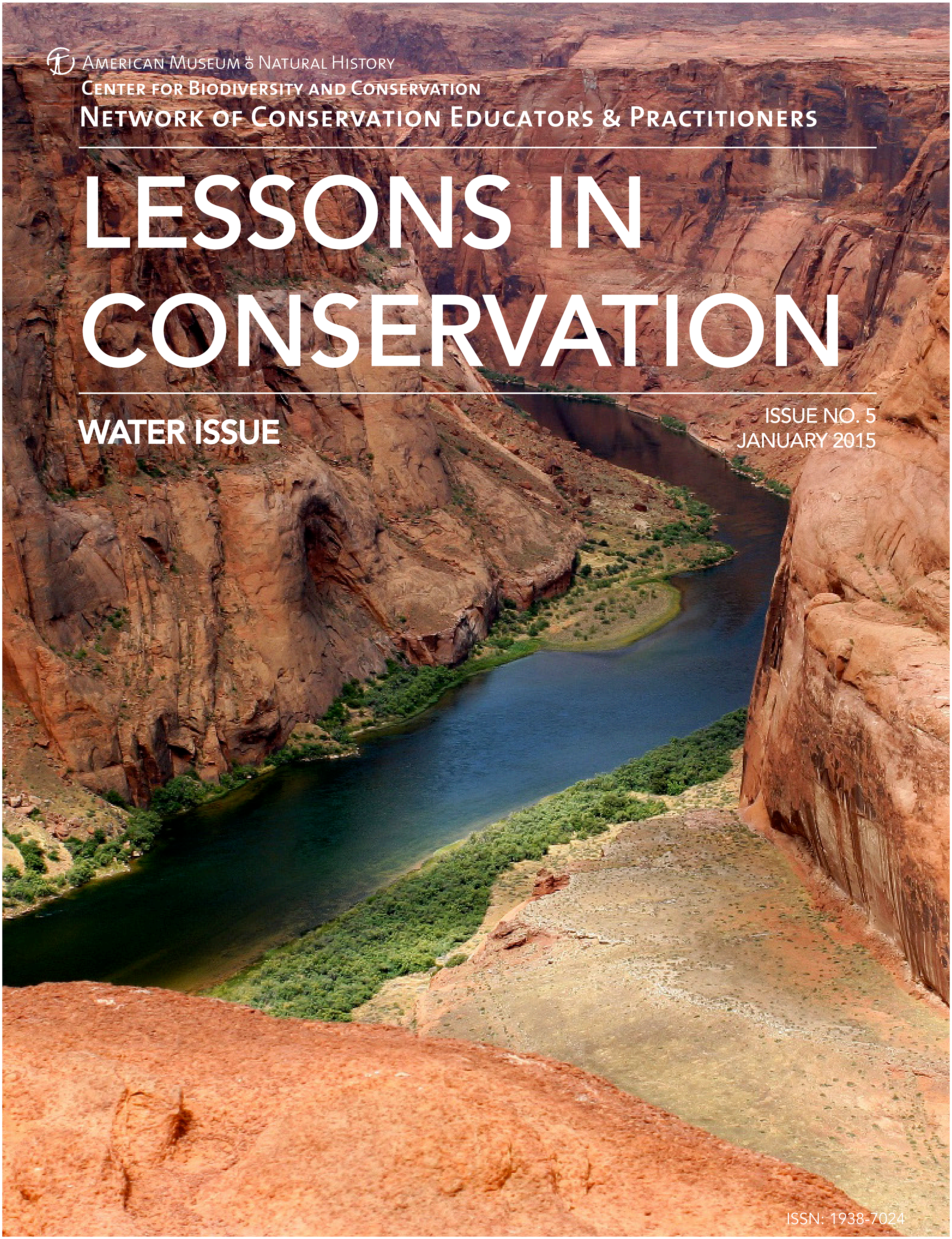
American Museum of Natural History
Center for Biodiversity and Conservation
Network of Conservation Educators & Practitioners

LESSONS IN CONSERVATION

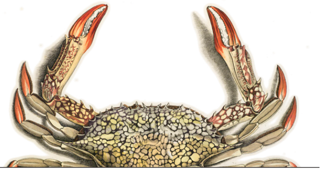
WATER ISSUE

ISSUE NO. 5
JANUARY 2015



ISSN: 1938-7024

American Museum of Natural History
Center for Biodiversity and Conservation
Network of Conservation Educators & Practitioners



Lessons in Conservation is the official journal of the Network of Conservation Educators and Practitioners (NCEP) and is published as issues become available. Teaching and learning modules presented here in Lessons in Conservation are available in modifiable form for teachers on the NCEP website (ncep.amnh.org). All materials are distributed free of charge. Any opinions, findings and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the American Museum of Natural History or the funders of this project. All components (Syntheses, Exercises, and Case Studies) have been peer-reviewed and approved for publication by NCEP.

Editor:
Tara Cornelisse
NCEP Science Editorial and Postdoctoral Fellow

Guest editor:
Erin Betley
CBC Biodiversity Specialist and Programs Coordinator

Production team:
Kimberley Landrigan
NCEP Assistant Director and Coordinator for Africa

Kristin Douglas
NCEP Production Coordinator

Nadav Gazit
NCEP and CBC Research and Production Assistant

Deena Lopez
NCEP Intern

Lessons in Conservation is available online at: ncep.amnh.org/linc

Cover photo: The Glen Canyon
By: Adrille, Wikimedia Commons, CC-BY-SA-3.0

Illustrations obtained from the American Museum of Natural History's library:
images.library.amnh.org/digital/

LETTER FROM THE EDITORS

Dear Reader,

Welcome to Lessons in Conservation, the official journal of the Network of Conservation Educators and Practitioners (NCEP). NCEP is a collaborative project of the American Museum of Natural History's Center for Biodiversity and Conservation (CBC) and a number of institutions and individuals around the world. This journal is designed to introduce NCEP teaching and learning resources (or "modules") to a broad audience. NCEP modules are designed for undergraduate and professional level education. These modules—and many more on a variety of conservation topics—are available for free download at our website, ncep.amnh.org.

For this issue, we present selected NCEP syntheses and case studies on freshwater ecosystems. Together, these module components examine the ecological structure, function, and distribution of freshwater ecosystems, their importance, threats, and actions taken to conserve freshwater resources. The topics range from invasive species to freshwater policy and focus on local issues of the Great Lakes, regional and international issues of the Colorado River, and global transboundary rivers. The Great Lakes and Colorado River case studies showcase not only complex conservation issues in an increasingly urbanized North America but also solutions that are rooted in the enduring conservation legacy of Theodore Roosevelt, lifelong naturalist and friend of the American Museum of Natural History. Often referred to as the Conservation President for his unprecedented efforts to protect wilderness areas and wildlife, Roosevelt placed some 230 million acres (93 million hectares) under federal protection, including the Grand Canyon, a gorge of the Colorado River, which he set aside as a national monument.

All module components can be used in a variety of academic or training courses and include questions designed to promote use of active learning techniques in the classroom and development of critical thinking skills in learners. We welcome feedback on our resources and we especially welcome those wishing to become further involved in the Network!

We are grateful to many people across the CBC and NCEP network for their contributions to the development of Lessons in Conservation. Please see the back cover for a full acknowledgement of the foundations and individuals that have supported this project.

Enjoy this issue of Lessons in Conservation and please visit our site to start using NCEP resources in your classroom! Questions and feedback are welcome at ncep@amnh.org.

Tara Cornelisse
Co-Editor

Erin Betley
Co-Editor

TABLE OF CONTENTS

Note: To access teaching notes for these case studies, visit our website: ncep.amnh.org and register as an educator.
Once registered, search for the case study by title to find its associated teaching and learning resources.

Freshwater Ecosystems and Biodiversity

Nathaniel P. Hitt[1], Lisa K. Bonneau[2], Kunjuraman V. Jayachandran[3], and Michael P. Marchetti[4]

[1]U.S. Geological Survey, Leetown Science Center, USA, [2]Metropolitan Community College-Blue River, USA, [3]Kerala Agricultural University, India, [4]School of Science, St. Mary's College of California, USA

Abstract

Freshwater ecosystems are important for many reasons, including their ecosystem services to humans. This module serves to help introduce students to thinking critically about the ecological structure, function, and distribution of freshwater systems. Freshwater ecosystems are driven by physical habitat, energy sources, water quality biotic interactions, hydrology and connectivity. Variations in these factors result in significantly different environments, including upland streams and rivers, large lakes, floodplain rivers and wetlands, and xeric freshwaters.

INTRODUCTION

Module Format

This module provides instructors with resources to teach a 45-minute lecture and 3-hour laboratory exercise on freshwater ecosystems and biodiversity. This module material should be appropriate in introductory college-level courses for either science majors or non-majors. The components of this module are designed be used together: the lecture introduces basic concepts that students subsequently explore in laboratory exercises. This module should also fit well with other NCEP modules and resources, such as *A Comprehensive Simulation of the Colorado River Basin: An Interactive Exercise*; we specifically recommend that this lecture and laboratory follow the NCEP module *Why is Biodiversity Important?* (All available at ncep.amnh.org). We hope that this module provides the basis for useful class and laboratory learning and we encourage instructors to adapt our template as necessary to suit their specific needs.

Module Scope

This module examines freshwater ecosystems from a global perspective, focusing on streams, rivers, lakes, and wetlands and their associated biota. Our intent is to help students develop mastery of four primary content areas. First, we provide a brief discussion of the hydrological cycle and fresh water availability, highlighting the global scarcity of useable freshwater. Second, we provide an overview of global biodiversity patterns in fresh water, highlighting the ideas of species richness and endemism. Third, we present a conceptual framework to understand how environmental factors influence freshwater biodiversity. Fourth, we apply this conceptual framework in a global survey of freshwater ecosystems.

Freshwater ecosystems are valued for many reasons, as they provide vital ecosystem services for humans (e.g., drinking water, flood control, climate regulation, food production) but such services are not the primary focus of this module. Likewise, specific conservation threats and strategies are also not the focus of this module. Instead, our goal is to help students develop a framework for critical thinking about the ecological structure, function, and distribution of freshwater ecosystems. We believe that such a framework is a prerequisite for further studies in freshwater conservation biology.

THE HYDROLOGICAL CYCLE AND FRESHWATER AVAILABILITY

Hydrological Cycle

All freshwater ecosystems are regulated by the hydrological cycle, the continuous process of water movement between states. This process can be viewed as steps of water storage and transport (Figure 1). Evaporation and evapotranspiration (i.e., water produced from vegetative respiration) move liquid water to atmospheric gas, then precipitation moves atmospheric water into liquid form and into streams, rivers, and lakes. Downstream flow then moves the liquid water into "storage" areas including groundwater, lakes, or the ocean. The length of time water remains

