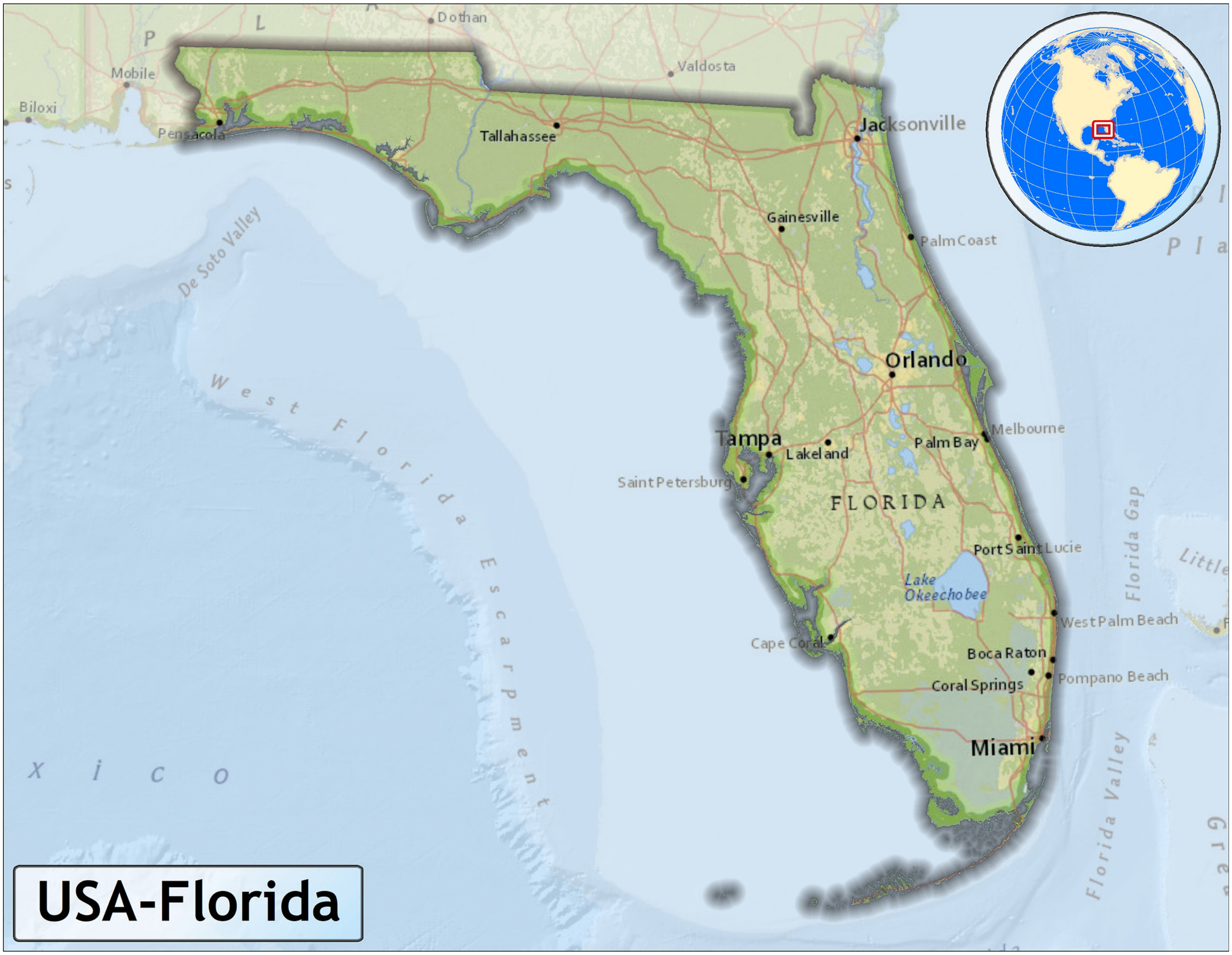

Figure 10-113. Map of Florida, USA.
Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 24.52°, 2nd Standard Parallel = 31.00°.

for irrigation and nutrient loading from fertilizers and wastewater sources (Florida Department of Environmental Protection 2008).

The estimated average spring flow decline in Florida is 32% compared to predevelopment conditions (Knight and Clark 2016). Dozens of formerly large-magnitude springs have stopped flowing during even moderate drought conditions. About 80% of all of the springs in Florida have average nitrate-nitrogen concentrations that exceed the state's springs standard of 0.35 mg/L (Florida Springs Institute 2019). Silver Springs in north-central Florida was long the largest tourist attraction in Florida (Knight 2015). Having lost more than 30% of its historic average flow and with a nitrate-nitrogen concentration four times higher than the state standard, Silver Springs has lost much of its former ecologic and economic functionality. Restoration actions needed there and across Florida's 10,000,000 ha Springs Region include significant reductions in fertilizer and wastewater loads, reduced reliance on groundwater for irrigation, and re-connection to adjacent waterways by dam removal (Knight 2015).

FSI (2019) assessed the ecosystem health of 32 "sentinel" springs in Florida's Springs Region. Using IUCN's methodology on these springs revealed the following assessment: Collapsed – 12.5% with F grade (including some large springs), Critically Endangered – 37.5% with D grade, Endangered – 50% with B or C grade. While those springs are all slightly to greatly impaired, many are endangered or more seriously impaired, and some have collapsed.

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Northeastern USA Springs

by Douglas S. Glazier

The 730,000 km² Appalachian Mountain region (including the 480,000 km² Appalachian Basin) in eastern North America consists of numerous mountains and valleys underlain by ancient sedimentary, volcanic and ocean floor rocks (Figure 10-114). Thousands of ambient springs and hundreds of thermal springs exist in this geologically diverse region, but they have never been fully counted. The state of Virginia alone, which is situated in the mid-Appalachian region, has >1,500 ambient springs and approximately 100 thermal springs. Appalachian springs are diverse in geology (including shale, sandstone, limestone and dolomite bedrock, substrates consisting of a variety of particle sizes [silt to boulders], and single conduit to diffuse spring sources), water chemistry (from highly acidic and mineral-poor to alkaline and mineral-rich [pH typically ≈ <4 to >8, and ionic conductivity ≈ <20 to >1,000 µS/cm]), discharge (seepage to flows >10,000 L/min), temporal persistence (intermittent to permanent) and habitat types (including sipeocrenes, rheocrenes, limnocrenes and helocrenes). Teal (1957) reported on the ecosystem metabolism of Root Spring, a limnocrene in Concord, Massachusetts. Other springs, especially in Pennsylvania, Virginia and West Virginia, also have been the subject of biological, ecological, geo-

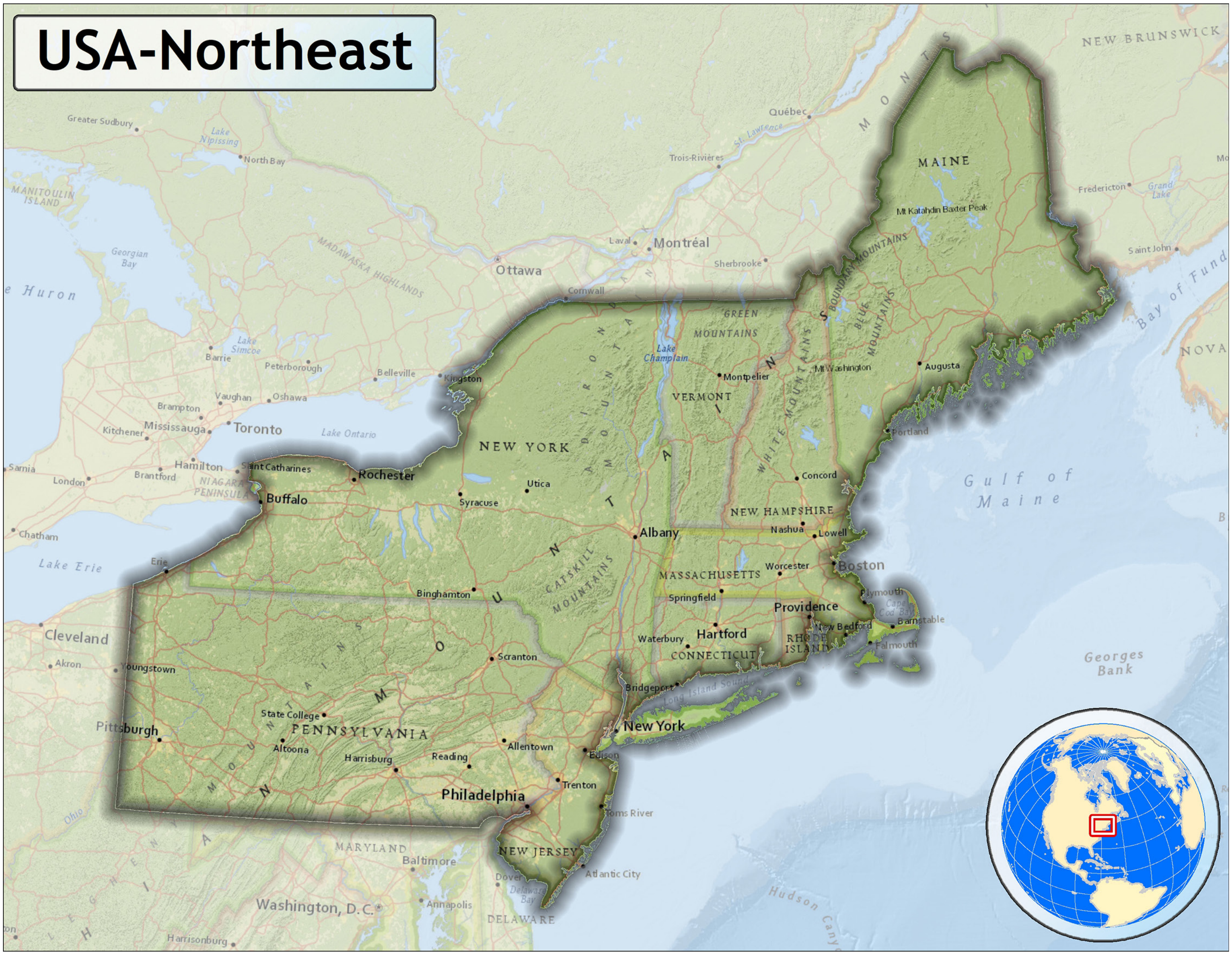

Figure 10-114. Map of the northeastern United States.
Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 38.93°, 2nd Standard Parallel = 47.46°.

chemical and hydrological studies. Various spring-dependent species occur in the Appalachian region (e.g., flatworm *Phagocata gracilis*, gastropod *Fontigens nickliniana*, amphipod *Gammarus minus*, isopod *Lirceus brachyurus*, and salamanders *Eurycea aquatica* and *Gyrinophilus porphyriticus*), some of which are federally endangered, (e.g., watercress darter *Etheostoma nuchale*).

In seven states, coal, oil and gas mining influences spring-supplying aquifers surrounded by Paleozoic rock formations. Resorts and spas have been developed at several mid- to southern Appalachian thermal springs (e.g., Berkeley Springs and Sweet Springs in West Virginia, Warm Springs and Hot Springs in Virginia, Hot Springs in North Carolina, and Warm Springs in Georgia). Introduced warm-adapted guppies (*Poecilia reticulata*) thrive in Berkeley Springs, to the delight of many visiting tourists. Some large springs are major sources of drinking water for humans and/or livestock at farms, resorts and small towns (e.g., Roaring Spring and Boiling Springs in Pennsylvania, Berkeley Springs in West Virginia, and Big Spring Farm in Virginia). Municipal, agricultural, recreational and commercial exploitation or diversion of spring- and groundwater via damming and/or the construction of channels, basins, cisterns and other structures has occurred (e.g., Bedford Springs, Bellefonte (Big) Spring, Boiling Springs, Hundred Springs and Roaring Spring in Pennsylvania, Berkeley Springs in West Virginia, and Radium Springs in Georgia). Recent droughts have caused large decreases in the discharges of some springs. For example, a 1999-2002 drought reduced the discharge of Berkeley Springs by nearly half. Springs located within agricultural or residential areas may be contaminated with herbicides, nitrates and human/livestock fecal matter/coliform bacteria. Most Appalachian roadside 'spout' springs tested (>80% of 21) contain coliform bacteria. A potential problem for mid- to northern Appalachian springs and groundwater is contamination by de-icing road salt, which is used extensively during the winter. Much needed ecological restoration of damaged springs is occurring in some places (e.g., Big Spring Run and Big Spring Creek in Pennsylvania).

