Chapter 2

The Demise of Desert Springs

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Why should we have concern for desert springs and biotas? Some simply say "because they are there" (Rolston 1991). Because surface water is quite uncommon in desert lands, springs often attract attention mostly as anomalies. These isolated oases harboring aquatic organisms in the midst of seas of arid land are also often described as "aquatic archipelagos," similar to oceanic islands that allow dry-land plants and animals to live surrounded by seawater. Most islands are, however, populated by organisms dispersing from elsewhere, such as an adjacent mainland. Conversely, biotas of desert springs often are remnants, left behind as surface water disappears with the expansion of deserts (Hubbs and Miller 1948; Hubbs et al. 1974; Dumont 1982; Por et al. 1986; Lévêque 1990). Thus, spring biotas are often relicts of wetter times, providing clues to conditions in the distant past (Scates 1968; Por 1984; Roth 1987; Hershler et al. 1999).

In many cases, individual species are restricted to one or only a few springs. Because dry land is a greater barrier to obligate aquatic organisms than water is to creatures that fly, swim, or float, their purity of isolation presents unmatched opportunities for evolutionists to study processes of speciation (e.g., Miller 1948, 1950; J. H. Brown 1971; Nxomani et al. 1994; Duvernell and Turner 1999). Field research on other important questions, such as thermal or physicochemical preferences or tolerances of species, can be undertaken in the unique up- to downstream gradients of spring-runs (Brues 1928, 1932; Mason 1939; Brain and Koste 1991).

A spring is difficult to define more precisely than a place where water rises at an intersection of groundwater and land surface (but see chapter 4). Springs vary from tiny seeps to the outflows of underground rivers, with the former being far more common. But even if tiny or ephemeral, desert springs are invariably characterized by the presence of plants and animals that cannot survive without surface water.

the development of new, more sustainable approaches to springs protection and restoration. We suggest that these efforts are among the most reasonable and worthy conservation tasks. They may quickly result in tangible, long-term protection of our natural heritage. We hope that this volume will illuminate these issues and foster discussion and further research into springs ecosystem ecology and conservation. This book is an invitation for all of us to help guarantee the long-term protection and sustainability of these diverse, threatened, and remarkable ecosystems.

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Organisms in springs and other perennial desert waters are often considered remarkable in their tenacity (or luck) in surviving. However, it must be remembered that they are in fact aquatic. As long as sufficient water of suitable quality is present, aquatic plants and animals care little or not at all about their terrestrial surroundings. With the obvious exceptions of those with life stages designed to resist drying (e.g., drought-resistant eggs and seeds), one should think of aquatic organisms as living "in" rather than being "of" deserts (Deacon and Minckley 1974; Smith 1981). Relative to other aquatic habitats, springs may even ensure far greater predictability in possessing the constancy of flow, temperature, and chemistry that characterizes many groundwater basins.

Disappearances of desert springs and their biotas have accelerated in the recent past (Shepard 1993; Minckley and Unmack 2000). Major reasons for this trend, and threats to remaining springs, are reviewed here in two parts. The first documents the loss of springs that is attributable to human activities, which demands an urgent program to minimize future losses. The second part discusses the problems faced by remaining springs; some of these problems may yet be corrected. We describe the impacts of spring alterations, demonstrating the magnitude and universality of ecological catastrophes involved as background for conservation efforts. Each system is unique, so anecdotes presented here will serve to alert others of what some danger signals may be and where to watch for them. Coverage is not comprehensive but emphasizes our aridland experiences in Australia and western North America, with the addition of world literature and some organisms other than fishes.

Groundwater Extraction: The Killer of Springs

Desert basins and uplands alike can hold great volumes of groundwater that rise as base flow in streams and springs (Maxey 1968). Water stored in such aquifers may have originated in the distant past, with the aquifer's volume being maintained by slow, sometimes long-distance percolation from distant recharge zones (Winograd and Thordarson 1975; Winograd and Pearson 1976; Habermehl 1980). Most natural events influencing water levels of aquifers — thus, spring outflows—are slow, accompanying global trends in climate: for example, from wetter to drier. Natural increasing aridity since

Cretaceous times (Axelrod 1979; Burkle 1995) doomed innumerable springs and their inhabitants to extinction. Springs that are "turned off" suddenly or that appear miraculously after earthquakes (DuBois and Smith 1980) or tilting (e.g., the floor of Death Valley, California) that dries some and creates other springs over a few thousand years (Hunt and Mabey 1966) are exceptions that likely have little influence on this overall trend.