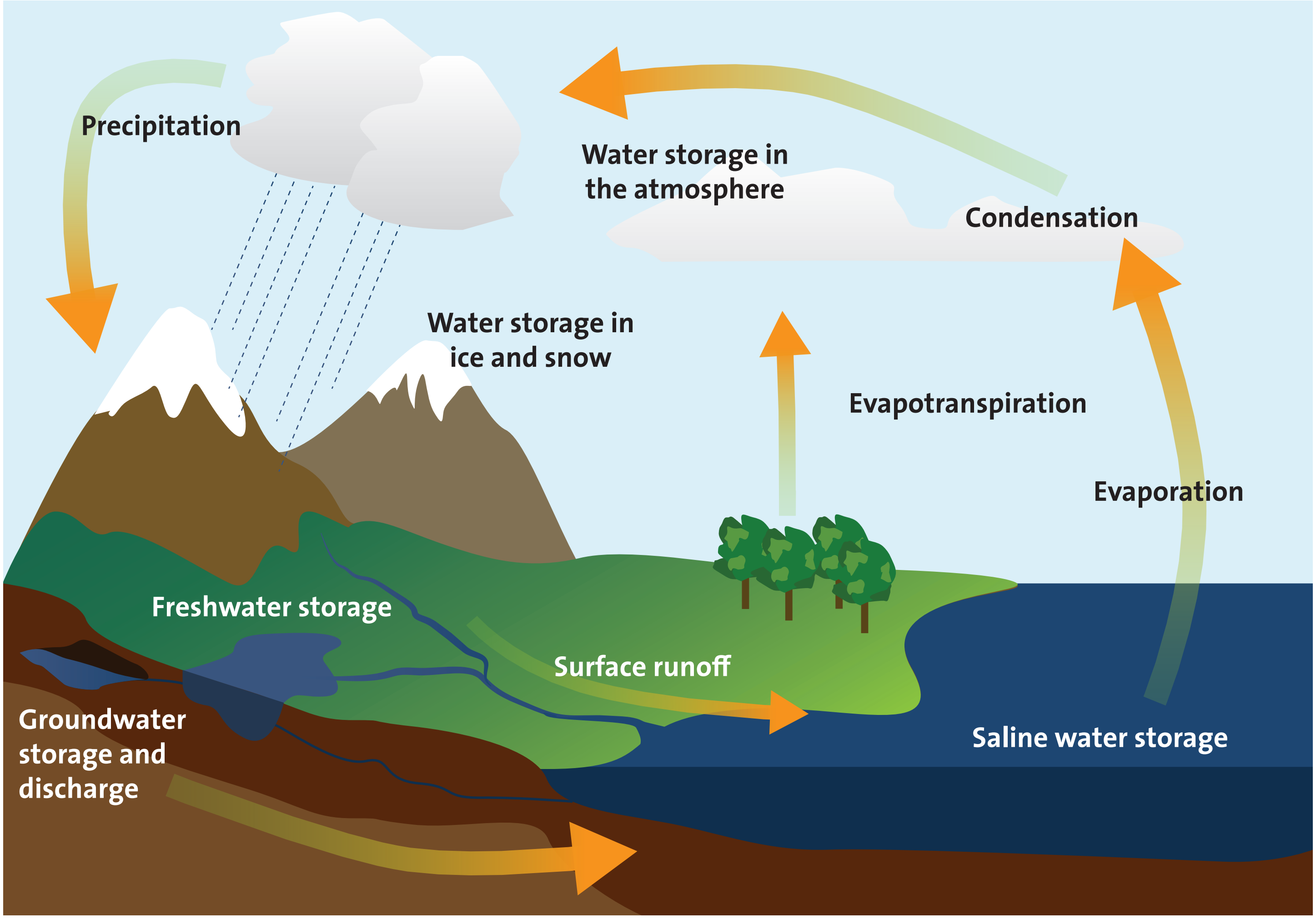


Figure 1. A simplistic model of the hydrological cycle. Illustration by Nadav Gazit.

in a particular place (i.e., retention time) varies based on several factors, including the size and shape of lakes, the connectivity to the groundwater (or water table, defined as the underground areas that are fully water-saturated), and the configuration of streams and rivers (e.g., flowing to oceans versus flowing to lakes). It is important to note that the hydrological cycle is ultimately driven by solar energy: without solar-driven evaporation, freshwater ecosystems as we know them would not exist.

Experimental research has demonstrated the importance of vegetation for stream flow. A classic example of this is from the Hubbard Brook Experimental Forest in New Hampshire, USA. After a deciduous forest was clear-cut (and regenerating vegetation was suppressed by herbicides), the annual volume of flow out of the watershed increased by 40% (and over 400% during the summer) (Allan 1995). This increased stream flow represents the volume of water moved by evapotranspiration through vegetation. Additional examples are provided in Likens and Bormann (1974).

Total Fresh Water

Depending on where one lives, freshwater ecosystems may seem endless (e.g., Boundary Waters and Voyagers National Park, North America or Lake Baikal, Russia) or limited and remote (e.g., Atacama Desert, South America). A global accounting is therefore necessary to comprehend the true abundance of fresh water. Of all the water on Earth, approximately 3% is considered "fresh water" (i.e., salinity < 0.5 parts per thousand) (Figure 2). Note that rivers and lakes are not visible on this pie chart because they comprise such a small proportion of the Earth's total water (Figure 3).

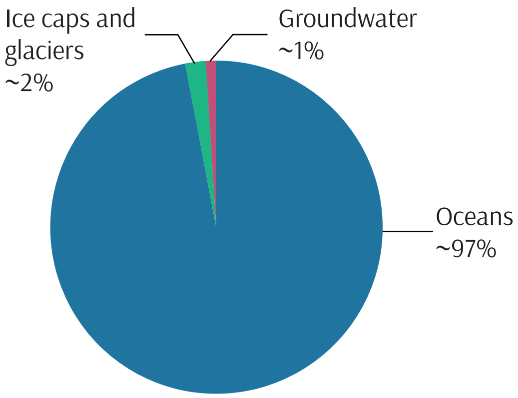


Figure 2. Global composition of fresh water

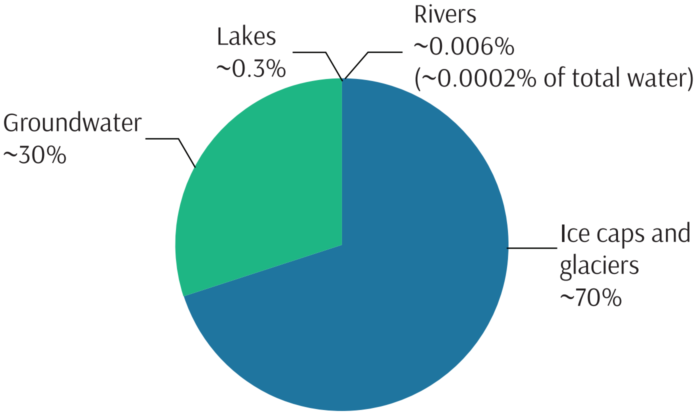


Figure 3. Global availability of fresh water

Fresh water Available for Habitat

Of the 3% of global water that is fresh water, only an extremely small proportion is available as habitat for living organisms on the surface of the Earth (Figure 3). The largest portions of the Earth's fresh water are locked up as frozen water in the polar ice caps and glaciers (approximately 70%) or buried underground as groundwater (approximately 30%). Lakes and rivers comprise a tiny portion of the total fresh water (approximately 0.3%). When compared to all water on Earth, rivers (including streams) comprise only 0.0002% of the total volume. In total, available freshwater ecosystems cover approximately 0.8% of the surface of the Earth. Interestingly, much of the Earth's aquatic biodiversity requires the freshwater flowing habitat found in these rare ecosystems. It is therefore not surprising that flowing-water habitats contain some of the most imperiled taxa on the planet (see Conservation section, below).

ECOSYSTEM TYPE	% EARTH AREA	% DESCRIBED SPECIES
Freshwater	0.8	2.4
Terrestrial	28.4	77.5
Marine	70.8	14.7

Table 1. Comparison of area and percent of described species for freshwater, terrestrial, and marine ecosystems. Note that the total percent of species described does not sum to 100 because symbiotic species are excluded. Data are from McAllister et al. (1997).

TAXONOMIC GROUP	APPROXIMATE NUMBER OF DESCRIBED FRESHWATER SPECIES
Insects (larval stage [a])	20,000
Fishes	13,000[b]
Amphibians	6,000
Snails	4,000
Mussels	1,000
Crayfishes	500

[a] Most freshwater insects emerge into a terrestrial adult stage, but egg deposition and juvenile development occurs in freshwater environments.

[b] Lévêque et al. (2008)

Table 2. Global freshwater species diversity. Note that data for small-bodied organisms (e.g., phytoplankton, zooplankton, amphipods, etc.) have not been well described and are not included here.

GLOBAL PATTERNS OF FRESHWATER BIODIVERSITY

Species richness is defined as the number of species found within a given area. Although many organisms require fresh water for survival, in this module we define freshwater species as those which spend at least a portion of their lives in freshwater habitats. Given the relative rarity of freshwater habitat (i.e., 0.8% of the Earth's total surface area), one might predict that freshwater ecosystems would support 0.8% of the freshwater biodiversity. However, this estimate is extremely low (McAllister et al. 1997) (Table 1).

In fact, tens of thousands of freshwater species have been described, including insects, fishes, amphibians, snails, mussels, crayfishes, and others (Table 2). However, the list of known freshwater species is likely an underestimate due to a known bias for describing large-bodied organisms first (Gaston 2000). However, we can use the distribution of some well-studied taxonomic groups (i.e., fishes and amphibians) (Table 2) to provide insight into global patterns of freshwater biodiversity (Abell et al. 2008).

Similar to terrestrial organisms, the species richness of freshwater fishes follows a latitudinal pattern and tends to increase towards the equator (Figure 4), (Gaston 2000). Interestingly this pattern is not distributed evenly over the planet as some non-tropical regions have higher than expected richness (i.e., Southeastern North America, and Western China) while other areas have lower than expected richness (i.e., Western North America and Australia). Globally, the greatest concentrations of freshwater fish species are found in South America and Southeast Asia (Figure 4). In addition taxonomic patterns among fish species are also not homogenous around the globe. For example, fishes in the families *Centrarchidae* (sunfish) and *Ictaluridae* (bullhead catfish) are indigenous only to North America (Jenkins and Burkhead 1994).

Amphibian species also follow the same latitudinal trend (Figure 5), but the total number of species is generally lower (Table 1). When compared to the distribution of fish species, two distinct patterns are evident: (1) amphibian richness tends to be more evenly distributed across South America and Central Africa; and (2) Australia supports relatively more species of amphibians

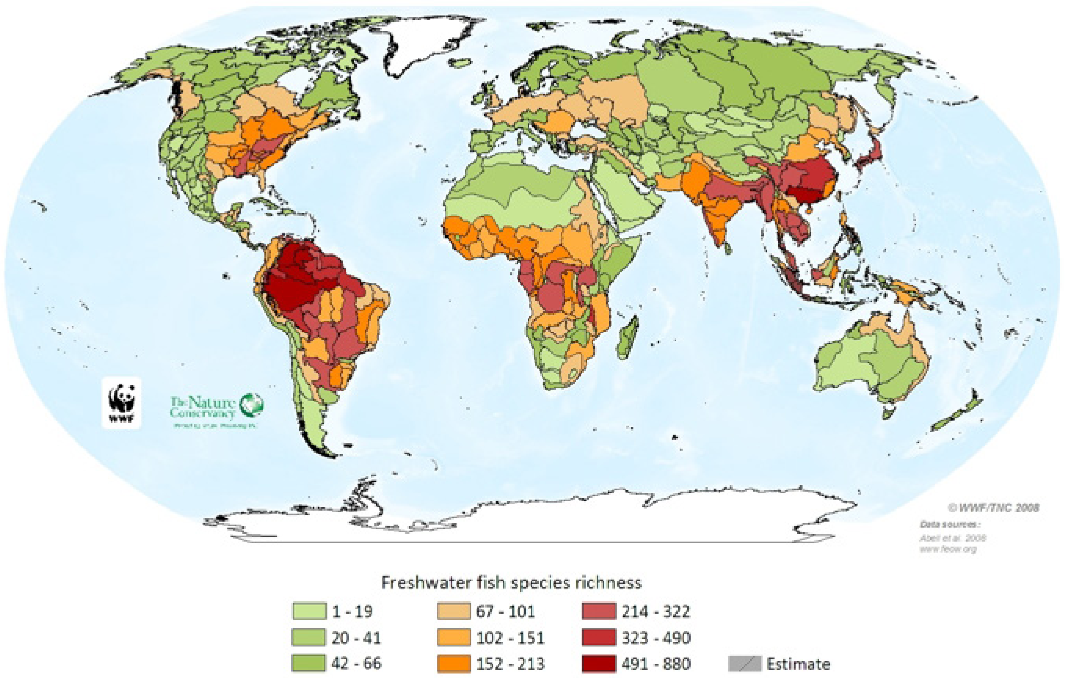


Figure 4. Freshwater fish species richness (from Freshwater Ecoregions of the World [FEOW] database, www.feow.org)

