Chapter 4: Subsystem Models for the Wet System

By D.R. Bedford and D.M. Miller

As described in the Wet Systems model, subsystem models can be built along many schemes, such as gradients between fresh and hypersaline water, between flowing and standing water, and between groundwater-controlled systems and runoff systems such as streams. In the Great Basin, most streams and lakes are interconnected with groundwater, which indicates that an approach using groundwater flow regime is best for a primary classification system. Secondary classifications we use are flowing versus standing water and salinity.

Groundwater Model

By D.M. Miller and D.R. Bedford

The following treatment of groundwater systems is based in large part on a report for the National Park Service Mojave Network (Miller and others, 2006), which included part of the Great Basin.

Distribution and Management Significance

By definition, groundwater systems occur wherever there is water in a porous medium (that is, rock and soil) beneath the Earth's surface. We restrict most of our discussion of groundwater systems to those that are saturated with respect to water. Most groundwater occurs in valley/basin sediments, and to a lesser degree, in bedrock in mountains. Surface expressions of groundwater occur in springs and seeps and a variety of ecosystems broadly categorized as "spring ecosystems" here. Groundwater systems often are connected to streams and rivers, and can be a source for streams (a gaining stream) or a net loss for streams (a losing stream).

The Great Basin region adopted by the GBILM project includes much of the northern Basin and Range physiographic province and parts of the Snake River Plain and adjacent plateaus; these provinces have distinctive hydrologic characteristics driven by distinctive geology. The Basin and Range province is marked by north-trending fault-block mountain ranges separated by wide valleys that have thick permeable valley-fill sequences. In the eastern part of the province, limestone and dolomite capable of transmitting and storing large quantities of water underlie the mountain blocks and valleys, creating an interconnected system generally known as the regional carbonate aquifer system. A consequence is that recharge in one mountain block aquifer may discharge in another area as a result of interbasin flow. On the scale of the entire Great Basin province, deep groundwater flow in the regional carbonate aquifer system generally is thought to be from the recharge area of eastern Nevada near and in Great Basin National Park; discharge occurs at low elevations such as Ash Meadows and Death Valley (Mifflin, 1968; Winograd and Thordarson, 1975) and the Bonneville Salt Flats. The Snake River Plain and adjacent plateaus primarily are underlain by volcanic rock that rapidly transmits water, and the region is drained externally by Snake River surface flow.

Groundwater maintains springs, wetlands, lakes, and many streams of the Great Basin, and thus is of primary importance for aquatic and riparian plants and animals. Many upland animals also depend on water supplied by these sources, as do migrating waterfowl.

Ecosystem Components and Processes

Very little is known about ecosystems in Great Basin groundwater systems. They likely support a wide array of microorganisms and potentially other life forms. Because the biology of surface ecosystems dependent on groundwater (springs and streams) is better understood, we focus the groundwater conceptual model on the physics and chemistry of groundwater systems, and describe how they may drive many of the spring and stream ecosystems, which are elaborated on as separate models.

As described in the wet systems conceptual model (figs. 2.14 and 2.15), water flows into an aquifer system primarily through mountain recharge, flows out at springs and playas, and is transpired by phreatophytic vegetation. Flow through porous media can be modeled with the use of a linear gradient law in hydrogeological models. This makes groundwater systems amenable to analytical techniques unlike biological systems, which are more commonly analyzed statistically. Uncertainty enters hydrogeological models due to the heterogeneity of geological materials, lack of data (for example, measurements of subsurface rock properties), and natural variability of some conditions, such as infiltration. A conceptual model of the hydrogeologic framework including recharge and discharge conditions is fundamental to any site-specific groundwater flow model. Hydraulic properties of rocks and sediment, and faults and other perturbations to groundwater flow comprise a hydrogeologic framework conceptual model. Subsurface properties can be interpreted remotely through geophysical techniques, well logs, surface maps, and pumping tests. Spring discharge can be measured with weirs and flumes, although discharge from combined plant and soil evapotranspiration is studied using heat and vapor flow methods. These measurements, combined with a hydrogeologic framework model and physical laws, can be used to model the response of a groundwater flow system.

The most fundamental law of groundwater flow is that mass must be conserved (that is, the sum of all flows into an aquifer, minus the sum of all flows out, must equal the change in aquifer storage; fig. 4.1). If the change in storage is negative then flow out of an aquifer is greater than flow in, groundwater levels are dropping, and the aquifer is being depleted. When groundwater levels and storage are static, it implies that flow into the aquifer (recharge) is equivalent to flow out of the aquifer (discharge). A steady state condition results when recharge is balanced by discharge over a sufficiently long time period.

A common conceptualization of an aquifer (fig. 4.2) presumes that recharge to the underlying formation is confined by the overlying impermeable layer so that the water level in a well penetrating the confining unit rises under pressure, perhaps even flowing to the ground surface in an artesian well. Water flows downhill from high elevations to low elevations and from high pressure to low pressure. Flow through a given cross-sectional area of a porous medium is proportional to the hydraulic gradient (difference in water-table elevation divided by the distance), where the constant of proportionality is called hydraulic conductivity—Darcy's Law (Darcy, 1856). A storage coefficient (either specific yield or storativity) and hydraulic conductivity are the core parameters of the groundwater flow conceptual model. Another useful parameter is aquifer transmissivity, which is the product of hydraulic conductivity and thickness of saturated material.

When an aquifer is perturbed from an equilibrium state by, for example, climatic variability or initiation of groundwater pumping, it responds at a rate controlled by its physical characteristics. The most important physical characteristic of an aquifer is its size, such that larger aquifers, both in area and volume, respond more slowly. Another important feature is whether the aquifer is confined by an impermeable layer and is under artesian pressure, or is an unconfined aquifer (fig. 4.2). Confined aquifers respond quickly—pulses of pressure are transmitted rapidly through the system; unconfined aquifers strongly dampen such pulses. Finally, there are the physical characteristics of the saturated thickness of the aquifer and the integrated hydraulic conductivity of its sediments, matrix, or fractures. Coarse gravel and fractured limestone more easily transmit water, whereas silt and clay layers and unfractured limestone do not. A larger transmissivity corresponds to a more rapid response. Estimating how quickly groundwater levels in an aquifer respond to perturbations requires information about the aquifer size, presence of a confining layer, depth to water, depth to bedrock, and hydraulic conductivity.

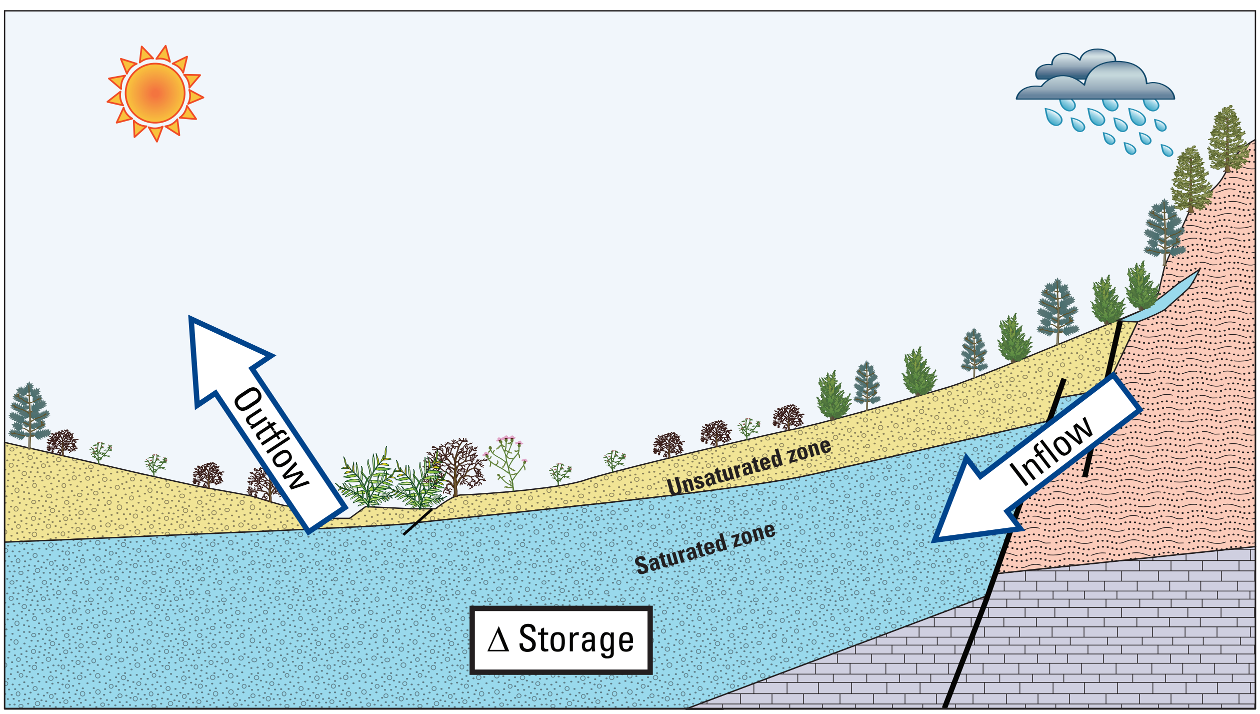

Figure 4.1. Conservation of mass implies that the difference between inflow (recharge) and outflow (discharge) is balanced by a change in aquifer storage.

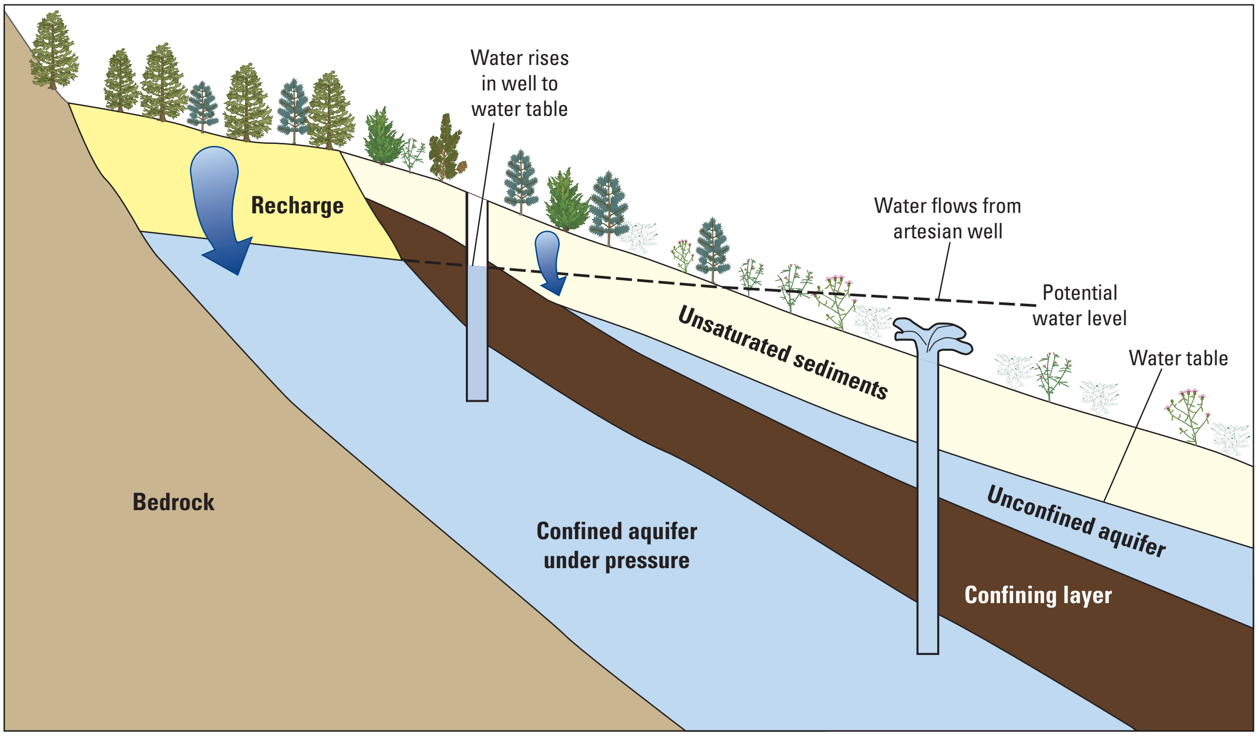

Figure 4.2. Illustration of confined and unconfined aquifers and associated potential water levels.