"Fossil" springs (fig. 2.1) are abundant (Waring 1965) and are marked by remnant, freshwater calcium deposits termed tufas or travertines and by beds of peat formed in marshes formerly fed by groundwater outflows (Meyer 1973; Roberts and Mitchell 1987; Boyd 1990a, 1990b, 1992, 1994). Each remnant also documents the former presence of species and communities now extinct, representing lost letters that may render sentences unintelligible in the volumes of our earth's history:

> [The naturalist] looks upon every species of animal and plant now living as the individual letters which go to make up one of the volumes of our earth's history; and, as a few lost letters may make a sentence unintelligible, so the extinction of the numerous forms of life which the progress of cultivation invariably entails will necessarily render obscure this invaluable record of the past. It is, therefore, an important object [to preserve them].
>
> If this is not done, future ages will certainly look back upon us as a people so immersed in the pursuit of wealth as to be blind to higher considerations. They will charge us with having culpably allowed the destruction of some of those records of Creation which we had it in our power to preserve; and, while professing to regard every living thing as the direct handiwork and best evidence of a Creator, yet, with a strange inconsistency, seeing many of them perish irrecoverably from the face of the earth, uncared for and unknown. (Alfred Russel Wallace 1863:264)

Subsurface water resources proved irresistible to the European-origin colonists of the western United States. Exploitation began with hand-dug wells or windmills: low-volume extraction with little effect on aquifer volumes except when uncontrolled flow from artesian bores led to depletion (Habermehl 1980; Brune 1981). Major impacts in the western United States closely followed the Rural Electrification Act of 1936, after which

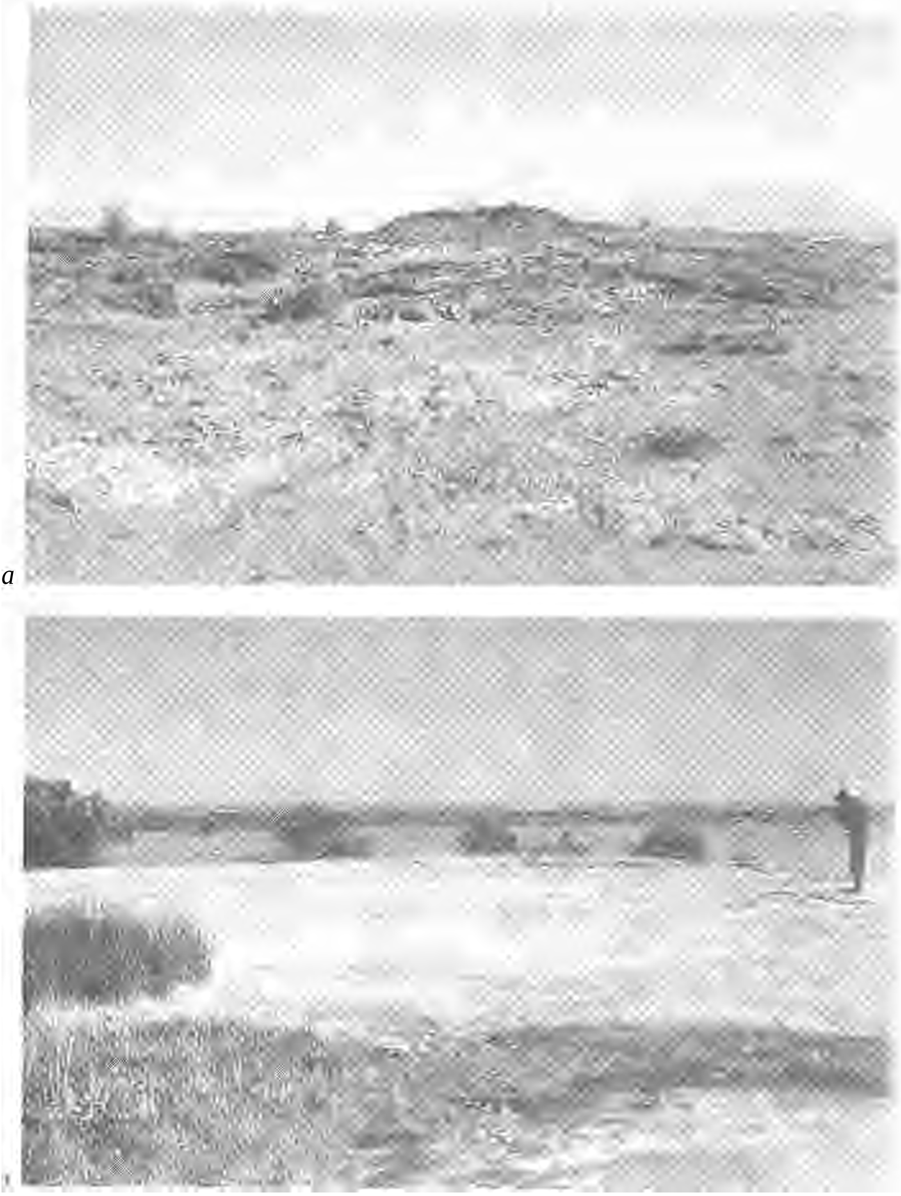
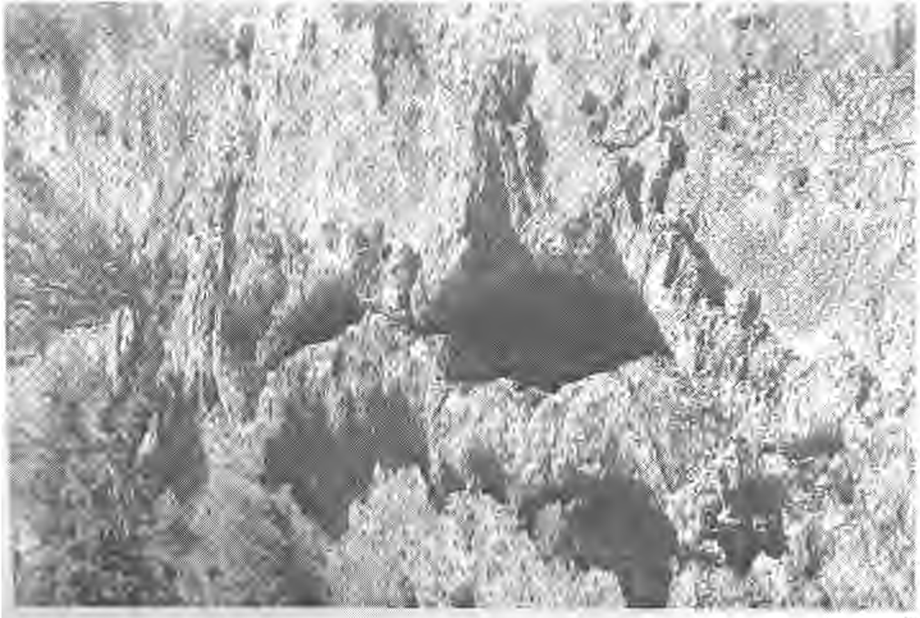