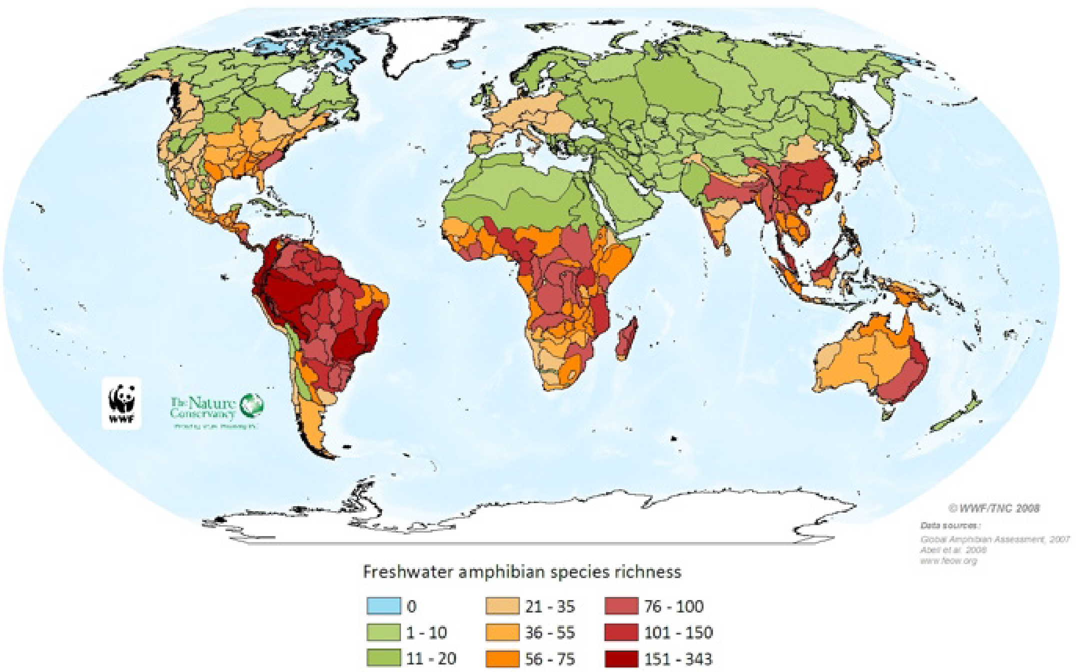


Figure 5. Freshwater amphibian species richness (from Freshwater Ecoregions of the World [FEOW] database, www.feow.org)

than fishes (Figure 5). However, when examining the distribution maps for fish and amphibian species (Figures 4 and 5), note that the numbers of species in each abundance category are different.

Another useful biodiversity measure is the idea of species endemism. Endemic species are ones whose global distribution is limited to a given area (i.e., they occur only within a particular ecoregion or watershed). Areas of high endemism often result from a combination of ecological forces including high biological productivity and geographic isolation. Patterns of endemism in freshwater fishes and amphibians generally follow species richness patterns. However, the southern hemisphere tends to support greater amphibian species endemism than the northern hemisphere (Abell et al. 2008). From a conservation perspective, endemic species are important because they contribute to global biodiversity and their extinction may be the result of small localized events.

ECOSYSTEM DRIVERS OF FRESHWATER BIODIVERSITY

Many environmental factors affect freshwater biodiversity (Wetzel 2001). The purpose of this section is to provide a systematic approach to understanding how environmental factors affect biota. We first describe each factor, and then return to these factors when examining the major types of freshwater ecosystem. Although each factor is presented separately, interactions among factors are important and commonplace (discussion questions are presented in this module's accompanying component "Presentation Notes and Discussion Questions" for students to explore how these factors are integrated in specific ecosystems, available at ncep.amnh.org).

Physical Habitat

Classifying aquatic habitat is not always straightforward and simple. Numerous systems of aquatic classification have been developed around the world (Higgins et al. 2005). Most systems are hierarchical and fall into one of two categories: 'top-down' approaches or 'bottom-up' approaches. 'Top-down' approaches start from large, ecologically diverse areas, and divide these into lower more homogeneous levels. 'Bottom-up' approaches begin in a completely different manner with the lowest levels of the hierarchy and group them according to shared characteristics (Ricklefs and Miller, 2000). It is generally agreed that understanding processes

and patterns of freshwater systems at multiple scales is critical for conserving freshwater biodiversity, yet there is still much debate over which approach is best to classify these processes and patterns (Frissell et al. 1986; Fausch et al. 2002).

In a very general sense, aquatic physical habitat may include any submerged materials or structures. One of the more important of these for flowing water is the substrate size of the benthos. Small substrates (e.g., clays) have a high surface-to-volume ratio and are relatively easily transported, as compared to larger substrates (e.g., boulders). In addition, high surface-to-volume ratios on substrate particles tend to support robust microbial communities (and thus affect dissolved oxygen levels via microbial respiration). Also, large amounts of surface area provide binding sites for ionic compounds such as dissolved nutrients (i.e., nitrogen and phosphorous). In streams and rivers, substrate size combined with flow patterns affect the development of instream habitat such as pools and riffles (Frissell et al. 1986). Woody debris, undercut banks, and rooted plants also provide important physical habitats. For example, large woody debris (e.g., root wads, logs) can affect the formation of instream pools by altering the direction of water flow (Shields et al. 2003).

Instream habitat features also provide organisms with physical structures that can be used for feeding or reproduction, as well as refugia from predators or disturbance events. For example, anadromous fishes (i.e., ones that migrate between fresh and salt water) at higher latitudes may travel hundreds of kilometers to reach habitat that has the appropriate physical conditions for spawning (often clean gravel in small streams). In addition, benthic macroinvertebrates may cluster together on patches of substrate with low flow velocity (i.e., low sheer stress) during high-flow events (Lancaster 2000). Because individual species need different types of physical habitat at different times, the spatial configuration of habitat patches may influence movement rates as well as population and community structure (Dunning et al. 1992).

The overall general importance of physical habitat may vary with the volume of water in an ecosystem. For example, in small streams or spring ecosystems, the percent of water in contact with the substrate is much higher than in large rivers or lakes. In lakes, the most important physical habitats are likely to be in the shallow and near-shore environments (Wetzel 2001).

Energy Sources

For our purposes, energy source refers to primary production or the basal level in the food web. Sunlight is the main factor regulating photosynthesis by green algae and some species of bacteria. Dissolved nutrients (particularly nitrogen and phosphorous) also promote algal growth and photosynthetic activity (Allan and Castillo 2007). In turn, the products of photosynthesis (carbohydrates and oxygen) are moved downstream and incorporated into biomass throughout the food web. In contrast, microbial respiration consumes dissolved oxygen and acts to somewhat counter-balance photosynthesis.

The River Continuum Concept is a general hypothesis about how rivers and streams are structured and suggests that the ratio of photosynthesis to respiration can be used as an index of energy transport in flowing water systems (Vannote et al. 1980). In small streams, overall instream photosynthesis may be limited either by riparian vegetative shading or the low concentration of dissolved nutrients. Most photosynthesis in small streams originates with attached tiny algae called periphyton. In contrast, most photosynthesis in large rivers originates with microscopic plants floating in the water column called phytoplankton. The volume and dynamics of water therefore have important consequences for freshwater energy sources.

Energy sources also influence the trophic structure of food webs at higher levels. Benthic (i.e., bottom-dwelling) macroinvertebrate (MI) communities tend to vary in relation to a stream's energy sources. For example, insects that shred coarse particulate organic matter tend to inhabit headwater streams where leaf-litter and coarse organic matter is abundant. Further downstream the abundance of collecting and grazing MI increases due to an abundance of fine particles of organic matter (Vannote 1980). In a similar manner, the abundance of insect eating fishes increases in downstream areas. However, food supply is not the only factor limiting

fish distributions as physical habitat and hydrological regimes also play a role (Hynes 1972).

Water Quality

For our purposes, water quality refers primarily to the chemical attributes of water. Dissolved oxygen (DO), pH, dissolved nutrients, dissolved metals, and suspended solids are some of the major components of water quality. DO and pH influence organismal physiology (i.e., respiration and metabolism) and therefore can regulate where organisms survive and reproduce. Dissolved nutrients are believed to have a large effect on algal growth, and therefore have an indirect effect on MI and fishes. Dissolved metals may be important for organismal physiology, but can also cause toxic effects at high levels. Suspended solids may affect the optical properties of water, therefore influencing visual communication as well as vulnerability to predators.

Biotic Interactions

Predation, competition, and hybridization are the major forms of biotic interactions. Predation rates can affect organismal behavior (i.e., predator avoidance) as well as population growth rates. In general, biotic interactions are considered to be density-dependent factors because the likelihood of biotic interactions will increase as the density of individuals increases (in contrast to density-independent factors that affect all individuals regardless of population numbers, e.g., a drought).

Anatomical features may provide clues about predator-prey relations. Among fishes, predators can often be identified by the size of their mouths (i.e., gape size). For example, bluegill sunfish (*Lepomis macrochirus*) and green sunfish (*L. cyanellus*) have a very similar body shape, but different gape sizes: fish-eating (piscivorous) green sunfish can be identified by their large mouths, when compared with insect-eating (insectivorous) bluegill with smaller mouths. Among benthic macroinvertebrates, mouth parts are also predictive of predatory behavior. For example, larval dragonflies (Odonata) have strong mandibles, which are used to pierce their prey.

Competition also may affect population growth rates through density-dependent processes. Although inter-specific competition may be important in some cases, intra-specific competition is expected to have the greatest effects because members of the same species share traits and physiological requirements. Although dispersal processes are thought to diffuse competition pressures, organisms need to achieve a threshold of physiological capacity in order to be successful in dispersal. As a result, competition is thought to be greatest during the first year of life for fishes and amphibians (Hynes 1972).

Hybridization is a population-level phenomenon, resulting from breeding of individuals among gene pools. Hybridization may result in increased fitness (defined in terms of survival and reproduction), and this process is referred to as heterosis. Alternatively, hybridization may result in decreased fitness, and this process is referred to as outbreeding depression. Interspecific hybridization is more common in fishes than among other vertebrate groups due to the lack of isolating mechanisms in freshwater environments (Arnold 1992). Hybridization between native and introduced fishes presents a challenging problem for biological conservation (e.g., Hitt et al. 2003).

Hydrology

Stream flow is thought to have five major defining features: magnitude, frequency, duration, predictability, and rate of change. These features have critical implications for freshwater ecosystems. When taken together, they define a particular stream's hydrological regime, which can affect aquatic organisms in direct and indirect ways. Direct effects can be through disturbances, such as floods that increase sheer stress on benthic organisms, or droughts that increase physiological stress. Hydrological regimes also indirectly influence biota by regulating the availability of habitat (e.g., seasonal floodplains) and the development of habitat types (e.g., scouring of pools and riffles during high flows). It is no surprise, therefore, that species traits are often linked to a region's hydrological regime (Poff and Ward 1989, Lytle and Poff 2004). For these reasons, hydrology is sometimes considered a 'master variable' because it affects many other environmental influences in freshwater ecosystems.

Connectivity

For our purposes, connectivity refers to the size and proximity of connected streams or lakes. As such, connectivity is not a feature of individual streams or lakes, but instead is an emergent property from the interactions of multiple freshwater habitats. In stream fishes, stream network connectivity affects seasonal movement to feeding and reproductive habitats (Osborne and Wiley 1992; Hitt and Angermeier 2008) as well as extinction probability (Campbell-Grant et al. 2007). Connectivity between lakes and rivers (i.e., lentic and lotic habitats, respectively) also helps predict the composition of the local community (Miranda 2005). As a result, the success of ecological restoration in freshwater ecosystems may be influenced by the degree of regional connectivity in addition to the restoration efforts themselves (Lake et al. 2007). Conversely, dams and culverts present major challenges for freshwater conservation at a landscape scale because they tend to block or restrict regional connectivity (Richter et al.1997; Cumming 2004; Gibson et al. 2005).