Groundwater Chemistry and Contamination

Evaporative moisture in the atmosphere, as well as transpiration from plants, is relatively pure water with little dissolved minerals. Condensation into raindrops, hail, snow, and sleet tends to form around dust particles, and precipitation delivers somewhat less pure water. Water is an effective solvent, reacting with most substances, and changes chemistry along its flowpath through the hydrologic cycle as it reacts with rock and sediment. Acidic precipitation facilitates dissolution of carbonate rocks, leading to enlarged solution cavities such as Lehman Cave in Great Basin National Park. Rock–water reactions dissolve mineral components so that the number of chemical species in solution and total concentration increases along a flowpath, usually measured in total dissolved solids (TDS). Groundwater in proximity to the zone of recharge at mountain fronts (usually high elevations) is generally low TDS (300–400 mg/L or less). Closer to discharge areas in valleys, TDS is usually greater than 1,000 mg/L. Groundwater flowing through the Great Basin regional carbonate aquifer system becomes saturated in carbonate and bicarbonate in isolation from the atmosphere. At groundwater discharge areas, such as Ash Meadows in Death Valley National Park, carbonate minerals are precipitated when groundwater comes into contact with the atmosphere, degasses, and evaporates. Evaporation from wet playas such as Devils Golf Course in Death Valley also leaves behind near-surface concentrated brine with TDS in excess of 50,000 mg/L, along with salt deposits and other evaporite minerals. Ions in solution in groundwater reflect the geologic materials through which groundwater has passed.

Groundwater quality is affected by natural and anthropogenic compounds, such as arsenic, nitrates, iron, manganese, hexavalent chromium, petroleum hydrocarbons and volatile organic compounds, as well as radon. Arsenic is a common naturally occurring groundwater contaminant in the desert, associated with sedimentary rocks derived from volcanic areas and geothermal systems. Arsenic contamination can be exacerbated by mining waste piles and by changes in oxidation-reduction conditions in the aquifer. Major sources of nitrates are fertilizer, animal wastes, and domestic sewage. Oxygen reacts with iron and manganese to form precipitates, so groundwater high in dissolved oxygen tends to be low in iron and manganese. Deep circulating groundwater, not exposed to the atmosphere for a long time, becomes depleted in dissolved oxygen and readily dissolves iron and manganese carbonates. A common indicator of overall groundwater quality is TDS, usually expressed in milligrams per liter or the equivalent parts per million.

Drivers of Ecosystem Change

Natural Drivers

Natural drivers of groundwater systems will vary in their significance depending on the aquifer type. For instance, regional groundwater systems are not likely to be affected by many biotic drivers, with the exception of evapotranspiration losses by phreatophytic vegetation. Smaller aquifers, particularly upland aquifers, are sensitive to climatic variations and biotic and physical losses in the form of evapotranspiration. Changes in discharge, water temperature, and water chemistry can be expected as a consequence of climate change.

Anthropogenic Drivers

Groundwater pumping has significant impacts on groundwater in the Great Basin. In addition to the direct effect on streams, diversion of streams that recharge aquifers also can affect groundwater systems. Pumping and diversion that reduce water tables can result in spring- and streamflow declines. Even when pumped at a rate that maintains water table levels, a pumped aquifer can alter the natural system by reducing water formerly available for plants and aquatic organisms, instead using the water for transpiring crops, for example.

Anthropogenic water contamination often is categorized as being derived from either a "point source" or a "non-point source." Point sources are leaking underground tanks, spills, landfills, mining spoils, and septic systems, whereas non-point sources are atmospheric nitrogen deposition, pesticides, and fertilizers sprayed on agricultural fields. Shallow, unconfined aquifers are most susceptible to contamination, especially near urban areas, farmland, and roads. Deep aquifers and confined aquifers are less susceptible, especially over the time span of a few decades. However, once large aquifer systems are contaminated they can remain contaminated for long periods.

Ecosystem Dynamics

Most aspects of ecosystem change are dealt with in ensuing aquatic models. As described above, changes in recharge can drive immediate or gradual changes in discharge, depending on aquifer characteristics. Likewise, contamination of aquifers can have immediate or gradual effects. Key to understanding the dynamics of groundwater is an understanding of the relevant aquifer system.

Summary Points

Knowledge of aquifer characteristics and climate is sparse in the Great Basin, save for a few areas with dense wells, large populations, and dense climate stations. Increased density of hydrologic and climate data will improve our ability to model aquifers. Improved modeling will increase our ability to respond to disasters such as contamination events and to anticipate effects of drivers, such as climate change and increased groundwater pumping.

Wetland and Spring Models

By D.R. Bedford and D.M. Miller

Spring systems in the Great Basin are found in settings ranging from alpine to desert valley floors and vary widely, and generally are poorly investigated and understood. The following treatment of spring systems is based in large part on a treatment of springs and wetlands for the National Park Service Mojave Network (Miller and others, 2006), which included part of the Great Basin.

Distribution and Management Significance

Spring systems in the most general sense are ecosystems formed where groundwater discharges at the Earth's surface. Here, we include a wide variety of discharging systems from seeps and wet meadows to springs and spring-marsh complexes. We exclude from this model (1) those marshes along the edges of lakes because those systems interact closely with lakes and are better described in lake models, and (2) wet (discharging) playas, which typically have no surface water or have extremely saline surface water, and support a unique ecosystem.

Spring systems vary widely, and can be described by a few fundamental variables that in general are related to aquifers. Aquifer characteristics (residence time, recharge source, lithology, chemistry) impart strong controls on groundwater discharge characteristics such as temperature, chemistry, and rates (Freeze and Cherry, 1979; Domenico and Schwartz, 1990; Fetter, 1994), as described in the groundwater model. In the Great Basin, springs often are the primary sources of water for small streams and riparian zones, and thus interact with surface-water systems.

Three types of aquifers described in the wet model serve to differentiate springs: (1) small, *upland* aquifers; (2) *local* valley aquifers; and (3) *regional* aquifers. The characteristics of these aquifer types as they relate to springs are summarized in table 4.1. Springs fed by upland aquifers tend to have cool water (<10 ^{o}C) and commonly go dry during droughts. Springs fed from local aquifers also may change seasonally and go dry during extended droughts. Springs fed by regional aquifers tend to be warmer (>20 ^{o}C), and high in solutes due to the depth and length of flow paths, and tend to have discharge rates that remain fairly constant over time intervals exceeding 50,000 years (Winograd and others, 1992). Size of spring ecosystems is a strong function of groundwater discharge. At the low end of discharge, seeps tend to support upland and facultative wetland species adapted to drier conditions. At the high end of spring discharge, permanent ponds and riparian corridors are common and may support many endemic and endangered species.

From the perspective of aquatic and riparian ecology of spring systems, the position in the landscape, discharge rates and persistence, and water chemistry are determinants of the spring ecosystems. However, the ecology in combination with hydrologic characteristics dictates many of the characteristics such as morphology of the spring system. For instance, ephemeral seeps and wet meadows occur in and near mountains as a result of the very low and variable discharge from upland aquifers; water is fresh and cold, and plants in that environment include luxuriant xerophytic growth and in some cases phreatophytes. In contrast, springs with local aquifer sources typically occur in piedmont settings and range from low, fluctuating discharge with salty water, which may create salt grass systems that tend to trap fine materials and create spring mounds, to moderate discharge spring complexes with diverse phreatophytes, wildlife, and spring geometries. Regional aquifers form one end-member of the range of spring systems, for which large marsh complexes with open pools, situated in valley bottoms, are common. A general diagram of aquifers, flow paths, spring discharge types, and their typical locations in the landscape and associated hydrologic systems is shown in figure 2.14.

Challenging issues regarding Great Basin spring ecosystems are important for nearly all land managers in the region. Because of their importance for surface and groundwater availability, springs often are managed under long-standing water rights legislation. They also tend to support species of interest, rare, threatened, and endangered species (for example, Devil's Hole pupfish [*Cyprinodon diabolis*] and redband trout [*Oncorhynchus mykiss*]) due to their isolation and endemism. Invasive species are common in springs, difficult to manage, and commonly alter habitat and lead to local extinction of native species.

Springs in arid regions may serve as keystone ecosystems, commonly providing the only available water and habitat for many plant and animal species. Steep gradients of moisture, soil types, biodiversity, competition, and productivity create abrupt ecotone boundaries. Springs also may serve as paleo-refugia and as habitats in which the evolutionary processes of natural selection, isolation, and adaptation are coupled to assemblage composition through island biogeographic and historical community development processes (Stevens and Springer, 2004).

Ecosystem Components and Processes

Spring systems are largely driven by spring morphology, and the persistence and physiochemistry of water discharge. Springs exhibit many morphologies and a single spring may change morphology with time. Common types range from lush open pools to seeps that exhibit damp earth with no open water; between these end members is a wide variety of wet meadows, marshes, permanently wet short stream segments in canyons, spring mounds, and saline springs with few vascular plants.

Aquatic organisms, riparian vegetation, and associated fauna all vary with spring type (Sada and others, 2005), but an anthropogenic influence is ubiquitous, complex, and severe. As a result, human modification of springs must be considered in classifications. For instance, a marsh that is cleared and dredged to provide open water for livestock may be functionally distinct from less-disturbed open-pool springs.

Table 4.1. Characteristics of springs related to three types of aquifers common in the Great Basin.

Characteristics	Aquifer type		
	Upland	**Local**	**Regional**
Aquifer size	Very small	Small	Large
Water temperature	Cold	Cool	Warm
Solute concentration	Very low	Low to moderate	Moderate to high
Total discharge	Very low	Low	Moderate to high
Discharge persistence	Highly ephemeral	Ephemeral	Invariant
Discharge site	Mountain	Piedmont	Valley bottom
Typical discharge morphology	Wet meadow, seep, pothole	Small spring, seep, spring mound	Spring-marsh complex, wet playa

Groundwater Flow Regime

Despite the human influence, groundwater characteristics are a primary determinant of many biotic characteristics of springs, providing a multi-dimensional space in which springs of various types lie. Figure 4.3 shows some of the primary dimensions that tend to structure biota, with biodiversity portrayed as one metric of biotic structuring. Springs and other discharge types also can be plotted in discharge-biodiversity space (fig. 4.4) with the observation that spring brook length and spring pool size correlate positively with biodiversity and negatively with spring salinity (Sada and Nachlinger, unpub. data, 2009).

Spring systems are dynamic systems with inherent and anthropogenic disturbance regimes. Excluding anthropogenic disturbance, spring variability mimics hydrologically determined environmental conditions, each of which can be mapped into biotic response. Variability of biota tends to be determined by aquifer size, gradients in microclimate (temperature and precipitation), variability in hydrologic regime, and size and length of runout spring brook, which is correlated with groundwater discharge. Figure 4.5 shows an idealized example of a spring system with associated runout stream, showing typical trends in environmental and biotic factors.