Figure 2.1. Fossil spring deposits come in a range of forms: *a*, Scattered travertine deposits with an extinct spring mound in the background at Chimney Hot: Springs, Nevada. *h,* The top of Coward Springs mound, South Australia, showing a round depression reminiscent of an old spring pool. A dying spring outflow is present in the foreground, while the main spring outflow comes out from lower down the mound. *c* and *d*, Spring deposits from Cuatro Cienegas: c is a fossil spring outflow channel; *d* is a fossil spring source. (Photos by P. J. Unmack, [illegible]



C.

Figure 2.2. Comanche Springs was once at least the eighth-largest spring in Texas and has been a valued community resource since at least the 1500s by providing water for human utilization, habitat for aquatic organisms, and recreational opportunities. These were all lost when declining groundwater levels caused the spring to dry in 1961 (Brune 1981). The extinct source of the main Comanche Spring is present just in front of the building. (Photo by P. J. Unmack, 1996)

high-volume electric pumps could be deployed. Agriculture expanded exponentially, even in remote areas, and rates of groundwater extraction soon became unsustainable (Postel 1992; Pringle and Triska 2000); far more water was removed than could be replenished by natural recharge.

Later, use of land for housing became lucrative in the western United States, and urbanization began to supplant agriculture. The population of Arizona grew from 2.7 million to 4.7 million people between 1980 and 1997 (U.S. Census Bureau 1999), and in adjacent and comparably arid northern Mexico population grew from 5.5 million to 8.3 million from 1980 to 1990 (Contreras-B. and Lozano-V. 1994). Although urbanization may be less demanding on water supplies than is irrigated agriculture, groundwater use has continued to rise with expanding human populations (Swanson 1989).

In Texas, 63 of 28) historically significant springs had gone dry by the 1970s (fig. 2.2), and fir more suffered reductions in volume (Brunc

Figure 2.3. Pahrump Spring, Nevada, dried between 1955 and 1957. It was one of three habitats in which the various Pahrump poolfish *Empetrichthys latos* subspecies were found, as well as several likely unique invertebrates. All have lost their natural habitat because of excessive groundwater extraction (Soltz and Naiman 1978). (Photo by P. J. Unmack, 1997)

1975, 1981). Unknown numbers of fishes and other biotic groups must have been impacted (Edwards et al. 1989; Longley 1981, 1992; Bowles and Arsuffi 1993). In northern Mexico, a known minimum of 92 springs (of an unknown total) failed in the two decades ending in 1993 (Contreras-B. and Lozano-V. 1994). Examples from other parts of this region (figs. 2.3 and 2.4) are summarized in Miller 1961, Minckley and Deacon 1968, Williams et al. 1985, Meffe 1989, and Minckley and Deacon 1991.

Such human-induced catastrophes can occur swiftly or take longer, depending on the volume of water extracted. Springs at several Australian sites dried or nearly dried soon after water extraction began (Ponder 1986; Ponder and Clark 1990), or they suffered progressive flow reductions because of groundwater removal (Harris 1981, 1992). A well-documented example is Elizabeth Springs, Queensland, which has suffered a reduction of approximately 95 percent since the 1880s (Habermehl 1982). Four pupfish (*Cyprinodon* spp.) along with unnamed unstudied invertebrates disap-

Figure 2.4. Part of the Laguna Chiqueros system in Cuatro Cienegas, which is the source of the Rio Garabatal and part of the type locality of the Cuatro Cienegas killifish *(Lucania interioris).* Lowered groundwater levels have reduced it to a tiny pool a few meters in area at the spring source. (Photo by P. J. Unmack, 1995)

peared when springs in two small Mexican basins were pumped dry in only a few years (Lozano-V. and Contreras-B. 1993; Contreras-B. and Lozano-V 1996). In the Middle East, Al Kahem and Behnke (1983) caught a minnow *(Cyprinion* sp.) in a spring in Khaybar City, Saudi Arabia, that was dry four years later. Several other springs reportedly failed in that same area and during that same period of time. By contrast, some places in that region occupied since the Pleistocene by humans with primitive extraction capabilities have persisted much longer; for example, water and endemic snails persist at the Palmyra Oasis in Syria despite human use for thousands of years (Schutt 1987).

