Chapter 14

Watershed Processes as Drivers for Aquatic Ecosystem Restoration

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Theory and Application

- In many aquatic and terrestrial ecosystems, alteration of local water stores and fluxes is the primary factor that causes degradation.
- Hydrological restoration requires a holistic approach that considers watersheds as geomorphological units in which directional water flows connect vegetation, soils, groundwater, and surface waters.
- Restoration of soil infiltration capacity and hydraulic conductivity must often be accomplished before ecosystems recover.
- In their restored state, hydrologic fluxes have characteristic magnitudes, timing, and frequency; these have shaped the evolution of organisms in the region and may be critical to the ability of those organisms to grow and reproduce.

Understanding the fundamentals of water flux and storage is essential to restoration ecology. Watersheds capture, store, and release water, and the flow of water links ecosystems, transports organisms and material, influences temperature regimes, and drives many biogeochemical processes. Losses and gains of water in one part of a watershed—whether through evapotranspiration, infiltration, or runoff—can influence the ecological status of adjacent and even distant parts. Despite the critical role water plays in all ecological systems, the water cycle has been disrupted in many regions of the world. The water cycle is driven by solar energy and gravity, but is dramatically influenced by human activities including the overextraction of water for agriculture or urban use, deforestation, and flow regulation. In fact, one of the factors that most limits restoration outcomes glob-

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ally is inadequate water availability. Even in regions that historically had adequate rainfall, availability may be increasingly limited due to unsustainable extractive uses, a changing climate, or poor land management. Herding of livestock and intensive agricultural practices have caused desertification, which is one of the most difficult syndromes to reverse through restoration actions.

Repairing heavily degraded landscapes requires a watershed approach including an understanding of what factors control infiltration and associated hydrologic processes as well as their interactions and feedbacks with ecological processes such as plant growth and water use. Repairing degraded waterways, forests, grasslands, and wetlands requires knowledge on how plant species and soil microbial processes interact with hydrological processes. In short, understanding the water cycle and watershed processes is fundamental to ecological restoration regardless of the ecosystem type of interest and a landscape perspective is integral to this. As emphasized in chapter 4, the spatial configuration of parcels of land and water and how organisms and propagules move across the landscape are critical to ecosystem restoration. The same is true with aquatic ecosystems: position in the watershed and position relative to other ecosystems determine the timing and quantity of water that is delivered, as well as its quality.

In this chapter, we provide a brief overview of the water cycle: interception, infiltration, evaporation, and transpiration; surface water and groundwater storage; water flow paths (runoff) and soil infiltration; and atmospheric moisture (fig. 14-1). These processes are in turn linked to watershed dynamics, including how land cover influences the quantity, quality, and timing of water yields and fluvial processes (erosion and sedimentation). Watersheds are partially independent geomorphological units because internal cycling is stronger than external inputs and there are strong linkages between the movement of geological and biological materials and the movement of water. Throughout, we stress how and why they are relevant to restoration in practice and provide specific examples of each. There is a body of theory and many concepts related to the larger fields of hydrology, geomorphology, and watershed sciences and we encourage the reader to supplement this primer by delving into those fields; this chapter merely serves as an entry point for restoration ecologists.

Building from the first principles of watershed and hydrologic science, several concepts and governing equations are central to understanding the role of water processes in ecological restoration. Six equations predict infiltration, soil water storage versus groundwater recharge, and soil loss (table 14-1). The basic gas laws and the adhesive/cohesive properties of water inform the practice of hydrologic restoration. The former are relevant to evaporative losses of water from plants and wet surfaces, while the latter help explain soil moisture retention.

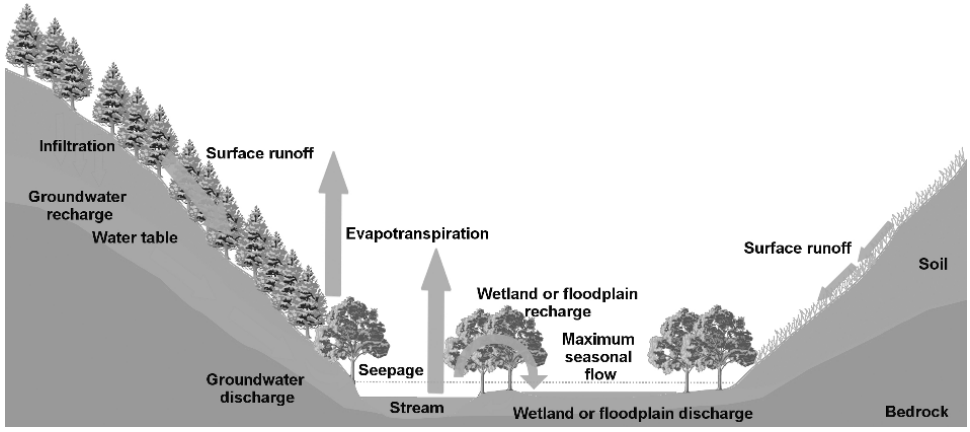

Figure 14-1. Recharge and discharge processes of streams and wetlands must be considered when restoring hydrologic dynamics at the watershed scale. Water table recharge and subsurface flow will replace overland flow as the dominant path of water to streams and wetlands when deforested or degraded hillslopes are reforested. Peak seasonal flows in free-flowing streams or restored hydrological flows can connect floodplains and wetlands with the main channel, allowing ground-water recharge and propagule dispersal.

Restoration of Governing Processes

Restoration requires a major focus on the soil system because of its importance to terrestrial vegetation and to water storage. Horizontal heterogeneity in soil moisture availability exerts a strong influence on plant community structure and biodiversity (Breshears et al. 2009). Combined with topographic complexity and vegetation characteristics (chap. 10), soil moisture influences runoff generation that drives hydrologic dynamics (Jencso and McGlynn 2011). Recovering the capacity of soils to absorb water may require mechanical "de-compaction," nutrient additions, organic amendments, initial watering, and even the introduction of bioturbators, such as earthworms. Over time, soil hydrological conditions are then restored sufficiently to support plants, and the forces of gravity and capillarity action are able to move water to deeper soil layers. Restoring the vegetative cover, especially as forests, in turn increases porosity, water retention capacity, and hydraulic conductivity (Bonell et al. 2010; Buttle 2011; Perkins et al. 2012). Mycorrhizal amendments can further enhance nutrient acquisition by soils and assimilation by plants as well as increase water retention (Ohsowski et al. 2012). Recent research by Chen et al. (2014a) suggests that restoration actions can result in significant increases in the rate of water flow through soils even on highly degraded landscapes (fig. 14-2).