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Cumberland Plateau Case Study: The Green River Basin in Kentucky

by Benjamin W. Tobin, Sarah M. Arpin, and Alan E. Fryar

The Green River basin of Kentucky is a preeminent example of a karst-dominated river system in the midwestern USA (Figure 10-115). Mississippian-age limestone aquifers (Dicken 1935; White et al. 1970; Paylor and Currens, 2001) underlie more than half of the basin and the majority of the river's baseflow is derived from karst groundwater discharge (Blair et al. 2012). This river basin contains the most extensive cave system in the world (Mammoth Cave; Brown 1966) and the largest spring in Kentucky, Gorin Mill Spring, which drains over 390 km^2 (Ray and Blair 2005) and has a discharge ranging from 1 m^3/s to > 40 m^3/s (Quinlan and Rowe 1977). There are 1,336 springs currently documented in the Green River Basin, and 5,284 documented springs in the Kentucky, although many undocumented springs exist (A. Arpin, written communication). Other large springs in the basin include Graham Spring (baseflow 0.6 m^3/s for a 315-km^2 area) and Lost River Rise (baseflow 0.4 m^3/s for a 155-km^2 area). Although the ecology of these springs has

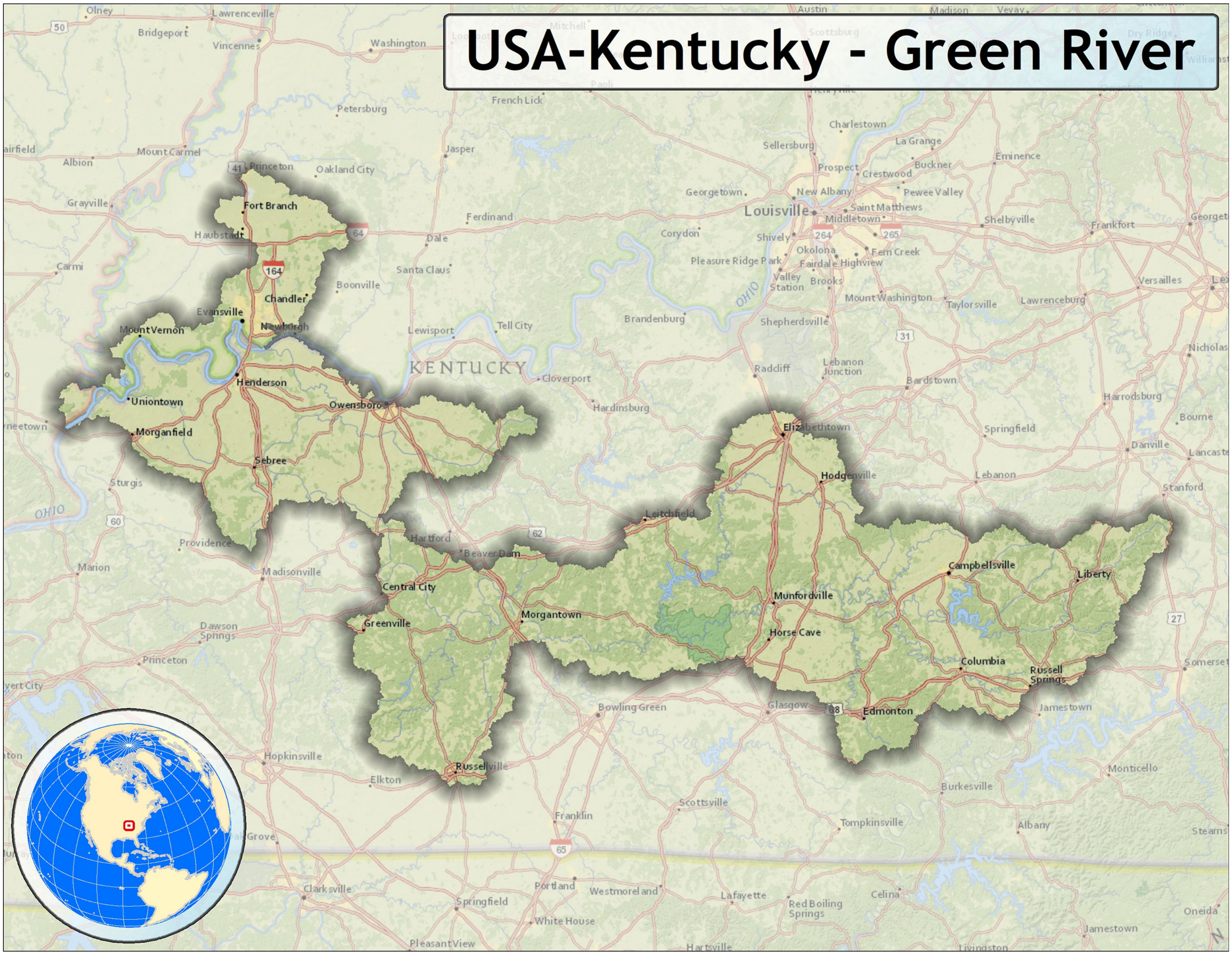

Figure 10-115. Map of the Green River basin in Kentucky, USA.
Map boundary data were derived from National Watershed Boundary Dataset Level 8 Hydrologic Unit Code (HUC) polygons that intersect the Green River in Kentucky, USA [https://prd-tnm.s3.amazonaws.com/index.html?prefix=StagedProducts/Hydrography/WBD/National/GDB/, accessed Dec. 27, 2022]. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 36.81°, 2nd Standard Parallel = 38.36°.

received little study, the Green River has been noted as a freshwater biodiversity hotspot (Masters et al. 1998).

Because surface and subsurface flow paths are well integrated in karst terrains, water and pollutants can move rapidly from sink points to springs (Penick 2010). Moreover, because of subsurface storage in less permeable zones, pollutants can continue to impact springs for long time periods (Vesper et al. 2001; Loop and White 2001). Land-use practices in springsheds have been shown to be the primary driver of spring water quality (Pfaff 2003; Tobin 2007). Impoundment of the Green River behind a series of dams has resulted in loss of habitat for many groundwater-dependent species, such as the endangered Kentucky Cave Shrimp (*Palaemonetes ganteri*; Olson 2006). Sediment movement through the groundwater system as a result of land-use changes and erosion from farmland has imperiled that species (Lisowski 1983; Olson 2006). However, springs such as Gorin Mill and Lost River Rise have shown excellent improvements in water quality since the 1970s, as knowledge of the groundwater basin connectivity and potential impacts has increased, along with techniques to mitigate and prevent impacts (Quinlan and Rowe 1977; Schindel et al. 1995; Ray and Blair 2005; Blair et al. 2012, Kaiser 2019).

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Ozark Mountains

by Teresa M. Carroll

The Ozark Plateaus Physiographic Province (the Ozarks), constitutes a large portion of the U.S. Interior Highlands between the Appalachian and Rocky Mountain ranges (Figure 10-116). The Ozarks, one of the major karst landscapes in the U.S., spans nearly 127,000 km^2 and consists of three physiographic sections (Fenneman 1938); the Springfield Plateau, Boston Mountains, and Salem Plateau. These sections encompass most of southern Missouri, northwest Arkansas (includes the St. Francois Mountains), and small parts of Oklahoma and Kansas. The Ozark aquifer system is comprised of three aquifers: the Springfield Plateau (SPA), the Ozark (OA), and the St. Francois (SFA); shallowest to deepest, respectively. With elevations ranging from 610 m below sea level to 488 m above sea level, the aquifer and confining unit lithologies consist primarily of limestones of Mississippian age and older, shales, sandstones, and dolomites of Ordovician and late Cambrian ages (Adamski et al. 1995; Hays et al. 2016) with dolomite and limestone serving as the major karst forming units (Bullard 2020). Dissolution of this lithology creates intense karst topography characterized by multiple caves, springs, fissures,

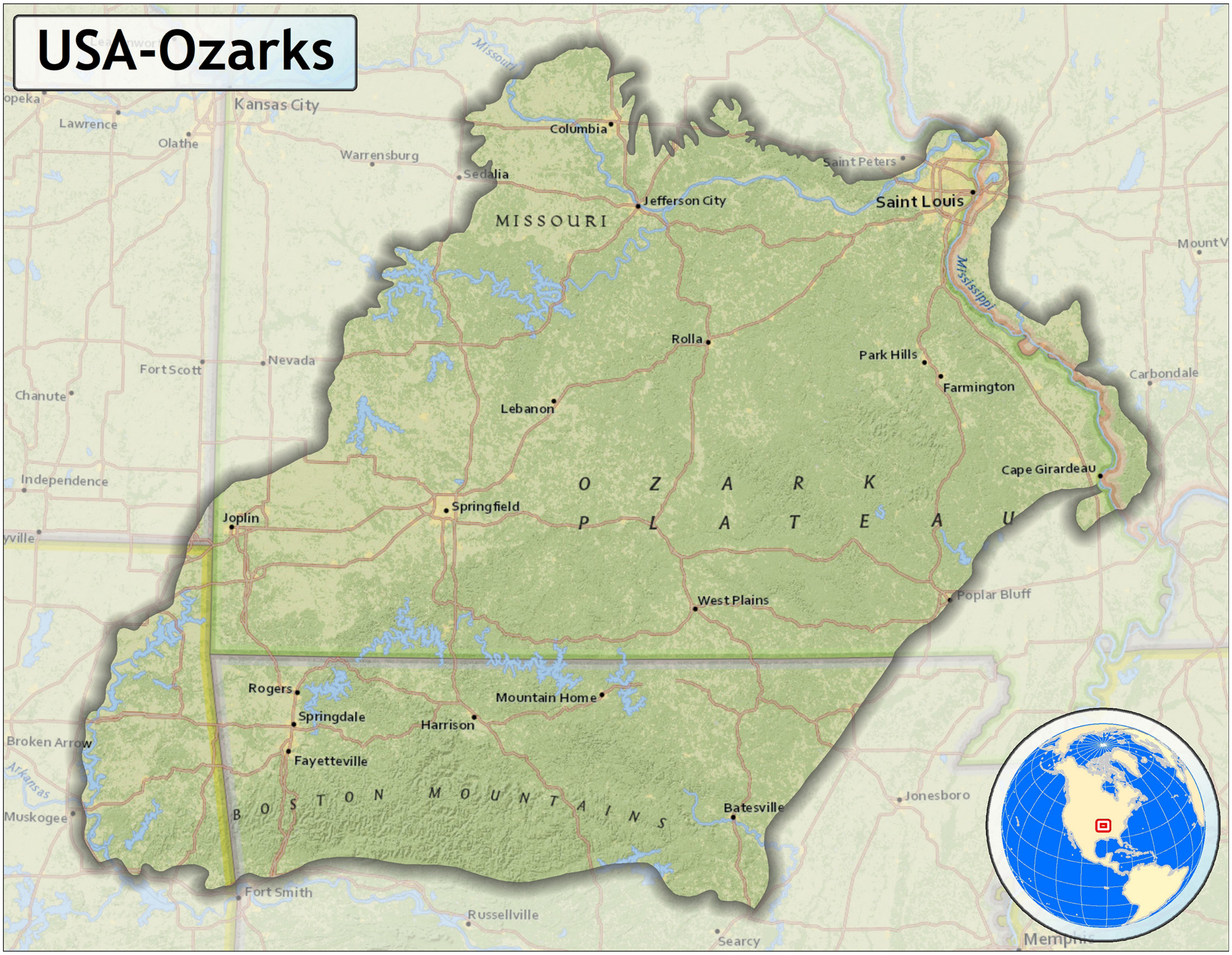

Figure 10-116. Map of the Ozark region, USA.

Map boundary data were derived from the Ecocode 'NA0413 (Ozarks)' class of Terrestrial Ecoregions The Nature Conservancey [https://geospatial.tnc.org/datasets/b1636d640ede4d6ca8f5e369f2dc368b/about, accessed Dec. 27, 2022]. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 35.35°, 2nd Standard Parallel = 39.31°.

sinkholes, and losing streams that recharge groundwater (Vineyard & Fender 1982). Nearly 6,000 springs are documented within these karsted carbonate lithologies dominated by rheocrene and cave emergence patterns, with moderate concentrations of gushet and limnocrene springs, but fewer helocrenes.

Groundwater flow in the SPA is typically shallower (<30 m below spring outlet) than in the deeper OA where phreatic channels may extend 90 or more m below the spring outlet (Bullard 2020). Groundwater travels rapidly through large solution openings often several meters in diameter, producing cold, freshwater carbonate springs. Exceptions exist in the lower thick limits of the OA where subsurface residence and surface return times increase, resulting in increased mineralization and the production of cold chalybeate and saline springs (Carroll 2009). These focused flow paths coupled with varying degrees of porosity and permeability of the karst bedrock system allows for rapid infiltration of surface pollutants (Carroll et al. 2021), but little information exists on the biological or physical impacts of contaminated groundwater within springs in this ecoregion (Bowles et al. 2018).

Significant portions of the Ozarks have been converted from forest to cattle grazing and agriculture, and urban and rural residential development (MDNR 2002; Nature Conservancy 2003; Karstensen 2010). The impact of these land use alterations, associated elimination of riparian vegetation and alterations in surface runoff or groundwater flow threaten to elevate herbicide, pesticide, and nutrient levels, sedimentation, inputs of sewage or fecal material, and represent the largest long-term threats to the physical and biological integrity of springs in this ecoregion (Davis and Bell 1998; USDASF 1999; Nature Conservancy 2003). Fecal indicator bacteria (often from land applied animal waste and poultry house bedding) are detected with increasing frequency in groundwater from the Ozark aquifer and associated springs, where conduit flow and rapid transport prevent effective filtering (Graening and Brown 2000; Vana-Miller 2007; Kresse 2014). Other threats come from hard rock extraction and heavy metal contamination from hundreds of abandoned historic mining sites in the area (USDAFS 1999; Carroll et al. 2021). Dewatering of shallow aquifers occurs in areas where sand and gravel mining occur. Moreover, research shows that the impacts of mining, even from a century or more ago, are still present today (Rösner 1998; Nimick et al. 2004; Church et al. 2007). Hence, these systems typically have high specific conductivity, lower dissolved oxygen concentrations, distinctly increased concentrations of heavy metals (iron, lead, zinc, and manganese) and elevated levels of chemical substances once used in ore processing such as arsenic and cadmium. All have been found in sediment, water, and aquatic organism samples in surface and ground water systems near areas where mining once occurred (Rösner 1998; Nimick et al. 2004; Saviour 2012). Iron concentrations in Ozark spring phreatic conduit sediments, for example, have been found to be as high as 15,000-25,000 mg/kg dry weight (T. Carroll unpublished data). Sinkhole dumping, spills and leaks of hazardous materials from pipeline breaks, and underground storage tanks and septic tanks are also problematic in karst areas (Bullard 2020). Finally, even though public, domestic and industrial groundwater use in the Ozarks increased 400% between 1962 and 2010 as population density increased 52% over that same time period (Hayes et al., 2016), groundwater withdrawal for these uses comes from the deeper OA, and thus has little to no effect on Ozark springs which pull from the shallower SPA (Kingsbury 2020; J. Vandike personal communication October 8, 2020).