In theory, if recharge balances extraction, then a large aquifer with an intact watershed can yield significant volumes of water indefinitely. Yet where reliable records exist, most springs fed by even the most extensive aquifers are affected by exploitation, and spring flow reductions relate directly to quantities of groundwater removed (Dudley and Larson 1976). As already noted, the great Edwards Aquifer of Texas is declining (Brown et al. 1992), with potentially catastrophic results for the indigenous biota of its springs (Longley 1981; Edwards et al. 1989; Longley 1992) as well as for humans depending on the resource. Similar situations are evident in the vast Ogallala aquifer of the North American High Plains (Winter et al. 1998), in comparably large aquifers of Saudi Arabia (Krupp et al. 1990), and elsewhere. Further development in Australia threatens aquifers: a mining venture extracting 1.5 × 0 cubic meters per day of water from the Great Artesian Basin in the 1990s increased to 3.3 x 10 cubic meters per day after the mine went into full production (Harris 1981, 1992). This has come to pass and bodes ill for the region's springs.

Reduction in discharge of a spring or spring group warns of unsustainable extraction somewhere. Because spring flow emerging many kilometers away may not be affected by groundwater interception for years, centuries, or even longer (Winograd and Pearson 1976), reduced discharge may portend uncorrectable failure in the future. Overgrazing, deforestation, and other land abuses are intuitive but largely undocumented factors reducing infiltration capacity and other features of a watershed, including recharge, which will ultimately influence the sustainability of the groundwater it feeds (Pringle and Triska 2000). Unfortunately, recharge rates, underground porosity, aquifer volume, and even the geographic extent of many aquifers are unknown. Such data are usually compiled only after some surface effect is detected, such as discharge fluctuations coincident with or related to pumping schedule, reduced flow, or even drying of springs (Dudley and Larson 1976; Habermehl 1980, 1982; Deacon and Williams 1991).

Less-than-Fatal Alterations, Some Correctable

Conservation Efforts

Early efforts at native-fish conservation involving desert springs, the training field for many of us now dedicated to such endeavors, resulted from events in Owens Valley, California, and Ash Meadows, Nevada. Spring development, artificial impoundment, and construction of canals to supply water for Los Angeles, followed by the stocking of non-native species for sport fisheries and release of bait, endangered the native biota of the long isolated Owens Valley, with its four endemic fishes. This stimulated formation of a native-fish sanctuary in 1967-68, a story in itself (Miller and Pister 1971; see also Perkins et al. 1984 and Minckley et al. 1991; for recovery perspectives, see U.S. Fish and Wildlife Service 1984, 1989).

In Ash Meadows, agriculture and urban development — especially groundwater pumping and clearing — threatened springs and their biotas and with them an evolutionary drama in progress for millennia (Pister 1991). A group of agency, academic, and private people deemed this unacceptable. They were able to rally support sufficient to stop the action and ultimately to result in the formation of Ash Meadows National Wildlife Refuge, but only after carrying their concerns to a favorable decision by the U.S. Supreme Court. These efforts and other details pertaining to saving and managing springs in arid lands, including litigation, are summarized in Dudley and Larson 1976, Deacon and Williams 1991, and Pister 1991.

As a generalization, changed volumes or patterns of flow of a spring or spring system have a "domino effect," involving numerous, diverse, and intertwined biotic and physicochemical shifts. Three major factors determine the severity of impact of reduction in flow or spring diversion: (i) proportion of flow lost; (2) reduction in downstream extent of the system as a result of less water or distance of interception from the source; and (3) new connections made by diversions between nearby spring outflows. Clearly, the smaller the proportion of water involved, the less the impact, and if flow reduction is small or diversion occurs far downstream, marshes can persist. When diversion is near the spring head, however, downflow marshes are drained and significant wetlands may be lost. This kind of damage has broader impacts than is often realized, because— in addition to containing indigenous, often-endemic resident biota —large, isolated desert marshes often are critical resting and feeding habitats for waterfowl and other migratory and resident birds (Minckley and Brown 1994).

Alterations of Head-Springs

Human alterations of head-springs, to concentrate or increase discharge, negatively impact spring systems and invariably result in loss of biota. Many springs in western Queensland, Australia, were excavated to increase water supply, with no success (Ponder and Clark 1990). Sometimes explosives have been used in an effort to increase discharge. Pumps inserted

figure 2.5. Jackrabbit Spring was repeatedly pumped dry over about a year during 1969-70. Because of the continuing poor condition of the habitat caused by nearby pumping, the spring was not restocked with fishes until 1977 (Williams and Sada 1985). (Photo by E. P. Pister, 1969)

directly into springs, or wells sunk nearby, dry them and destroy their biota. Jackrabbit Spring in Ash Meadows, Nevada, was repeatedly pumped dry for irrigation (fig. 2.5) (Pister 1991), a situation rectified when much of its biota was reintroduced and became reestablished (Soltz and Naiman 1978; Williams and Sada 1985). The common practice of capping springs and piping water away from the source for domestic or livestock water also destroys fishes, although seepage may continue to support small arthropods and snails (e.g., Shepard and Threloff 1997; Hershler 1998). Raycraft Spring in Pahrump Valley, Nevada, was simply filled with dirt in the 1950s to get rid of mosquitoes, and unintentionally the world's only population of Raycraft poolfish (*Empetrichthys latos latos*) was also eliminated (Minckley and Deacon 1968; Soltz and Naiman 1978).