Table 14-1.

Examples of important concepts and governing equations that influence dynamics relevant to ecological restoration at the watershed scale.

Concept	Equation	Description
Water budget equation	$\Delta S = P - ET - Q - \Delta G$, where ΔS is the change in water storage as a function of precipitation (P) minus losses due to evapotranspiration (ET), runoff (Q), and deep groundwater seepage (G, could be inflows or outflows).	The amount of water stored in soils, aquifers, or the water table is influenced by evaporative losses from soils, water bodies, plants, and plant transpiration. It affects water yield (flow to surface waters) and is influenced by land use.
Interception	$I_c = P_g - T - S_f$, where I_c is the amount of water intercepted by the canopy, P_g the gross precipitation, T the throughfall, and S_f the stemflow.	The process of water interception by the canopy and how that water is partitioned among the plant assemblage structures. Typically as restoration from new forest planting proceeds, T decreases and S_f increases.
Soil infiltration	$F_c(t) = f_1 + (f_o - f_1)e^{-kt}$ (Horton's eq), where f is the infiltration capacity at time t, f_o is initial and f_c final infiltration capacity, and k is an empirical constant.	The process by which water on the ground surface enters the soil. It varies with soil texture, structure, surface features, amount of organic matter, depth of impermeable layers, and presence of macropores.
Soil hydraulic conductivity	$k = Q \cdot L/A \cdot \Delta H$ (Darcy's Law), where k is the soil hydraulic conductivity, Q the rate of water flow, A the cross-sectional area, ΔH the change in head, and L the length of soil column.	Soil attribute describing the ease with which water moves through pore spaces or fractures. It depends on the intrinsic permeability of the soil, which relates to its texture, composition, and structure.
Topographic index	$TI = ln\ (A/tan\ G)$, where A is the contributing area and G the slope gradient at a site.	Index that takes both local geometry and site location into account to measure the extent of flow accumulation at a given point on a topographic surface. It can be used to describe how soil moisture varies across the landscape.
Modified universal soil loss equation	$A = R \cdot K \cdot LS \cdot VM$, where A is the soil loss, R the rainfall erosive factor, K the soil erodibility, LS the topographic factor (slope length, steepness), and VM relates to land cover with subcomponents like canopy cover and presence of vegetation close to the ground.	Erosion is the process of relocation of soil and rock due to the action of water flow or wind. GIS and modeling facilitate predictions of soil erosion over a wide range of spatial scales.

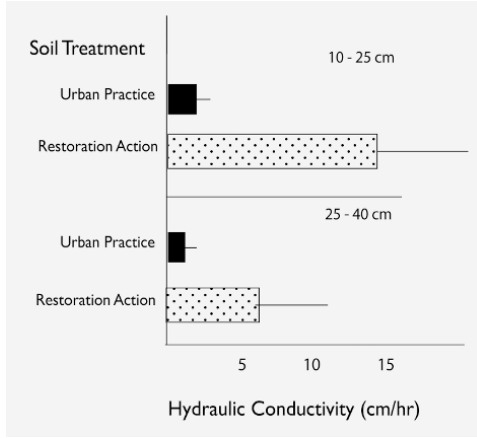

Figure 14-2. Restoration actions to improve the rate at which water flows through soil (hydraulic conductivity) can be critical to ecological recovery in areas with highly compacted soils, such as those in urban regions, mined areas, and some agricultural lands. Experiments demonstrated that deep tillage combined with organic amendments and tree planting ("restoration actions") greatly increased the saturated soil hydraulic conductivity (k_{sat}) compared to simpler restoration actions that only partially replace the A soil horizons. Modified from Chen et al. 2014a.

Infiltration and Soil Water Storage

Restoring more natural hydroperiods and associated biogeochemical processes in degraded watersheds is essential to the provision of water quantity and quality needed to support healthy ecosystems. The rate at which water enters the soil is influenced by rainfall (intensity, duration), characteristics of the land cover, and properties of the soil. Landscapes with dense plant canopies and broad leaves may intercept a large amount of rainfall, and much of what is not passed through the canopy as throughfall or stemflow may be lost due to evapotranspiration, depending on humidity, temperature, and wind conditions. Of that moving through the canopy, a fraction may be taken up by groundcover vegetation or stored in litter layers. Water infiltration into the soil due to capillary action and gravity is influenced by the presence of colloidal materials; soil pore space; and presence of macropores, organic matter content, and soil texture.

Land clearing reduces interception and infiltration so the most common restoration action is to revegetate. Planting of rapidly growing nonnative species may stabilize soils (García-Palacios et al. 2010); however, such species could reduce soil moisture enough to outcompete native species (Thaxton et al. 2012). Large-scale land clearing in the form of deforestation not only influences soil moisture by reducing infiltration but can also lead to changes in the rainfall amount, location, or distribution over time (Lawrence and Vandecar 2015). Replanting forests

is now a major restoration enterprise, but how and if it increases net water storage is complex and controversial (box 14-1). For example, although deforestation may increase flooding risk because it reduces the water-holding capacity, reforestation may have negative effects on wetlands, through a decrease in the amount of water available to maintain wetland functions (Woodward et al. 2014). Thus, trade-offs may exist between restoring forests and restoring wetlands in the same watershed, and in some cases, restoring historical extents of both might not be possible.

Box 14-1
Water Yield and Forest Restoration: Not a Simple Story

Restoration of forests is a common environmental policy for recovering lost water resources. Most forest restoration for water programs are based on the assumption that forest area is a proxy for water-based ecosystem services. However, water flows that result from reforestation are rarely quantified. Empirical research on reforestation and water dynamics has been done at local scales—typically small watersheds where reforested areas clearly have higher soil infiltration rates. But since evapotranspiration is typically higher in forested areas, water yield to streams can change little or even decrease. There is little empirical evidence that total annual yields are increased, although forest restoration can change the seasonality of water yield—most often increasing dry season flows. Reforestation can provide water regulation benefits, meaning less variability in yields such that flooding is less likely following rainstorms. Presumably, variability is reduced with greater shallow subsurface storage capacity given more plant roots or macropores.