A GLOBAL SURVEY OF FRESHWATER ECOSYSTEMS AND BIOTA

This section provides a brief introduction to four common freshwater ecosystem types: upland streams and rivers, floodplain rivers and wetlands, large lakes, and xeric freshwaters. These categories are drawn from the Freshwater Ecoregions of the World database (Abell et al. 2008); however, for simplicity, we have collapsed two categories (montane freshwaters and upland streams) into a single category we call "upland streams and rivers." We also combined temperate and tropical categories for upland streams and rivers, as well as floodplain rivers and wetlands. The purpose of this section is to provide an introduction to major ecological features of these habitat types, using the general framework provided above. Each of these habitat types is explored in more detail in the accompanying laboratory Exercise (online at ncep.amnh.org). Although our freshwater ecosystem classifications were developed for a global-scale analysis, we recognize that other classification schemes may be more appropriate for finer-scale assessments.[1]

Upland Streams and Rivers

Upland stream and rivers occur in mountainous zones worldwide. Examples include the Himalayan mountains (Asia), the Amazon River uplands (South America), the Appalachian and Rocky Mountains (North America), and the Congo River uplands (Africa). Following the framework presented above, several environmental factors characterize upland streams and rivers:

- ***Physical habitat***: Large substrate, copious woody debris
- ***Energy sources***: Sunlight limited by riparian zone, energy mostly allochthonous (derived from outside the stream) in origin
- ***Water quality***: High levels of dissolved oxygen and low levels of dissolved nutrients
- ***Biotic interactions***: Weak biotic interactions (because large predators are generally excluded due to habitat limitations)
- ***Hydrology***: Chaotic, non linear and disorganized flow
- ***Connectivity***: High levels of connectivity among streams affects recolonization rates

Organisms and communities in upland streams and rivers must be able to cope with relatively harsh environmental conditions. Many larval insects are well-adapted in this regard. For example, black fly larvae (Simullidae) use hooks and silk threads to attach themselves to substrate surfaces (Voshell 2002). Fishes tend to be benthically-oriented and often dorsoventrally (top to bottom) flattened (Poff and Ward 1989). Overall, species richness in upland streams and rivers tends to be relatively low, presumably due to the exclusion of biota in the harsh environmental conditions. Tropical upland systems tend to support a much greater diversity of aquatic organisms and have a higher degree of endemism than temperate regions (Gaston 2000). However, some upland streams and rivers in the Southern Appalachian mountains (North America) support levels of species richness comparable to tropical systems (e.g., Duck River and Clinch River, Tennessee, USA) (Benz and Collins 1997).

Large Lakes

Large lakes are formed by geologic processes, including

---

[1] For a more comprehensive introduction to freshwater ecosystem types, see Silk and Ciruna (2004).

tectonic, glacial, or volcanic activity (Table 3). Tectonic lakes, formed by the separation of continental plates, are the largest and deepest lakes on Earth (e.g., Lake Tanganyika in Africa, and Lake Baikal in Central Asia). Lake Baikal is the deepest lake on Earth, reaching approximately 1600 meters in depth (Wetzel 1983). In contrast glacial lakes are formed by the movement of glaciers across a landscape: advancing glaciers will carve geological basins and the retreating (melting) glaciers can fill these basins (e.g., Flathead Lake and the Laurentian Great Lakes in North America). Finally, volcanic lakes are formed by volcanic eruptions and magma flow and often tend to be smaller than tectonic or glacial lakes (Wetzel 1983) (Table 3).

Large lakes share several features that influence biotic composition:

- ***Physical habitat***: Near-shore and shallow water habitat most important
- ***Energy sources***: Energy mostly autochthonous (produced in place) by phytoplankton; highly productive in tropics
- ***Water quality***: Oxygen varies with depth and season
- ***Biotic interactions***: Predation important
- ***Hydrology***: Stable systems often with seasonal pattern in turnover
- ***Connectivity***: Isolation permits adaptive radiation (i.e., endemism)

Biota of large lakes are often distinct from those in upland rivers and streams in several ways. First, phytoplankton and zooplankton are generally more important in lake ecosystems than in upland rivers (phyto = "plants," zoo = "animals," plankton = "floating"). This is because turbulent flow and riparian cover in small streams is not conducive for plankton (although in very large rivers, plankton are often important in food webs). Insects in large lakes are generally limited to the lighted or photic zone (and therefore water turbidity is important). Fishes in large lakes are typically segregated by near-shore and open-water habitats (and therefore lake morphology is important). Interestingly, fish diversity reaches its zenith in tropical rift valley lake ecosystems, such as Lake Malawi (Africa) where more than 850 species of cichlids have been described, which are thought to have diverged from a common ancestor (Moyle and Cech 2003).

Floodplain Rivers and Wetlands

Floodplain rivers and wetlands are distributed worldwide. Notable examples include the Nile and Zambezi Rivers (Africa), the Mississippi River (North America), the Amazon River (South America), the Indus River (South Asia), and the Lower Mekong River (Southeast Asia). In each case, these ecosystems are characterized by hydrological connectivity to their floodplains and associated wetlands. Unlike upland streams and rivers, floodplain rivers occur in low-gradient terrain and exhibit a sinuous pattern across a landscape. Several environmental features typify floodplain rivers and wetlands:

- ***Physical habitat***: Fine substrates in river; wetlands provide diverse physical habitats
- ***Energy sources***: Highly productive autochthonous systems
- ***Water quality***: Nutrients entrained from wetland soils; relatively low dissolved oxygen
- ***Biotic interactions***: Competition/predation rates vary between wet and dry seasons
- ***Hydrology***: Seasonal flooding
- ***Connectivity***: Connectivity with floodplain provides breeding and feeding habitats

Floodplain rivers and wetlands are highly-productive systems, yielding some of the highest levels of fish biomass on Earth (Bayley 1995, Balcombe et al. 2007). Tropical systems are notable in this regard. For example,

LAKE TYPE	FORMATION PROCESS	EXAMPLES
Tectonic	Separation of continental plates	African Rift Valley lakes
Glacial	Glaciers advance and melt	North American Laurentian Great Lakes
Volcanic	Crater formation, magma flow	Crater Lake, Oregon, USA

Table 3. Lake types and formation processes

the Amazon River supports over 2500 species of fishes (Allan and Castillo 2007), whereas the Mississippi River supports approximately 433 fish species (Muneepeerakul et al. 2008). Hydrological connectivity to wetlands also increases predation of fishes by terrestrial predators. For example, floodplain wetlands characteristically support high levels of bird diversity (Bayley 1995).

Xeric Freshwaters

Xeric[2] freshwaters occur in dry climates. There are two primary types of xeric freshwaters: endorheic basins and isolated springs. Here, we focus on endorheic basins, watersheds that flow inland instead of to an ocean outlet. This type of system occurs in arid regions worldwide, including, for example, the Sahel and Sahara deserts (Africa), the Tibetan plateau (Asia), Lake Erye (Australia), the Sonoran and Gila deserts (North America), and Mar Chiquita (South America). These ecosystems provide important freshwater habitats in arid regions, but are subject to several important ecological constraints:

- ***Physical habitat***: Sandy substrate, low physical habitat diversity
- ***Energy sources***: Low productivity (phytoplankton exclusion due to salinity)
- ***Water quality***: High salinity from evaporation
- ***Biotic interactions***: Weak biotic interactions (because harsh environmental conditions exclude potential predators and competitors)
- ***Hydrology***: Ephemeral and unpredictable water levels
- ***Connectivity***: Isolation yields high levels of endemism

Biota of xeric freshwaters are characterized by low diversity (species richness) but high endemism. Endemism is particularly high for turtle and amphibian species (Abell et al. 2008). Given the temporal variability in flows, organisms inhabiting xeric freshwaters commonly exhibit estivation (i.e., dormancy during dry periods) or diapause (e.g., delayed development of fertilized eggs). For example, the four species of African lungfishes can burrow into the substrate and estivate during the long dry season, only to recover and swim away when the waters return (Moyle and Cech 2003). In general, large-bodied fishes are often absent from these freshwater habitats (Skelton 2001).

CONSERVATION

As explained above, rather than specifically focusing on conservation of freshwater ecosystems, this module attempts to provide an ecological framework as a precursor for further studies in freshwater conservation biology. However, information on conservation status, trends, and threats will be useful for instructors to introduce the lecture and/or laboratory exercise. We therefore provide a brief summary of these issues here. (For more information on conservation and freshwater ecosystems, please see the relevant NCEP case studies and modules in this issue and *A Comprehensive Simulation of the Colorado River Basin: An Interactive Exercise.*)

Extinction rates for freshwater species are higher than for terrestrial species (Ricciardi and Rasmussen 1999). Of the more than 5,000 freshwater fish species assessed by the World Conservation Union (IUCN), over 40% are classified as threatened with extinction (Reid et al. 2013). Moreover, Jelks et al. (2008) estimated that over 120 freshwater species have gone extinct in North America since 1900. In addition, approximately 32% of the 338 crayfish species in North America are considered to be threatened or endangered (Taylor et al. 1996). Likewise, approximately 72% of mussel species in Canada and the United States are endangered, threatened, or of special concern (Williams et al. 1993). The American Fisheries Society Endangered Species Committee is currently in the process of revising the status list for mussel species of North America (USGS 2013).

Five major causes of freshwater ecosystem degradation are widely recognized:

1. Habitat loss and degradation: land use practices, water abstraction, impoundments (e.g., Moyle and Leidy 1992; Richter et al. 1997; Dudgeon et al. 2006);
2. Overexploitation: unsustainable fisheries harvest (e.g., Dudgeon et al. 2006);
3. Invasive species: evolutionarily-novel competition, predation, and hybridization (e.g.,

---

[2] Xeric = a dry habitat.

Moyle and Cech 2003; Light and Marchetti 2007);

4. Fragmentation: impassible dams and culverts (e.g., Wang et al. 2006); and
5. Climate change: synergistic effects with all of the above (e.g., Aston 2007).

However, the relative importance of these influences will vary among locations. For example, Richter et al. (1997) conclude that Eastern North America is primary affected by altered sediment loads from agricultural activities, whereas Western North America is primary affected by exotic species, altered hydrologic regimes, and drought (For example, see NCEP case study *How the West Was Watered: A Case Study of the Colorado River* available in this issue and online at ncep.amnh.org).

Angermeier (2007) argues that society needs to acknowledge three fundamental facts regarding freshwater conservation: (1) freshwater biota are critically imperiled; (2) human actions are causing this imperilment; and (3) current conservation efforts are not sufficient. He argues that the role of the freshwater biologist is not only to conduct ecological investigations, but also to educate the public and policy-makers about the role of freshwater ecosystems for biodiversity and human quality of life. We hope that the module provided here will contribute in this regard.

LITERATURE CITED

Abell, R., et al. 2008. Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. BioScience 58:403-414.

Allan, J.D. and M.M. Castillo. 2007. Stream ecology: structure and function of running waters. 2nd edition. Springer, Dordrecht, The Netherlands.

Angermeier, P.L. 2007. The role of fish biologists in helping society build ecological sustainability. Fisheries 32:9-20.

Arnold, M.L. 1992. Natural hybridization as an evolutionary process. Annual Review of Ecology and Systematics 23:237-261.

Aston, P.J. 2007. Riverine biodiversity conservation in South Africa: current situation and future prospects. Aquatic Conservation: Marine and Freshwater Ecosystems 17:441-445.

Balcombe, S.R., S.E. Bunn, A.H. Arthington, J.H. Fawcett, F.J. Mckenzie-Smith, and A. Wright. 2007. Fish larvae, growth and biomass relationships in an Australian arid zone river: links between floodplains and waterholes. Freshwater Biology 52: 2385-2398.

Bayley, P.B. 1995. Understanding large river-floodplain ecosystems. BioScience 45:153-158.

Benz, G.W. and D.E. Collins, editors. 1997. Aquatic fauna in peril. Lenz Design and Communications, Decatur, Georgia, USA.

Campbell-Grant, E.H., W.H. Lowe, and W.F. Fagan. 2007. Living in the branches: population dynamics and ecological processes in dendritic networks. Ecology Letters 10:165-175.

Cumming, G.S. 2004. The impact of low-head dams on fish species richness in Wisconsin, USA. Ecological Applications 14:1495-1506.

Dudgeon, D., A.H. Arthington, M.O. Gessner, Z. Kawabata, D.J. Knowler, C. Lévêque, R.J. Naiman, A. Prieur-Richard, D. Soto, M.L.J. Stiassny, and C.A. Sullivan. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biological reviews 81(2): 163-182.

Dunning, J.B., B.J. Danielson, and H.R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65:169-175.

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. Bioscience 52:483-498.

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199-214.

Gaston, K.J. 2000. Global patterns in biodiversity. Nature 405:220-227.

Gibson, R.J., R.L. Haedrich, and C.M. Wernerheim. 2005. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. Fisheries 30:10-17.