Mineral precipitation, which is driven by physiochemistry of water, flow rate, and evapotranspiration, may be important in springs. Precipitation of calcite (calcareous muds and travertine) or silica (opal or sinter) is especially pronounced in thermal springs but also occurs in cold water springs. Precipitation and sedimentation modifies discharge geomorphology, changing aquatic and riparian habitat.

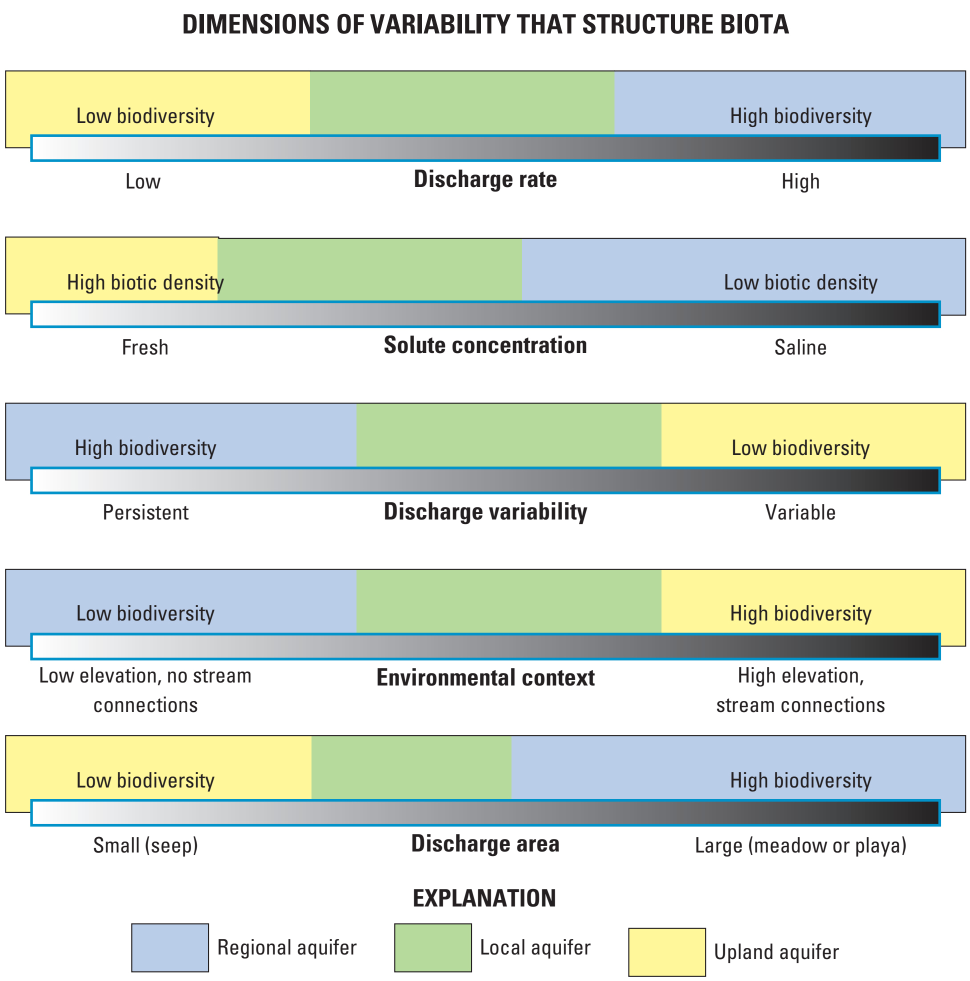

Figure 4.3. Illustration of five gradients in spring discharge environment and effects on biodiversity. Each gradient can be related to aquifer characteristics, as shown qualitatively with colors.

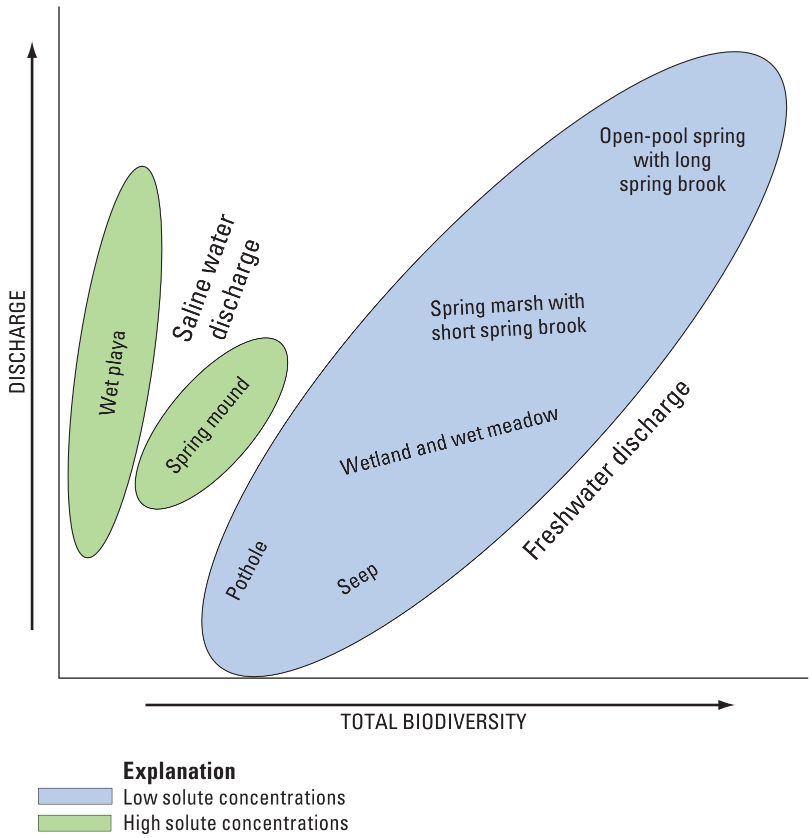

Figure 4.4. Illustration of spring types and how they vary with discharge and total biodiversity.

Spring Vegetation

With the exception of species that tolerate extremes in spring physiochemistry, such as geothermal, saline, alkaline, and anoxic conditions, spring vegetation is similar to stream-side riparian vegetation communities, particularly the presence of grasses and sedges. Large springs with associated streams may support riparian trees, as discussed in the stream and riparian model. In addition to emergent vegetation, spring systems typically include subaquatic macrophytes and planktonic and benthic algae.

Primary productivity in springs and wetlands primarily is determined by the amount and quality of flowing water. Stagnant or deep-water wetlands tend to have low productivity, while slowly flowing springs have high productivity (Mitsch and Gosselink, 2000).

Spring vegetation interacts with geomorphic processes by capturing fluvial and eolian sediment, causing infilling of open water. This alteration of habitat is counteracted by natural disturbance events such as scour by floods and digging by animals. In addition, algae-mediated calcite deposition as tufa or calcareous muds causes infilling.

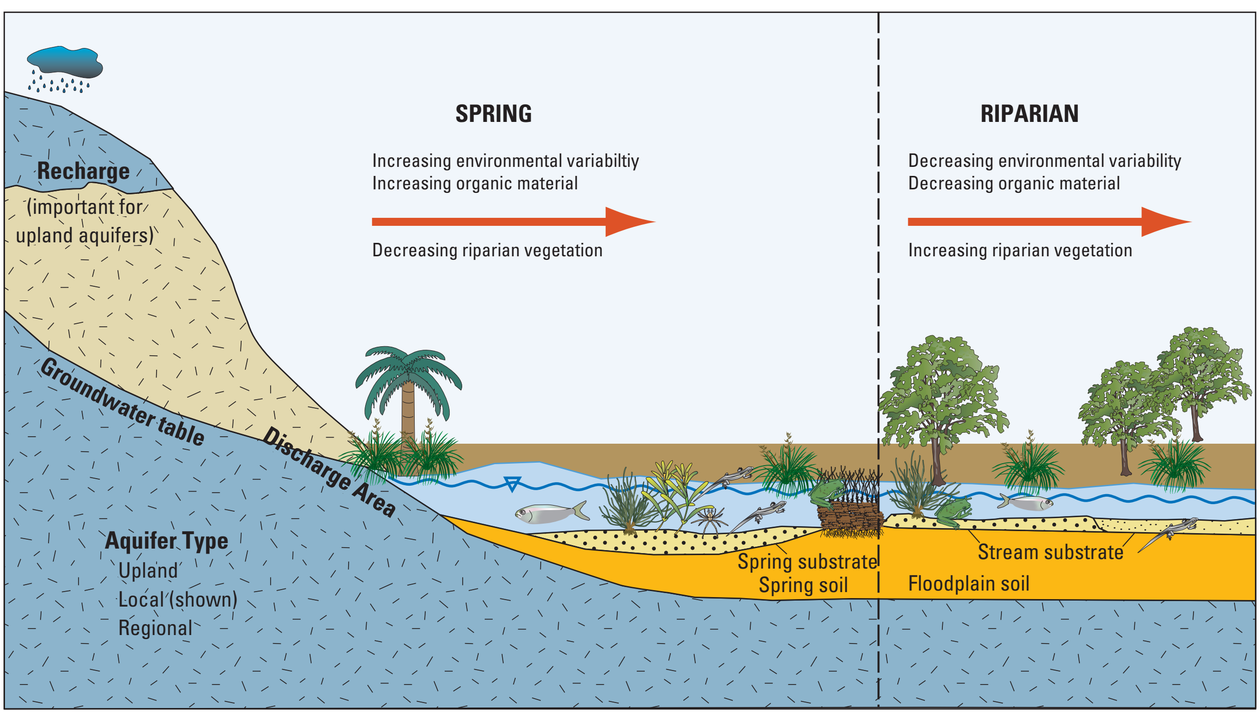

Figure 4.5. Illustration of typical components and gradients in open-pool springs and associated runout stream/riparian zone.

Geomorphic Processes

The geomorphic setting of springs as well as processes dictated by the setting (for example, slope, substrate characteristics, soils) and discharge all affect spring orifice and stream runout characteristics. The geomorphic setting affects streams in numerous ways. Lithology and soil characteristics can determine how discharge is manifested spatially, for example, as point sources, seeps, and discharge lineaments. Surface slope determines the flow rates away from discharge locations, and aspect has strong effects on evaporation rates.

Geomorphic processes acting in or near spring systems can maintain and modify orifice and stream runout characteristics. Processes affecting springs include flooding, scouring, and filling. External processes include erosion/deposition of sediments, rockfall, and freeze-thaw disturbances. Little is known about potential feedbacks of springs on the surrounding landscape (Stevens and Springer, 2004).

Spring Invertebrates and Vertebrates

Spring invertebrates are important consumers, shredders, and detritovores whose life cycles are tied to hydrology, vegetation floristics, and physiognomy (Mitsch and Gosselink, 2000). Sada and others (2005) determined that species richness of aquatic macroinvertebrates may be greatest at intermediate levels of natural and anthropogenic disturbance, and that general macroinvertebrate characteristics could not be predicted from simple metrics of environment, such as elevation, and disturbance (that is, springs are highly individualistic, as are their macroinvertebrate characteristics at a large scale).

Fishes are important consumers in springs, and are affected by water level, spring “openness” (a function of hydrology, geomorphology, and vegetation), chemistry, and temperature (Mitsch and Gosselink, 2000; Andersen and Deacon, 2001). Birds are abundant at springs, including obligate and migratory species (Mitsch and Gosselink, 2000). Birds act as secondary consumers, can maintain moderate levels of disturbance through bottom feeding activities, and can be important vectors for transmittal of seeds and organisms into and out of spring systems. Little is known about the characteristics of springs that determine bird community characteristics. Mammals (for example, beaver and muskrat) probably are unevenly distributed among Great Basin springs. However, mammals of all types extensively use springs, and act as consumers, ecosystem engineers, and seed and organism vectors.