While wetlands and streams have been observed to dry up following deforestation, such observations have also followed forest restoration. In fact, deforestation and timber harvest may result in a rapid increase in water yield compared to nearby forested watersheds. This is largely due to a reduction in plant uptake of water and changes in evapotranspiration. While there are fewer data on deep recharge, it is possible that lower water interception and infiltration rates in deforested watersheds result in less water moving to deep storage; thus, more is available as streamflow. If, however, the deforested land is permanently converted to a high impact use (e.g., livestock, urbanization), then decreases in recharge are certain, so that eventually baseflow water yields may decline.

Modeling studies at regional and global scales suggest that deforestation will lead to decreases in rainfall largely due to changes in the distribution of evapotranspiration (less moisture returned to the atmosphere). If the reverse is true and forest restoration results in an increase in rainfall and perhaps eventual increases in water yield, two questions remain: Where will this precipitation fall, and will restoration at local scales scale up to help solve regional water problems? In sum, research thus far is simply inadequate to sort out the array of interacting factors that influence the effects of forest restoration across a variety of scales and locations.

References: Bruinjzeel 2004; Abjornsen et al. 2011; Roa-Garcia et al. 2011; Ellison et al. 2012; Perkins et al. 2012; Salemi et al. 2012; Gageler et al. 2014; Li et al. 2014; Ponette-González et al. 2014; Woodward et al. 2014.

Despite these complexities, forest restoration can enhance soil conditions, which in turn leads to increased infiltration rates with subsequent positive feedbacks to growth of the forest. On the island of Maui, Hawaii, less than 10% of the original dry forest remained when actions were taken to restore disturbed grassland to forest. Beginning in 1997, scientists, natural resource managers, and landowners worked together to restore a four-hectare tract of land. They fenced out grazing animals; removed an invasive grass; and replanted native grasses, shrubs, trees, and vines. After fourteen years, soil properties had changed significantly including a twofold increase in saturated hydraulic conductivity that further enhanced plant growth in this low-rainfall region (Perkins et al. 2012). Additionally, water infiltration rapidly reached depths of a meter or greater during the measurement period, leading scientists to suggest the potential for aquifer recharge (Perkins et al. 2014).

Water percolating to deeper soil layers or bedrock becomes groundwater and may recharge aquifers or flow along impermeable geological substrates in sedimentary formations or along subterranean crags and channels in calcareous rock formations (e.g., Karst). Groundwater recharge can also occur through seepage from lakes and ponds or from streams (fig.14-1). Recharge of aquifers and the water table is a core watershed process that must be tackled to achieve certain hydrological goals. Based on studies documenting increased stream flows following loss of vegetation (Brown et al. 2013) and increased soil infiltration rates following replanting (Perkins et al. 2012), watershed revegetation is commonly assumed to increase groundwater recharge (Buttle 2011; Perkins et al. 2012). However, the effect of terrestrial plant restoration on below groundwater storage is complex, and if it occurs, recharge takes a very long time (decades to millennia). For example, the enhanced recharge reported by Buttle (2011), was not verified in many other cases.

Studying groundwater dynamics in response to restoration is difficult because surface watersheds and subterranean watersheds do not always coincide. In sedimentary watersheds, groundwater flows may travel and emerge to create seepages, springs or wetlands, often many kilometers away or even in topographically independent watersheds (Toth 1963). This means that local restoration actions may not promote ecosystem recovery if the distant source of water is not restored or preserved as well.

Terrestrial-atmospheric interactions contribute to the complexity of hydrologic responses to restoration. Surface water, soil water, and water in the plant canopy evaporates to the atmosphere at rates varying with temperature, relative humidity, and wind speed. Vegetation, particularly forest cover, may retain and evaporate rainfall at rates ranging from 4% to >90% depending on forest type, rainfall intensity, or temperature (Crockford and Richardson 2000). The same vegetation will release water to the atmosphere via transpiration, regardless of the amount of

rainfall. Losses due to evapotranspiration translate to decreased replenishment of groundwater and outflow, and thus reduced supply of water to downstream ecosystems and water bodies (Oishi et al. 2010).

Other hydrological and hydrometeorological processes may have local importance in some watersheds. For example, water is lost to the atmosphere through sublimation in boreal and alpine watersheds (Friesen et al. 2015). Elsewhere, fog water may provide up to 40% of the total water throughfall in watersheds (Ritter et al. 2008). Fog water captured by tree leaves is diffused through leaf cuticles, reducing root water uptake and reducing tree evapotranspiration in adverse seasons; or, it drips onto the soil and increases soil moisture (Ewing et al. 2009; Eller et al. 2013). As a consequence, fog water reduces water loss, which could potentially support groundwater recharge. For these reasons, restoring trees to capture fog water might be essential in some watersheds, but it may take long periods to reach predisturbance levels. A viable forest restoration strategy in some regions is to harvest fog water mechanically and use this to enhance survival of young seedlings until trees grow large enough to capture fog water themselves (Domen et al. 2014).

Runoff and Stream Flows to Support Aquatic Ecosystems

Water not infiltrating to deeper soil layers or bedrock becomes runoff, either above- or belowground, and flows downslope toward streams, lakes, wetlands, or the sea. Depending on regional geology, these processes may act at the entire watershed scale (e.g., in areas underlain by granite) or only subareas (e.g., in karstic watersheds). Runoff moves through a network connecting every topographic point in the watershed with the outflow (mouth). Thus, any action that affects the hydrological conditions or water quality at any point will have a downstream effect.

Largely due to changes in infiltration and soil storage capacity, water runoff to streams varies greatly in quantity, timing, and quality among landscapes subjected to different types and levels of human impacts. Thus, watersheds that are fully forested have significantly different discharge patterns compared to nearby urban or agricultural watersheds (fig. 14-3). The most difficult restoration challenges are associated with excessive runoff in urban regions with extensive pavement and compacted soils. In urban watersheds, peak stream flows during rainstorms can be much higher than in vegetated rural areas, and summer baseflows can be highly altered by reduced groundwater recharge (Fletcher et al. 2014). Direct runoff from impervious surfaces causes stream channels to incise, and stream biota are impoverished. As we describe later, restoration actions that focus only on in-channel structural changes (e.g., adding large boulders and constructing weirs to slow flows) have not been shown to recover urban stream ecosystems biologically