Higgins, J.V., M.T. Bryer, M.L. Khoury, and T.W. Fitzhugh. 2005. A freshwater classification approach for biodiversity conservation planning. Conservation Biology 19:432-445.

Hitt, N.P., C.A. Frissell, C.C. Muhlfeld, and F.W. Allendorf. 2003. Spread of hybridization between native westslope cutthroat trout, Oncorhynchus clarki lewisi, and nonnative rainbow trout, Oncorhynchus mykiss. Canadian Journal of Fisheries and Aquatic Sciences 60:1440-1451.

Hitt, N. P., and P. L. Angermeier. 2008. Evidence for fish dispersal from spatial analysis of stream network topology. Journal of the North American Benthological Society 27:304-320.

Hynes, H.B.N. 1972. The ecology of running waters. University of Toronto Press, Toronto, Canada.

Jelks, H.L. et al. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33:372-407.

Jenkins, R.E. and N.M. Burkhead. 1994. Freshwater fishes of Virginia. American Fisheries Society, Bethesda, Maryland, USA.

Lake, P.S., N. Bond, and P. Reich. 2007. Linking ecological theory with stream restoration. Freshwater Biology 52:597-615.

Lancaster, J. 2000. Geometric scaling of habitat patches and their efficiency as refugia during disturbance. Journal of Animal Ecology 69:442-457.

Lévêque, C., T. Oberdorff, D. Paugy, M.L.J. Stiassny, and P.A. Tedesco. 2008. Global diversity of fish (Pisces) in freshwater. Hydrobiologia 595:545-567

Light, T. and M.P. Marchetti. 2007. Distinguishing between invasions and habitat changes as drivers of diversity loss among California's freshwater fishes. Conservation Biology

21:434-446.

Likens, G.E. and F.H. Bormann. 1974. Linkages between terrestrial and aquatic ecosystems. BioScience 24:447-456.

Lytle, D.A. and N.L. Poff. 2004. Adaptation to natural flow regimes. TRENDS in Ecology and Evolution 19(2): 94-100.

McAllister, D.E., A.L. Hamilton, and B. Harvey. 1997. Global freshwater biodiversity: striving for the integrity of freshwater ecosystems. Bulletin of Ocean Voice International 11(3):1-14.

Miranda, L.E. 2005. Fish assemblages in oxbow lakes relative to connectivity with the Mississippi River. Transactions of the American Fisheries Society 134:1480-1489.

Moyle, P.B., and R.A. Leidy. 1992. Loss of biodiversity in aquatic ecosystems: evidence from fish faunas. Pages 127-169 in P. L. Fiedler and S. K. Jain, editors. Conservation biology: the theory and practice of nature conservation, preservation, and management. Clapman and Hall, New York, USA.

Moyle, P.B. and J.J. Cech, Jr. 2003. Fishes: an introduction to ichthyology. Prentice Hall, New Jersey, USA.

Muneepeerakul, R., E. Bertuzzo, H.J. Lynch, W.F. Fagan, A. Rinaldo, and I. Rodriguez-Iturbe. 2008. Neutral metacommunity models predict fish diversity patterns in Mississippi–Missouri basin. Nature 453:220-223.

Osborne, L.L., and M.J. Wiley. 1992. Influence of tributary spatial position on the structure of warmwater fish communities. Canadian Journal of Fisheries and Aquatic Sciences 49:671-681.

Pister, E.P. 1985. Desert pupfishes: reflections on reality, desirability, and conscience. Environmental Biology of Fishes 12:3-11.

Poff, N.L., and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46:1805-1818.

Reid, G.M., T.C. MacBeath, and K. Csatádi. 2013. Global challenges in freshwater-fish conservation related to public aquariums and the aquarium industry. International Zoo Yearbook 47(1): 6-45.

Ricciardi, A., and J.B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220-1222.

Richter, B.D., D.P. Braun, M.A. Mendelson, and L.L. Master. 1997. Threats to imperiled freshwater fauna. Conservation Biology 11:1081-1093.

Ricklefs, R.E. and G.L. Miller. 2000. Ecology. W.H. Freeman and Company, New York, USA.

Shields, F.D., S.S. Knight, N. Morin, and J. Blank. 2003. Response of fishes and aquatic habitats to sand-bed stream restoration using large woody debris. Hydrobiologia 494:251-257.

Silk, N. and K. Circuna, editors. 2004. A practitioner's guide to freshwater biodiversity conservation. The Nature Conservancy, Boulder, Colorado, USA.

Skelton, P.H. 2001. A complete guide to the freshwater fishes of southern Africa. 2nd edition. Struik Publishers, Capetown, South Africa.

Taylor, C.A., M.L. Warren, Jr., J.F. Fitzpatrick, H.H.I. Hobbs, R.F. Jezerinac, W.L. Pflieger, and H.W. Robison. 1996. Conservation status of crayfishes of the United States and Canada. Fisheries 21:25-38.

USGS (United States Geological Survey). 2013. Imperiled freshwater organisms of North America. Available from http://fl.biology.usgs.gov/afs/.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Voshell, J.R. 2002. A guide to common freshwater invertebrates of North America. McDonald and Woodward Publishing Co., Blacksburg, Virginia, USA.

Wang, L., P. Seelbach, and R.M. Hughes. 2006. Introduction to landscape influences on stream habitats and biological assemblages. American Fisheries Society Symposium 48:1-23.

Wetzel, R.G. 2001. Limnology: lake and river ecosystems. 3rd edition. Academic Press, San Diego, California, USA.

Williams, J.D., M.L. Warren, Jr., K.S. Cummings, J.L. Harris, and R.J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18:6-22.

Great Lakes Under Stress: Invasive Species as Agents of Ecosystem Change

Joseph F. Atkinson[1] and Helen M. Domske[2]

[1]Department of Civil, Structural and Environmental Engineering, University at Buffalo, USA, [2]New York Sea Grant, Cornell Cooperative Extension, USA

Abstract

This case study explores invasive species as agents of ecosystem change in the Laurentian Great Lakes of North America, focusing specifically on Lake Erie and Lake Ontario. Following a brief introduction to the Great Lakes ecosystem, the case study describes several key invasive species and the roles they play in disrupting natural ecosystem behavior and function. It then concludes with an overview of control strategies and mitigation efforts. Discussion questions are provided throughout the text, designed to stimulate critical thinking among students; these can either be examined by students independently, or used to guide class discussion.

INTRODUCTION AND BACKGROUND

The Great Lakes Ecosystem

The Laurentian Great Lakes of North America – Lakes Superior, Michigan, Huron, Erie, and Ontario (Figure 1a,b) – together represent nearly 20% of the surface freshwater resources of the Earth (Atkinson 2002). With horizontal scales of hundreds of kilometers and depths up to several hundred meters, the Great Lakes share a number of characteristics associated with coastal regions and inland seas, including influence of the Earth's rotation on circulation patterns, thermal stratification, wind-generated upwelling and downwelling events, the presence of coastal currents, coupling between the benthic and pelagic regions of the lake, cross-margin transport (between near shore and offshore regions), significant interaction with human populations, and both shallow and deep water environments (Boyce et al. 1989). The Great Lakes are not large enough to experience tides, but wind setup can cause significant short-term water level fluctuations and internal seiches (standing waves), which are characterized by a "rocking" or "sloshing" of the lake waters back and forth, and a cyclic variation of water depths. The circulation is primarily driven by local meteorology (wind speed and direction, air temperature, etc.) and influenced by the proximity of the shoreline, bottom bathymetry, and local inflows and outflows (Boyce et al. 1989). The flow field, in turn, controls transport and distribution of nutrients, contaminants, and planktonic organisms, as well as bottom shear stress and corresponding potential for erosion and sediment transport. All of these features comprise the physical components of the lake ecosystem, controlling habitat and other features of ecosystem structure within which the biological system functions. In general, the lake ecosystem should be defined as the lakes themselves, plus the surrounding drainage areas that impact water quality and incorporate a more complete range of human influences; however, in this case study, emphasis is on the aquatic environment. Environmental stressors have impacted all the Great Lakes, but we are focusing on the lower lakes, Lake Erie and Lake Ontario, since they have high human population and the least volume, which makes them the quickest to respond to changes.

The waters of the Great Lakes provide hydroelectric power, irrigation, drinking water, fishing, recreational activities, and other benefits for millions of people who live in the basin. These benefits are called ecosystem services, since they are support human life through the functioning of natural ecosystems. Changes in an ecosystem, through natural or human-based causes, can lead to changes in the services, or benefits, that the ecosystem can provide. Maintenance of ecosystem services is often at the core of the concept of sustainability, and changes in ecosystem structure affect the way in which the ecosystem functions, thus impacting the ability of the ecosystem to continue to provide the same services as had been provided historically.

Although large, the Great Lakes have been subject to

Discussion Question 1:

What is your definition of sustainability, and how do you think it relates to the concept of ecosystem services? List examples of ecosystem services that are provided by an ecosystem near you (here, define "ecosystem" as a local waterway, lake, or pond, or a terrestrial system such as a forest), and give an example of a situation where an ecosystem service has been harmed because of an unsustainable practice.

significant ecosystem changes, many of which are a direct result of human activities. For example, in the 1960s Lake Erie was often described as being "dead" with massive algae blooms, taste and odor problems, hypoxia, fish kills, and other issues (Atkinson 2002). Studies identified phosphorus as the source for over-fertilization (note that "fertilization" here refers to the supply of food for growing algae), and phosphorus abatement programs were put in place (Atkinson 2002). Following these restrictions, Lake Erie and other Great Lakes showed dramatic reductions in algal production and general improvements in water quality (Makarewicz and Bertram 1991; Mills et al. 2003). However, algae blooms have started to reoccur with greater frequency in recent years, particularly in shallower, near shore areas, and differences in water quality between near shore and offshore regions have been growing (Makarewicz 2000; Makarewicz and Howell 2007). These observations are likely related to changes in ecosystem structure and function, and theories proposed to explain these problems involve possible impacts of invasive species.

Various factors may generate stresses on an ecosystem, causing it to change. These factors are called ecosystem stressors , and in the Great Lakes these stressors include invasive species, as well as sewage and industrial discharges, inappropriate land use, habitat changes, water level fluctuations, agricultural and urban storm water runoff, airborne pollutants, "legacy" contaminants in sediments, water withdrawals and diversions, and climate change (Atkinson 2002; Bails et al. 2005). The response of the ecosystem to these stressors is difficult to predict, especially when there are multiple stressors acting in concert, and when there is uncertainty in each of the stressors, themselves. Given these uncertainties and interacting effects, it is difficult to separate the specific impacts of any one stressor, such as invasive species or multiple invasives acting in concert. However, it is clear that invasive species have played a major role in ecosystem change in the Great Lakes. In the following sections we describe some of the invasive species in the Great Lakes and the roles they play in disrupting natural ecosystem behavior and function.