The relative degree of isolation of spring systems either leads to endemism or development of dispersal mechanisms. Dispersal mechanisms vary with organism type, and include passive or active dispersal. Passive dispersal includes dispersal by wind, water, gravity, or other organisms. Active dispersal is exhibited in strong-flying invertebrates, birds, bats, and larger mammals including humans (Stevens and Springer, 2004).

General Spring Model

Figure 4.6 presents a general spring system control model incorporating key system components, processes, and drivers. Springs are driven predominantly by groundwater discharge, which determines the amounts and basic physiochemistry of water emerging from an aquifer. The orifice type determines the general shape of a spring, which is in part determined by the landscape template (not shown). Orifices with large discharges and appropriate configurations will have outflow in pools, marshes, and streams that are important parts of spring habitat.

Water physiochemistry and the configuration (geometry, soils, etc) of the orifice and outflow channels determine habitat characteristics of spring systems because vegetation communities are dependent on spring water physiochemical conditions, as well as community dynamics. Spring systems often support aquatic and terrestrial organisms, which sets up interspecific and intraspecific competition, facilitation, and food webs. A more detailed treatment of aquatic terrestrial dynamics is provided in the “Aquatic Ecology Control Model” section.

Geomorphic processes in springs with sufficient discharge create a dynamic system. Fluvial erosion or deposition and dust trapping (not shown in conceptual model) is enhanced by vegetation and the presence of moisture at the surface. Dust-trapping and vegetation expansion compete with orifice flow and scour to maintain a dynamic spring pool and spring brook system.

Geothermal Springs

The Great Basin is home to dozens of thermal springs that have many characteristics that set them apart from cool springs. Although temperatures range widely, springs that are warm (~20°C) to hot (>38°C) [70; >100°F] are generated from regional, deep aquifers that encounter hot rocks at great depth. Most occur in valley bottoms. They exhibit persistent flow but may have several spring pools and brooks with different temperatures and discharge. Edifices typically are large tufa mounds, although siliceous sinter complexes (for example, Fish Lake Valley) occur as well. Mineral deposition by precipitation and algal-mediated processes strongly shape edifices of many thermal springs. Complex ecosystems of thermophilic organisms may be present. However, these hot spring systems have been widely targeted for development by humans, and nearly all probably are highly disturbed. Water in runout brooks commonly is sufficiently cool to support cool spring aquatic communities and to be used by humans. However, some geothermal springs have unusually high concentrations of trace metals, minerals, or salts that make the waters toxic to many life forms.

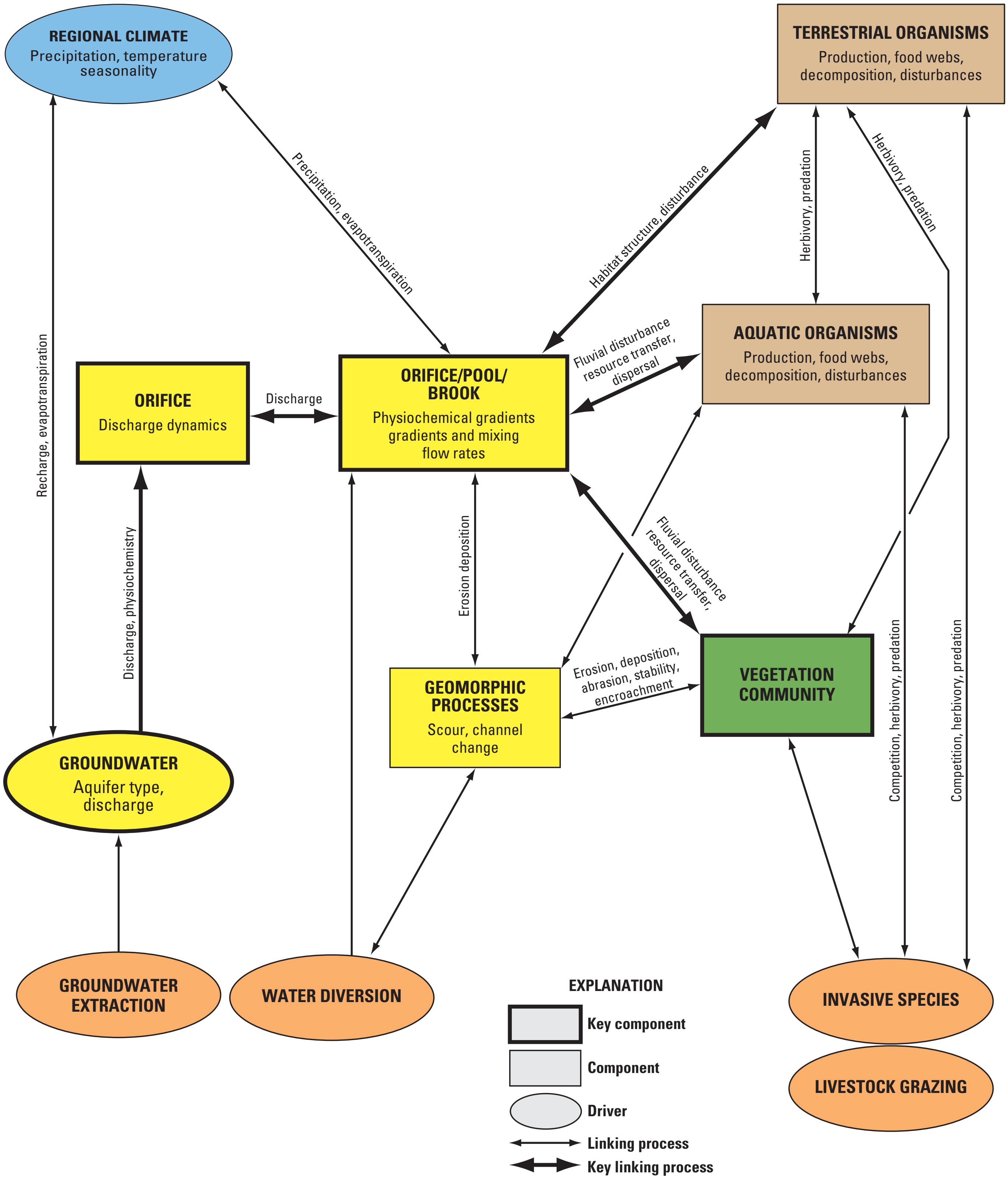

Figure 4.6. Control model of spring ecosystems including key processes (arrows), components (boxes), and drivers (ellipses).

Drivers of Ecosystem Change

Natural Drivers

The primary determinates of spring ecosystem form and function are aquifer type/discharge characteristics, environmental gradients away from discharge site, and anthropogenic modifications. Springs, by definition, are where the groundwater table intersects the ground surface, thus groundwater is the primary determinate of the physiochemistry of water delivered to springs. Changes in discharge rates or physiochemistry can dramatically alter spring characteristics and function, as well as cause them to dry out. However, due to the nearly ubiquitous modification of springs in the Great Basin by human activities, land use disturbance clearly is an important anthropogenic driver.

Anthropogenic Drivers

Pre-historic and historic use of large flowing springs is important to understand for assessments of modern spring biotic conditions. Seeps, spring mounds, and wet meadows have been widely developed as local water supplies that are not robust enough for irrigation. Nearly all springs and wetlands in arid environments have been severely impacted by human activity (Sada and Pohlmann, 2006). A survey of 505 springs in northern Nevada (Sada and others, 1992) determined that more than 85 percent of these springs were moderately or highly disturbed by diversion and livestock. Less than 5 percent of the springs in this study were unaffected by human activity. Shepard (1993) noted that human activities have altered the physical and biological condition of most springs in western North America. Anthropogenic stress factors include diversion (groundwater pumping, spring box capture and piping to troughs, channelization, etc.), impoundment, nutrient pollution, introduction of non-native plants and animals, and trampling by humans and non-native ungulates (Sada and Pohlmann, 2006). Water diversions, predation by exotic species, grazing, pollution, urbanization, and recreation have caused extinctions of spring populations since the late 1800s. Across the Great Basin, there is a loss exhibited by 60 percent of the endemic species (virtually all fishes, insects, and amphibians), of which all but 2 percent have had major declines, and 8 percent have been extirpated. Spring habitat and population loss peaked after each world war and was static during wars, indicating a tight connection to economic conditions (Sada and Vinyard, 2002).

Historical ecology has many potentially large applications for springs and wetlands. Paleoclimate and paleobotanical records describe the sediments under springs and marshes, and faunal records, though limited, typically are available as well. Study of past hydrologic and ecologic conditions can be valuable for establishing reference conditions with which modern conditions can be compared (Swetnam and others, 1999) and future conditions projected.

Decreased discharge increases the variability of the spring environment and shortens spring runout length, which alters aquatic species composition. Native Americans and early settlers commonly increased access to water by excavating the pools and digging shallow wells. It is difficult to determine original characteristics for these modified springs. Some of the anthropogenic modification likely involved removal of phreatophytic vegetation to enhance water availability.

Introduction of non-native species also has been a consequence of historical activities. Sport fish, aquarium fish, and mosquitofish introductions were widespread. Trampling by non-native ungulates such as livestock, wild horse, and burro populations has impacted springs in ways similar to excessive grazing in riparian systems by increasing temperature, fine substrate sediments, and nutrient loading (Kauffman and Krueger, 1984; Fleischner, 1994). More recently, groundwater contamination by pollution, increased nutrient concentrations, and refuse disposal from mine stockpiles and tailings, landfills, sewage treatment ponds, fertilizers and pesticides, hazardous waste disposal, and accidental spills of hazardous chemicals and waste have become significant problems.

Modern increases in groundwater extraction is likely the single greatest threat to springs by reducing or eliminating discharge. Paving over or otherwise disturbing groundwater recharge zones, especially in mountainous areas and along mountain fronts, may significantly impact groundwater flow systems. The effects of groundwater extraction may take decades to centuries to manifest. Effects of water diversions and pumping are similar to the consequences of drought. Reduced discharge results in loss of endemic species and reduction of biodiversity. Drought-intolerant aquatic species (for example, mayflies, caddisflies, and crenobiontics) are replaced by drought tolerant taxa (for example, midges, beetles, corixids, etc.) and non-native and upland vegetation may become dominant members of the riparian community following reduction or elimination of surface discharge (Sada and Pohlmann, 2006).

Changes in climate can stress all aquifers but effects will be most immediate in upland and local aquifers with short flow paths. Alterations in watershed budgets through increased aridity (that is, little recharge occurs) or altered amounts and timing of snowmelt can decrease discharge or otherwise disturb spring ecosystems. Springs in deserts are highly likely to respond to climate changes and such changes can have cascading effects on wildlife dependent on the water sources.

Invasive species threaten nearly all water sources in the Great Basin, and include invasive plants (for example, saltcedar and annual grasses), invertebrates, fish, and mammals.

Ecosystem Dynamics

Spring ecology in arid regions generally remains unsynthesized and relatively poorly studied. Studies have focused on characteristics of springs (for example, flow and water quality), individual taxa or biota, or on selected topics at local, or rarely, regional scales. High demands for water in arid lands and the inherent complexity of springs likely have retarded development of comprehensive understandings of spring ecosystem (Stevens and Springer, 2004). As a result, much is known about biotic composition of Great Basin spring systems, and little is known about the processes and dynamics that act in them. Consequently, we develop our conceptual model primarily around studies from other regions that have applicability to Great Basin springs.