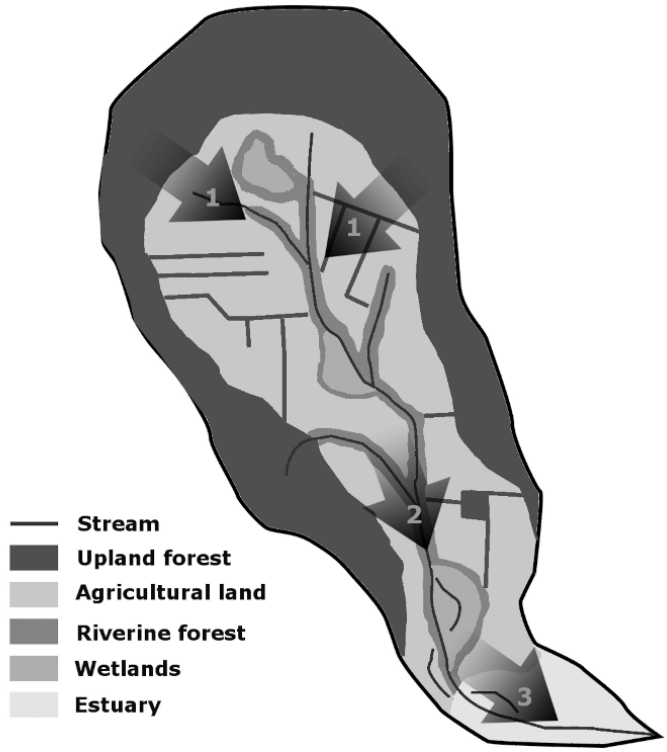

Figure 14-3. A three-step approach to watershed restoration. First, restore the headwaters' plant cover, forests, shrubland, grasslands, or mixed vegetation to restore processes such us soil retention, propagule dispersion, and nutrient cycling. Second, restore the intermediate stream reaches where agricultural areas are located by restoring hedgerows, forest patches, and riparian vegetation. This second phase may also involve restoring floodplains and inland wetlands. The aims are to reduce the impacts of agricultural production (e.g., reducing erosion and export of agricultural nutrients and sediments) and recover processes related to landscape connectivity (e.g., plant and animal dispersal). If the stream channel is incised or otherwise degraded to the point that ecological processes are impeded, a third phase could involve channel adjustments down to the delta, estuary, or other mouth geomorphology. This third phase could involve increasing in-channel heterogeneity (e.g., adding log-jams and boulders) and restoring estuarine hydrological gradients.

(Palmer et al. 2014). Current research suggests biodiversity loss in urban streams is driven by high levels of conductivity and metal pollutants that are washed into streams by excessive runoff (Vander Laan 2013). Watershed approaches are needed to reduce flows and minimize pollutant loads (Fletcher et al. 2014).

Reduction or elimination of vegetation by logging or agriculture also increases overland flows, which often increases soil erosion resulting in large inputs of sediments to downstream networks. Restoration of landscape vegetation has been

shown to reduce runoff and the input of sediments to streams (Miller et al. 2015). The same happens when restoring riparian vegetation if the riparian cover aligns with the dominant flow paths (Weller and Baker 2014) and if there are no significant gaps in the riparian cover or gullies that cut through the cover. Restoration is also used to reverse the impacts of excessive groundwater pumping for consumptive uses. Large-scale restoration approaches include restricting pumping and constructing artificial wetlands and recharge basins near the river to return baseflows. These ecologically engineered systems must be strategically placed to provide appropriate depth to groundwater, to augment locally depleted aquifers, and where hydraulic conductivity can facilitate recharge. Such approaches may be key to recovering groundwater-dependent streams and wetlands in arid and semiarid regions (Lacher et al. 2014). For example, much of the riparian vegetation along the Upper San Pedro River basin in Arizona (US) relies on groundwater. To offset water pumping and diversion, a network of recharge sites is being designed to return treated effluent or stormwater runoff to the aquifer to sustain riparian vegetation and associated wildlife (Lacher et al. 2014).

Restoration is increasingly focusing on reversing the hydrological and ecological impacts of dams. Typically built to retain water for agriculture or hydropower, dams homogenize downstream flow regimes by modifying the magnitude and timing of ecologically critical extreme flows (high and low) and sediment fluxes (Poff et al. 2007). River flows below dams are usually very different than they were historically (fig. 14-4), often being driven by reservoir releases to meet daily power needs. When dam removal is not an option, efforts to restore downstream riverine ecosystems including sandbars for habitat have involved planned releases from the reservoir (Grams et al. 2015). Deliberate flows can be planned to mimic historical flow and thermal regimes (Warner et al. 2014). High flows during parts of the year can inundate floodplains ("making room for the river"; Overton et al. 2014).

Ecological flow releases in the dry season that are necessary to support fish are also a restoration option (e.g., as in plans for the Dahewan Reach of the Yalongjiang River in southwestern China; Chen et al. 2014b). Additionally, temperature control devices (TCD) on dams can allow for variable water withdrawals from the reservoir to control temperatures in water released downriver (e.g., Shasta dam TCD on the Sacramento River; Caldwell et al. 2015). Some of the most high-profile restoration projects have removed dams to restore anadromous fisheries. For example, along coastal Maine (US) dam removals have restored the density and biomass of Atlantic salmon, alewife, and sea lamprey in previously inaccessible upstream reaches (Hogg et al. 2015). As we describe later, scientists have made good use of these projects to advance their understanding of hydrogeomorphological processes.