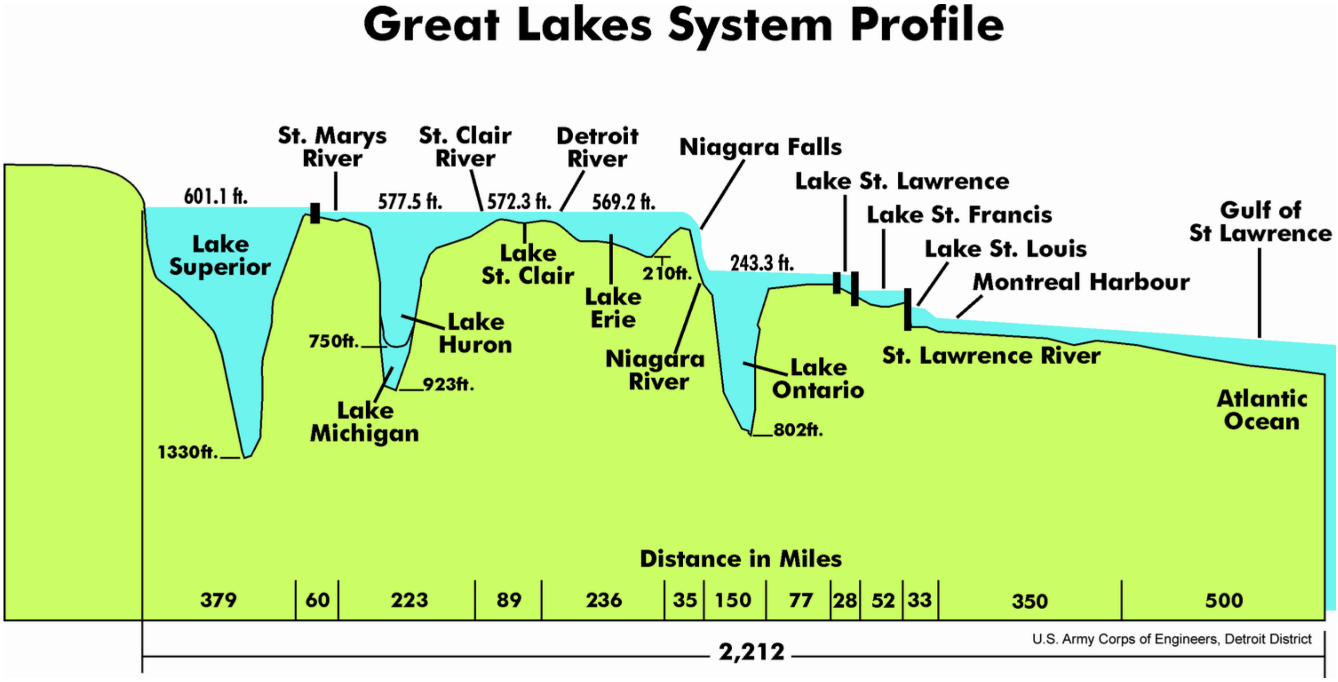


Figure 1a. The Great Lakes System Profile.

U.S. Army Corps of Engineers, Detroit District

Figure 1b. The Great Lakes of North America.

Discussion Question 2:

Given the known causes of ecosystem stressors in the Great Lakes and issues of fertilization, what are some potential strategies for reducing phosphorus input into lake systems? What might be some drawbacks of such strategies?

What Is an Invasive Species?

Habitat destruction, over-fishing, industrial discharges, and toxic chemical releases have been altering the Great Lakes ecosystem for the past 200 years (Bails et al. 2005). In contrast to these (perhaps) more obvious stressors, one of the more important and unusual forms of pollution impacting the Great Lakes is not from industrial sources, municipal sewage, or atmospheric deposition, but in the form of non-native plants and animals. These non-native species are transported by humans and transport can occur over much greater distances and over much shorter time frames than by natural means. The relatively sudden introduction of non-native species in this manner produces a shock to the native ecosystem, which then tries to adjust.

For this Case Study, the term invasive species will be used, with the understanding that the species highlighted are invasive, non-indigenous, and nuisances. Whatever they are called, these species have been transported by human activities – intentionally or unintentionally – into a geographic region outside their native range and are now reproducing and establishing populations throughout the Great Lakes.

More than 180 non-native aquatic species have entered the Great Lakes and many scientists believe that aquatic invasive species are the greatest threat to the Great Lakes ecosystem (Mills et al. 1993; GLANSIS 2012). These species have the ability to spread throughout the ecosystem, limiting food and habitat, and out-competing or even displacing native species, causing them to become extirpated due to competition with invasive species. Some invasive species, such as the sea lamprey and the zebra mussel, have had significant economic impacts, costing billions of dollars in the US (Pimentel et al. 2000).

Invasive species share some or all of a number of biological characteristics (See also the NCEP module, *Invasive Species and Mechanisms of Invasions*), such as:

- High abundance in their native range;
- High fecundity rates (produce many surviving offspring);
- A short generation time (offspring mature to a reproductive age quickly);
- Polyphagous feeding habits (utilize more than one food source);
- An ability to occupy diverse habitats;
- High genetic variability (allowing for "plasticity" in adapting to new environments);
- Proximity to a transmittal vector (exists in a location where it can be acquired and moved).

Origins and Transport Pathways of Invasive Species in the Great Lakes

The Great Lakes have been especially hard-hit by invasive species due to the presence of canals and international ship traffic, which have facilitated the movement of these species into the region. During the early years of European colonization of the Great Lakes Basin, Niagara Falls served as an impenetrable barrier to the dispersal of many non-native species that had been introduced into the Lake Ontario Basin (Mills 1999).

The opening of the St. Lawrence Seaway in 1959 allowed large, ocean-going ships to enter the Great Lakes, carrying millions of gallons of ballast water, which greatly accelerated this process by providing an avenue for introductions of invasive aquatic species from across the globe. Ballast water transfers from such ships have introduced invasive species such as zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostiformis bugensis*), spiny waterfleas (*Bythotrephes cederstroemi*), Eurasian ruffe (*Gymnocephalus cernuus*), and the round goby (*Apollonia melanostoma*) (Mills et al. 1993).

Discussion Question 3:

How have man-made structures helped invasive species enter the Great Lakes? How does the movement of invasive species into the Great Lakes compare to the movement of terrestrial invasive species? What are some differences and similarities?

Some introductions of invasive plants and animals, however, had no links to waterways or shipping. A number of invasive species have entered the Great Lakes through the release of aquarium pets, fish aquaculture operations, bait-bucket releases, and even intentional releases that proved to be environmental mistakes. The common carp (*Cyprinus carpio*) is an example of an intentional release that went awry. Once released to natural environments, these benthic (bottom dwelling) fishes uprooted native aquatic vegetation, caused excessive turbidity, and competed with native fish for food and habitat (Nico et al. 2011). (For another example, see NCEP case study *Story of An Invasion: A Case Study of Rusty Crayfish in the Great Lakes* available online at ncep.amnh.org).

Discussion Question 4:

What are other examples of the intentional spread of invasive species in the Great Lakes or elsewhere? What has been the result? Can you think of any cases in which invasive species have caused a beneficial result?

In other cases, stocking of non-indigenous fish was implemented to control the spread of other invasive species such as alewives and smelt (Mills et al. 2003). While the stocking of Pacific salmonids has successfully reduced the numbers of those non-indigenous forage fishes, such introductions have contributed significantly to the overall artificiality of the modern Great Lakes ecosystem.

ECOSYSTEM IMPACTS

Direct Impact on Native Species; Changes in Biodiversity

The combined effect of invasive species has been to change the food webs in the Great Lakes, altering trophic levels from small plankton to the top predatory fishes. For example, zebra and quagga (dreissenid) mussels are effective filter feeders and have outcompeted other planktivores, thus altering a critical element at the base of the normal food chain in the lakes (Mills et al. 2003). Filtering of particulate matter by invasive mussels also has led to a significant clearing of the water, allowing greater penetration of sunlight and leading to increased growth rates for benthic algae such as *Cladophora* (Mills et al. 2003; DePinto et al. 2006). In turn, the proliferation of benthic algae has led to unsightly and foul smelling deposits washing up on beaches (Figure 2). Aquatic invaders can have a catastrophic impact on the ecosystem by displacing native species, sometimes to the point of local extinction, thereby reducing biological diversity. Several native species of mussels in Lake St. Clair have been extirpated, and in some areas of Lake Erie, dreissenid mussels jeopardize native populations.

Invasive Species of Lakes Erie and Ontario

The following are several of the important invasive species in Lakes Erie and Ontario, the conservation issues they cause, and, where applicable, some of the management methods that have been used to control them (full details can be found at: www.seagrant.sunysb.edu/ais/pdfs/ais-lerieont.pdf):

Zebra mussel (Dreissena polymorpha) and quagga mussel (Dreissena rostiformis bugensis)
Zebra and quagga larvae were introduced into the Great Lakes in freshwater ballast of freighters from the Black and Caspian Seas (O'Neill and MacNeill 1991). The mussels quickly invaded, as they can produce up to 1,000,000 eggs per year, larvae are easily dispersed through the water currents, and larvae form colonies of over 35,000 per square meter. Mussels filter feed, drawing up to two liters of water per day to consume phytoplankton, substantially clearing the water (O'Neill and MacNeill 1991). Despite the clean look of water invaded by mussels, the filter feeder causes loss of important nutrients for fish and other organisms (O'Neill

Figure 2. Cladophora (benthic algae) that has been dislodged from beds farther offshore and washing up on Lake Ontario beach, near Oak Orchard, New York

(a) decaying algae biomass on shore

(b) algae mat washed up near jetty.

and MacNeill 1991). Further, the rapidly reproducing mussels form dense mats and are referred to as "biofoulers," causing hundreds of millions of dollars in damage and maintenance costs for fouled pipes, drinking water treatment, and industrial and power plant intakes.

Discussion Question 5:

What characteristics of zebra and quagga mussels have made them such successful invasive species? What are some of the possible reasons that the control of these species has been so challenging?

Spiny waterflea (Bythotrephes cederstroemi) and fishhook waterflea (Cercopagis pengoi)
The spiny waterflea is a small (5 - 15 mm in length), predatory crustacean with a long, barbed tail spine that serves as protection from predators. The waterflea competes with fishes for zooplankton. Spiny waterfleas entered Lake Ontario in the early 1980s from their native northern Europe via ballast water discharges. They have now spread to all five Great Lakes. Waterfleas reproduce rapidly, up to 10 offspring every two weeks in warmer months. Another similar species, commonly called the fishhook waterflea (*C. pengoi*) has also now invaded the Great Lakes. Both waterfleas form thick masses that are often found on the fishing lines and nets of anglers. The food web impacts of these invaders are still unknown.

Sea lamprey (Petromyzon marinus)
The sea lamprey is a predatory, eel-like fish native to the coastal regions of the Eastern US. The lamprey was first discovered in Lake Ontario in the 1830s and then Lake Erie in 1921, probably invading via the Hudson River and Erie Canal (GLFC 2000). The sea lamprey predates on fish, including economically valuable sport fish, such as trout and salmon, by attaching itself to the side of its prey with a sucking disk. The sea lamprey then consumes its prey by sucking its blood and body fluids (GLFC 2000). Sea lampreys have been blamed for the decline in many Great Lakes fish species, as a single adult lamprey can kill up to 18.14 kilograms of fish in its lifetime of two years (GLFC 2000). To control sea lampreys, the Great Lakes Fishery Commission constructs barriers and uses chemical lampricide treatments in spawning streams, sometimes spending millions of dollars in lampricide treatments (GLFC 1998). In addition, male sterilization and use of pheromone attractants are being tested as potential controlling methods.

Discussion Question 6:

What challenges do the sea lamprey's unique physical adaptations create for Great Lakes Fishery Commission biologists as they attempt to control this aquatic invader?

Alewife (Alosa pseudoharengus)
The origin of alewife in Lake Ontario is unknown, but they were first "discovered" there in 1873 and may, in fact, be native to the Lake. It is also theorized that alewife may have been misidentified as juvenile shad and stocked into the lake accidentally. Alewives are both able to out-compete other Lake fish as well as readily consume their young, including those of lake trout, yellow perch, walleye, and whitefish. In addition, Alewife populations can increase rapidly and, during bouts of cold water, can create massive die-offs that can foul beaches. In Lake Erie and Lake Ontario, alewives have also become the primary food resource for introduced Pacific salmon and lake trout.

Common carp (Cyprinus carpio)
Carp were originally stocked into the Great Lakes region from Asia as a future food source, which has not panned out as hoped. Initially, the fish were kept in farm ponds, but they entered the Great Lakes during floods and quickly spread throughout the US. Carp feed by rooting aquatic plants and disturbing the lakebeds. This feeding behavior can dramatically alter the aquatic environment by causing excessive turbidity, leading to declines in submerged aquatic plants and the many organisms that depend on them. It is also hypothesized that common carp prey on the eggs of other, native, fish species (Nico et al. 2011).

Round goby (Apollonia melanostoma – formerly Neogobius melanostomus)
Originally from the Black and Caspian Seas, round gobies were first discovered in the Great Lakes (St. Clair River) in 1990. These benthic fish have many adaptations that allow them to outcompete native fish and spread throughout the Great Lakes region including: a highly developed sensory system that allows them to

find food and avoid predation as well as feed at night; an aggressive nature; the ability to spawn several times each year; paternal care and guarding of nests reduces predation and increases survival rates. To view the spread of round gobies from their discovery site near Lake St. Clair, see: http://nas.er.usgs.gov/taxgroup/fish/roundgobydistribution.aspx.