In some cases, spring biotas persist to recover after major disturbance. One unusual catastrophe related to blasting had such an unexpected result. A drill centered in a hot spring for geothermal exploration near El Doctor, Sonora, Mexico, apparently penetrated a high-pressure zone that caused an explosion resulting in human injury and loss of life, destruction of the rig, and ejection of water, substrate, and adjacent marshes into the surrounding desert. A year later, WLM found that native desert pupfish *(Cyprinodon macularius),* snails (*Tryonia* sp.), and a suite of introduced fishes had recolonized the spring—a remarkable feat!

Kings Pool and Point-of-Rocks springs and their outflows and marshes in Ash Meadows suffered repeated dredging, ditching, and diversion (fig. 2.6) (Soltz and Naiman 1978), some even after they had become part of Ash Meadows National Wildlife Refuge (Polhemus 1993), yet much of their original biotas persisted. Big Bend gambusia *(Gambusia gaigei),* adapted to thermal springs in Texas, essentially disappeared when its habitat was dammed in 1953 to make a fishing pond. The endemic fish survived sport-fish predation by living along weedy margins, but some were brought into captivity just before the species' elimination in nature when mosquitofish *(G. speciosa)* gained access (Hubbs and Broderick 1963). The pond leaked, spring conditions were re-created in 1972, and by 1983 the endemic gambusia had reestablished naturally from a nearby, but unknown, refuge (Hubbs et al. 1986).

It bears noting that alteration for recreation or domestic water supply can also, sometimes, result in inadvertent protection of springs and their biotas. Survival of endemic Mexican fishes, crustaceans, snails, and other groups was reported by Contreras-B. (1991) in four of five large springs in Chihuahua, Mexico, that were modified into reservoirs, swimming pools, or thermal baths. He further noted that three other springs (one each in the desert states of Coahuila, Durango, and Nuevo Leon) were also modified for recreation in ways that resulted in protection for endemic biota. Five other large Mexican springs, some modified and some not, suffered reduced flow because of pumping or lost their endemics after non-native fishes appeared. In cases when springs managers zealously protect their local water supply, associated organisms may be maintained in a seminatural state (fig. 2.7) (Schoenherr 1988; Shepard 1993).

Alterations of Outflow

The effects of erecting a barrier across an outflow can vary from system disruption if the spring head is inundated (fig. 2.8) to both up- and

Figure 2.6. Kings Pool was totally [illegible] using heavy [illegible] equipment. All of the spring's outflow was diverted into canals for use in [illegible] alfalfa to feed cattle (Soltz [illegible] Naiman 1978). Today the spring pool [illegible] has removed by the U.S. Fish and \\ [illegible] (Photo by [illegible] P

Figure 2.7. **In** the 1930s, San Solomon Spring in Texas was converted into a swimming pool and its outflow diverted into a concrete channel, from which the water is taken for irrigation. Despite this, the native fauna has persisted. The area has been protected by Balmorhea State Park since 1968. More recently, a ciénega was created as a refugium for native pupfish with a public underwater viewing area (Garrett 1999). (Photo by P. J. Unmack, 1995)

downstream changes in chemistry, physics, and biology related mostly to barrier size and its distance from the source. Similar impacts occur when levels in a spring source decline below natural outflow elevation because of diversion or other reduction in flow.

Riparian vegetation has an early and evident response to reduction in flow. Plants characterizing spring outflows are typically stable for extended periods. These plants include sedges, grasses, and allies, adapted for life in waterlogged, reducing soil (Hendrickson and Minckley 1985; Boyd 1990a, 1990b, 1992, 1994). As the water level declines, soil dries and becomes aerated, so forbs, shrubs, and trees can invade. New water depths and soil conditions may also allow stands of cattails (*Typha* spp.) and reeds (native *Phragmites* spp. and African *Arundo donax,* widely introduced in North America and elsewhere) to expand, sometimes choking the habitat (see later discussion).

Figure 2.8. Poza de la Becerra was significantly reduced in size over a few days in 1964 upon completion of the canal shown from the upper right to the upper left of the remaining spring pool (Minckley 1969, 1992). The outline of the former spring pool/marsh can still be seen behind the present spring pool. (Photo by P. J. Unmack, 1995)

An example of the beheading of a large, complex system was photographically documented by WLM (Minckley 1969, 1992) for Poza de la Becerra in the Cuatro Ciénegas basin, Coahuila, Mexico, where a marshland covering approximately 10 square kilometers was reduced in a few days to less than 10-15 hectares by diversion for irrigation (fig. 2.9). No species was known to be lost, but habitats for populations of three turtles, seven fishes, and at least eight snails, all endemic to the basin, were eliminated, and numerous other indigenous creatures died. In a comparable event, Carson Slough in Ash Meadows was drained to facilitate the mining of a thick deposit of peat, resulting in significant loss of habitat for endemic speckled dace *(Rhinichtk)'s osculus nevadensis)*, Ash Meadows pupfish *(Cyprinodon nevadensis mionectes)*, and other organisms (Soltz and Naiman 1978). An example in Israel involved draining a lake and associated marshes for flood control and soil reclamation, followed by diversion of the spring that resulted (among other things) in a loss of refuge from winter cold for warm-adapted fishes