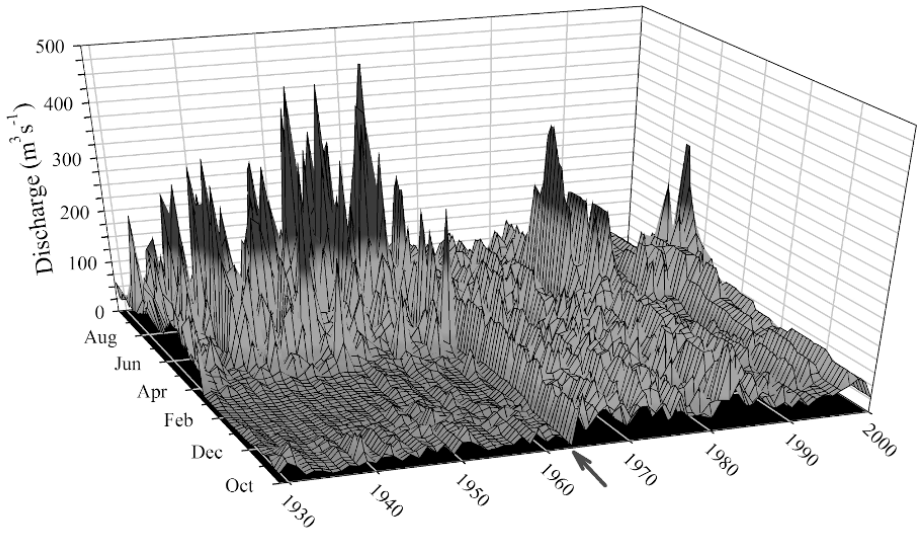

Figure 14-4. The construction of dams fundamentally alters the timing and magnitude of river flows below reservoirs (Lytle and Poff 2004). Here, the Green River in Utah, US, historically had extremely low flows throughout the winter and fall and high, somewhat flashy flows starting in the spring when snowmelt runoff began. Once the dam was built (arrow), variability in flows was dramatically reduced so there were fewer droughts and floods. To fully restore river biota and ecosystem processes under such conditions, some or all of the historic flow regime will need to be restored. Modified from Lytle and Poff (2004).

Geomorphological Processes

Among the multiple geomorphological processes shaping Earth's surface (e.g., glacial, volcanic, tectonic, eolian processes), a few can be framed in a generalizable watershed context. Some of the most relevant are fluvial processes, including erosion and sediment deposition, and hillslope processes, including landslides or rock-falls. Land erosion is a natural process that drives important geomorphological processes, like meandering, scouring, or sediment accumulation in streams, rivers, and estuaries. Erosion is accelerated by the loss of plant cover derived from human and natural disturbances, and extreme rainfall events can enhance erosion, particularly where bare soil is exposed.

Four erosion processes affect bare soils: (i) splash erosion caused by the force of water hitting the soil and releasing fine particles, (ii) sheet erosion caused by laminar water flowing over land, (iii) rill erosion caused by water that concentrates in small rivulets, and (iv) gully erosion caused by large, rapid flows. As flowing water accumulates the released sediments, its viscosity increases, thus increasing

its energy to transport more sediments until the energy dissipates in flatter areas (Julien 2010). Erosion increases the steepness of hillslopes, washes nutrients and organic matter from soils, and reduces soil cohesion. Sediments are transported downstream and deposited in stream valleys, pools within streams and in nearby wetlands, eventually filling them in.

Sediment accumulation negatively affects the structure and functioning of wetlands and streams. Coarse stream sediments can clog with excessive fine-grain deposits, which affects invertebrate and fish communities (Rehg et al. 2005). Sedimentation also complicates the restoration of vegetation. Restoration to reduce the impacts of excessive erosion and downhill/stream sedimentation typically occurs through native plantings. Restoring dense plant cover in the headwaters has proven effective in reducing soil erosion (Zhang et al. 2015). In southeast China, forest restoration on former agricultural areas reduced soil loss from 53 to 256 tons ha^{-1} to no loss after eight years (Zhang et al. 2004), and except in very high rainfall years, soil loss has continued to remain low (Zhang et al. 2015). Similarly, in Mediterranean watersheds, plant cover was restored and sediment yields were reduced by three orders of magnitude after eighty years, compared with the prerestoration state ($>10^5$ mg L^{-1}) (Navarro Hevia et al. 2014).

It is not always excessive sediment that degrades streams and rivers; deficits of sediment can be just as damaging. Restoration in such cases involves inputs of sediment or gravel, which is often done below a dam or other permanent flow-reducing structures. This can benefit aquatic food webs and fish that depend on specific particle sizes for spawning. However, the gravel is rarely retained over the long term, so repeated efforts are needed (Pander et al. 2015). Alternatively, sediment might be passed through or around reservoirs an action that comes closer to restoring a natural sediment regime (Wohl et al. 2015). In salt marshes sedimentation must keep up with rising sea level to sustain current ecosystems. Additionally, urbanization, dikes, and levees have reduced sediment flux down rivers resulting in subsidence of marshes (Wigand et al. 2014).

In coastal Louisiana, US, where wetland loss has been and continues to be extreme (estimated at 5,000 km^2 since 1932; average rate >40 km^2 per year between 1985 and 2010) restoration measures could include large sediment diversions to the marshes to increase accretion rates (Wang et al. 2014). Restorationists need to anticipate negative impacts of sea level rise and treat sediment as a resource; for example, dredge spoils from maintenance of boat channels can be used to elevate marsh plains that have subsided behind dikes in coastal wetlands (e.g., San Francisco Baylands; Callaway and Parker 2012).

Other biogeomorphological processes are being restored in a variety of ecosystem types. Inputs of wood from fallen trees and associated log-jams can increase

aquatic habitat heterogeneity and reduce flow speed, positively affecting the diversity of aquatic macroinvertebrates, purifying water, controlling erosion, and enhancing fish populations (Beechie et al. 2010; Acuña et al. 2013). Indeed, one of the most common and simple restoration actions for streams is to add large woody debris. For example, adding large wood and boulders to northwest streams of the US increased coho salmon-rearing capacity by 32% in about six years (Jones et al. 2014) and increased juvenile coho salmon density from 0.19 to 2.32 individual m^{-1} (Beechie et al. 2010). At larger scales, adding wood and log jams helps trap sediment, organic matter, and plant propagules. Over the long term, these processes help recover degraded rivers (Osei et al. 2015). The presence of woody debris may be particularly important in mid to lower watershed areas that lack steep slopes (about 6%). Beaver dams strongly affect sedimentation, morphology, and stream species diversity (Burchsted et al. 2010). They can also help recover the hydrology and biogeochemical processes of highly incised stream channels (Pollock et al. 2014). In such cases, reintroducing beaver populations where they have been extirpated may be an essential management tool integrated in watershed restoration programs, including those targeting wetland and stream restoration (Gibson and Olden 2014).

Watershed Perspective on Restoration of Aquatic Ecosystems

The relative importance of various hydrologic processes to ecological recovery varies regionally and among ecosystem types, and restoration of water dynamics largely defines recovery of aquatic ecosystems. We provide brief overviews of the role of hydrology in the recovery of two types of aquatic systems; more in-depth treatments of riverine and wetland restoration appear in general texts (e.g., Moreno-Mateos et al. 2012); and new findings are continually emerging on the link between watershed processes and restoration of ecological structure and function in these systems (Meli et al. 2014; Palmer et al. 2014).