Benthic macroinvertebrates, aquatic insects, reptiles, amphibians, and (mostly endemic) fish species in springs and seeps in the Great Basin have been identified as a high priority by land management agencies, highlighting a need for integrated eco-hydrologic models for these systems. Rather than attempt over-simplified, and probably incorrect, conceptual models on the basis of inadequate data, the approach taken here is to present conceptual models of what is known about spring-fed ecosystems and highlight information gaps. This approach emphasizes springs with pools and outflow streams, about which most is known.

Despite the unique characteristics of individual desert springs, some aspects of their ecological relationships may be generalized. Small springs tend to be autotrophic, with little dependence on allochothonous carbon sources (Minshall, 1978; Cushing and Wolf, 1984). Within large spring systems, environmental variation tends to be lowest near the source, where conditions are more stable, and higher downgradient where variability in temperature, discharge, and dissolved oxygen concentration is greater (Deacon and Minckley, 1974). Abundance of plant and animal populations may vary seasonally as a function of food availability, temperature, reproduction, and migration of species along a spring brook (Sada and Pohlmann, 2006), although spring morphology influences the types of species present. Habitats may be partitioned based on factors such as water depth and velocity, and substrate (Deacon and Deacon, 1979; Sada and Herbst, unpub. data, 1999). Aquatic organisms in thermally and geochemically stressed springs, where osmoregulation and respiration are difficult (Brock, 1994; McCabe, 1998), tend to be tolerant of harsh conditions; some flies and cyanobacteria are examples.

Most springs in the Great Basin host saltgrass (*Distichlis spicata*) and many host sedges (*Carex sp.*). Deeper waters commonly have bulrushes (*Scirpus sp*.) and lizardtail, and larger marshes and riparian zones may have mesquite (*Prosopis sp.*), willow (*Salix sp.*), or salt cedar (*Tamarix ramosissima*). Marsh birds and waterfowl use springs during migration, and nesting by blue-winged teal (*Anas discors*), cinnamon teal (*A. cyanoptera*), and ruddy ducks (*Oxyura jamaicensis*) is common. There are many aquatic amphibians such as toads and salamanders. Spring ecosystems also support enhanced populations of mammals such as rodents, bats, rabbits and ungulates (Minckley and Brown, 1994).

The biota of arid land spring systems show characteristics attributed to the colonization and extirpation dynamics of small, isolated habitats (Sada and Pohlmann, 2006). Isolation of springs and relatively small habitat patch size may promote aspects of island biogeography, including endemism and rarity. Both the occurrence and geographic sparseness of Great Basin springs certainly has significant effects on birds, reptiles, amphibians, and mammals. Ephemeral springs, and springs with harsh thermal and geochemical conditions, tend to have low species richness whereas perennial springs typically include more species and larger populations (Erman and Erman, 1995). Compared to perennial springs, ephemeral springs tend to harbor more upland and drought resistant plant species and include more vagile aquatic organisms capable of rapid colonization and recolonization. Spring ecosystems also are influenced by elevation-determined climatic gradients and by natural and anthropogenic disturbance stressors.

Groundwater Orifice and Discharge Dynamics

Discharge is determined by groundwater characteristics and orifice type, and may be augmented by stream runoff (fig. 4.7). Local slope and microtopography may allow runout (that is draining of springs), which creates (commonly short-length) streams and associated riparian features. Flow conditions (depth, velocity) and local soils (texture, structure) determine sediment transport rates, which can result in erosion or deposition in runout channels or the spring orifice. Organisms are sensitive to water depth; for instance, the Devils Hole pupfish is extremely sensitive to small changes in water levels and other environmental factors (Chernoff, 1985; Andersen and Deacon, 2001). Vegetation communities and associated invertebrates (not shown) respond to water physiochemical conditions (temperature, chemistry, flow rates) depending on their adaptations to those types of environments and disturbances. As stated previously, vegetation (possibly facilitated by dust deposition) may encroach into runout or orifice features given appropriate (that is low velocity, aerobic) water conditions.

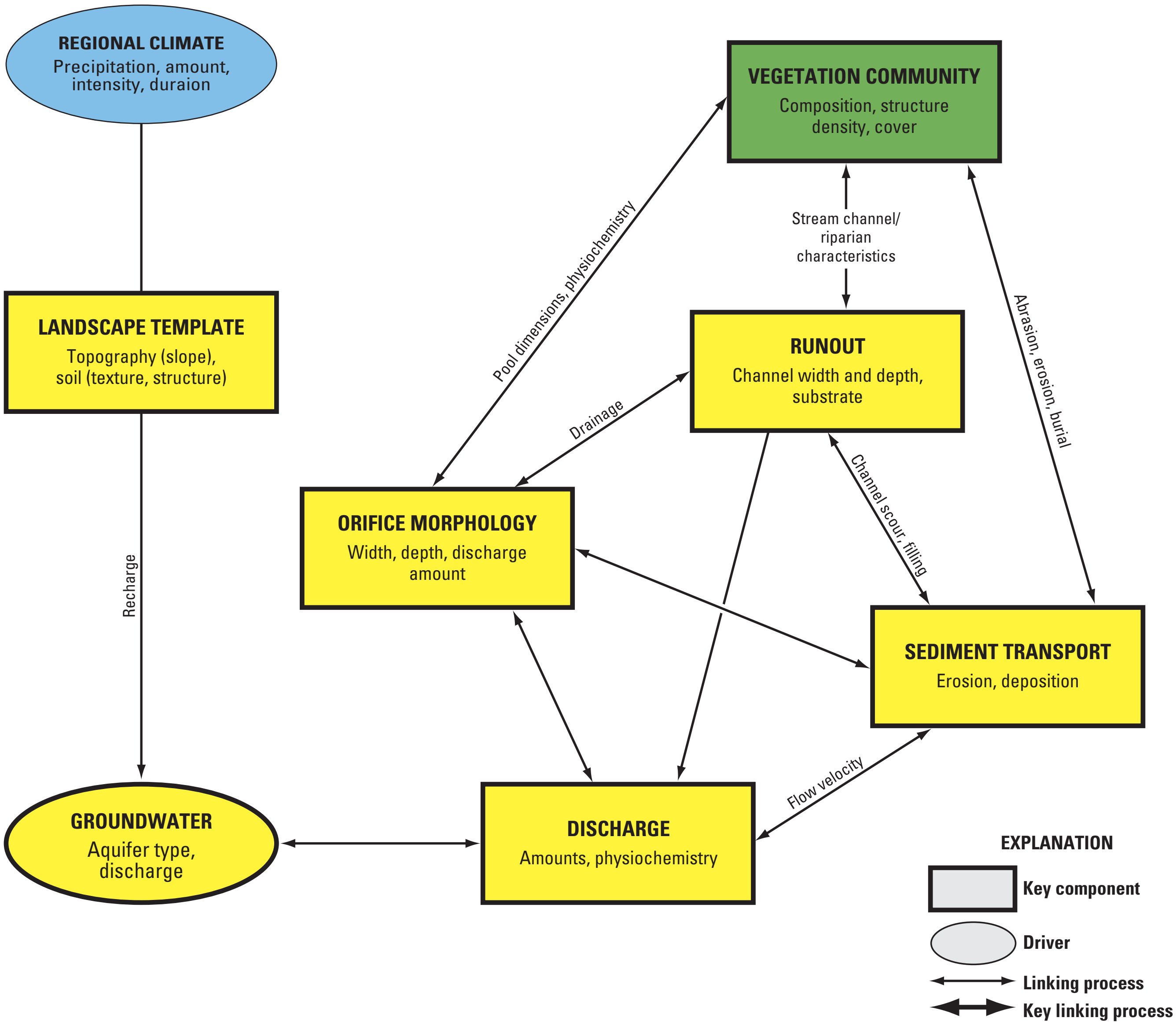

Figure 4.7. Control model emphasizing interactions between discharge dynamics and geomorphology. Bold outline indicates key components.

Spring Vegetation Dynamics

A more detailed model of emergent vegetation dynamics in spring systems (fig. 4.8) is based on Stevens and Springer (2004) and Plumb and others (2005). The structure, composition, density, and cover of vegetation communities are determined by discharge/flow dynamics, which may be modified by trampling, other natural causes, or through anthropogenic mechanisms. The model considers how ungulates and other mammals interact with predators, and how both affect the local environment through trampling, seed dispersal, and as consumers. Riparian overstory and understory plants tend to be denser near spring brook channel heads, where flow is most consistent, and less dense and spread more widely farther down the spring brook. Plant diversity tends to increase with distance from the spring as well. Wildlife habitat varies with these plant patterns. Invasive species may create new disturbances or may out-compete native species.

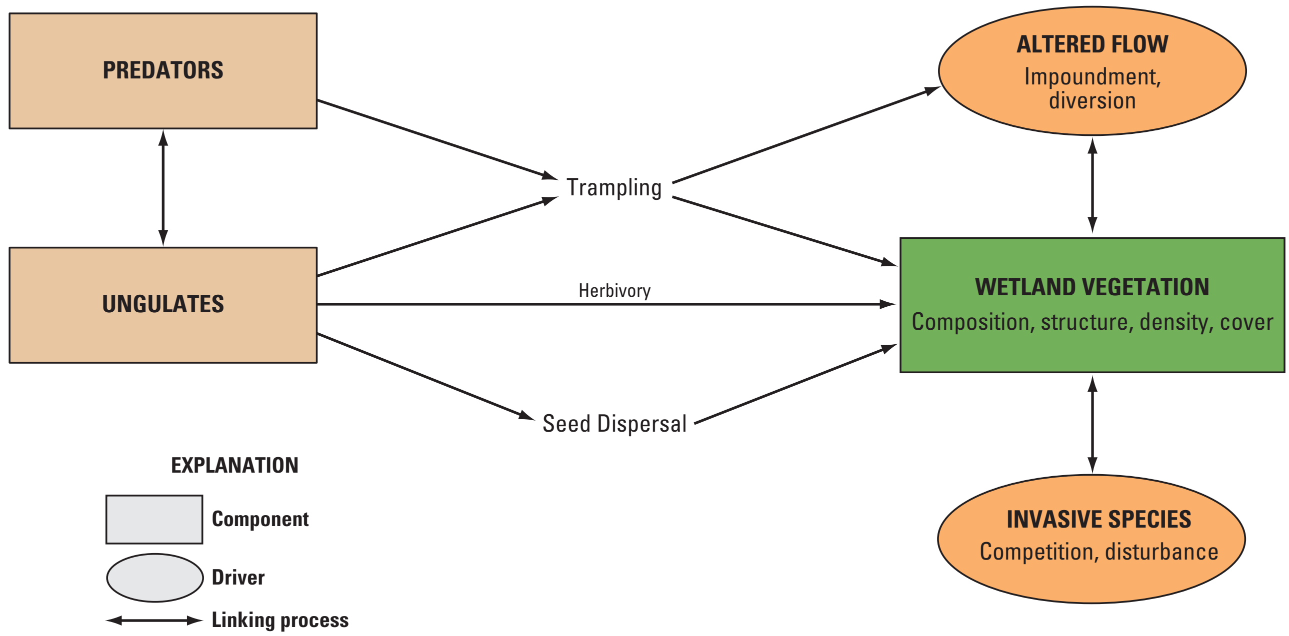

Figure 4.8. Stressor model of emergent vegetation in spring systems showing structural components (rectangles), anthropogenic (ovals) drivers, and functional relations (arrows).