Regardless of these threats, groundwater quality for the Ozark aquifer system remains good, with inorganic and organic constituents remaining at low concentrations relative to benchmarks in 87-100% of the study area (Kingsbury 2020). This explains why long-term monitoring of plant and invertebrate communities in large Ozark springs (1st and 2nd magnitude) indicates that the ecological integrity is very good. A broad diversity of aquatic plants occurs among and within springs (69 taxa and 11-23 species, respectively); varying little since the 1940's (Steyermark 1941; Bowles and Cheri 2019). Faunal communities also sustain high levels of biodiversity. Analysis and summary of data derived from all pertinent data sources show that fauna reported from Ozark springs includes more than 355 taxa represented by more than 225 genera from over 100 families. Large-spring studies report faunal communities with greater than 100 invertebrate taxa representing more than 66 genera from over 50 families, with 12-30 species residing within a given spring (Bowles et al. 2011; Bowles et al. 2018). These data are similar to that reported over 20 years ago; evidence of long-term physicochemical stability (Nielsen 1996; Sarver et al. 2002). Comparable diversity is found in smaller springs (4th - 6th magnitude) which harbor 30-50 invertebrate families and 11-45 species among and within springs, respectively (Zeller 2010; Carroll and Thorp 2014). Consistency in the level of diversity among spring sizes confirms, as others have found, that invertebrate assemblages represent about one third of that found in the region's streams (Danks and Williams 1991; Bowles and Dodd 2016).

Common invertebrate taxa include platyhelminth and annelid worm species, over 15 families of snails (Gastropoda), and over 26 genera of chironomid midges. None have been characterized as spring dependent taxa (SDT). The most abundant taxonomic group is Peracarida (arthropod crustaceans; amphipods and isopods) with numbers, on average in some springs, reaching more 7,710 individuals/m^2 (Carroll and Thorp 2014). Those reported as "spring and cave stream" species include amphipods *Allocrangonyx hubrichti*, *Crangonx forbesi*, and several *Bactrurus*, *Stygobromus*, and *Gammarus* species; as well as the isopod *Lirceus hoppinae*. The amphipod *Stygobromus heteropodus*, and isopods *Caecidotea dimorpha* and *Lirceus megapodus* are reported as SDT. Crustacean decapods are dominated by the *Cambarus* and *Faxonius* (formerly *Orconectes*) genera. *Cambarus setosus* and *Faxonius marchandi* are reported to be SDT.

Trichoptera is consistently cited as the most species-rich taxonomic group with over 55 taxa representing 34 genera from over 16 families being reported in Ozark springs. *Micrasema ozarkana*, *Agapetus artesus*, *Ceratopsyche piatrix*, *Cheumatopsyche robisoni* and *C. rossi*, *Ochrotrichia contorta*, *Ceraclea maccalmonti*, and *Glyphopsyche missouri* are considered SDT. Because these trichopterans are known to be environmentally intolerant and often rare endemic taxa, they serve as evidence to the good water quality of Ozark springs (USDAFS 1999).

Common vertebrate taxa include salamanders and fishes. Fish communities typically range from only 3-5 species per spring, but more than 20 species have been recorded among Ozark springs. Of those, *Etheostoma microperca* and *E. parvipinne* have been cited as SDT. While *Amblyopsis rosae* (Ozark Cavefish) and *Typhlichthys subterraneus* (Southern Cavefish) have been collected in spring samples, they are typically reported as being cave or subterranean-dependent species. Salamanders are common constituents of spring faunal communities with *Eurycea multiplicata griseogaster* noted as being dominant and a "spring and cave stream" species.

This depiction of common spring biota does not include zooplankton, mites, spiders, springtails, snakes, frogs, bristletails or anything that could have entered or fallen into the spring habitat from adjoining terrestrial settings (centipedes, millipedes crickets, birds, terrestrial dipterans, rodents, mammals etc.). Pertinent data sources included published and unpublished records from agency reports and scientific literature, as well as personal interviews with experienced biologists and correspondence with many representatives from relevant scientific and environmental agencies in the Ozarks. The full data base, including all spring SDT, and cave-obligate or cave-dependent aquatic species will be shared in a forth-coming paper (Carroll, T. in prep).

One of the most noted large-scale imperilment events occurred in Maramec Spring, a 1st magnitude limnocrene. Contamination by a pipeline release of 91,000 L of ammonium nitrate and urea fertilizer obliterated dissolved oxygen levels and severely reduced trout populations and several species of cave fauna (Vandike 2007). Rapid water transport (a natural artifact of these very open flow systems) often serves as a self-flushing method of remediation in Ozark springs, and took approximately six weeks.

Springs have long been revered by the people of the Ozarks. Their consistency of flow made them an invaluable source for power generation, food procurement, domestic water supplies, refrigeration, and recreation; more so in the past than now. Today, their permanency of flow and relative constancy of other physicochemical conditions enables the establishment and survival of a disproportionately large number of rare, relict, and endemic spring species (Glazier 2012), contributes to the success of the large number of taxa in Ozarks springs that reproduce asynchronously all year, and accentuates the dominance of non-insect invertebrate taxa lacking a life cycle with an aerial dispersal phase (ex. crayfish). Ozarks springs are often responsible for sustaining the flow of karst-associated surface streams, but also function as refugia for surface stream invertebrate communities during floods and droughts. While most give little thought to preserving or protecting our springs, we must do so before it is too late.

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Wisconsin

by Susan K. Swanson

Largely undeformed Paleozoic sedimentary rocks gently dip away from a high point of Precambrian parent rock in north-central Wisconsin, USA (Figure 10-117), and Pleistocene glacial deposits cover bedrock over approximately three-quarters of the state (Mudrey et al. 2007). Most springs in this 169,639 km^2 state emerge as a result of preferential groundwater flow through fractures in exposed or shallowly buried Paleozoic sedimentary strata, and many are located within the unglaciated Driftless Area in southwestern Wisconsin. They are rheocrene, fracture or contact springs that emerge along hillslopes or at a break in slope, primarily in valleys that have downcut into the Paleozoic sandstones, limestones, and dolomites. Bedrock fracture-controlled springs also occur in glaciated regions where unlithified materials are thin or absent. For example, springs emerge from the Prairie du Chien Group in central Wisconsin, where streams have incised through glacial materials and into the shallow bedrock, and along the Niagara Escarpment where Silurian dolomite is exposed or shallowly buried. These springs exhibit fracture or seepage-filtration morphologies depending

Figure 10-117. Map of Wisconsin, USA.
Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 42.49°, 2nd Standard Parallel = 47.08°.

on whether the fractured rocks are exposed or buried by glacial materials. Other springs in glaciated regions of Wisconsin are controlled by variations in topography and shallow aquifer lithology. These rheocrene or limnocrene, seepage-filtration springs commonly form at the break in slope along and between end moraines and interlobate moraines, or near the margins of former glacial lakebeds.

The mean flow rate of over 400 recently surveyed springs was 27 L/sec, with values ranging from 4 to 518 L/sec (Swanson et al. 2019). Most of those springs flow perennially and have cold and constant temperatures capable of supporting fisheries and creating habitat for endangered and threatened species (Bradbury and Cobb 2008; Swanson et al. 2020). However, more than half of the inventoried springs exhibited moderate to high levels of anthropogenic disturbance due to dredging or impoundment, presence of a spring house, proximity to roads, or access by livestock. Wisconsin also contains many other smaller springs and seeps, although they often are difficult to distinguish from the region's vast wetlands and lakes (Swanson et al. 2019).

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Great Plains

by Lawrence E. Stevens

The Great Plains occupy 2.8 million km^2 of central North America, and extend from the Mississippi River west to the Rocky Mountains, and from Texas northward into 12 more northerly US states, as well as into the Canadian provinces of Alberta, Saskatchewan, and Manitoba (Figure 10-118). Formerly the largest grassland in the world, the Great Plains are dominated by rolling prairie hills, underlain in part by Cretaceous seaway strata. The Great Plains also contain the "badlands" and the Black Hills of South Dakota (the latter extending into northeastern Wyoming), and give rise to several major river systems.

The largest aquifer in the Great Plains is the High Plains Aquifer (HPA), which contains the Ogallala Aquifer and occupies 452,439 km^2 across Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The Ogallala Formation is a Miocene to Pliocene fluvial deposit underlain by Permian to Cretaceous strata and overlain in the south by the Blancan Formation and in the north by glacial loess. It and the rest of the HPA produce many springs, some of the larger of which are recreational destinations, and some springs are protected as state parks (e.g., Smith Falls State Park,

Figure 10-118. Map of the Great Plains region, USA and Canada.
Map boundary data were derived from 'Temperate Grasslands, Savannas and Shrublands' class of Terrestrial Ecoregions The Nature Conservancy [https://geospatial.tnc.org/datasets/b1636d640ede4d6ca8f5e369f2dc368b/about, accessed Dec. 27, 2022]. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 28.93°, 2nd Standard Parallel = 54.13°.

northern Cherry County, Nebraska; Black Hawk Springs at Crapo Park in Burlington Iowa). While a great many springs are used for domestic water, agricultural and livestock support, waterfowl and wildlife production, as well as recreation, their regional conservation status has not been intensively studied.

Due to concerns about aquifer overdraft, the US Geological Survey is required by Congress to report on HPA groundwater status from well (bore) data every two years, reports that provide trends in groundwater levels from predevelopment time prior to 1950 to the present. Recent reports document pronounced declines in HPA groundwater from predevelopment time to 2013, ranging up to 78 m, but with increases in storage of up to 26 m in the northern HPA. Groundwater depletion rates are most pronounced in the southern Great Plains. For example, much of the Ogallala Aquifer in Kansas has already been depleted or has a remaining lifespan of less than 25 yr (e.g., Buchanan et al. 2015), and similar conditions exist in northern Texas. However, depletion rates are lower in South Dakota and Wyoming. Overall, the mean area-weighted mean decline in the aquifer elevation was 4.7 m from 1950-2013 (McGuire 2014). The total volume of water stored in the aquifer in 2013 was about 3,602 km^3, a decline of 329 km^3 (8.4%), with a 2011-2013 decline of 44.4 km^3 (1.1%).

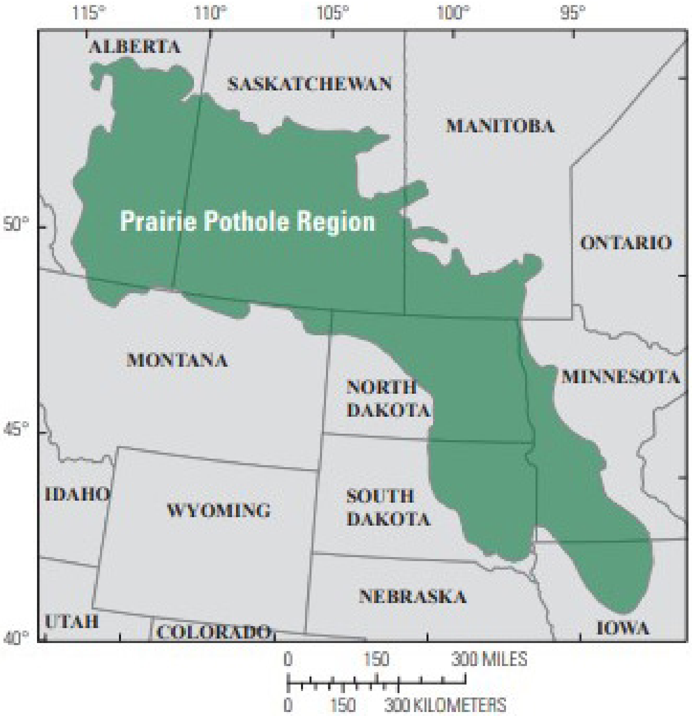

Figure 10-119. USA Map of the Prairie Pothole Region in the United States and Canada (modified from Figure 1 in Renton et al. 2015).

Prairie potholes are abundant small- to medium-sized ponds in the central and northern Great Plains of the USA and Canada (Figure 10-119). Prairie potholes are natural depressions in this Pleistocene-glaciated landscape (Doherty et al. 2018), reaching densities of up to 70 ponds/km^2 and comprising 16,880 km^2 of wetland habitat **(Fig. NoAm-GrP2)**. Prairie potholes are sourced through complex interactions between groundwater and infiltrating surface water. Many researchers regard prairie potholes as non-groundwater-dependent jurisdictional wetlands, in accord with the lexicon of the United States Environmental Protection Agency and Army Corps of Engineers (WOTUS 2020). However, abundant evidence indicates that many prairie potholes are exposural or limnocrenic springs (sensu Springer and Stevens 2009, Stevens et al. 2020; e.g., Sloan 1972, Winter and Rosenberry 1995, Hayashi et al. 2016). Estimates of impairment of prairie potholes range from 50-90% in the USA and Canada, with degradation attributed to groundwater pumping, drainage, and in-filling (Dahl 1990), and climate change predicted to further reduce their abundance and productivity (e.g., Anteau et al. 2016). Despite their declining habitat area and quality, during wet years the remaining water bodies produce an estimated 70% of North American waterfowl (e.g., Batt et al. 1989) and support a vast array of migratory, riparian, and upland faunal species. Strategies to improve prairie pothole stewardship under changing climate conditions include developing conservation easements and implementing appropriate levels of upland grazing and burning practices (Renton et al. 2015).