Purple loosestrife (Lythrum salicaria)
Purple loosestrife is an emergent aquatic plant native to Eurasia, first introduced into North America in the early 1800s, most likely as both an ornamental plant and medicinal herb, and as a seed in soil. Purple loosestrife was found throughout the northeastern United States and southeastern Canada by the late 1800s in wetlands. Purple loosestrife invades disturbed habitat and forms dense stands in which few other plant species can survive. This loss of native vegetation is followed by a loss in native wetland wildlife, as loosestrife provides little nutritional value and can reduce the productivity of shallow waters utilized as spawning habitat by native fish. Hand pulling, treatment with broad-spectrum herbicides, and flooding can control small, newly introduced patches of purple loosestrife; however, these methods are generally ineffective, too costly, or physically difficult to be used against well-established stands. Biological control (explained in further detail in the Control Strategies and Mitigation Efforts section) has proven to be somewhat effective and five species of insects have been approved for control of purple loosestrife, including a root-mining weevil, two leaf-eating beetles, a flower-feeding weevil, and a seed-feeding weevil.

Water chestnut (Trapa natans)
Water chestnut was first introduced to North America as an ornamental plant as well as for the food and medicinal value of its fruit. The first Great Lakes basin introduction of water chestnut was in Collins Lake in New York around 1884; since then, the plant has spread in waterways throughout the Northeast and has been found along the south shore of Lake Ontario since the 1960s. Water chestnut grows in lakes, ponds, and in slow moving streams and rivers, preferring shallow, calm, nutrient-rich waters with soft, muddy bottoms. The plant's cord-like stems can reach up to ~4.88 meters and, if uncontrolled, can develop dense mats across wide areas, creating a hazard for boaters. Dense mats of water chestnuts create a floating canopy that shades out native plants. Water chestnut also out-competes native vegetation and is of little nutritional value to wildlife.

Eurasian watermilfoil (Myriophyllum spicatum L.)
Eurasian watermilfoil, native to Europe and Asia, is believed to have been brought into the United States intentionally as an ornamental plant in the early 1900s and can now be found in 45 states and three Canadian provinces. Watermilfoil favors disturbed habitat and forms colonies that rapidly spread in by stem-like branches via water currents, recreational boating, and intentional harvesting. Watermilfoil is not a food source for waterfowl and its dense colonies shade out native vegetation as well as reduce the abundance and diversity of invertebrates. While Eurasian watermilfoil cannot be completely eradicated, the spread can be stemmed by removing all fragments of the plant from boats and ensuring fragments do not reenter any body of water. Other control measures have included bottom barriers, suction harvesting, and raking the lake bottom to remove roots, stems, and fragments.

The Role of Invasive Species in Broader Ecosystem Changes

In the previous section a number of invasive species in the Great Lakes are described, along with the direct impacts they have on the native ecosystem, as well as broader changes in food web structure. As previously described, broader ecosystem changes may occur as a result of the combined impacts (with possible multiplicative effects) of invasive species and other components of the ecosystem. Here we describe several examples of such ecosystem impacts.

Botulism outbreaks and the link to invasive species
Since 1999, botulism has caused large die-offs of fish and waterfowl in Lake Erie, Lake Ontario, and Lake Michigan. Botulism is a disease caused by the bacterium *Clostridium botulinum*, and has been a major cause of mortality in migratory birds since the 1900s. Botulism spores are naturally found in anaerobic habitats, can remain in the ecosystem for extended periods of time, and under the right conditions, can produce a powerful neurotoxin (Leighton 2000).

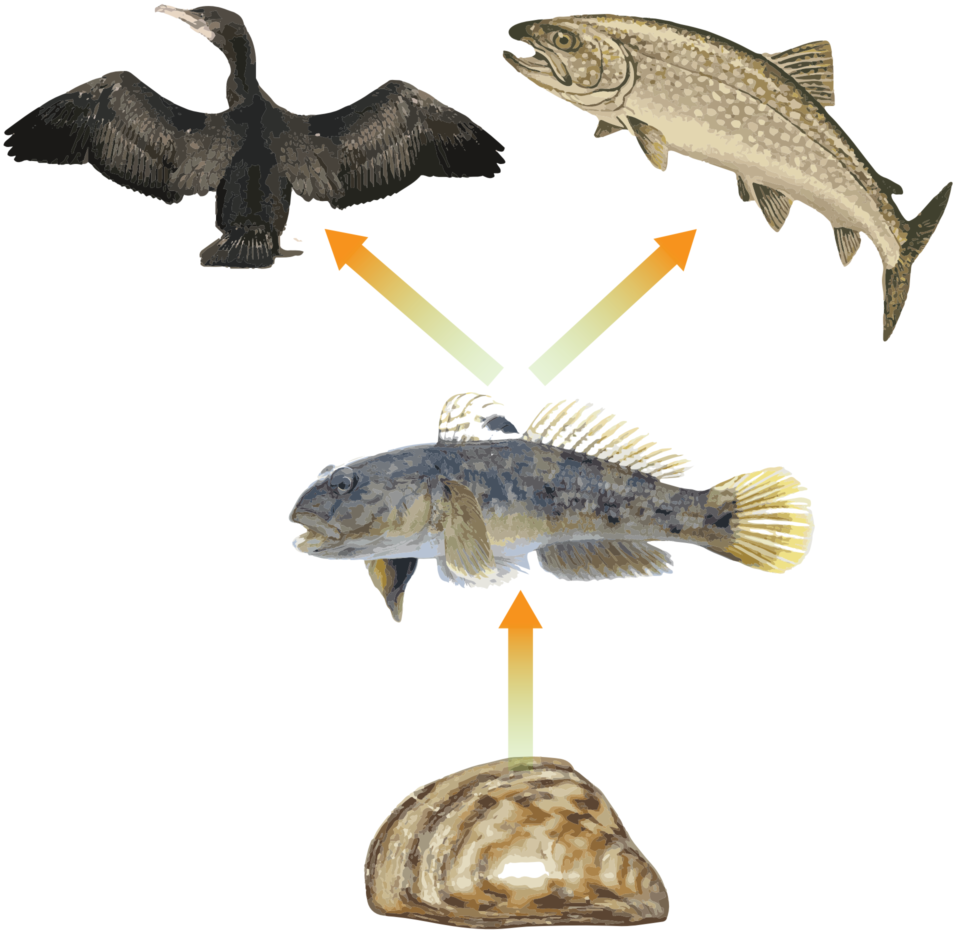
There is speculation that recent botulism outbreaks in the Great Lakes have a connection to abundances of zebra and quagga mussels and the round goby (Leighton 2000), as the mussels disturb the sediment where *Clostridium botulinum* can be found. The mussels also release pseudofeces that, when decaying, creates anoxic conditions that favor anaerobic *Clostridium* bacteria. Diet studies have shown that large round gobies feed primarily on the mussels and sure enough, botulism has been found in round gobies. Thus, these invasive species are collectively increasing the prevalence of botulism and moving the toxin up the food web, as fishes or waterfowl consume the infected round gobies (Figure 3).

Further information on botulism may be found at www.seagrant.sunysb.edu/botulism/article.asp?ArticleID=139 and www.miseagrant.umich.edu/downloads/habitat/botulism-FAQ-030107.pdf

Discussion Question 7:

What combination of ecosystem stressors has (most likely) led to the botulism problem in the Great Lakes?

Figure 3. Transfer of C. botulinum bacteria through the food chain: dreissenid mussels filter water in anaerobic benthic areas at the sediment bed where bacteria grow, round gobies eat the mussels and are in turn eaten by predator fish (lake trout is pictured here) or water fowl (cormorant is pictured here). Illustration by Nadav Gazit.



Round Goby image By Peter van der Sluijs (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Cormorant Image by Walter Baxter. This work is licensed under the Creative Commons Attribution-Share Alike 2.0 Generic License.

Phosphorus distributions and nearshore/offshore water quality differences

In the 1970s research determined that phosphorus was the primary limiting nutrient for algae growth (Atkinson 2002). Since then, multiple billions of dollars have been spent on phosphorus abatement programs to clean up the Great Lakes (GLWQA 1978; DePinto et al. 1986; Makarewicz and Bertram 1991). On a volume-weighted average basis, the lake concentrations are either at or are approaching the long-term phosphorus targets determined by mathematical models of eutrophication in the lakes. Results of those early models were used to determine the amount of phosphorus that could be accommodated in a sustainable manner. However, many near shore areas, where the public most often interacts with the lakes, are experiencing a return to eutrophic conditions along with significant deterioration of water quality. At the same time, offshore ecological productivity is below the level expected based on nutrient loadings (DePinto et al. 2006). Recent changes in the ecology and land use patterns along the coastal zones of these lakes, particularly with respect to agricultural practices, appear to be causing the reappearance of eutrophic conditions similar to those existing prior to the phosphorus reductions. Managers, resource beneficiaries, and other stakeholders are becoming increasingly frustrated in their efforts to understand the deteriorating coastal environment. Better controls on tributary, municipal and industrial outfalls, and non-point sources related to agricultural activity were a primary element in reversing the overall decline in Great Lakes water quality, so why is the nearshore experiencing this relatively new problem with water quality?

<u>Discussion Question 8</u>:

Why is eutrophication an undesirable condition in a waterway?

<u>Discussion Question 9</u>:

For eutrophication problems in the Great Lakes (and elsewhere), why is there a major focus on phosphorus? What are some of the factors that should be considered in developing phosphorus loading goals?

One of the possible explanations for these observations has been suggested in terms of a near shore "biological filter", also known as the "near shore shunt" hypothesis, whereby nutrients are filtered out and sequestered in the near shore region, reducing their transport into deeper waters (Hecky et al. 2004). This process has been observed in lakes around the world, is apparently exacerbated by invasive mussel species, and has recently been hypothesized as the cause of near shore/offshore water quality differences observed in the Great Lakes (Hecky et al. 2004; Depew et al. 2006; Makarewicz and Howell 2007). The "filter" effect is especially relevant to phosphorus, since much of the total phosphorus input to the lake is in particulate form, originates from land adjoining the near shore, and is more susceptible to being retained in the near shore by dreissenid mussels. The reduction of phosphorus transport offshore could thus be a result of the removal and retention of material in the Dreissena and Cladophora beds. Therefore, the combination of changed land use patterns, proliferation of non-native mussels, and possible changes in water temperatures due to climate change (leading to increased growth rates) is a likely explanation for near shore water quality problems.

The mathematical models initially used to establish phosphorus goals were based on an abstraction of the physical system in the form of a set of mathematical statements developed to represent the main system processes of interest. In this case the main concept is that of mass balance. In other words, we can formulate a statement for a particular system, or control volume , that equates the rate of change of mass of a particular material of interest (like phosphorus) to the rate at which that material is transported into the volume, minus the rate at which it is transported out of the volume, plus or minus the rates of mass production or decay due to

<u>Discussion Question 10</u>:

Test your ability to formulate a simple mass balance statement, using mass of water as an example. If a hose is used to fill a bucket, but the bucket has a hole in the bottom, how would you express a statement based on water mass balance that would describe the amount of water in the bucket?

any internal sources or sinks of that material. In other words, the mass does not have to remain constant, but any transport or transformations must be accounted for explicitly. Mathematical modeling is explained in greater detail in the Modeling Supplement for this Case Study and in the NCEP module *Mathematical Modeling and Conservation* (ncep.amnh.org).

Anoxic zones

One further example of the impact of invasive species on an established ecosystem may be associated with the recurrence of anoxic regions in the hypolimnion of the central basin of Lake Erie (Figure 4) (Conroy et al. 2005). The hypolimnion is the region near the bottom, below the summer thermocline as shown in Figure 5, which is a schematic of the general thermal structure of the lake in summer. Lakes with this sort of vertical temperature distribution are called stratified. The upper layer, or epilimnion, is usually relatively well-mixed due to wind action, is warmer because of greater solar radiation intensity and absorption near the surface, and has greater levels of dissolved oxygen because of its contact with the air. The hypolimnion is cooler and less well-mixed. The thermocline is in a region called the metalimnion, which separates the epilimnion and hypolimnion, and is characterized by steep temperature gradients (leading to strong density variations) that inhibit mixing and transport of materials such as heat and dissolved oxygen between the upper and lower layers. The thermocline is usually defined as the location where the temperature gradient (where "gradient" means rate of change of temperature with changes in depth) is the largest.