Spring Fauna

Variability in physiochemical properties is small near spring mouths and increases farther downstream, leading to variations in fauna according to their tolerance for environmental variability. Aquatic communities structured by variability are further modified by availability of organic material, which typically is limited near the spring source but increases downstream (Thorup, 1974). As a result of these environmental factors, aquatic communities tend to be low diversity in and near spring sources. Species richness also is correlated with variable substrate composition and current velocity (Sada and Nachlinger, unpub. data, 2009). Greater amphibian density is found downstream in open and varied vegetation than near springs (Bradford and others, 2003).

Summary Points

Wetland and spring ecosystems involve complex interactions of groundwater systems, discharge regime, orifice geometries, vegetation, and faunal use. They are very sensitive to physical and chemical disturbances as well as groundwater withdrawals and diversions. Nearly all spring and wetlands in the Great Basin have experienced anthropogenic impacts for as much as several thousands of years. There is much research needed to understand the ecology of Great Basin spring ecosystems because they commonly are isolated and contain endemic organisms that may make many systems unique. More information also is needed to assess the resilience of spring systems to climate change, increased water pumping and diversion, invasive species, fire regimes, and pollution.

Stream and Riparian Models

By D.R. Bedford

Distribution and Management Significance

Streams and their adjacent riparian zones are widespread in the Great Basin, and yet encompass less than 3 percent of the area. Several alluvial-valley rivers lie within the Great Basin area: Humboldt, Snake, and White Rivers, and Meadow Valley Wash. In addition, lower reaches of several rivers that head in the Sierra Nevada, Uinta Mountains, and the Owyhee and Colorado Plateaus also lie within the Great Basin. Countless small streams lie in mountain blocks, the larger of which have lower reaches that extend onto adjacent alluvial piedmonts. More ephemeral, intermittent streams exist; these flow only in response to seasonal snowmelt or rainfall-induced flooding.

The widespread distribution of countless perennial and ephemeral streams in the Great Basin has been a resource for ranchers, farmers, miners, and many others in need of water. As a consequence, most of these streams have been significantly modified in historic and prehistoric times.

Stream and streambank (riparian) systems consist of flowing water and associated channel bed and floodplain environments. Two aspects of stream and riparian zones separate them from other systems in semi-arid regions. The presence of (1) perennially or intermittently flowing water that typically spans multiple environmental zones creates, (2) unique mosaics of heterogeneous flow and bank environments that support a high degree of biodiversity. However, because all streams and rivers are dynamic and adjust their characteristics to climate, geology, topography, base level, and vegetation (Fitzpatrick, 2001), they often share common processes, features, and interactions across a wide range of environments (Patten, 1998). Streams with intermittent flow generally lack riparian zones and aquatic species, although enhanced xerophytic growth adjacent to channels is common in these areas. Ephemeral streamflow provides some geomorphic and hydrologic spanning across environmental zones, similar to perennial streams. The following model development does not consider the poorly studied intermittent streams further.

Stream and riparian areas of semi-arid landscapes, despite their small total cover, are among the biologically most diverse and important ecosystem components in the Great Basin (Naiman and Decamps, 1997; Patten, 1998). In addition to obligate aquatic species, up to 80 percent of all vertebrates depend on stream and riparian areas for at least one-half of their life cycles, and more than one-half are completely dependent on these habitats (Chaney and others, 1993). Stream and riparian areas also serve as important connectors for energy and materials among nearly all Great Basin ecosystem components. They integrate effects from upstream and downstream regions, and in essence affect and are affected by all ecosystems.

The primary distinction in Great Basin riparian systems is between alluvial rivers and mountain streams. Most perennial streams in the Great Basin are mountain streams. Mountain streams tend to have distinct channel morphology because they are constrained by bedrock. Habitat in mountain streams varies relatively systematically with position in the watershed (Montgomery and Buffington, 1997). Mountain streams respond more quickly to precipitation and snowmelt and tend to be connected to small (and thus more climatically sensitive) aquifers. In contrast, alluvial rivers occupy wide, low relief valleys, and tend to have relatively high and mobile sediment concentrations. The course of alluvial rivers in wide valleys vary with dynamics of channel form determined through interactions with water and sediment supply, and riparian vegetation (Montgomery and Buffington, 1997; Murray and Paola, 2003), and these systems largely are driven by long-term groundwater and climate characteristics. In this section, we focus on the majority of riparian systems: mountain streams.

Ecosystem Components and Processes

Stream and riparian systems are best described by the interactions among precipitation, flow, and geomorphic dynamics through the channel and floodplain, and aquatic and riparian biota. These systems commonly transect large areas with significant altitude ranges and thus interact with diverse dryland systems in the watershed. Because stream and riparian systems integrate processes in the watershed, we use upland watersheds models and theory as part of our modeling construct. The complex interactions among the upland systems are not treated here, and much more work is needed in order to better understand stream riparian connections with each other.

Figure 4.9 presents our conceptual model for riparian systems, which is modified from models for adjacent ecosystems (Miller and others, 2006). The top-level driver is regional climate, which affects riparian systems by adding water through precipitation and determining environmental gradients in wind, radiation, and temperature. This, in turn, affects water and energy budgets (for example evapotranspiration, snowmelt). Precipitation is partitioned into soil moisture, streamflow, and recharge to groundwater as represented in the model by "*Upland Watershed Hydrology*." The upland watershed configuration also controls sediment delivery and flux of organic matter and nutrients to stream channels. Depending on upland watershed characteristics, *groundwater* may significantly affect stream levels. The *flow regime* determines magnitudes and temporal characteristics of streamflow, which interacts dynamically with the *stream channel* and sediment load to determine channel geometry. The channel and its flow interact with *vegetation* and *floodplain soils*, determining the water, chemical, and sediment budgets for each. The *vegetation community* and *fauna* experience facilitation and competition among various species and functional types.

Anthropogenic drivers (orange ovals) also are shown in figure 4.9 to illustrate where each has its greatest effects on the stream-riparian system. The drivers are discussed in section, "Drivers of Ecosystem Change."

Upland Watershed Hydrology

Most water in any section of stream and riparian zones has sources in the upland watershed. Water entering the watershed as precipitation or snowmelt must make its way to stream channels by surface or subsurface (groundwater) flow. The partitioning of precipitation into surface and groundwater will be determined by the type of precipitation, other climate parameters such as temperature, as well as the spatial configuration of watershed characteristics, which integrates its long-term geomorphic history. An example of the effects of upland watershed characteristics and processes on riparian form and function is through long- and short-term effects on basin shape and interactions with groundwater. Steep, narrow basins tend to have narrow riparian zones with plant communities dominated by alder (*Alnus sp.*), and gentle, wider basins tend to have wide riparian zones with complex riparian vegetation and aquatic community structure (Patten, 1998; see fig. 4.10).

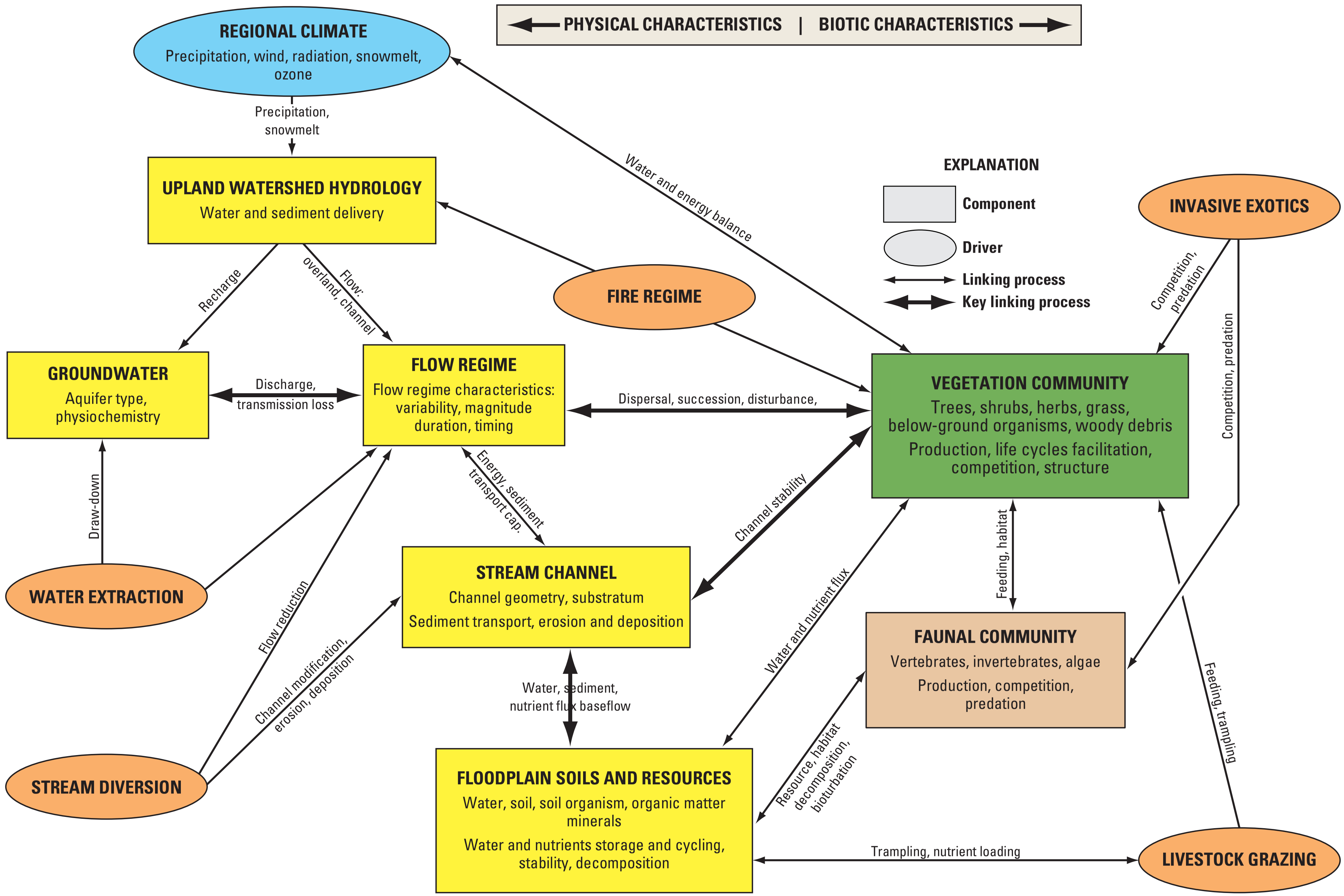

Figure 4.9. Control model of stream and riparian systems, illustrating dynamic coupling of climate, watershed characteristics, streamflow and sediment transport, and vegetation and faunal communities. Double arrows between stream channel, floodplain soil, vegetation, and faunal community boxes include numerous feedbacks. Drivers such as fire, land use, stream diversion and groundwater extraction enter into the model in several places (not all shown), with complex effects. Heavy line weight and boxes with color represent key components.