Running Water Ecosystems

Hydrologic regime has long been considered a master variable in riverine ecosystems because it, along with sediment dynamics, directly affects channel form and consequently the biota and ecological processes within the channel. Aside from dams and diversions, one of the most significant impacts on streams is a reduction in watershed infiltration capacity due to land use changes. In such cases, there is disagreement over whether manipulating various aspects of the flow regime (e.g., restoring or reducing peak flows) is sufficient for full recovery of stream ecosys-

tems. This controversy has arisen because the dominant restoration practices for streams have been focused on direct manipulation of the stream channel in order to alter in-channel flow velocity (Palmer et al. 2014); restoration focused on entire watersheds is far less common (Smucker and Detenbeck 2014).

Most stream restoration has centered on channel morphology: how to design a channel given the water discharge and sediment regime in the context of a particular watershed and landscape (Smith et al. 2011). Restoration designs typically use a "reference reach" (section of a nondegraded or less degraded nearby stream channel) to identify the channel patterns and processes that need to be achieved. The assumption is that once a channel is manipulated to handle the prevailing flow and sediment fluxes and habitat heterogeneity is enhanced, then species assemblages, primary production, decomposition, nutrient processing, and other ecological processes will be restored (i.e., the "field of dream hypothesis"; Palmer et al. 1997). However, this assumption is rarely valid (Palmer et al. 2014; Kitto et al. 2015). Similarly, while habitat influences ecosystem processes and species interactions (chaps. 3 and 10), if the water is polluted, restoration of processes and species will be very difficult. The source of ecological degradation for most streams and rivers is at the watershed scale and is most often associated with poor land use management that leads to polluted water or highly eroded stream channels; this is why landscape scale restoration approaches (chap. 4) must be taken.

Manipulating channel shape to convey flow does not necessarily restore the hydrological and geomorphological processes necessary to support healthy ecological communities. Restoration of several processes is critical for recovery of stream and river ecosystems (Wohl et al. 2005). Examples of such processes extend well beyond water infiltration to include the subsequent biogeochemical transformations as water is routed from the soils to streams, the dynamic water exchanges between the groundwater, hyporheic zone, and surface water, and the overbank flows into vegetated floodplains.

Restoration ecologists are now working actively with practitioners to apply hydrologic, geomorphologic, and ecological principles to advance our understanding of how the complex interactions between vegetation, groundwater, river flows, channel morphology, and water quality determine restoration outcome (Booth and Loheide 2010; Hall et al. 2014). There is an increasing emphasis on defining "process-based watershed restoration" and the best way to undertake it (Beechie et al. 2010; see case study box 14-1). Many of the watershed actions involve stormwater management, wastewater treatment, wetland restoration, revegetation, and other forms of land management, such as no-till agriculture that have not previously been considered as "restoration," but in fact may be necessary for restoration of streams and rivers impacted by major changes in land use (Richardson et al. 2011; Palmer et al. 2014; Smucker and Detenbeck 2014). Stormwater management

Case Study Box 14-1
Hydrologic Restoration to Facilitate Native Prairie Grasses and Water Quality Improvements

Walnut Creek watershed, IA: Beginning in 1992, the Walnut Creek watershed restoration project was initiated by the US Fish and Wildlife Service (USFWS) at the Neal Smith National Wildlife Refuge in Jasper County, Iowa, to restore native prairie and improve water quality in the watershed's streams.

Test of theory: Importance of restoring key hydrological processes

Took parcels of land out of row agriculture and planted native grasses. A paired watershed study, led by Dr. Keith Schilling (University of Iowa) and colleagues, accompanied the project. The result is based on watershed data minus the contribution of row crop flow; thus, this result represents the contribution of prairie restoration to hydrology.

Progress: By 2005, 23.5% of the watershed had been planted in native prairie. Full recovery of hydrologic processes at watershed scales takes a long time, particularly because parts of Walnut Creek are still in agriculture and tiled land use. Despite this, progress is being made as summarized below, where Q = discharge, ET = evapotranspiration, [NO_3] = nitrate concentration; [P] = phosphate concentration, and W:D = width:depth.

Progress toward hydrologic restoration →

None	Some	Measurable
Discharge (watershed scale) • no decrease in stormflow Q • no decrease in contribution of stormflows to annual Q	**Discharge** (scale) • increased baseflow Q in lower watershed • increased baseflow contribution to annual Q	**Discharge** (plot scale) • decreased stormflow Q • decreased infiltration
Channel • W:D not same as historic • channel & floodplain disconnected	**Channel** • some channel widening	**Channel** • none
Groundwater (riparian zone) • depth not changed	**Groundwater** • increased ET suggests potential groundwater change (plot scale)	**Groundwater** (uplands) • increased groundwater recharge
Water quality (watershed scale) • [P] not reduced • sediment export not reduced	**Water quality**	**Water quality** • lower [P] (plot scale) • less sediment export (plot scale) • lower [NO_3] (watershed scale)

Case Study Box 14-1 continued

Long-term outcomes: Through this project, a series of key restoration lessons were learned:

- Restoring the hydrology is key to restoring the land.
- Monitoring hydrologic restoration is best suited at the plot or subcatchment scale, but results from the plot scale do not necessarily scale up to the watershed level.
- Uplands offer a much greater opportunity for restoring hydrologic processes than lower in the watershed, because the former are primary sites of groundwater recharge, while lowland areas integrate hydrologic inputs from all upslope areas and often contain a legacy of historical alterations.
- Headwater areas must be restored before hydrologic conditions in downstream areas.
- Restoring the stream channel is a long-term project.
- The timeframe for hydrologic restoration should be realistic.

References: Schilling et al. 2006; Schilling and Drobney 2014.

and revegetation at watershed scales can contribute significantly to the restoration of urban stream water quantity, quality, and habitat (Rios-Touma et al. 2014).

Slow Water Ecosystems

Restoration of lakes can require recovering the hydrologic dynamics of their tributaries. Changes in lake water depth are usually related to seasonal changes in tributary inputs but can also result from changes in the groundwater, the water table, and from losses through evaporation and infiltration. These changes can be heavily influenced by water management in agricultural or highly developed watersheds. Recovering lake water quality is also a challenge. With their high water residence times and slow turnover, lakes accumulate pollutants which are most commonly derived from fertilizer application. This can render lakes eutrophic, completely changing their biology. For example, eutrophication can increase phytoplankton production and water turbidity, decreasing subsurface oxygen and phytoplankton grazers, creating a feedback loop where clean water and predators mostly disappear (chap. 11) leaving bottom feeders that maintain turbid water (Carpenter et al. 2001).