Figure 2.9. Big Spring at Panaca, Nevada, was dammed and its outflow ditched sometime between 1939 and 1959. Damming flooded the original spring source, and outflow marshes were lost when the outflow was channelized, resulting in extinction of the cyprinid fish, *Lepidomeda mollispinis pratensis* (Miller and Hubbs 1960). Today the spring contains only non-native fishes, some of which were introduced prior to 1959. None of the three original native fishes persists here today. (Photo by P. J. Unmack, 2000)

(Goren and Ortal 1999). Only two of seventeen indigenous fishes survived. Another example at an opposite extreme, the flooding of a spring, followed the closure of Amistad Reservoir on the Rio Grande, the boundary for the states of Texas and Coahuila, that inundated Goodenough Spring and destroyed endemic Amistad gambusia (*Gambusia amistadensis)* (Peden 1973; Minckley et al. 1991). Other examples relating to spring outflow diversions are shown in figures 2.10 and 2.11.

Downstream connections of diverted water, like the flooding of spring heads and breaching of critical barriers, may also prov We access for other species from distant places. In Death Valley, Tecopa pupfish (*Cyprinodon nevadensis calidae*) occupied a warm spring isolated by tiny but impassable waterfalls from the adjacent Amargosa River. When the falls were altered hilc building public baths, Amargosa pupfish (*C. n. amargosae*) gained ac-

Figure 2.10. Little Warm Spring in Railroad Valley, Nevada, drains via several artificial outflow ditches. Depending on where water is needed, an outflow may be cut off and dried, with the loss of any fauna that has colonized it. The head-spring has been left somewhat intact, allowing some fauna to persist and recolonize the outflows. (Photo by P. J. Unmack, 1994)

cess and hybridized Tecopa pupfish out of existence (Soltz and Naiman 1978). in Chihuahua, Conchos pupfish *(C)!prinodon eximius)* invaded thermal springs occupied by big-head pupfish (C. *pachycephalus*) through artificial channels, which also led to hybridization (Smith and Chernoff 1981; Minckley and Minckley 1986). Artificial canals in Cuatro Ciénegas allowed two other pupfishes (C. *atrorus, C. bifasciatus)* to intermingle and hybridize between their distinctive habitats (Miller 1968; Minckley 1984; Carson and Dowling 2006). Far more subtle are situations in which special conditions in a spring head, often not well understood (Hubbs 1995; Minckley and Unmack 2000), are abrogated to allow access to aliens. In Clear Creek, Texas, partial flooding of a spring head allowed invasion of ihe habitat of endemic Clear Creek gambusia (*Gambusia heterochir*) by western mosquitofish (*G. affinis*), again resulting in hybridization (Hubbs 1957, 199, [illegible]

In another case temperatures in excess of [illegible] in some spring heads in Soldier Meadows, Nevada, exceed the thermal tolerance of

Figure 2.11. The outflow of Preston Big Spring at Preston, Nevada, is diverted into pipes for irrigation 1.7 kilometers from the spring source. This type of diversion is as problematic as that shown in figure 2.10 but is made far worse when diversion occurs close to the spring source. This has resulted in the extirpation of three of four native fishes in nearby Lund Town Spring at Lund, Nevada, when it was diverted 50 meters from the spring source. (Photo by P. J. Unmack, 2000)

demic desert dace (*Eremichthys acros*). The fish lived downstream from hot-water sources, and the water was cooled by flowing a considerable distance before entering the habitat of the dace (Ono et al. 1983). When water was diverted too near a source, cool water was unavailable downstream, extirpating many populations. Similarly, WLM visited a hot spring (the temperature was more than 50°C at the source) in Oman where resident minnows (*Garra harreimiae, C)'rinion microphthalmum*) occurred below, but not above, a vertical barrier measuring 1.5 meters high, formed by a road. A knowledgeable resident reported both that fishes invaded upstream of the barrier during overland runoff and that they retreated downstream or suffered thermal death when base flow resumed. No thermometer was available, but base-flow temperatures (approximately 40°C) seemed identical to the hand above and below the road crossing; yet fishes were absent upstream.

Subtle but rarely mentioned changes may also occur with altered flow of carbonate-rich waters. Underground water is often charged with carbon dioxide (CO_2) from decomposing organics in strata through which it moves. CO_2 combines with water to form weak carbonic acid, which dissolves calcium carbonate ($CaCO_3$) rocks to form the more soluble bicarbonate (HCO_3). Concentrations of groundwater gases vary with pressure and temperature, so when a spring emerges, CO_2 is driven off by reduced pressure, temperature changes, and channel irregularities that cause agitation. Biology also comes into play because photosynthetic microphytes use both gaseous CO_2 and that carried in HCO_3. Acid-base relations change through all of these processes, resulting in deposition of insoluble $CaCO_3$ as travertine (Minckley 1999a). Precipitation is greatest near areas of channel roughness that promote agitation and enhance microphytes, thus resulting in an even greater loss of CO_2. These deposits, in turn, create more turbulence and thus more deposition, and a carbonate "dam" may form, sometimes extensive enough to impound and isolate a spring or modify a channel by creating pools and other complexity (e.g., Roberts and Mitchell 1987; Drysdale and Gale 1997). The length of spring outflow over which carbonate precipitates varies with distance from a spring source as a function of ion concentration, temperature, and so forth. Thus, speed and amount of carbonate precipitation vary with changes in volume and patterns of water flow, channel alterations such as artificial dams reducing or creating turbulence, or diversion and channelization that concentrate volume and change speed of flow.