The Black Hills of western South Dakota and eastern Wyoming are an elongated, uplifted dome dominated by generally low permeability Precambrian igneous and metamorphic strata exposed in the central region, southward from Lead beyond Custer, South Dakota (Driscoll et al. 2002). While small, localized aquifers exist in the crystalline core, an approximately concentric ring of stacked, sedimentary strata (e.g., Deadwood, Madison Limestone, Minnelusa, and Minnekahta Limestone formations, the Inyan Kara Group, and other strata) are substantial aquifers, containing an estimated 316 km^3 of groundwater. Considerable aquifer recharge occurs in karstic "loss zones" at the periphery of the Black Hills, particularly where surface streams cross outcropping of the Madison and Minnekahta Limestone and Minnelusa formations. Within the Black Hills as well as downgradient from the loss zones, large artesian springs emerge, providing baseflow for many of the region's streams, some of which are renowned recreation areas (e.g., Roughlock Falls Nature Area on Little Spearfish Creek, Lawrence County, SD). Black Hills aquifers have become contaminated by agricultural, urban, and rural practices (including septic tank leakage), as well as by the region's long history of gold-mining. Dissolved solids, metals, and sulfate pollutants from old mines have become the focus of remedial actions.

The northern half of the Great Plains was covered by Pleistocene glaciers; hence, there has been insufficient time for the evolution of springs-dependent endemism, except in unglaciated "islands" (nunataks). Nekola (1999) examined terrestrial gastropods in Iowa, finding that lowland fens functioned as neorefugia, supporting weedy, habitat generalist taxa, while unglaciated algific talus slopes functioned as paleorefugia, supporting higher numbers of rare species with limited dispersal capacity. Consequently, most aquatic invertebrates in the northern Great Plains are neorefugial habitat generalists (Wrubleski and Ross 2011). However, regular disturbance by bison, wildfire, and anthropogenic impacts can create and maintain neorefugial conditions in unglaciated springs. For example, Gaskin and Bass (2000) examined the invertebrates at seven large springs distributed across the state of Oklahoma. They detected a total of 88 taxa, primarily widespread habitat generalists, and noted high among-springs turnover: no species occurred at all sites, four species were found in >3 springs, and 70% of the taxa were detected at only one site. Although their identifications were restricted to genus level taxonomy, they concluded that the fauna was not truly springs-dependent.

Springs dependence among wetland biota is apparently relatively uncommon in the Great Plains. The list of nearly 230 rare plants compiled by the South Dakota Natural Heritage Program (2018) includes about 50 wetland species, including *Carex*, *Eleocharis*, *Juncus*, orchids, *Utricularia*, ferns, and other taxa; however, none of those appear to be springs-dependent, and while rare in South Dakota, all but two are apparently globally secure. Similarly, the list of nearly 220 rare animals recognized by the state include many river and riparian species of mussels, fish, and amphibians, as well as American Dipper (*Cinclus mexicanus*), water shrews (*Sorex palustris*), and other birds and mammals. However, only a few animals are federally listed and none are regarded as being springs-dependent. More detailed analyses of individual species distribution and habitat use is likely to reveal higher levels of springs dependence among South Dakota's rare fauna.

Overall, the ecological integrity of Great Plains springs remains data deficient; however, clearly described and modeled declining groundwater levels inevitably mean the loss of springs and springs assemblages. Relatively few data exist on the status and trends of individual springs. Nonetheless, known aquifer depletion rates in this large landscape places springs in the southern HPA in a state of critical endangerment (CE), and many have collapsed. While some parts of the northern aquifer and associated springs exist in a state of least concern (LC), the majority there are likely in a state of near endangerment (NE) or are endangered (EN), with some critically endangered (CE).

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Texas

by Benjamin F. Schwartz, Robert E. Mace, and Peter Sprouse

Geology and geomorphology studies define seven physiographic provinces in Texas (695,663 km^2), which contains many springs of diverse types and sizes (Figure 10-120). Large climatic gradients (warm, humid, and subtropical in the south and east to hot and cold arid and semi-arid in the west and northwest) are superimposed on these provinces, ranging from the arid Basin and Range province along the western Rio Grande, to the humid southeastern Gulf Coastal Plains. Elevations range from 0 to 2667 m.

The number of springs in Texas is not known but works by Brune (1975, 1981) and recent work by the authors to document unreported springs suggest that at least 5,600 springs exist(ed). All types of springs occur in Texas, with the possible exception of thermal geyser and/or fountain type springs (Springer and Stevens, 2008). Most of the state is private property, so many regions remain poorly surveyed, and very few springs have received assessments for flow persistence and/or ecological condition.

Figure 10-120. Map of Texas, USA.

Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 25.84°, 2nd Standard Parallel = 36.50°.

Incomplete historical data suggest that ‘thousands of springs’ no longer flow (Brune 1981); primarily due to over-extraction of groundwater (e.g., the High Plains Aquifer). This number has risen in the last 40 years and will continue to increase in the future, leaving large uncertainty in baseflows to the state’s rivers and streams. Extraction of groundwater and climate change threaten many springs in Texas, especially in semi-arid and arid regions with agricultural irrigation. Many formerly-prolific springs no longer flow continuously (e.g., Comanche Springs in Fort Stockton, Texas), or have ceased flowing (e.g., Big Spring, Big Spring, Texas) for decades. An unknown number of small springs and groundwater-supported tributaries have also ceased flowing. With a few exceptions, the state does not mandate sustainable groundwater management (Mace 2019).

Few springs or groundwater-dependent ecosystems in Texas receive formal protection, and many that do are threatened by regional groundwater extraction (e.g., Diamond Y complex; springhead and run owned by The Nature Conservancy). At least one spring-dependent species, the poecilid fish *Gambusia amistadensis* is now extinct due to human activity, after Goodenough Springs was inundated in July 1968 by Amistad Reservoir. Hundreds of spring-associated or endemic species in Texas are listed as Species of Greatest Conservation Need by the Texas Parks and Wildlife Department, and dozens are listed as Federally Threatened or Endangered by the US Fish and Wildlife Service. Based on very limited data, and the fact that private agriculture is widespread, a large proportion of springs in Texas are ecologically impaired. Relative to other states and regions in the USA, much work remains to inventory and assess the status of springs in Texas.

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Rocky Mountains - Northern, Middle (Central) and Southern

by Kathleen A. Dwire and Joseph T. Gurrieri

The Rocky Mountains in the USA encompass 559,500 km^2 of mountainous terrain with elevations ranging from 1,500 m to > 4,200 m, and extending from the Canadian/US border, south through the states of Montana, Idaho, Washington, Oregon, Utah, Wyoming, Colorado, and New Mexico (Figure 10-121). The numerous aquifers in the region vary greatly in composition including unconsolidated sand and gravel, sedimentary rocks, and hard, crystalline, igneous and metamorphic rocks that are impermeable except where fractured. A total of 29,365 springs are reported in the region, dominated by helocrenes and rheocrenes, and including some hillslope springs and limnocrenes, (Springer and Stevens 2009; Springs Online 2020; Jones 2017, 2020; Chimner et al. 2017). Mapped fens (mostly helocrenes) are estimated to number approximately 23,000 (Johnston et al. 2012, Colorado Natural Heritage Program 2011, 2016, 2017, 2018, 2020); although numerous, these groundwater-dependent mountain peatlands are small, generally occupying <1% of the mapped area. These totals underestimate the true number of springs, as knowledge of Rocky Mountain springs is extremely limited in some portions of the region, and only about 15% of the area has been explicitly mapped for fens and other spring-dependent wetlands.

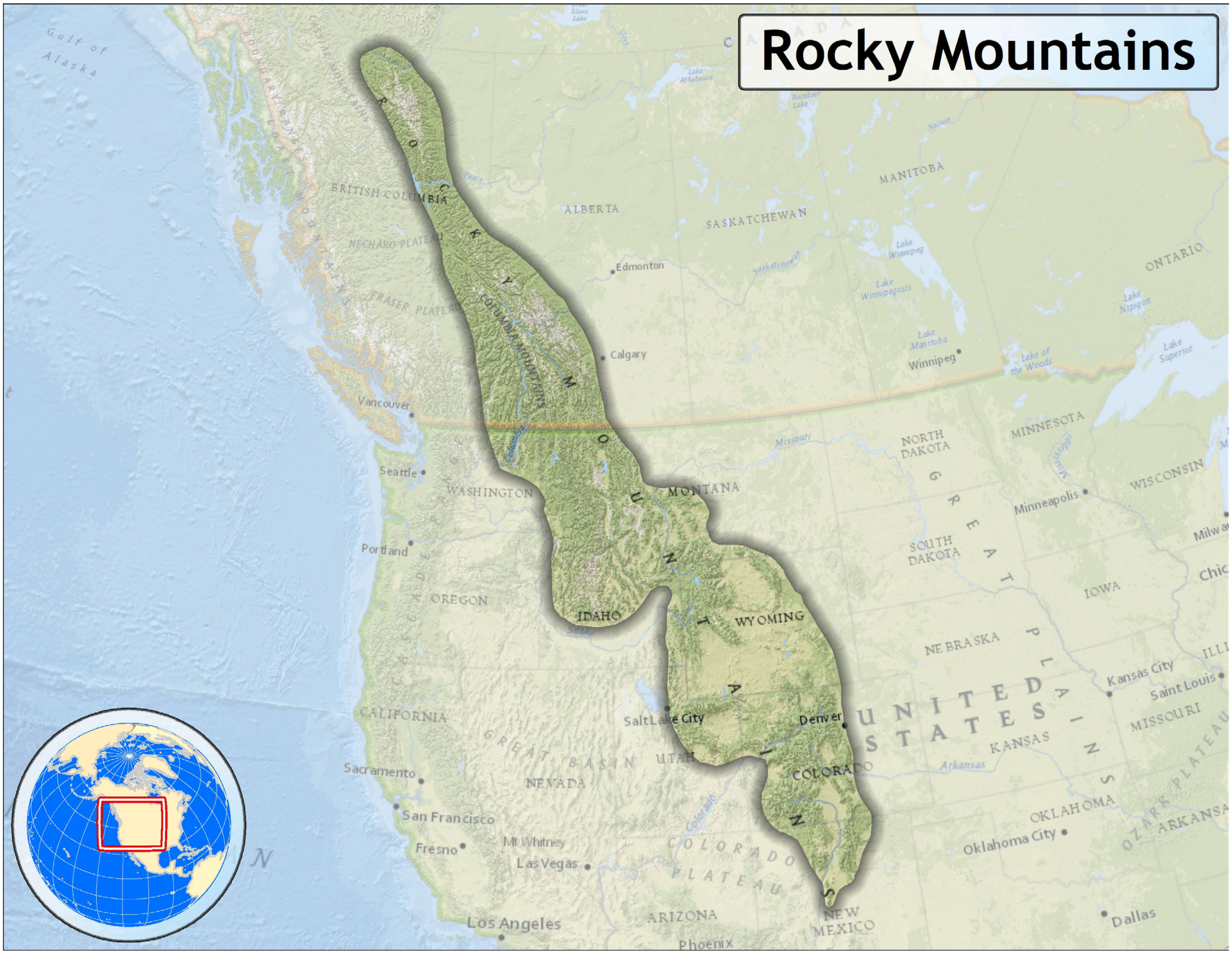

Figure 10-121. Map of the Rocky Mountains region, USA.
Map boundaries were drawn manually around visible topographic relief. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 34.46°, 2nd Standard Parallel = 59.87°.

Undisturbed springs are found in protected or inaccessible areas (Chimner et al. 2010), but elsewhere springs and fens are heavily used by livestock and native ungulates, with 70-90% of visited sites on federal public lands negatively affected by grazing, browsing, soil trampling and/or compaction (Johnston et al. 2012; Jones 2017, 2020). Other impacts include ditching and dewatering, roads, mining, and vehicular rutting (Chimner et al. 2010; Austin and Cooper 2015). Climate change projections include shifts in current precipitation and temperature regimes, which vary across the region depending on latitude, altitude, aspect, and other factors, and will likely reduce water discharge from many springs (Kittel et al. 2002). Some lower mid-elevation fens may shift from carbon sinks to carbon sources; as air temperature increases, hydrology is altered, and peat accumulation ceases (Millar et al. 2017). Across the region, fens support >75 rare vascular plant and bryophyte species (Chadde et al. 1998; Heidel et al. 2017), mostly boreal disjuncts at the southernmost extensions of their range distributions. For example, although widespread across boreal North America, roundleaf sundew (Droseraceae: *Drosera rotundifolia*) is regarded as imperiled in Colorado montane fens (Wolf et al. 2006). Rare springs-dependent vertebrate species include northern bog lemming (Cricetidae: *Synaptomys borealis*) in the Northern Rockies (Chadde et al. 1998), boreal toad, (Bufonidae: *Anaxyrus boreas*) primarily in the Central and Southern Rockies, and Columbia spotted frog (Ranidae: *Lithobates luteiventris*) in portions of the Northern and Central Rockies.