When planned at a watershed scale, wetland restoration can help retain nitrogen and phosphorus in agricultural subwatersheds (Moreno-Mateos et al. 2010), although the extent to which this leads to lake recovery varies. When phosphorus, a highly conservative element, is the dominant pollutant, it may be necessary to excavate the lake sediments that store it, because once phosphorus precipitates and binds to mineral soil components the biological system cannot readily remove it (Kadlec and Wallace 2009).

Wetlands may accumulate pollutants and become eutrophic, fostering regime shifts to alternative states with different species composition (chap. 2). For example, along a gradient of phosphorus concentration in inflowing water, the Everglades marsh shifted from dominance by *Cladium* to *Typha* when it crossed a first threshold, and from *Typha* to *Nymphaea* after a second threshold of phosphorus concentration (Hagerthey et al. 2008). The removal of the phosphorus that has already infiltrated in groundwater flows or reached wetlands and lakes may be impossible with present technology although extensive studies and restoration modeling projects are still under way (Long et al. 2015). Invasive species dominate wetlands in many other regions because they are highly efficient at taking up nutrients. In Wisconsin, >200,000 ha are now invaded by the exotic, clonal, invasive grass *Phalaris arundinacea* due to its ability to uptake nitrogen from water eutrophicated by agriculture (Hatch and Bernthal 2008).

Overall, restoring historical hydroperiods increases wetland functionality although not necessarily to levels similar to those in reference wetlands (Moreno-Mateos et al. 2012; Meli et al. 2014). Restored hydroperiods have been reported to increase biogeochemical processes, such as denitrification and carbon mineralization (Roley et al. 2012; Hunt et al. 2014), organic matter accumulation (Ballantine and Schneider 2009), and nitrogen and phosphorus removal from water (Ardón et al. 2010). Restored hydroperiods can also help recover ecological processes, such as propagule dispersion via hydrochory (Nilsson et al. 2010) and macroinvertebrate colonization (Paillex et al. 2009). Beyond these few examples on the effects of restoring hydrological function to wetlands, there is a vast literature that cannot be fairly addressed in this chapter.

Coupling Hydrological and Ecological Theory for Restoration

Ecology and hydrology are tightly linked, and there are a variety of theoretical frameworks that are common to both, including a central focus on spatial structure, connectivity and boundary fluxes, and cross-scale interactions. Here, we provide examples in which hydrological dynamics are major determinants of an ecological process that in turn influences ecological theory or in which ecological theory guides hydrological restoration and also is advanced by restoration.

Ecosystem Subsidies and Hydrological Dynamics

Ecological theory on the importance of cross-system subsidies has been developed and refined for many years (Polis et al. 1997). Loreau et al. (2003) extended this to the concept of metaecosystems outlining a theoretical framework on the ecological role of spatial flows of materials and organisms across ecosystem boundaries.

Recognizing these flows helps ecologists and restoration practitioners understand unexpected emergent properties that come from the spatial coupling of ecosystems. Many of these subsidies are tightly linked to hydrological dynamics.

The abundance and diversity of aquatic insects emerging from streams toward terrestrial habitats are affected by multiple watershed factors. For example, the amount and diversity of mayflies, stoneflies, and caddisflies in alpine watersheds may increase with watershed area and may be higher in central streams at mid-elevations (Altermatt et al. 2013). Thus, steeper alpine streams with less water flow in secondary tributaries could host smaller and less diverse insect communities and produce fewer emerging insects that serve as prey for terrestrial predators. Changes in aquatic insect communities caused by hydrological alterations associated with restoration actions can also influence prey abundance (Heinrich et al. 2014). The abundance of riparian fishing spiders feeding on aquatic insects can be lower in streams that are less flood prone due to flow management than in more dynamic streams because the management action has led to changes in the in-stream habitat of the insects (Greenwood and McIntosh 2008). Similarly, the abundance and richness of riparian arthropod communities, including spiders, ground beetles, and rove beetles, inhabiting regulated steams was lower than in unregulated streams, again caused by changes to the stream substrate (Paetzold et al. 2007).

In aquatic ecosystems, the duration of the hydroperiod can affect emergence. For example, Schriever et al. (2014) found that insect emergence from ponds to forests is highest with intermediate hydroperiods while for amphibians emergence is highest with short hydroperiods. In some systems, if the hydroperiod is shortened by anthropogenic activities, a species might survive but have reduced activity or change its emergence timing (Leberfinger et al. 2010). For all these reasons, restoring hydroperiods will improve aquatic vertebrate and invertebrate communities as well as those in the surrounding terrestrial landscapes. In some places, the effects of emerging aquatic invertebrates can be detected beyond 0.5 km from the stream (Muehlbauer et al. 2014).

We emphasize the phenomenon of insect emergence as a resource "subsidy" for terrestrial species because it is far less well known than its reciprocal. Terrestrial subsidies to waterways are extremely important and for freshwaters, are strongly influenced by hydrological regime including periodic floodplain inundation. Decades of work demonstrating the importance of riparian litter inputs to aquatic systems can be found in numerous texts. Certainly, loss of riparian vegetation and even deforestation in a watershed's headwaters can reduce in-stream food web dependence on terrestrial subsidies (Wallace et al. 2015). Extended periods of low flows or droughts can influence the accumulation and decomposition of ter-

restrial litter inputs, which, in turn, advantages certain stream species over others (Wallace et al. 2015). Similarly, floodplain inundation results in significant inputs of nutrients to streams—a healthy process unless the system is under intense agriculture or there are other sources of pollution.

Metapopulation Theory, Restoration of Populations, and Restoration of River Networks

Seasonal or drought-induced drying of some aquatic systems is normal but spatially variable and is especially common in small streams and many wetlands. Large rivers in arid regions may have sections that dry every year. There are diverse life history strategies that help aquatic species persist in such systems and many rely on nearby refuges that retain surface water even during dry periods. Ponds, streams, or wetlands in low-lying areas may retain water during summer months, and these can provide colonists to other sites that become rewetted after rains. In such cases, one of the most important bodies of theory in ecology may be useful: metapopulation theory (chaps. 3 and 7). This body of theory views landscapes as networks of idealized habitat patches in which species occur as discrete local populations connected by migration (chap. 4). The theory is broadly recognized as useful in guiding restoration of species that are dependent on some degree of movement between spatially separated habitat patches. Decisions such as how many individuals to reintroduce, how many habitat patches to restore, what their degree of connectivity should be, and where on the landscape restoration efforts should be targeted all benefit from metapopulation models (chap. 7).