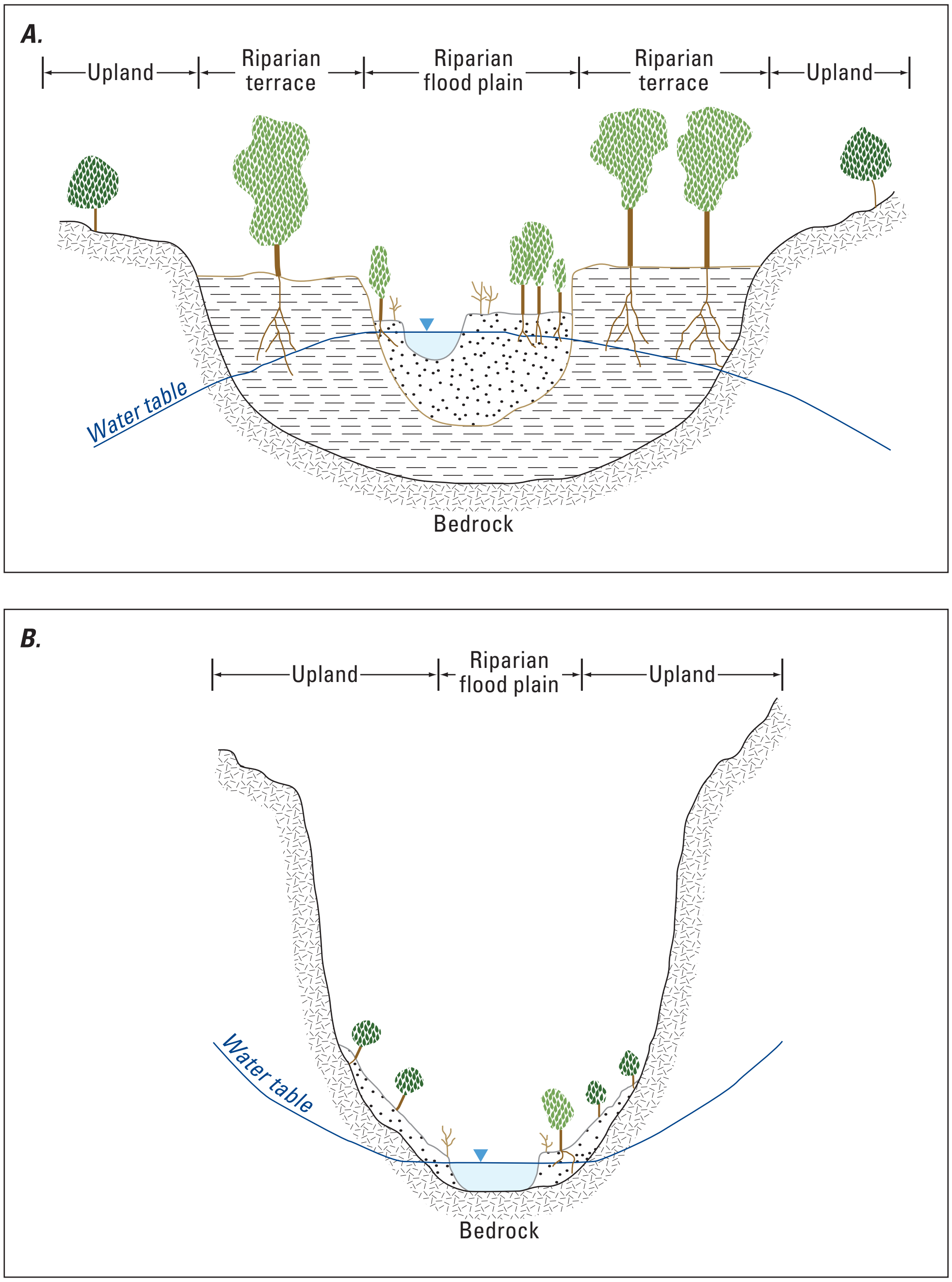

Figure 4.10. Influence of upland watersheds through basin geometry on the structure of riparian system components. (*A*) wide valley with a losing stream, (*B*) narrow valley with a gaining stream. (From Scott and others, 2005, which is modified from Goodwin and others, 1997.)

The delivery of materials from upland watersheds also is determined by the dry upland ecosystems. Stream channel networks act as a template for organizing vegetation and hydrological (ecosystem) dynamics within the upland watershed through processes such as incision and aggradation (Caylor and others, 2005). In turn, the timing, amounts, and quality of water, organic material, nutrients, and sediments delivered to channels from upland watersheds exerts strong controls on riparian systems (Frissell and others, 1986) as well as helping to shape the long-term evolution of drainage basins (Collins and others, 2004).

Flow Regime

The streamflow regime describes magnitude and timing of flowing water and varies greatly depending on the spatial and temporal scales. Modern theory of streams and rivers recognizes that they are complex networks that include distinct zones where hydrogeomorphological processes and ecology are very similar (Poole, 2002; Benda and others, 2004; Thorp and others, 2006). These zones form in response to long-term geomorphic processes and, barring anthropogenic modification, set the inherent scale in determining a flow regime. In short, determining the flow regime for monitoring goals depends on the location and time scale of interest and the geomorphic history.

The flow regime is one of the primary determinates of ecosystem form and function in stream and riparian systems (Chambers and others, 2004). Ecologically important aspects of flow regime include the magnitude, frequency, duration, predictability, and rate of change of flow conditions (Poff and others, 1997; Lytle and Poff, 2004). Morphological, behavioral, and life history adaptations of numerous aquatic and riparian organisms appear to have evolved in response to different components of the flow regime (Lytle and Poff, 2004) and are discussed in subsequent sections. Flood-related disturbances are important ecological processes, contributing to temporary loss of vegetation, but also expanding riparian habitats and allowing establishment of riparian vegetation (Naiman and Decamps, 1997; Friedman and Lee, 2002).

Stream Channel

Interactions between flowing water (defined by the flow regime) and stream channel geometry dictate most of the characteristics of stream and riparian ecosystems. Fluvial geomorphic processes are responsible for the entrainment, transport, and deposition of sediments in streams and rivers, and determine stream channel geometry, stability, and water physiochemistry. Stream channels adjust their geometry, bed substrate characteristics, and sediment loads to variations in water discharge and size and amount of sediment delivered to channels from upland watersheds. Channel geometry plays a significant ecological role by structuring flow width, depth, and velocity conditions. These stream conditions are crucial for stream and streambank communities because they determine disturbance (shear stress) on the channel bed, stability of channel walls, and light and temperature regimes (Allan, 1995). Over the long term, geomorphic processes shape drainage basins, and over short terms, they structure ecological processes, habitat characteristics, and their interactions (Frissell and others, 1986; Montgomery, 2001). Fluvial geomorphic processes are affected by streambed and bank vegetation through stability provided by roots and algae and decreases in flow velocity by vegetation. Riparian vegetation is implicated in providing channel stability in wide valley alluvial rivers (for example, Murray and Paola, 2003), and degradation of vegetation commonly precedes gully formation (Prosser and Slade, 1994).

Floodplain Soils and Resources

Floodplain soils are those immediately adjacent to streams that are continuously or periodically inundated by shallow stream-related groundwater or by overtopping of streambanks. Floodplain soils and resources provide many important ecosystem services. Repeated flooding of floodplain soils commonly limits their nutrient and water holding capacity (Scott and others, 2005). Recently flooded or scoured floodplain soils commonly are occupied by early colonizing vegetation, which is replaced by later succession vegetation as soil resources develop (Allan, 1995).

Water-table depth in floodplains is critical for riparian vegetation, and fluctuations can create lethal moisture stress (Busch and Smith, 1995; Shafroth and others, 2000; Snyder and Williams, 2000). Typically, depth to water is less than 4 m and needs to be 1–2 m deep for riparian vegetation recruitment (Stromberg and others, 1996; Horton and others, 2001). Floodplain microorganisms play important roles in watershed-wide nutrient dynamics. Organic matter from riparian vegetation is converted to particulate and dissolved organic matter for use by floodplain and stream organisms (Naiman and Decamps, 1997). Nitrogen uptake by riparian vegetation and microbes may render riparian zones as sites of net accumulation, which may help remediate nitrogen loading in upper watersheds (Naiman and Decamps, 1997).

Vegetation Community

Stream and riparian vegetation communities serve several ecosystem functions. Aquatic plants serve as filters for water, sediment, and nutrients, and can help control non-point sources of pollution. Aquatic and riparian plants provide detritus as a raw material for nutrient cycles on which riparian vegetation and aquatic communities rely (Naiman and Decamps, 1997). Aquatic plants provide microclimate control on extreme temperature and water-level fluctuations and stabilize streambanks (Naiman and Decamps, 1997; Patten, 1998). The many physiological and structural adaptations of riparian plants to their environments facilitate the utilization and conservation of resource flushes. Habitat for many vertebrates, such as birds and mammals, is linked to canopy structure (physiognomy) and structure variability (Mac Nally and others, 2002), which are maximized in riparian habitat.

Native riparian tree species are early successional, colonizing bare wet surfaces, and are tolerant of nutrient-poor soils and burial. Their life cycles are intimately tied to flow regime dynamics: release of seeds and dispersal occurs during periods of high flood flows, and recruitment occurs during intervening low flow periods (Bagstad and others, 2005; Scott and others, 2005). The invasive Eurasian species salt cedar and Russian-olive (*Elaeagnus angustifolia*) reproduce opportunistically, are tolerant of stress, high salinity, drought, and repeated burning (Stromberg, 2001), and particularly for saltcedar, have expanded rapidly throughout the Southwest (Webb and Leake, 2006). Recruitment of saltcedar is similar to cottonwood and willows, although saltcedar appears to be able to actively recruit on floodplains without being flooded (Birken and Cooper, 2006). Saltcedar appears to tolerate low water tables by using unsaturated zone moisture, which can lead to complete replacement of native trees; replacement in some cases increases total vegetative cover (Busch and others, 1992; Birken and Cooper, 2006; Webb and Leake, 2006), but reduces biodiversity.

Faunal Community

Insects and other invertebrates play important roles in food webs of stream and riparian ecosystems as secondary consumers and as prey for fish, other insects, birds, and mammals (Power and Dietrich, 2002; Paetzold and Tockner, 2005). Aquatic species commonly respond to pulses in stream water or chemistry, which leads to similar pulses in aquatic and streambank predator populations (Paetzold and others, 2006). Fish act as consumers for many ecosystem components (algae, benthic invertebrates, insects, vertebrates), and as prey for other vertebrates. Fish and other aquatic fauna are structured by flow regimes, as well as water quality and temperature. Geomorphic processes determine channel form and in conjunction with flow regime influence habitat features, such as bed substrate characteristics (Biggs and others, 2005).

Riparian vegetation is an important determinant of bird communities. Birds are widely used as targets for management strategies, ecological assessments, and monitoring programs because they are scientifically and socially well known, and responsive to natural and anthropogenic environmental change (Fleishman and Mac Nally, 2006). Studies of desert bird species show that they are sensitive to total vegetation volume, and that the spatial structure of vegetation composition is reflected by bird assemblages, rather than metrics such as vegetation structure or primary productivity (Fleishman and others, 2003, 2004; Fleishman and Mac Nally, 2006). Birds also serve in nearly all trophic roles and as vectors for seed and organism dispersal from isolated habitats.

Aquatic Ecology Control Model

The conceptual model for aquatic ecosystems portrayed in figure 4.11 is modified from Scott and others (2005). The model expands the stream and riparian model (fig. 4.9) to emphasize aquatic biota. Stream physiochemistry represents physical characteristics such as bed and bank characteristics (grain-size distributions and roughness, temperature and velocity profiles), as well as chemical properties such as pH, conductivity, dissolved and suspended organic material, and potential contaminants. Stream physiochemistry plays a key role in aquatic ecosystems and is a dynamic function of climate, streamflow, riparian and floodplain vegetation, and fluvial geomorphic processes. Stream physiochemistry sets the habitat and resource template for aquatic biota. Streamflow directly affects aquatic biota by fluvial disturbances affecting flow and sediment transport and indirectly through its influence on temperature. Streamflow characteristics such as timing of flooding can influence behavioral characteristics, such as dispersal mechanisms and developmental cues (Stevens and Springer, 2004; Scott and others, 2005). Fluvial disturbance is technically a function of bed characteristics (and thus stream physiochemistry in the aquatic model) because bed geometry determines velocity profiles; we show it as directly affecting aquatic biota for simplicity.