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Colorado River Basin

by Lawrence E. Stevens, Jeffrey Jenness, and Jeri D. Ledbetter

The 627,824 km^2 Colorado River basin (CRB) in the American Southwest is equally divided between the upper basin Colorado Plateau and the lower CRB Basin and Range geologic province (Stevens et al. 2020). With elevations ranging from sea level up to 4,365 m in the Rocky Mountains, the aquifers of this arid river basin include surficial basalts and deeper sandstone and karstic strata, conformably perched in the upper basin, but highly deformed in the lower basin (Figure 10-122). A total of 20,872 springs are reported in the CRB, co-dominated by rheocrene, hillslope, and helocrenes, and with a globally significant concentration of hanging gardens in the upper basin but few limnocrenes and no natural geysers. Those springs support at least 330 CRB springs-dependent taxa (SDT; crenobiontic taxa), and Montezuma Well in central Arizona supports six unique SDT (Blinn 2008), the highest point-source concentration of endemic SDT in North America to our knowledge (Figure 10-123).

Human use of CRB springs extends back to the late Pleistocene in the American Southwest (Stevens and Meretsky 2008); however, contemporary threats include livestock management, groundwater pumping, flow diversion, recreational use, and climate change. Intensive livestock management at springs over the past two

Figure 10-122. Map of the Colorado River Basin, USA and Mexico.
Map boundaries were created by identifying watershed that drained the Colorado River, exiting into the Sea of Cortez. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 30.97°, 2nd Standard Parallel = 43.45°.

Figure 10-123. Montezuma Well, a collapsed carbonate mound spring in Central Arizona supports the highest endemic diversity of any spring in the United States.

centuries has had the most widespread impact on CRB springs. While pristine springs are found in some CRB national parks and at high elevations on the west slope of the Rocky Mountains, even those protected springs often have prior histories of livestock impacts. Estimates of ecological impairment exceed 70% on private ranches and federally and state-managed forests and rangelands. Many ranches and some settlements and towns rely on springs as potable water sources, and many aquifers near urban areas are subject to poorly-regulated pumping, particularly near Phoenix, Tucson, and Las Vegas. Arizona has five Active Management Areas for groundwater protection, but none are meeting long-term sustainability goals. Many aquifers have been affected by mining, including high elevation Rocky Mountain springs, as well as large open-pit mines. Hydraulic fracturing and deep aquifer contamination have recently become common in the central portions of the upper CRB. Climate change impacts in the CRB may reduce winter snowpack at higher elevations and increase evapotranspiration at middle and lower elevations, reducing infiltration and springs discharge. However, wildfire may reduce forest cover in middle and upper elevation landscapes, potentially increasing infiltration and springs discharge. In addition, springs mapping and assessment are data deficient throughout most of the CRB.

Overall, CRB spring ecosystem integrity ranges from near endangered (NE) to collapsed (CO), and is generally low across the entire region, with higher threat levels at low-middle elevations and in low-relief landscapes in both the lower and upper sub-basins. Some springs and springs-supported streams are nearing a state of ecosystem collapse. For example, springs provide the baseflow for the Verde River in central northern Arizona, but groundwater pumping for domestic water use has reduced the discharge of its headwaters at Del Rio Springs from a mean of 57 L/sec in 1996 to 13 L/sec in 2020 (US Geological Survey 2021). This is occurring despite downstream designation of the river as a Wild and Scenic River. Although state and national parks provide relatively well-enforced land protection, many CRB aquifers extend beyond the boundaries of protected areas, where they are subject to groundwater pumping. Therefore, even in highly protected landscapes like Grand Canyon National Park, springs are threatened by anthropogenic activities, including aquifer depletion, legacy livestock management, intensive recreation impacts, and climate change. An example of an endangered spring is Roaring Springs in Grand Canyon. This karstic gushet is fed by snowmelt through sinkholes on the Kaibab Plateau to the north. Through a complex pipeline and pumping system, and with extensive manipulation of the surficial habitat, the springs provide potable water for the South Rim village and several million visitors to this world-renowned national park each year (Tobin et al. 2017; Figure 10-124).

Figure 10-124. One of several sources at Roaring Springs that provide water to Grand Canyon National Park visitors.

Thus, the primary threats to CRB springs are under-informed livestock and mining management practices, local and regional groundwater depletion, recreation, the introduction of non-native species, climate change, and ineffective groundwater and SDT population protection policies. However, when aquifers are relatively intact, as shown in Finland (e.g., Lehosmaa et al. 2017) and across the American Southwest (e.g., Davis et al. 2011), CRB springs have been shown to be remarkably resilient and restorable. For example, Pakoon Springs, a large springs complex in northwestern Arizona, was successfully rehabilitated after more than a century of intensive cattle and ostrich ranching (Burke et al. 2015). Therefore, because of their ecological, societal, and biodiversity value and sustainability for both nature and humans, CRB springs warrant far more intensive stewardship attention, protection, and rehabilitation.

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The Great Basin

by Donald W. Sada

The Great Basin (GB) and Mojave Desert (MD) collectively encompass 492,000 km^2 (~ 7 % of the coterminous USA) of the western US (Figure 10-125). This includes the region extending south of the Snake River Plain to the Colorado River, and eastward from the Sierra Nevada to the Wasatch Mountains. This is the most mountainous (>150 ranges) and driest region in the US, making it a land of contrasts (Pavlik 2008, Grayson 2011). More than 30,000 isolated springs occur from < 80 m below sea level to almost 4,000 m in all mountains and valleys where they are supported by aquifers flowing through granite, carbonates, and igneous geology (Thomas et al. 1994). Most springs are small and are rheocrenes and hillslope, followed by helocrenes and limnocrenes that support at least 180 springs-dependent taxa (SDT; crenobiontic taxa), many occupying a single spring or one endorehic basin (Keleher and Sada (2012).

Sada and Lutz (2013) reported that among 2,256 springs inventoried from 1991-2013, approximately 3% were disturbed by natural factors, evidence of human disturbance was at about 83%, and about 65% were moderately or highly disturbed by diversion, feral horse or burro presence, cattle, recreational uses, or dredging, and

Figure 10-125. Map of the Great Basin region, USA.

Map boundary data were derived from National Watershed Boundary Dataset Level 2 Hydrologic Unit Code (HUC) 'Great Basin Region' (ID 16) [https://prd-tnm.s3.amazonaws.com/index.html?prefix=StagedProducts/Hydrography/WBD/National/GDB/, accessed Dec. 27, 2022]. The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 35.21°, 2nd Standard Parallel = 42.86°.

many springs were degraded by multiple uses. Moderately and highly degraded springs were most common on Bureau of Land Management land, followed by private land, U.S. Forest Service land, and then U.S. Fish and Wildlife Service land. They also analyzed 265 springs that had been surveyed several times over 20 yr, finding improved condition at 16%, unchanged conditions at 40%, and degraded conditions at 44% of those springs. Further evidence of degrading conditions were noted by Sada and Vinyard (2002) and Sada and Lutz (2016) who tallied extirpations, and Williams and Sada (2020) who reported at least 12 extinctions of SDT in the region. Extensive habitat restoration efforts by the US Fish and Wildlife Service in the Desert Wildlife Refuge have resulted in the protection of several dozen endemic SDT in southern Nevada (Abele et al. 2011).

Ecosystem endangerment scores for GB and MD springs were estimated using information summarized in Sada and Lutz (2016) and Williams and Sada (2020). This information is considered in context of springs across the landscape, their present condition, changes in condition since 1750, between 1990 and 2013, and extinctions and extirpations of regional SDT. First, in addition to observed conditions and declines describe below, and due to their small size and drying trends forecast due to climate change, all of the more than 25,000 springs in these regions are currently in the European Union's Red Listed Ecosystem (RLE; Bland 2017) Vulnerable condition. Before livestock use began in the mid-1700s, GB and MD springs were in reference condition, although they had long been used by Native Americans (Sada and Vinyard 2002). Sada and Lutz (2016) found that while 6% of springs were influenced by natural disturbances, >80% of springs were affected by contemporary human uses, and the functional characteristics of approximately 65% of springs in this region were severely altered, thereby qualifying as RLE Endangered. More than 90 populations of SDT taxa have been extirpated from at least 65 springs, including 12 reported extinctions (Sada and Lutz 2016). Because SDT taxa often are endemic to individual springs or limited groups of springs, and since SDTs often dominate those habitats, springs that have lost SDT are regarded as RLE Collapsed ecosystems. This constitutes a minimum of 3% of springs in the region. Sada and Lutz (2016) documented a net decline in condition of 28% of 265 springs surveyed several times over approximately 20 years. If this decline continues, all springs may be severely degraded and Endangered or Critically Endangered within 75 years.

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California

by Lawrence E. Stevens

At 423,970 km^2 in area, California lies along the southern and central Pacific coast of the USA (Figure 10-126). As the third largest state, California is topographically and ecologically the most diverse state in the nation, with elevations ranging from -88 m in Death Valley to 4,421 m at the summit of Mt. Whitney. California supports more than 5,280 vascular plant species, of which 1,311 (24.8%) are endemic, distributed among hundreds of ecosystems, and has had a long history of interest in its >10,000 springs (Waring 1915). However, the ecological status of the state's springs is jeopardized by groundwater overdraft, with 9% of the state's 450 aquifer in serious decline, as well as increasing drought, and intensifying climate change and wildfire conditions.

Howard and Merrifield (2010) compiled mapping data on California groundwater dependent ecosystems (GDEs), distinguishing springs from GDE wetlands (helocrenic wet meadows and fens) and GDE streams. They reported the highest concentration of springs in the North and Central Coast areas, and fewest in the Colorado River desert in the southeastern part of the state. Overall springs density for the state was 0.07 springs/km, ranging from 0.04 springs/km^2 in the Colorado River

Figure 10-126. Map of California, USA.

Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 32.53°, 2nd Standard Parallel = 42.01°.

Desert to 0.09 springs/km^2 in the North Coast region. They reported wide variation in helocrene distribution (<0.1 to 81 springs/km^2 in the North Lahontah region), as well as area (0.013% cover in the Central Coast to 0.8% cover in the North Lahontan region). They also reported that groundwater supported 27-60% of perennial stream baseflow, depending on location. Similar findings were reported by Stevens et al. (2020) for the Colorado River that forms the southeastern boundary of the state, and which provides much water to the cities of Los Angeles and San Diego through the All-American Canal. Thus, whether mapped or not, subaerial and subaqueous springs support more than half of the perennial streams in the state and much of its surface water supplies.

California has one of the best inventories of biota of any state in the USA, and publicly reports on its rare, sensitive, endemic, and state or federally protected species. A total of 928 animal taxa are state and/or federally listed (California Natural Diversity Database 2020a), of which at least 116 species (11.1 %) are springs-dependent. Among these sensitive invertebrate taxa, at least 32 of 121 listed Mollusca (26.4%) are SDT, particularly among the truncatelloidean springsnails (particularly hydrobiid *Pyrgulopsis*, cocliopid *Tryonia*, and pleurocerid *Juga*). These aquatic snail taxa often are narrowly endemic and restricted to one to several individual springs (Hershler and Liu 2017). Among the sensitive Arthropoda, at least 22 of 275 taxa (7.5%) are SDT, including aquatic Hemiptera (naucorid *Ambrysus*, belostomatid *Belostoma*), aquatic and riparian Coleoptera. Many of California's Megaloptera, and diverse Trichoptera also may be SDT. Although their distributions and life histories are less well known, Erman and Erman (1990) documented that 21 of 36 (58.3%) of Sierra Nevada Trichoptera at 21 coldwater springs were SDT. In addition, hundreds of other poorly known invertebrate taxa, mostly not formally listed, remain unrecognized as SDT and many likely remain undescribed, particularly among Nematoda, turbellarian flatworms, Physidae snails, microcrustaceans and Amphipoda, and other taxa. Among the 488 listed vertebrates, at least 47 (9.6%) are SDT, 21 of 105 fish (20%), 21 of 48 (41.7%) amphibians, and 5 of 335 other vertebrates (1.5%) are SDT (CaliforniaHerps.com 2020; California Natural Diversity Database 2020a). As with invertebrates, many amphibian and reptile species distributions, habitat requirements, and life histories are too poorly known to clarify the extent of springs-dependence.

My review of the habitat requirements of the state's vascular flora indicates that about 195 (8.5%) of all taxa are springs-dependent. A total of 287 (5.4%) vascular plant taxa are state and/or federally listed in California, including 23 taxa (5.6% of the sensitive species, 0.4% of the state's total flora) that appear from habitat descriptions to be springs-restricted (e.g., *Panicum acuminatum* var. *thermale*) or at least groundwater-dependent (e.g., *Taraxacum californicum*; California Natural Diversity Database 2020b, University and Jepson Herbaria 2020). The relatively low percent of springs-dependent and sensitive vascular plant taxa stands in striking contrast to the relatively high percent of SDT invertebrate taxa in California and throughout the southern USA.

Reports of extirpation abound among California SDT biota, and many populations are likely in worse condition than is presently recognized. Despite the deficiency of basic data and the status and taxonomy of many unknown additional faunal taxa, a remarkably high concentration of listed SDT exist in California springs. Springs in this landscape make up approximately 0.01% of the state's total land area. Therefore, recognition of groundwater-dependence in species habitat description, and improved protection of the state's spring ecosystems will provide order-of-magnitude greater biodiversity conservation effectiveness for this remarkably biologically diverse state.