While metapopulation theory can provide guidance on the restoration of systems with variable hydrological dynamics, these same systems can provide fertile ground for testing and advancing metapopulation theory (case study box 14-2). For example, isolated ponds distributed across the landscape that support breeding populations of frogs have been used experimentally to show that predators or invasive species may respond to patch structure in ways that increase the risk to species that are of restoration or conservation interest (Atobe et al. 2014). Plans to restore and conserve "metapopulations species" that disperse in stream or river networks must take a different approach from linear or two-dimensional descriptions of dispersal across landscapes (Fagan 2002). In addition to the fact that regions of river networks may experience different levels of connectivity due to hydrologic conditions, their hierarchical, branching geometries directly influence ecological processes and patterns (Perkin et al. 2015). Patch geometry alone does not determine persistence; instead, it is the combination of network geometry, hydrology, and dispersal mechanisms (Mari et al. 2014). Species that are confined to water

Case Study Box 14-2
Restoring Hydrological Dynamics in Doñana (Guadalquivir Estuary, Spain)

Doñana wetlands, Spain: Doñana is Spain's largest wetland complex and provides one of the most important wintering sites for waterfowl in Europe. Despite the site's protected status, the marshes are threatened by eutrophication due to pollution and severely altered hydrological conditions that promote toxic cyanobacterial blooms and dominance by invasive floating plants that cause anoxia in subsurface waters. The loss of Doñana wetland area dates to the eighteenth century, when people began to drain marshes for agriculture. This practice continued until the 1970s. The drainage and isolation of marshes from their main water courses and tidal waters altered virtually every ecological process and caused drastic reductions of fish, mammal, amphibian, and bird populations.

Supporting theory: Restoring hydrological connectivity will increase biodiversity by reducing sedimentation and increasing ground-water recharge.

Expected outcomes and progress: In the early 1990s, initial attempts were made to recover lost biodiversity and ecological functions by reconnecting marshes with old inflowing streams. However, expected benefits to fish and bird populations were not achieved due to inadequate understanding of marsh hydrodynamics. In 1998, a major spill of toxic mine wastes (millions of cubic meters of pyrite sludge) catalyzed major restoration efforts. The efforts, based on numerical hydrodynamic models, focused on restoring the complex hydrology of most of the watersheds feeding the marsh, as well as reducing pollution from agricultural and developed areas. The models convinced decision makers to reconnect the marsh to the old streams that provided water inflows, to reduce sedimentation from agricultural watersheds, to permeabilize water barriers (road walls) within the marsh, to reduce groundwater extraction, and allow groundwater recharge. Additionally, actions were taken to reduce pollution from urban areas in and around the marsh.

Long-term outcomes: Fourteen years after the larger projects began, most plans have been implemented and long-term monitoring shows rewards. Watershed restoration catalyzed the recovery of bird communities in one of the streams affected by the spill. In fact, the bird richness, abundance, and diversity matched those of reference areas within five years. Similarly, zooplankton communities in temporary ponds recovered about 80% of their diversity of cladocera, copepods, and rotifers within two years.

Case Study 14-2: Restoration of the Caracoles farmland within the Doñana 2005 restoration project. Multiple circular ponds of different sizes were created to mimic natural temporary ponds and to study the effects of pond size, distance, and connectivity on the long-term recovery of invertebrate communities.

References: Bayán-Jardín 2006; García Novo and Marín Cabrera 2006; Badosa et al. 2010; Ontiveros et al. 2013; Scheffer et al. 2015.

and subject to unidirectional flows will respond differently to network patch structure than aquatic species capable of overland dispersal.

Closing Remarks

Restoration of degraded ecosystems, regardless of the type or position, involves a reestablishment or rebalancing of water processes, that is, hydrological restoration. Among others, four theories and concepts are essential to understanding how to accomplish this, and why some ecosystems recover while others do not. First, hydrological restoration requires a holistic approach that considers watersheds as geomorphological units in which water flows connect vegetation, soils, groundwater, and surface waters. Restoration of any of these—plant communities, forests, aquifers, lakes, wetlands, streams—requires a focus on the interaction among these four components. Second, movement of water among these four components via surface flows occurs directionally downslope while subsurface flows occur in more dimensions: upward from soils and plants as evaporation, vertically downward into soils toward groundwater storage, and laterally as flows in subsurface layers. This means that, for a given climate, position on the landscape with respect to topographic relief, geology, and connectivity to water (across all dimensions) will determine an ecosystem's restoration potential, particularly if water is a limiting factor in the region.

Third, restoration of soil conditions—its ability to absorb, hold, and transport water—is critical to the restoration of degraded terrestrial and aquatic ecosystems. If soil infiltration capacity or hydraulic conductivity is low, access to water may limit plant growth; too much water along with eroded soils may continue to degrade wetlands, lakes, and streams. Fourth, the frequency, timing, and magnitude of hydrologic fluxes can influence restoration trajectory. Many wetlands require distinct hydroperiods in which water elevation changes; streams and rivers have flow regimes that are characteristic of their region; and that aquatic organisms have evolved in response to, and many lakes are fed by groundwater fluxes that vary seasonally in a predictable way.

Restorationists need to couple hydrological and ecological theory because water fluxes play an essential role in many key processes ecologists have come to understand and predict. These include, for example, dispersal dynamics, seasonal variation in growth and reproduction, metapopulation dynamics, and ecosystem subsidies. Restoring hydrological dynamics, and thus populations, communities, and ecosystems, often involves actions at different scales, on different elements, and at different locations within degraded watersheds. To restore aquatic ecosystems that have been degraded by mining, agriculture, or other activities that have dramatically altered the landscape, actions may involve influencing infiltration

capacity at the scale of the entire watershed. Restoring water flows in areas with massive deforestation may take decades to centuries if the aquifers have been depleted; they will only slowly recharge and, in fact, water yield may initially or permanently decrease after planting. Thus, one of the main challenges in applying and growing what is now being called "ecohydrology" is the mismatch between the time-scale of ecological studies (<20 years), the real time for ecosystem recovery (up to centuries), and the social pressure to see results quickly. However, we will meet these challenges as we continue to learn more through careful studies of how water fluxes change during restoration, and the reciprocal effects they have on ecological processes.

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