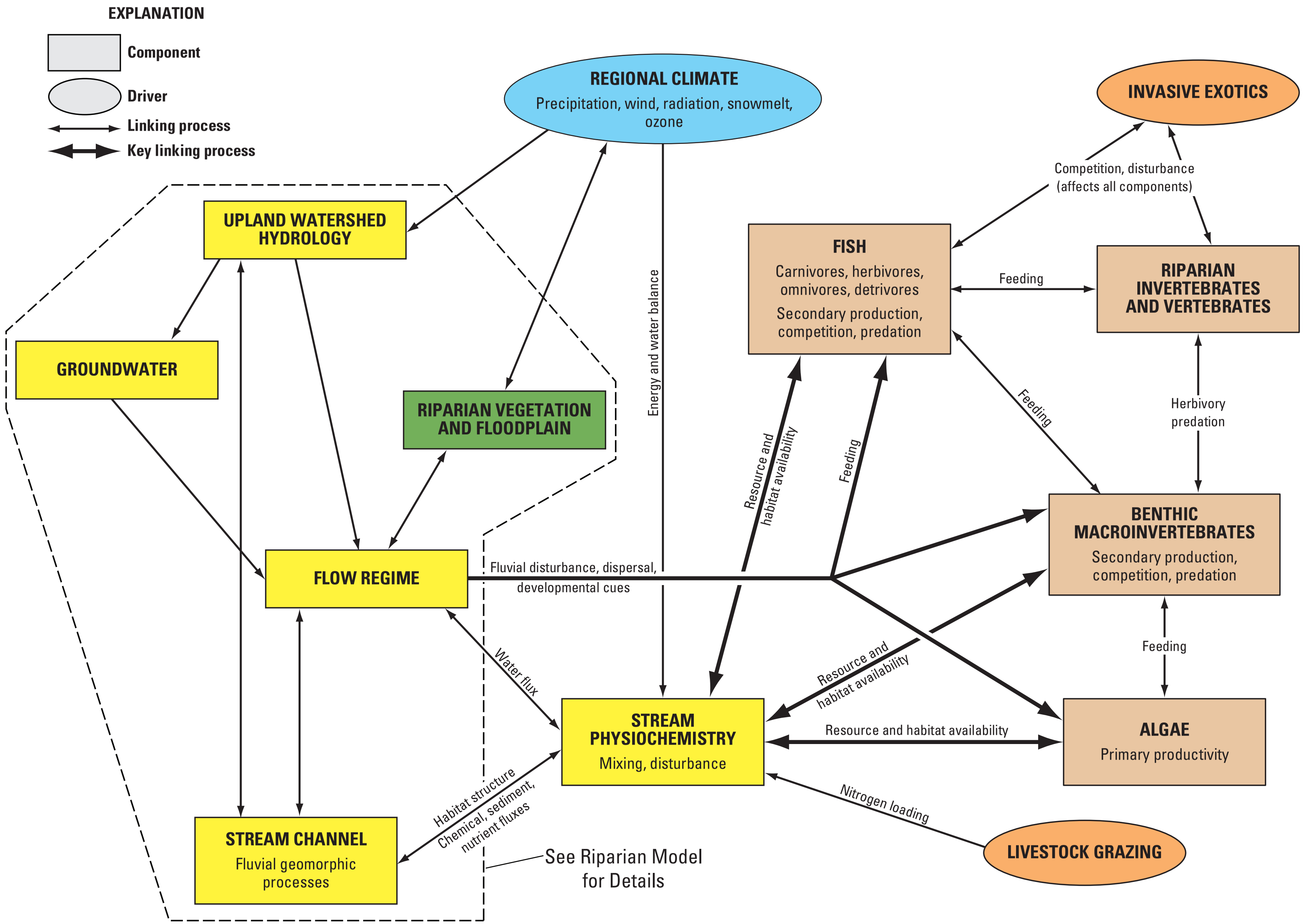

Figure 4.11. Control model describing components and relations for aquatic stream ecology showing drivers (orange ellipses), key systems (colored rectangles), and linking processes (arrows). Modified from Scott and others (2005).

Algae serve as primary producers in riparian aquatic systems and are consumed by benthic macroinvertebrates, fish, and riparian invertebrates and vertebrates. Benthic macroinvertebrates play key roles in aquatic ecosystems as secondary producers; functional behavior includes shredders, grazers, omnivores, detritovores, filter feeders, and decomposers. Fish functional types include carnivores, herbivores, omnivores, and detritovores; thus, all other biotic components impact and are impacted by fish.

Drivers of Ecosystem Change

Natural Drivers

Climate is a key driver of stream and riparian ecosystems at all temporal scales. Great Basin riparian areas are strongly affected by past and present climatic characteristics, largely through climatic effects on the coupling of geomorphic processes and vegetation (Chambers and others, 2004). Magnitude and timing of precipitation and snowmelt drive many ecosystem processes (Loik and others, 2004), and despite inherent high variability of precipitation, semi-arid ecosystems are adapted to an envelope or reference range of climatic variability.

Groundwater levels generally determine water levels in stream and riparian systems and *vice versa* in losing reaches. The aquifer type for a given system determines sensitivity to drivers such as climate and land use. Stream and riparian zones fed by regional aquifers may be relatively insensitive to precipitation over the short term (but not necessarily climatic affects on other ecosystem processes and drivers) because regional aquifers have slow response to changes in climate.

Stream and riparian zones are inherently dynamic, interrelated systems encompassing external and internal processes and their feedbacks. However, the primary characteristic in arid stream and riparian zones for describing ecosystem function (including biotic and abiotic characteristics) is that of the hydrologic flow regime (Naiman and Decamps, 1997; Poff and others, 1997; Patten, 1998; Ward and Tockner, 2001; Friedman and Lee, 2002; Power and Dietrich, 2002; Carsey and others, 2003; Benda and others, 2004; Bagstad and others, 2005; Biggs and others, 2005; Thorp and others, 2006). The flow regime determines, and is determined by, hillslope hydrology and ecology of the watershed (including climatic processes), geomorphic processes, vegetation communities, fire regimes, and macro and micro invertebrates and vertebrate dynamics. Conceptual frameworks for riparian ecosystems and how they function in landscapes are remarkably similar across semi-arid regions.

Anthropogenic Drivers

Land uses that act as drivers in stream and riparian systems include stream diversion, livestock grazing, groundwater extraction, logging and other land treatments, irrigated agriculture, urbanization, and mining activities. Each of these can affect stream and riparian zones directly through physical disruptions to streams and floodplains, vegetation, and other biota. Indirectly, these land uses can impact riparian ecosystems through effects in adjacent dryland systems that may modify water or sediment budgets (Chaney and others, 1993; Naiman and Decamps, 1997; Patten, 1998).

Future climate change may include increased variability in timing and amount of precipitation, and warm water temperatures (see Chapter 2, section "Climate Change and Forecasts"). Perched and local aquifers likely will be affected strongly by climate change because residence times for water in these aquifers generally is short. Riparian trees are sensitive to groundwater depth, and invasive species may be more tolerant of low groundwater levels (Horton and others, 2001), high CO_2, and high air temperatures.

Riparian vegetation is particularly susceptible to impacts from livestock grazing because livestock tend to congregate in riparian areas due to the presence of water, nutrient-rich forage, and shade (Beever and others, 2005). Livestock foraging and trampling can alter vegetation characteristics such as height, density, connectedness, complexity, and composition, as well as alter soils by compaction and other disturbances (Fleischner, 1994; Belnap, 1995; Beever and others, 2005). These effects can cascade into destabilizing stream banks causing increased erosion.

Fire regime plays an important role in riparian ecosystems, with potential feedback mechanisms between riparian zones and upland dry ecosystems. Fire may affect riparian ecosystems more than xeric systems because of the greater density of connected fuels than in xeric systems, but this effect is balanced by greater moisture content of riparian plants. Erosion may be increased following fires due to reduced riparian vegetation, and may lead to altered channel geometry and flow regime, causing significant changes to stream and riparian processes such as incision of channels. Fire regimes in adjacent dry ecosystems may alter the sediment budget to streams and riparian zones, affecting geomorphic processes, flow regime, and aquatic and riparian ecosystems.

Invasive species can out-compete native biota and introduce new disturbance regimes. If invasive species alter the structure of ecosystems (for example, monospecific stands of riparian trees with simple canopy structure), the effects may be expressed in other biota that rely on structural diversity such as birds (Fleishman and others, 2003). Saltcedar and Russian olive are present, if not dominant, in most Great Basin riparian areas (Friedman and others, 2005; Webb and Leake, 2006). Saltcedar is associated with modification of vegetation structure, reduced groundwater depths, and has been causally linked to floodplain development and channel narrowing (Busch and Smith, 1995; Stromberg and others, 1996; Birken and Cooper, 2006). Exotic fish and snails are prevalent in many streams and rivers, and often out-compete natives, lowering gene pool diversity. Hybridization of fish can lead to extirpation of native species.

Other drivers include non-point source pollution introduced through overland flow and groundwater, animal harvesting, and nutrient loading (particularly nitrogen). Increased nitrogen deposition occurs through anthropogenic airborne sources as well as local pollution.

Ecosystem Dynamics

Streams and riparian areas are highly dynamic systems. Although described in detail in the section, "Drivers of Ecosystem Change," they involve interactions with groundwater systems, climate, the landscape configuration and natural and anthropogenic drivers, such as climate, grazing, and fire.

Summary Points

Great Basin riparian systems involve complex interactions between groundwater, surface water, vegetation, and climate. Because of this, they are sensitive to all natural and anthropogenic impacts that affect the interacting systems. They are particularly sensitive due to the high demand from the availability of water in this desert landscape. Historical ecology and paleoclimate are not well studied, but can provide a reference range of conditions to compare with current and future conditions. This is particularly important for wetland ecosystems in which human modification occurred prior to scientific and most historical records. Invasive riparian plants, such as saltcedar, potentially change habitat and affect local and migratory species, but studies are inadequate to fully document these effects. Improved understanding of the ecology and drivers of ephemeral streams is needed. Do they function similar to dryland or wetland ecosystems, or as a hybrid? What changes to stream flow regime will cause transitions in vegetation from riparian assemblages to xeric assemblages and vice versa? Little is known about nitrogen deposition in Western riparian ecosystems. Because most streams are in the alpine, subalpine, and forest biomes, nitrogen deposition and other pollutants may be rapidly transferred to streams and their biota. Improved understanding of the buffering capacity of alpine streams is needed in order to predict the effects of wet and dry deposition.

Freshwater Lakes Model

Freshwater lakes of the Great Basin can be divided into three types: (1) manmade reservoirs and ponds, (2) valley-bottom natural terminal lakes that are fed by perennial streams and springs, and (3) high-mountain small lakes, commonly restricted to glacial cirque basins. Reservoirs are managed systems that are not conducive to ecological modeling. Valley-bottom lakes such as Pyramid Lake fluctuate markedly in depth and water quality with climatic episodes, and thus tend to have sparsely vegetated shores. Mountain lakes are small and range from deep, perennial rocky lakes with lush lake-edge vegetation to shallow, seasonally variable lakes in moraines that have sparsely vegetated shores. Developing a specific set of conceptual models for this system is beyond the scope of this study.

Saline Lakes and Marshes Model

Saline and hypersaline lakes are common in valley bottoms of the Great Basin. Great Salt Lake, the most famous of these lakes, is a terminal lake fed by major streams and springs. Hypersaline waters in these lakes support a limited flora and fauna, but brackish marshes bordering them often teem with wildlife and support a diverse flora. Developing a specific set of conceptual models for this system is beyond the scope of this study.

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