General threats to California springs have been identified by Mooney and Zaveleta (2016), including: damage by feral horses, livestock (cattle and sheep), and unregulated pack animals; recreational and other vehicular impacts; and pollution from livestock, recreation, and domestic wastes. While quantification of threats and springs habitat losses has not been reported to our knowledge, our studies in the state support these claims. Federally protected nonnative feral burros (*Equus asinus*) have devastated springs habitats throughout the eastern and southeastern deserts. Excessive groundwater extraction has led to land subsidence and influx of seawater into coastal aquifers. Abstraction of springs water and manipulation of springs for, and overuse by, livestock are common practices throughout central and northeastern California. Springs are appropriated for domestic uses, and are widely affected by urbanization, road use and fugitive dust, and non-native species introductions. Climate change threatens springs even in the state's most strongly protected landscapes, by reducing infiltration and exacerbating evapotranspiration and drought, which in turn intensify reliance on groundwater extraction. From these observations and data, California springs are regarded as ranging from endangered (EN) to critically endangered (CE) status, with many individual cases of ecosystem collapse (CO).

Dire as the above impacts on groundwater and springs are, recent drought has forced the state to adopt preliminary groundwater protection legislation. While passage of the 2014 Sustainable Groundwater Management Act is an important step forward, appropriate adaptive implementation still faces many challenges, and the future of sustainable groundwater supplies for the state remains uncertain (Conrad et al. 2019). Nonetheless, at the local scale of individual springs, California has made important strides forward in wet meadow ecology, inventory, assessment, and restoration, with major advances in GDE fen rehabilitation and management in the Sierra Nevada and other montane settings (e.g., Cooper and Wolf 2015; Patterson and Cooper 2007).

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Pacific Northwest

by Bianca Perla

Springs and seeps in the Pacific Northwest (PNW) are not well studied, especially those located in the wet maritime climate west of the Cascade Crest (Figure 10-127). Major hot spring locations are well known due to the recreational benefits of these types of springs (i.e., Jackson 2014). Some inventories of locations and ecology of cold springs and seeps east of the Cascade crest have been conducted (e.g., Summers et al. 1978, Schwab et al. 1979). Such studies report that many springs act as important water resources that concentrate animal activity and host rare and endemic species that cannot exist in the drier surrounding landscapes (Wilson et al. 2019, Cushing and Vaughn 1988, WDFW 2015).

On the wet west side of the Cascade Range, springs are plentiful but do not starkly contrast to their surroundings, and for this reason may have been largely overlooked in terms of ecological value. However, small ground-fed streams and springs, as well as large cold water spring complexes (like those along the McKenzie River in Oregon; Jefferson et al. 2007) are associated with cold and steady water flow. Such conditions support important habitat for a variety species, including freshwater mollusks (Frest and Johannes 2001) and endangered fish (USFWS 1991, Ebersole et al. 2020). Springs in Puget

Figure 10-127. Map of the Pacific Northwest, USA.

Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 41.99°, 2nd Standard Parallel = 49.00°.

Sound watersheds commonly are used as municipal and private water sources, and are also extremely important in maintaining stream flows for fish and wildlife during the dry mid-summer months (Richardson et al. 1968).

Of particular interest but scarcely studied are the ecological values of freshwater beach seeps and springs that exist in great abundance along the shore of the Puget Sound and greater Salish Sea. For example, anecdotal evidence indicates that forage fish, like surf smelt (Osmeridae: *Hypomesus pretiosus*), which underpin the entire marine foodweb, spawn preferentially on beaches with freshwater seeps and springs (Beamer and Fresh 2012). Perennial streams exist on the more than 350 islands in the Salish Sea and are baseflow fed by groundwater from springs (i.e., Booth 1991). Some of these island streams host spawning populations of salmonids, including coho, chum, steelhead, chinook, and sea run cutthroat trout (King County 2009). In some cases, cutthroat trout populations in these island spring systems are genetically distinct from mainland populations (Glasglow et al. 2020). A systematic survey of beach seeps and springs, along with a study of their ecological value and role in imprinting on larval fishes would be exceptionally beneficial.

Sea-level rise due to climate change may put sea-level springs at particular risk for inundation or saltwater intrusion. In addition, considering that most of the large urban areas in the Salish Sea exist along shorelines, more attention to the ecological value of highly threatened beach seep and spring systems is warranted. Other threats to springs in the PNW include earthquakes (Grasby and Bartier 2017), groundwater pumping, and groundwater contamination (Delistraty and Yokel 1999).

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Alaska

by Lawrence E. Stevens

Alaska, the largest of the 50 United States, occupies 1.72 million km^2 across six regions, including southeastern, south-central, southwestern, western, interior, and arctic regions (Figure 10-128). Along with most of western North America, Alaska is "suspect terrain", a tectonic landscape that has been appended to North America west of the Rocky Mountains over the past several hundred million years. At 6,190 m, Mt. Denali in central Alaska is the tallest peak in North America. The southwestern portion of the state is warmed by the Pacific Japanese current, and is occupied by temperate rainforest vegetation, while the central interior region has a boreal continental climate. The northern quarter of the state has long been locked in permafrost, limiting the emergence of groundwater, a condition that is rapidly changing as regional climate warms.

Alaskan groundwater is a critically important source of local and urban potable water. Aquifers in this enormous state are, of course, enormously variable, with many influenced by the actions and processes of surface and subsurface snow, ice, and particularly permafrost, as well as glacial activity. Although non-intuitive, strong interactions exist between permafrost and volcanic activity. 1996). At latitudes below the permafrost zone, freezing

Figure 10-128. Map of Alaska, USA.
Map boundary data were derived from Esri ArcGIS Data and Maps, version 10.8 (Sources are ESRI, Tele Atlas North America, Inc., Department of Commerce, Census Bureau, U.S. Department of Agriculture [USDA], National Agricultural Statistics Service [NASS]) The background reference map was developed by National Geographic and Esri (https://server.arcgisonline.com/arcgis/rest/services/NatGeo_World_Map/MapServer). The map was projected into the USA Contiguous Albers Equal Area Conic coordinate system; Central Meridian = 0.00°, 1st Standard Parallel = 41.99°, 2nd Standard Parallel = 49.00°.

surfaces can reduce or eliminate springs discharge. However, within the permafrost zone, soil piping commonly develops in permafrost hillslope settings (e.g., Carey and Woo 2002). Snowmelt on Yukon hillslopes subject to permafrost generates excess soil pore pressure between the surface and the subsiding permafrost boundary. The thaw front reduces soil stability, generating thaw-zone detachment failure, which consequently creates seepage erosion. Soil piping, in turn, generates rills and minor drainages, which integrate into hillslope drainage networks.

Several unusual springs types occur in the permafrost landscapes. "Pingos" are groundwater-fed, vegetated ice mounds up to 60 m tall and several hundred meters in diameter. The rapid onset of global climate changes are melting permafrost and loss of pingos, not only constituting a loss in boreal habitat diversity, but also creating deep circular pits that may function as wildlife traps. Another unusual permafrost spring type are "aufweis" ice sheets. In addition, other mineral mound-form and many other springs types exist in Alaska (Stevens et al. 2021).

With a population of approximately 300,000, Anchorage, the capital of Alaska, relies extensively on groundwater for domestic use. Two aquifers in the area are dominated by gravel, sand, silt, and clay range in thickness from a few meters to nearly 500 m depth. Groundwater withdrawal in the 1970s and early 1980s decreased the flow of the local Ship River (Moran and Galloway 2006), suggesting a likely (but undocumented) impact on area springs. Groundwater use in Anchorage decreased to 14-30% of total annual water use since the late 1980's due to importation of water from Eklutna Lake. However, increasing demands may again require increased reliance on local groundwater, requiring development of a more sustainable water management strategy.

Among the more widely recognized sites are Chena, Manley, and Tolovana Hot Springs near Fairbanks, Pilgrim Hot Springs near Nome, and Tenakee and White Sulpher Springs in southeastern Alaska. A well-known developed coolwater site is Beluga Point Fresh Water Spring near Anchorage. However, despite the geological complexity and economic interests in Alaska, and the rapid onset of climate change impacts there, Stevens and Meretsky (2008) noted that only 35 Alaska springs had been named; however, estimates of the number of springs in the state are likely orders of magnitude greater.

Although groundwater for potable supplies, mining, fish farming, and other uses is likely high, little information is available for this large state. Due to the extremely limited information on Alaska springs, their conservation status at present is data deficient and many more data are needed.

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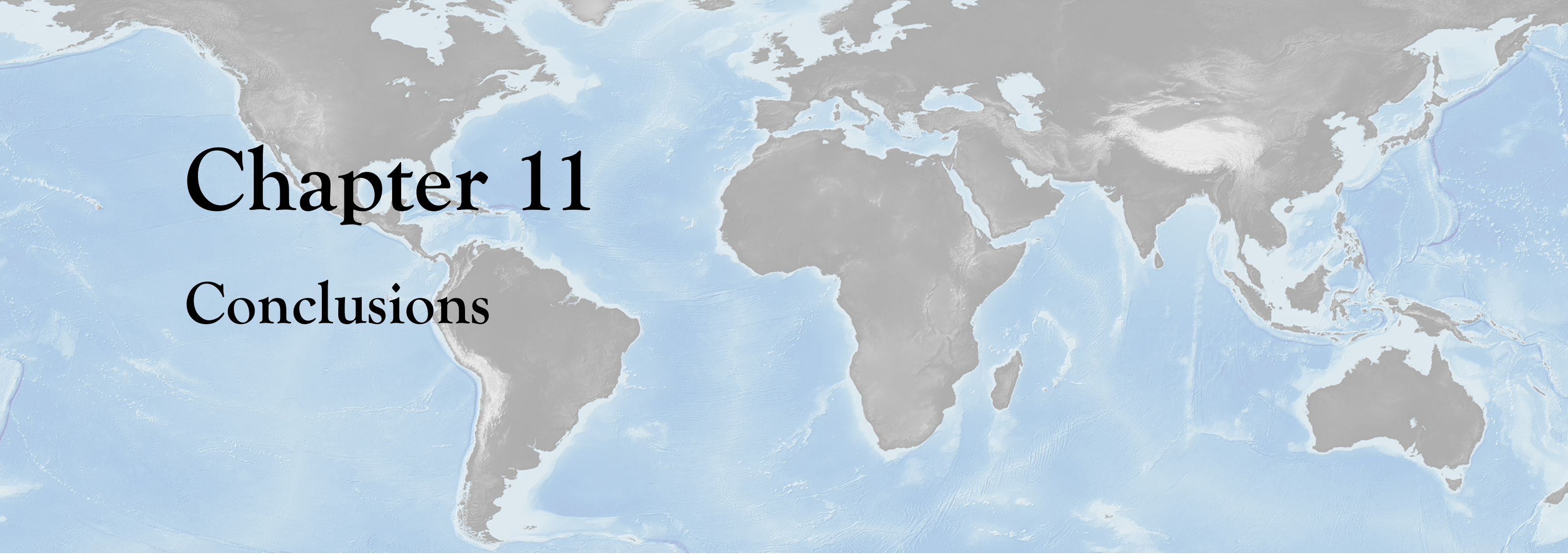

Chapter 11

Conclusions

Overview

Basic and applied research over the past seven decades has provided insight into spring ecosystem ecohydrology, as well as community and ecosystem ecology, ecosystem individuality, ecological interactivity, biodiversity, and evolution (e.g., Odum 1957; Williams and Danks 1991; Botosaneanu 1998; Stevens and Meretsky 2008; Glazier 2014; Knight 2015; Kreamer et al. 2015; Rossini et al. 2018, and others). Springs have been focal landscapes for human evolution and attention over Neogene time (e.g., Pliny the Elder 77; Cuthbert and Ashley 2014; Haynes 2008; Sistiaga et al. 2020). Most scientific attention has been devoted to physical hydrogeology, groundwater supplies and quality, and related hydrological economics across local to international scales (e.g., Guzman-Rfos 1988; Krešić and Stevanović 2009; van Beynen 2021). While hydrogeologic study has dominated springs research over the past several centuries, less attention has been given to understanding springs ecosystem ecology, dependent species biology, ethnography, and socio-cultural aspects. Given the many and complex interactions and values among springs, a more deeply integrated understanding is warranted.

Spring ecosystems have several traits that greatly distinguish them from other ecosystems. They are perhaps best described as subsurface-to-surface, groundwater-dependent headwater wetland ecosystems, fixed in place by underlying geologic structure and aquifer characteristics. Springs are usually small in area, geochemically distinctive, and isolated; therefore, they may lack ecological and evolutionary connectivity and promote fixation of unique genotypes. As a consequence, some springs develop high levels of endemic biodiversity (e.g., Montezuma Well, Arizona; Blinn 2008). Such springs may substantially contribute to gamma diversity (Cantonati et al. 2020b). These characteristics also contribute to high levels of ecosystem individuality, a trait little recognized or studied among other ecosystem types. Some springs have the highest productivity known (Odum 1957); however, productivity and attendant biodiversity are a function of exposure, and shaded springs in forested landscapes may be relatively unremarkable features (Stevens 2020). Spring types are diverse, and are made more so by the co-occurrence of multiple microhabitats within the spring (Stevens et al. 2021b). Typology, microhabitat diversity, and habitat area all contribute to a spring's biodiversity, whereas geochemistry, isolation, and habitat constancy contribute to endemism. In addition to these complex intrinsic functions, springs also serve as keystone ecosystems, highly ecologically interactive habitat patches that strongly influence surrounding upland and downstream aquatic ecosystems. Springs provide baseflow to all natural rivers on Earth except some of those in ice-dominated landscapes. Collectively, this suite of characteristics and processes contribute to landscape and seascape integrity, and warrant more attention to the roles and functions of these remarkable ecosystems.