Biological Problems

Other major impacts leading to biotic damage can result from livestock (Ponder and Clark 1990; Krupp et al. 1990; Harris 1992; Hershler 1998). Large ungulates — domestic, feral, or otherwise—seek springs for food and water, both limiting in deserts. Unless specifically protected, the majority of springs that we have visited in deserts of North America, Australia, and the Middle East have clearly suffered from livestock damage. Palatable plants are eaten and trampled, local soils compacted, and banks collapsed. Increased input of organic wastes increases nutrient concentrations. Some nutrients (e.g., nitrogen compounds) can themselves be toxic, and their presence can result in increases in potentially damaging microbes (Taylor et al. 1989). Domestic animals can also be trapped in soft spring deposits, with disastrous results when they die and decompose, resulting in the decline or loss of fauna (Unmack 1995). Outflows with livestock bones scattered over boggy areas are mute testimony to such accidents.

Nonetheless, most springs were originally grazed by native herbivores, so their natural biota evolved in concert with grazing pressure. Changes in grazing regime are followed by vegetation change, especially in smaller systems. Typically, the removal of grazing results in invasion by cattail, reeds, or both. Examples of this phenomenon include Mexican Spring in Ash Meadows, formerly supporting the smallest-known self-sustaining vertebrate population in the world (between twenty and forty-seven warm-springs pupfish, *Cyprinodon nevadensis pectoralis* [J. H. Brown 1971]), which dried in 1973 by evapotranspiration when cattails expanded after fencing to exclude grazing (Soltz and Naiman 1978). Soon after being enclosed by a fence, a similarly tiny spring near Bylas, Arizona, was choked and desiccated by cattails, eliminating a population of the endangered Gila topminnow *(Poeciliopsis occidentalis)* (Marsh and Minckley 1990). Overgrowth by cattails required periodic clearing of Corn Creek Spring, Nevada, a refuge for Manse Spring poolfish *(Empetrichthys latos concavus)* (Minckley et al. 1991); the same problem existed in Australian springs that became densely vegetated with *Phragmites* soon after fencing (fig. 2.12) (Harris 1981; Wager and Unmack 2000). Alternatively, some springs have had surrounding vegetation physically removed to reduce water loss, but the concomitant reduction in shade cover resulted in increased temperature and evaporation from exposed water surfaces, as well as a decrease in organic inputs, all of which also may negatively influence the biota.

Thus, grazing and other manipulations of natural vegetation are double-edged swords, dangerous at extremes. But controlled grazing and other clearing methods can be used to manage amounts and kinds of vegetation, allowing manipulation of evapotranspiration to result in more or less water and moderation of organic inputs to maintain a spring nearer its natural state.

Finally, accompanying (even, in some cases, barring) changes in discharge and impacts other than desiccation, the single most destructive force influencing desert-spring biotas of western North America, and increasingly elsewhere, is the ongoing invasion by alien organisms. Floating water plants such as water hyacinth *(Eichhornia crassipes)* can cover the surface, as in some

Figure 2.12. Outside Spring in South Australia was fenced in 1988 and exemplifies the complexities involved in spring conservation. The area inside the fence contained dense stands of reeds in 1994, with unknown effects on the flora and fauna, yet outside the fence the spring outflow was devastated by cattle grazing, with obvious effects. How to compromise between these two problems is not yet clear. (Photo by P. J. Unmack, 1994)

springs of Cuatro Cienegas (Contreras-B. 1991). Large, non-native plants such as salt-cedar *(Tamarix* spp.) and giant African reed are ever-increasing problems in North America. Palm trees have become established in locations such as Dalhousie Springs, South Australia *(Phoenix dactylifera)* (Mollemans 1989), and warm springs on the Moapa River, Nevada (*Washingtonia filifera*). They develop dense stands, shade out native vegetation, reduce solar input, contribute far more organic material than natural vegetation does, increase evapotranspiration, change outflow channel morphology, and also provide fuel for devastating wildfire (White et al. 1995).

Alien aquatic animals naturalized to western North American springs include a number of large invertebrates, especially the snail (*Thiara [Melanoides] tuberculata*) and crayfishes (mostly *Procambarus clarkii),* that prey on, compete with, or otherwise displace native biota (Williams et al. 1985; Contreras-A. et al. 1995). Among vertebrates, bullfrogs *(Rana* [illegible] *beiana)* have proven especially damaging. Adults feed voraciously on native frogs, snakes, and toads, often extirpating them, and eating fishes as well (Rosen et al. 1995). To our knowledge, the impacts of bullfrog tadpoles, which often swarm and may remain aquatic for up to two years, are as yet unassessed.