Cultural ethnographic and historic studies of spring ecosystems have been relatively few and primarily have been conducted in developed regions; nonetheless, such studies have been enormously informative. For example, Cuthbert and Ashley (2014) reported that early hominin remains occurred at springs in the Olduvai Gorge, and Sistiaga et al. (2020) postulated that geothermal springs there may have been used for cooking before fire. Broad (2007) described the history, importance, and geochemistry of the Greek Oracle of Delphi, and Robinson (2011) used archelogy, architecture, and ancient literature to reconstruct the ethnography of the Peirene Fountains in Corinth, Greece over the past three millennia. Strang (2004) conducted an in-depth anthropological investigation of the spring-sourced River Staur near Dorset, England, tracing widespread cultural hydrolatry there in relation to evolving beliefs across Europe from prehistoric, Celtic and Pagan, Roman, Catholic, Reformation, and modern times. Bord and Bord (1986) studied the profound beliefs associated with springs and holy wells in England and Ireland. Johansen (1997) reported that regard for springs as holy sites was prohibited by the Reformation in western Europe, but relatively quickly came back into practice for balneological purposes. In the USA Bullard's (2020) study of the past two centuries of use and impacts to springs in Missouri similarly revealed their focal societal importance in that state. The role of springs in contemporary socio-economics is also beginning to receive attention: Mueller et al. (2017) used a willingness-to-pay analysis to assess valuation of springs in Grand Canyon National Park, Arizona, reporting high value based on both natural resources and recreational benefits. Similarly, Wu et al. (2018) reported enormous recreational socio-economic benefits derived from tourism at four large limnocrene springs in Florida, USA. These many converging lines of evidence indicate that spring ecosystems everywhere are critically important landscape features that exert multi-dimensional, highly interactive biological and socio-cultural impacts at local to regional scales. Ecohydrogeologic and socio-cultural studies indicate that springs merit far more stewardship concern than previously has been recognized.

As a consequence of humanity's long-term and intensive association, springs everywhere are threatened by local, regional, and global anthropogenic impacts (Stevens et al. 2021a). Local impacts include abstraction of flow and land use of the source area and springbrooks. When managed poorly, such factors degrade springs discharge and water quality, habitat integrity, biodiversity, and cultural values, as well as their diverse ecological and socioeconomic roles within the landscape. Aquifer-wide, regional, and global anthropogenic impacts to springs include non-sustainable land use practices, urbanization and mining, groundwater depletion and pollution, and, at the broadest scale, climate change (e.g., Government of India 2010; Cross et al. 2016; Cantonati et al. 2020a; Goldschneider et al. 2020; UNESCO 2020). Reconciliation of local and regional impacts to aquifers and springs involves societal discussion about conservation, a conversation that in most cases has not achieved much success. Nonetheless, improving spring ecosystem and SDT protection and sustainability requires education to advance stewardship attention to the aquifer supporting the springs, as well as to the adjacent landscapes that both influence and rely on springs emergence.

Ecological Status

In this compendium we provide information on the distribution, ecology, and conservation status of nearly 300,000 spring ecosystems among and within 75 nations on all continents except Antarctica, as well as information on many springs-dependent taxa (SDT; Table 11-53; Figure 11-129; Stevens et al. 2021a). The literature and our data demonstrate that springs play important physical, ecological, and cultural socio-economic roles throughout the world in arid, mesic, and subaqueous (e.g., submarine, sub-lacustrine, benthic fluvial) environments. However, springs are widely recognized as threatened and endangered ecosystems in all landscapes where their conservation status has been assessed (Table 11-5). Although data are limited, countries with greater availability of information reveal that anthropogenic impairment of springs is widespread, sometimes exceeding 90% in developed landscapes, and particularly at lower latitudes and elevations in both mesic and arid regions. Thus, the synopses presented here collectively indicate that springs are highly imperiled ecosystems across the planet.

Table 11-5. Variation in severity of anthropogenic impacts to springs based on 52 regional, national, and international synopses of the springs in 75 countries presented in this book. Impact severity scores were ranked from low to moderate to high. Data were augmented and refined from Stevens et al. (2021a).

Continent	Average Severity of Impact	No. of Synopses
Marine Springs	Low-moderate	2
Europe (EUR)	Moderate-high	12
Middle East	High	2
Africa	High	6
Western Eurasia	Likely moderate-high	3
Asia	High	3
Oceania-Australasia	Moderate-high	3
Latin America-Caribbean	Moderate-high	6
North America	Moderate-high	14

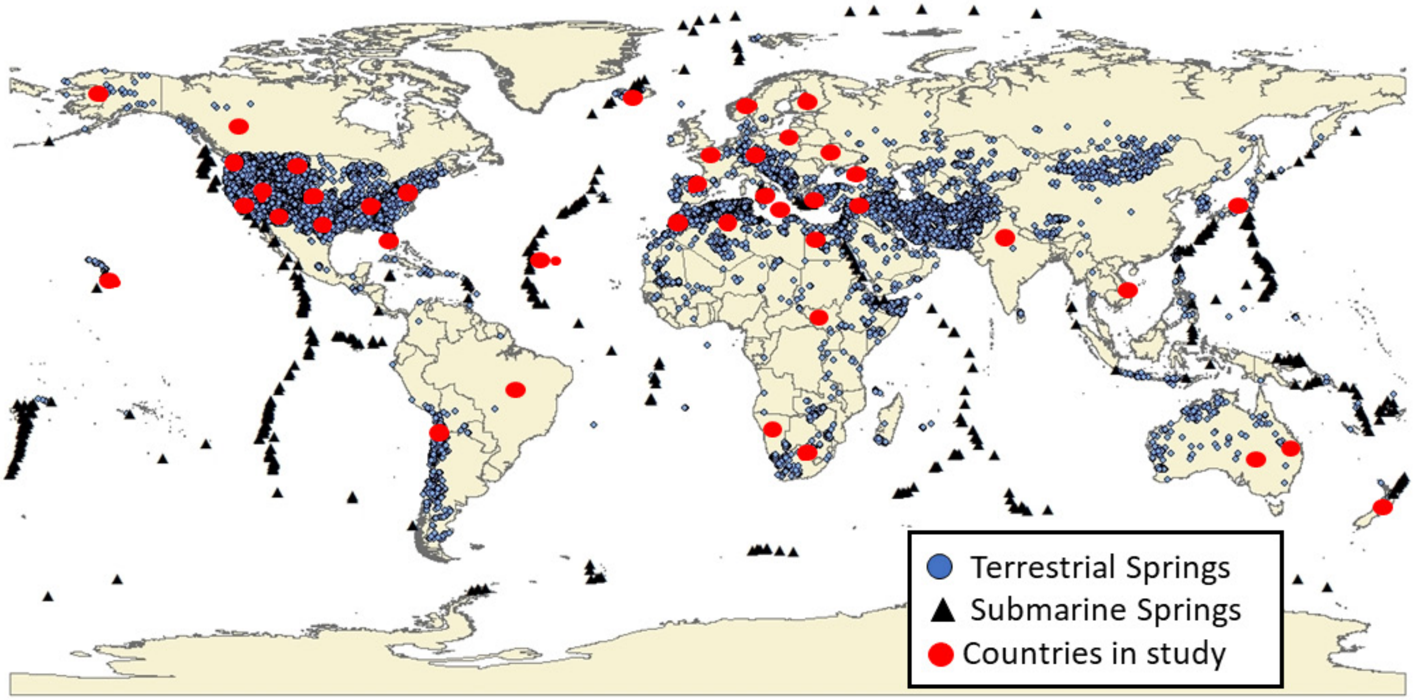

Figure 11-129. Map of the global distribution of springs reported among the synopses presented in this book.

Threats and Stressors

Ecological threats to spring ecosystems involve a wide array of local stressors, as well as regional and global factors. Local stressors particularly include: consumptive extraction for domestic use (i.e., potable supplies); agriculture (irrigation and livestock watering); flow regulation; geomorphic alteration; mineral extraction; introduction of non-native species; and exploitation for fish, wildlife, and wood. The use of geothermal waters for energy production, balneology, and recreation has everywhere been so intensive that few ecologically intact hot springs remain in many regions. These localized impacts often are responsible for springs habitat and SDS population losses, with many recent cases of SDT endangerment and extinction in the USA (e.g., Williams and Sada 2020; Stevens et al. 2022), as well as losses of traditional lifeways and essential human goods and services.

Regional and national to international threats involve aquifer drawdown and contamination with agricultural, industrial, mining, or military pollutants. Regional water table lowering is well-documented in urbanized and intensively cultivated areas occurring, for example, across North Africa, India, and the American Great Plains, and beneath many cities in arid regions throughout the world. Aquifer contamination from agricultural and mining wastes is widely reported by our co-authors on all continents. For example, groundwater contamination by agricultural wastes has led to springs habitat degradation in Florida, USA, detracting from recreational quality and socio-economics (Knight 2015; Wu et al. 2018). Solving the problem of protecting potable water supplies in Florida by reducing fertilizer loading and improving water conservation is <20% of the cost of constructing additional reservoirs there (estimated at $4.5 billion USD; van Beynen 2021). Global climate change impacts on aquifers principally involve increasing temperature and reduced snowpack and glacial cover, leading to increased evapotranspiration and sublimation, and reduced infiltration.

Ecosystem disturbance types described by Salafsky et al. (2008) and were tallied from the original and additional synopses presented above and in Stevens et al. (2021a). Such information improves understanding of the extent and intensity of springs-specific ecosystem threats. These data reveal the following ranking of different threats (Figure 11-130):

Agriculture and Livestock > Groundwater Depletion and Mining > Groundwater Pollution > Climate Change = Geomorphologic Alteration = Recreational Uses > Exotic Species > Other

The ubiquitous inadequacy and low quality of information on springs as ecosystems also must be regarded as a primary threat to sustainable stewardship. Our collaborators in this compendium uniformly reported widespread deficiency of geographic and assessment

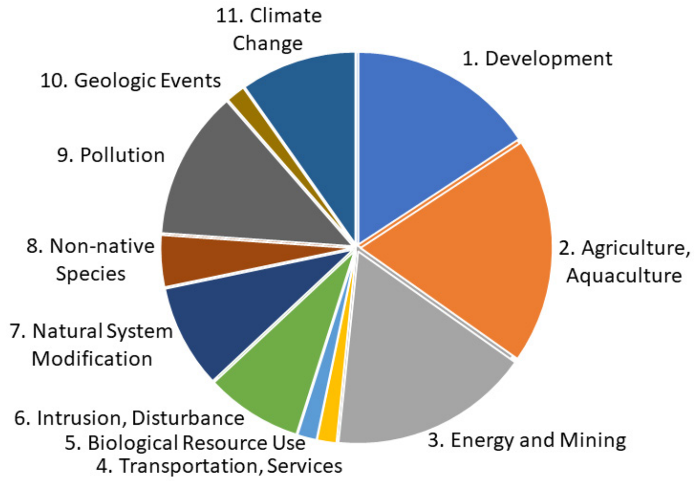

Figure 11-130. Stressors influencing springs ecological integrity among 52 studies in 77 regions or nations on all continents except Antarctica. Red dots indicate study areas reported in the synopses presented in chapters 2-10.

data. Mapping of springs is only of moderate quality even in the most highly developed nations, and is generally inadequate for useful understanding of the distribution, typology, and conservation status of springs. Integrated information management, including ecosystem assessment is also lacking, hindering basic and applied research and stewardship. This short-coming can be addressed by using the Springs Stewardship Institute's Springs Online database (https://springsdata.org) for data archival, reporting, and where appropriate, sharing. While a synthesis of impacts to springs can be garnered from the synopses presented here, widespread data deficiency limits global understanding of the severity of factors threatening spring ecosystem integrity, particular spring types, and springs-dependent biota.

Ecosystem Classification and Assessment

Assessment of spring ecosystems is an important step in formulating management responses for mitigation and ecosystem rehabilitation. The usual formula for natural resource management is based on development and management of baseline information, assessment and integration, planning, implementation, with feedback monitoring to improve management (Stevens and Meretsky 2008). Thus, improving stewardship requires clear, comparative evaluation of springs integrity and is challenged by data limitations and ecosystem complexity, as well as by unresolved debate over classification and appropriate protocols (Cantonati et al. 2020a). Stevens et al. (2021b) examined the springs classification literature, noting that a century of hydrogeology had failed to produce a usable classification system. They presented a conceptual bottom-up model of springs as surface-linked, groundwater-dependent headwater wetland ecosystems, whose emergence environment ("sphere of discharge"), microclimate, biogeography, and land use histories generate unique and complex microhabitat arrays. For these reasons, spring ecosystems are highly individualistic ecosystems, with even closely adjacent springs sometimes supporting very different assemblages. Nonetheless, macroecological processes may prevail, at least for some spring assemblages. For example, Kodrick-Brown and Brown (2007) showed that Australian springs fish assemblages followed predicted hierarchical biogeographic nesting based on spring habitat area and isolation. Nonetheless, ecosystem individuality challenges nomothetic classification of spring ecosystems and therefore ecological assessment and stewardship.