Introduced fishes have appeared in springs of arid zones throughout the world (e.g., Coad 1980; Ben-Tuvia 1981; Ross 1985; Moyle et al. 1986; Krupp and Schneider 1989; Courtenay and Moyle 1992; Coad and Abdoli 1993; Wager and Unmack 2000), with tropical species even appearing in warm springs in Canada (Nelson 1984). Introductions of small taxa often originate from the disposal of unwanted aquarium and bait fishes, but others are stocked for control of mosquitoes, as escapees from commercial facilities, or with the intent to harvest them later for profit. Larger species originate from stocking for sport or food or as escapees from aquaculture ventures (Courtenay and Stauffer 1994). The primary impacts of alien fishes are predation, competition for space or other resources, and hybridization.

In western North America, many native populations and species of fishes have disappeared in the face of large, efficient non-native predators such as largemouth bass *(Micropterus salmoides),* other centrarchids (e.g., green sunfish, *Lepomis cyanellus*), a number of African and Central American cichlids, and others (Minckley et al. 1991). Smaller .but equally efficient predators, mosquitofish *(Gambusia affinis, G. holbrooki)*, have been translocated worldwide for control of pestiferous insects. They have also been implicated, repeatedly, in the disappearance of Gila topminnow (Meffe 1985; Courtenay and Meffe 1989; Minckley 1999b) and numerous other taxa (Myers 1965). Impacts of the remarkable number of alien predatory fishes established in the western United States (Fuller et al. 1999) are yet to be quantified.

Various levels of competition must exist between native and non-native species (Schoenherr 1981; Douglas et al. 1994) but are difficult to prove; relationships are rarely clear-cut. By contrast, hybridization between related native and non-native species is readily documented by molecular and other methods and is clearly of concern. In addition to those discussed already, examples include Owens tui chub *(Siphateles bicolor snyderi),* now restricted to isolated springs in Owens Valley, as those in other habitats of that area become hybridized with non-native chubs brought as hail from elsewhere (U.S. Fish and Wildlife Service 1989). Leon Springs and Comanche pupfishes (C. *bovinus, C. elegans)* are similarly imperiled in Texas because of hybridization with an alien pupfish, the sheepshead minnow (C. *variegatus)* (Hubbs 1980; Echelle and Echelle 1994; 1997), also likely originating as discarded bait (Stevenson and Buchanan 1973; Garrett 1999 . Pecos pupfish C. *pecosensis)* is also being replaced by hybrids with sheepshead minnow in that same part of Texas and northward in New Mexico (Echelle and Conner 1989).

Transmission of alien diseases and parasites along with introduced non-native fishes and other organisms may also constitute a significant threat now and in the future (Hoffman 1970; Ho'ffman and Schubert 1984; Langdon 1988). Williams and colleagues (1985) suggested that anchor-worm *(Learnea* sp.), an ectoparasite appearing along with alien fishes, contributed to the decline of endemic springfish *(Crenichthys baileyi grandis)* in Hiko and Crystal Springs, Nevada. Asian tapeworm *(Bothriocephalus acheilognathi)* has become widespread in the western United States (Heckman et al. 1993; Clarkson et al. 1997 and has been recorded in Australia Dove et al. 1997 , originating along with non-native species and even with native fishes restocked from hatcheries for recovery purposes WLM, personal observation . Amin and Minckley 1996 found an alien nematode *(Hysterothylacium* sp.) in an endangered Gila topminnow. Although not previously reported in Arizona, the nematode was common in non-native fishes of a Colorado River reservoir. Few studies have as yet been performed in these areas of concern, and the disciplines of fish disease and parasitology beg for additional work immediately.

The Big Picture

A relevant special issue of *BioScience* Rosenberg et al. 2000) was dedicated to "global-scale environmental effects of hydrological alterations." Although emphasizing the damming of major rivers, many authors in that special issue focused on the intimate connections between surface and subsurface waters, as well as the broad linkages in physical, chemical, and biological relationships that are being dramatically modified as human development proceeds. Reflection of these changes in the biodiversity of whole river basins and subcontinental regions, even in well-watered zones such a the tropics, is of major concern Pringle 2000; Pringle and Triska z000 .

loss of springs is but one symptom of the broader problem of our ignorance in using Earth's resources.

In the "big picture," the disappearance of springs may seem a minor event, but to depauperate deserts, springs are often essential for much of the biota and thus become a major focus of biodiversity. Because of their regional importance, uniqueness, and vulnerability, recognition of the problem of loss and decline of springs and their biotas came early. Their conservation lagged behind, but recent attention in the literature, an establishment of refuges and protected areas in North America and Australia (Zeidler and Ponder 1989; U.S. Fish and Wildlife Service 1990; Williams 1991; U.S. Fish and Wildlife Service 1995; Abell et al. 2000), and greater emphasis on such habitats in other world deserts (Scates 1968; Skelton 1990) suggest that springs are now receiving increasing interest.

In most instances, managing springs is an exercise in informed guesswork. Things that one should know in advance include definitions of aquifer and recharge zones, their geographic extent, recharge volumes, and subsurface transmission rates, all of which are critical in evaluating vulnerabilities and potentials for damage by water extraction. Such information is often unavailable or becomes so too late, after a change in spring flow is detected — or even worse, after the spring is but a memory. An aggressive international program is needed that defines springs and educates people regarding their uniqueness and value as part of our world heritage; this requires that we take action to set aside, restore, and perpetuate as many examples as possible, before they all are gone.

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