Stevens (2020) proposed that springs constitute a distinctive cluster of aquatic ecosystems that are best regarded as a biome. Springs differ from most other aquatic biomes by occurring as widely distributed point-sources of biodiversity throughout the world and by functioning as islands or archipelagos of habitat. Resolving this challenge to ecosystem classification is likely to enrich that conceptual discussion, as well as facilitate ecosystem stewardship. Springs are most clearly distinguished on the basis of geomorphology, rather than on vegetation, geochemistry, or the services they provide (Stevens et al. 2021b). To improve classification and ecosystem assessment, those authors used source geomorphology to develop and test a dichotomous key to more than a dozen typical terrestrial spring types.

Ecologically appropriate stewardship of springs is challenged not only by the individuality and insular nature of spring ecosystems and their complex geomorphologies, but also by data deficiency and confusion as to appropriate protocols for comparative assessment. Although critically important and often highly productive hotspots of ecological and cultural interactivity, springs are small and often obscured in coarse-scale ecosystem mapping efforts. For these and other reasons, spring ecosystems have not received adequate geographic, scientific, and political attention.

The International Union for the Conservation of Nature (IUCN) developed a protocol for assessing the status of different types of ecosystems in its Red List of Ecosystems (RLE; Bland et al. 2017). Using best available data, the protocol identifies six levels of ecosystem risk, ranging in severity from Least Concern to Near Threatened, to Critically Endangered, to Collapsed, with categories of Data Deficiency and Not Evaluated. RLE analysis has been conducted to assess ecosystem threat levels in more than 20 countries, and Finland has used it to assess the status of its springs (Kontula and Raunio 2018). However, springs remain under-represented in the IUCN Global Ecosystem Typology (Keith et al. 2020).

An important shortcoming of many ecological studies and most Western ecosystem assessment approaches has been the failure to adequately consider the long-term role of humans on springs. Abundant fossil evidence clearly demonstrates that throughout our evolutionary history, humans have had close associations and impacts on springs (e.g., Cuthbert and Ashley 2014). It is likely that most large springs, many smaller springs, and the large assemblages of springs-dependent species have sustained nearly continuous anthropogenic presence since at least late Pleistocene time. Besides use for water, springs have long been used as ambush sites by hunter-gatherers (e.g., Haynes 2008), and springs may have been burned regularly to chase out game and open up the habitat for access. Rather than from fire, cooking may have arisen by early homonin use of geothermal springs (Sistiaga et al. 2020). The ancient literature abundantly points to the use of springs for livestock watering, and as agriculture became important, spring waters have been appropriated for irrigation. Unfortunately, contemporary impacts on groundwater supplies and springs have become far more intensive and far less sustainable. Nonetheless, appropriate stewardship of spring ecosystems in most landscapes demands consideration of humans as agents of ecological function, rather than management for an illusory pristine condition free from anthropogenic impacts.

To help springs managers recognize and prioritize actions to understand the extent of human impacts and improve ecological integrity, the Springs Stewardship Institute (Ledbetter 2023) developed and promoted quantitative springs ecosystem Level 1 (georeferencing) and Level 2 (rapid comprehensive inventory) protocols, as well as a spring ecosystem assessment protocol (SEAP). The SEAP involves inventory-based and expert-opinion-based scoring of the coupled conditions and risks among four natural resource information categories (aquifer, geomorphology, habitat, and biota), against the condition and risk of human influences. The SEAP also includes consideration of the administrative context of a spring ecosystem, as such considerations may override natural and human use functions. The SEAP was designed to summarize inventory information to provide prioritized guidance to springs stewards on natural resource condition and risk, as well as ecosystem goods and services in the context of site administration. The SEAP has been used to prioritize management actions among and within springs in multiple arid to mesic landscapes in western North America (e.g., Springer et al. 2015; Paffett et al. 2018; Kurzweil et al., 2021).

Paffett et al.'s (2018) review of spring assessment protocols reported that SEAP generated sufficiently robust guidance to facilitate further discussion of practical management planning. In addition, SSI's SEAP analysis is derived from Level 2 inventory data to provide a quantitative baseline and monitoring approach for assessment of management actions. Thus, the SEAP can provide prioritized guidance on ecosystem management needs among springs across a landscape, as well as within a spring ecosystem over the course of a management action, such as site rehabilitation. However, metrics relating assessment of multiple spring types to other ecosystems remain to be developed in a manner compatible with that for IUCN RLE assessment.

Consideration of the cultural, sociological, and economic values of individual springs often indicates that some individual springs or springs types play disproportionally larger socio-cultural roles and receive preferential attention, use, and valuation. In the American Southwest, several Native American tribes distinguish individual, relatively large springs for medicinal or spiritual properties. In addition, certain springs are regarded as places of cultural emergence. Similarly, springs in some Scandinavian countries are protected for cultural reasons. Travertine-depositing springs are recognized by the European Union as a protected habitat type. Such springs around the world are heralded as points of recreational use and visitation (e.g., Huanglong Pools, Sichuan, China; Semuc Champey, Alta Verapaz, Guatemala; Pammukakale Terraces, Denizli, Turkey; Mammoth Hot Springs, Yellowstone National Park, Wyoming, USA; and others). Such sites naturally attract more scientific and management attention, while other smaller, more normal spring ecosystems do not.

Conservation Solutions

Information Management

Cantonati et al. (2020a) pled for improvement of scientific, public, and managerial attention to globally improve stewardship of spring ecosystems, including more comprehensive conservation policy and practices, considerably more ecohydrogeological research, comprehensive information management (e.g., Springs Online –

springsdata.org), and enhancing public and governmental awareness of the importance of springs. From local to global scales, improvement of spring ecosystem stewardship requires clear understanding of the distribution and contemporary status of springs and their supporting aquifers and associated assemblages. To be efficient, stewardship must be based on well-managed, high-quality geographic and inventory data, and consistently collected and statistically credible comparative assessment information that can be applied within springs over time and comparatively among springs within a landscape. The Springs Stewardship Institute provides rapid springs inventory and assessment protocols and information management tools and assistance (SpringStewardshipInstitute.org). These tools are designed to improve scientific understanding of springs, as well as planning and implementation of ecological status and management actions, and provide a means for back-up and long-term archival of data for future study and management. The results of SSI's springs-centric approach can be applied to the IUCN RLE protocols for comparison with other ecosystem types (e.g., the section in Chapter 10 by Robert Knight in Florida, above).

Management of such information is best accomplished using a relational database structure for collaborative involvement of the spring ecosystem stakeholders – the public, researchers, managers, and policy stakeholders who are responsible for stewardship. This will help ensure transparent and credible identification of the distribution, types, associated resources, ecological status and uses, and the stewardship needs for conservation of springs, springs biota, and the aquifers that support them. Reliable, accessible, high-quality classification, inventory and assessment information provides the foundation of support for the often-contentious societal discussion around basic principles, existing conditions, ownership, management options, and policy needed to improve spring ecosystem stewardship (Stevens et al. 2021a, Ledbetter et al. 2023).

Local Ecosystem Rehabilitation

Spring managers can face many challenges in improving spring ecosystem stewardship. Paffett et al. (2018) reported that using assessment for ecosystem planning and implementation included practical concerns about cost, compliance, ease of access, maintenance, management, guarantee of success, and other factors. However, due to their usually small habitat area and the few stakeholders usually involved, simple actions to protect and rehabilitate springs often can be achieved at low cost. However, springs rehabilitation at the local scale requires consideration of the aquifer status: if the aquifer is reasonably intact, local impacts often can be managed to conserve some or much of the springs' ecological function, while still allowing for anthropogenic uses. If the aquifer is compromised and its rehabilitation is warranted, artificial means such as groundwater pumping may be required to maintain it.

Common practices for balancing local sustainable use with ecological integrity of springs include: protection of the ecologically important source habitat; the use of flow splitters so that only required flow is abstracted; construction of stepping stone trails to protect spring habitats from erosion, particularly for springs on hillslopes; removal of non-native species; revegetation; and reduction of noise and other disturbances that enhance wildlife use (Stevens and Meretsky 2008). Such approaches primarily focus on enhancement of site geomorphology, but also can include flow regulation, control of non-native species, revegetation and translocation with native stock, and implementation of recreational management (e.g., trails, information kiosks; Burke et al. 2015). Additional practical recommendations regarding best management practices for ecologically conservative development of springs are provided by Gurrieri (2020).

Co-occurring impacts of water extraction and livestock use on springs water quality, geomorphology, habitat, and biota are common, and require integrated ecological assessment, planning, implementation, and feedback monitoring. For example, simply protecting the source from livestock impacts by fencing may be insufficient for long-term protection of springs-dependent fish and other taxa. Once a site has been fenced and protected from grazing disturbance and fire, wetland vegetation can quickly overgrow open space and may take up or cover all open water, eliminating aquatic habitat and jeopardizing focal species (e.g., Grand Canyon Wildlands Council 2002; Kodrick-Brown and Brown 2007). Therefore, consideration of the natural disturbance regime is required to maintain open water, and monitoring the spring at least occasionally are essential elements of appropriate management.

Regional to International Conservation

Regional and global threats to springs can only be resolved through regional, national, and international societal-level discussion, valuation, and enforceable policy. Present discussion and conflict resolution is primarily driven by necessity and typically focuses on water supplies management, with inadequate conservation emphasis on springs. We echo the plea of Cantonati et al. (2020a) that such discussion includes the issue of improved management of springs ecosystem integrity as important point-sources of biological and cultural diversity and significance.

Global climate change impacts on aquifers principally involve increasing temperature and reduced snowpacks that lead to increased evapotranspiration and sublimation, and reduced infiltration (Groundwater Project 2023). These impacts are of dire concern for heavily populated regions, such as India, China, and several other nations that rely on water from snowmelt from 6127 km3 of ice reserves in the Hindu Kush Himalayan glaciers (e.g., Prakash 2020). Regional and far-field impacts of aquifer depletion and pollution require time-consuming, expensive, and generally slow societal-level discussion and policy changes. However, such societal discussion is absolutely essential for sustainable use of aquifers. We note that terrestrial mining operations often involve overdraft of aquifers to prevent inundation of mines, and submarine mining now threatens many of the world's newly discovered marine springs. Enhanced societal discussion, resolve, and action are needed to promote and enforce proactive policy to reduce impacts to aquifers and the springs they source at broad spatial scales.

Summary

Despite their recognized value, importance, and threatened status, spring ecosystems remain disregarded and poorly protected nearly everywhere. Based on evaluation of approximately 300,000 springs among 75 nations, we report that spring ecosystems are globally imperiled, with many examples of RLE Critically Imperiled and Collapsed ecosystems. Rates of spring ecosystem loss have rarely been compiled, and while hydrogeological analyses and models have been conducted in many landscapes, studies of the ecological integrity of springs as ecosystems often have been neglected. Springs ecological integrity is particularly threatened in arid and semi-arid regions, at low to middle latitudes and elevations, and in urban areas and regions that are subject to intensive agricultural activities, particularly livestock watering. Our data indicate that ecological impairment can exceed 90% in such regions, and we report widespread ecological impairment and loss of springs in many settings and nations. This synthesis clearly demonstrates that springs are ecologically valued and highly compromised by anthropogenic impacts, but not just in arid regions: springs are imperiled across all humidity provinces throughout the world. Human populations have repeatedly retreated to springs for critical water supplies during times of crisis, such as famine, drought, and other climate emergencies - a lesson from history that by itself should inspire greater protection of springs and the aquifers that support them.

Critical information gaps remain that limit stewardship - particularly mapping and inventory, agreement on ecosystem assessment protocols, best practices, management policy, and public and governmental awareness (Cantonati et al. 2020a). Here and summarized in Stevens et al. (2021a), we describe the current state of knowledge of the world's springs, which indicate grave threats to these commonly overlooked but abundant and important ecosystems. Inventory and assessment approaches, such as the SSI rapid spring ecosystem inventory and assessment protocols, can provide stewardship guidance within and among springs within landscapes, and can be readily used to track ecosystem management success. Such metrics also need to be integrated with the EU's RLE protocol (Bland et al. 2017) to facilitate among-ecosystem comparison on a regional to global basis.

Sustainable stewardship of societally important resources like groundwater and springs requires a structured approach. A formula for such management includes: 1) robust valuation and a well-supported administrative context to achieve clearly defined and societally appropriate objectives; 2) a thorough, easily used and readily accessed relational information management system; 3) public trust, support, and open communication; 4) sufficient technical knowledge and information management to accomplish inventory and assessment for planning, implementation, and monitoring; 5) clear, well-reported metrics of success that are communicated to all levels of society; and 6) appropriately rigorous conduct of monitoring and information management to ensure long-term success (Stevens and Meretsky 2008; Cantonati et al. 2020a; Feio et al. 2021). Application of this approach to sustainable management of springs and the aquifers that support them is essential and much needed across all levels of governance to ensure sustainability of groundwater and springs (Cross et al. 2016).

The synopses presented here are sketches of springs distribution, ecosystem ecology, and conservation status across the world. We recognize that much information remains poorly known or has yet to be compiled and synthesized. Nonetheless, the synopses presented above provide a foundation for improving understanding the status of the world's springs. This document remains a work in progress, and is archived at the Springs Stewardship Institute website (SpringStewardshipInstitute.org/Research/GlobalSpringsImperilment) and the Groundwater Project (https://gw-project.org). The information here remains available to the authors, to be edited and updated as additional information emerges. In addition, new contributions on the distribution and status of springs from regions not yet reported upon here also are warmly welcomed. For more information, please contact the Springs Stewardship Institute and the Groundwater Project.

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