Figure 4. Central basin of Lake Erie. Image source: NOAA

Discussion Question 11:

What is the relationship between temperature and density in freshwater? What is the significance of the fact that ice is lighter than water at temperatures near freezing?

Due to the reduced transport rates across the thermocline, the dissolved oxygen in the hypolimnion is often reduced, relative to the epilimnion, since various biological processes (respiration, decomposition) deplete oxygen. In addition, the supply is limited because the only appreciable source of oxygen is the atmosphere, and oxygen cannot be moved downward because of the density increase through the metalimnion. Although this condition does not directly depend on invasive species, it is believed that invasive mussels exacerbate the problem because (i) by clearing the water, more sunlight can reach the bottom and cause algae growth and decomposition (any photosynthetic production of oxygen is overshadowed by respiration

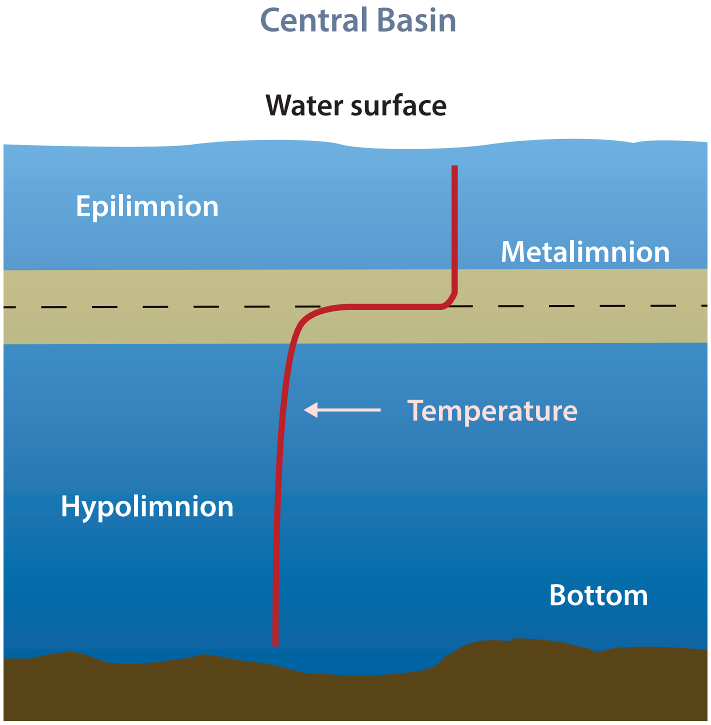


Figure 5. General thermal structure of a stratified lake in summer; the maximum rate of change of temperature (i.e., the maximum gradient) in the metalimnion is called the thermocline. Illustration by Nadav Gazit.

and decomposition); and (ii) they create additional organic material for decomposition through excretion of pseudofeces, and partially undigested material from their filter feeding may drift into the central basin from mussel beds located elsewhere in the lake. Further discussion of the oxygen dynamics in Lake Erie is provided by Edwards et al. (2005).

CONTROL STRATEGIES AND MITIGATION EFFORTS

Control and Mitigation

Preventing the introduction of invasive species into the ecosystem is always better than trying to control species once they have become established. Once non-native plants and animals have been introduced into the wild, it is often difficult and expensive to control them. Control strategies include biological, chemical, and mechanical methods – several examples of these methods are discussed in the “Invasive Species of Lakes Erie and Ontario” section.

Biological control involves the purposeful release of a predator, parasite, or pathogen that can be used to control the invasive plant or animal. An example of biological control in the Great Lakes is the use of *Galerucella* beetles for the control of purple loosestrife. These leaf-eating beetles have been successfully used by managers in selected regions of the Great Lakes to reduce stands of purple loosestrife (Wilson et al. 2009). Often, however, the use of biological controls means introducing yet another non-native species, so this approach must be taken with extreme care.

Chemical control involves the use of herbicides or pesticides to control invasive species and is routinely used for the control of terrestrial plants. There is concern about the addition of noxious chemicals to aquatic ecosystems, so this method of control is seldom used in a lake environment. However, chlorination has been extensively used in water treatment and industrial settings to control zebra and quagga mussels and to prevent their fouling of pipes (O’Neill and MacNeill 1991).

Mechanical control involves the physical removal of invasive species. These controls include hand-pulling, cutting, or the use of machinery such as harvesters. Although mechanical control can be effective, it is often expensive due to the high cost of special machinery or the labor costs involved. In addition, this approach is usually a temporary solution, since the invasive is rarely completely eliminated. In certain areas of the Great Lakes, floating mechanical harvesters are used to control Eurasian watermilfoil on a continuing basis.

Public Efforts and Stewardship

Stakeholders need to become aware of this biological pollution and join in efforts to limit the introduction and spread of invasive organisms. Education and outreach are important elements, especially since many “invasions” occur accidentally, when the people involved do not know they may be contributing to the spread of a non-native species. In addition, research, monitoring, and management must be utilized in the battle to stop the spread and mitigate the impacts of invasive non-indigenous species on our environment.

Once informed of the ecosystem damage caused by aquatic invasive species, most stakeholders will eagerly take steps to reduce their spread. Informed anglers, boaters, and scuba divers realize that their actions are helping to protect the environment they depend on for their recreational pursuit or livelihood. The Great Lakes Sea Grant Network has a listing of resources that stakeholders can use to learn more about aquatic invasive species and what they can do to mitigate the damage from the spread of these invaders.

Spreading information, rather than spreading invasive species, has become a goal of many agencies and organizations around the Great Lakes. Many boat launches and marinas now have signs warning boaters and personal watercraft operators about the threat of aquatic invasive species and steps that they can take to prevent the movement of these unwanted invaders. Sea Grant programs and state agencies have created flyers and factsheets that are distributed at bait shops, park offices, and marinas to help inform boaters and anglers what they can do to reduce the spread of aquatic invasive species.

Many successful stewardship projects have been developed by the Great Lakes Sea Grant Network, including AIS HACCP (Hazard Analysis and Critical Control Point) and Nab the Aquatic Invader. The AIS HACCP program focuses on the spread of invasive species through aquaculture, hatchery, scientific, natural resource, and baitfish harvesting activities. The program is a self-inspection effort based on plans that are created, followed and periodically evaluated for effectiveness.

Discussion Question 12:

How might mitigation efforts for dealing with invasive species in the Great Lakes, or other aquatic ecosystems, be similar or different to efforts made for terrestrial invasive species?

On-Going Issues

Perhaps the most well known on-going issue with respect to invasive species is that of ballast water exchanges. It is hoped that governmental agencies in the United States and Canada will continue their efforts to prevent new invasive aquatic species from entering the Great Lakes. Ballast water management efforts (mainly exchange of freshwater ballast for saltwater ballast 200 miles offshore prior to entry into the St. Lawrence River) are already underway, but have not yet proven to be totally effective at keeping out new invaders. New technologies for ballast water management are being researched and tested. Many Great Lakes states are also exploring legislative means to reduce the introduction of invasive species through ballast water release. The Northeast-Midwest Institute has initiated the Great Ships Initiative to control ship-mediated introductions of invasive species in the Great Lakes.

A number of states around the Great Lakes have decided to take matters into their own hands by developing legislation focusing on stricter ballast water regulations and control. The legislation is in its early stages and the powerful shipping industry may challenge these legislative efforts due to added costs and regulations, but it is a positive step. It seems that Great Lakes legislators realize the additional costs for industries (water and hydroelectricity) and the ecosystem damages are good reasons to make these ballast water regulations a part of the law. The next few years should bring about some interesting changes in the way ballast water is treated and or discharged in the Great Lakes.

The other current issue related to aquatic invasive species in the Great Lakes is concern over the introduction of Asian carp. Both the bighead carp (*Hypophthalmichthys nobilis*) and the jumping silver carp (*Hypophthalmichthys molitrix*) were originally imported by fish farmers in the southern United States to reduce algae growth in their fish ponds. Unfortunately, as a result of flooding near the Mississippi River these fish escaped the ponds and eventually made their way into the environment. Both species have continued to move northward towards the Great Lakes. An electric barrier that was originally designed to keep the round goby from leaving the Great Lakes and heading down the Mississippi River, was seen as a way to stop the fish from entering the Great Lakes. Due to concern over the possible impacts of these plankton-eating fish on the food web of the Great Lakes, the electric barrier system was enlarged and improved.

Recently, E-DNA (environmental DNA) from Asian carp was discovered in Lake Michigan, creating much concern from scientists and stakeholders alike. Although the impact of such plankton-hungry fish on the environment of the Great Lakes is unknown, managers and researchers agree that it is essential to keep reproductive numbers of these fish out of Lake Michigan and the rest of the watershed.

How Can You Help Stop the Spread of Invasive Species?

People who fish, own boats, or have backyard water gardens or aquariums, can either help spread aquatic invasive species or take steps to reduce the spread of these plants and animals by their actions. Although many of the aquatic invasive species in the Great Lakes originally entered through the ballast water of ships, individuals have contributed to the spread of some of these invasive species from one area of the basin to another.

There are recorded cases of "bearded" boats, or boats on trailers full of aquatic plants being moved from one area of the Great Lakes to another. Not only could the aquatic plants prove to be invasive, but other invasive species like zebra or quagga mussels could be attached to the plants and these aquatic hitchhikers could begin an invasion in a new area. The live wells or bait buckets on trailer-pulled boats could also hold the microscopic larvae (veligers) of mussels, helping to spread these unwanted invaders to a new location.

It is believed that the 2007 introduction of the quagga mussel into Lake Mead came from a pleasure boat that was moved from the Great Lakes. Since that time, the mussels have been spreading quickly throughout connected waterways, even proving a threat to Hoover Dam and the water supply systems for Las Vegas, Nevada.

Discussion Question 13:

Knowing the ways that invasive species have been, and continue to be introduced to the Great Lakes, what are some precautions that boat owners, or recreational users of the Lakes can take to reduce the spread of these species? What might be the pros and cons of each strategy?

CONCLUSION

The Great Lakes face a challenging future. Issues associated with habitat destruction and global climate change will create challenges to the ecosystem, but the 180 aquatic invasive species that have entered the Great Lakes will continue to cause ecosystem changes that will have a dramatic impact on the basin for years to come. As described above, these impacts can go beyond local effects on habitat or direct competition with native species, and have resulted in ecosystem-wide consequences. It is likely that new invaders will appear in the future, and although the specific impact of a new invader is impossible to predict, it may be concluded that ecosystem changes will result. In addition, many of the impacts of invasive species have very significant economic as well as ecological ramifications.

It is important to educate stakeholders about the impact of invasive species and the changes that aquatic invasive species have created in the Great Lakes. Although individuals often feel that their actions have little impact, this is one situation in which individuals play an important role. Will it be a home aquarist who releases the next aquatic invasive plant or animal into the Great Lakes? Or, will an angler fishing in Lake Erie unknowingly dump the contents of a bait bucket into Lake Huron as he moves his boat into Lake Huron during his vacation? These actions may seem insignificant, but the potential harm of aquatic invasive species is dramatic. To illustrate the impact of aquatic invasive species, scientists have coined the term "benthification" to refer to changes that have occurred in Lake Erie and other of the Great Lakes. The actions of zebra and quagga mussels have changed the food web in Lake Erie from a system that was driven by interactions in the open water to a system that is driven by benthic (bottom surface) interactions. This is an extreme example of the type of ecosystem change that can be brought about by invasive species. When an entire lake ecosystem is changed by an invader, it is time for scientists, citizens and legislators to realize that the probable impact of aquatic invasive species can be dramatic.

GLOSSARY

Anaerobic (habitat): Areas where there is no oxygen
Anoxia: Condition where the dissolved oxygen of the water drops to zero
Bathymetry: The distribution of water depth (or bottom elevation) below the water surface
Benthic (region of the lake): Relating to the near-bottom environment
Control volume: A volume, or system, with well-defined boundaries over which fluxes of mass or other properties can be characterized
Cross-margin transport: Movement of water and other materials in the water between nearshore and offshore regions of the lake
Detritus: Organic "litter," usually found at the bottom in or on sediments
Downwelling: A physical phenomenon caused by wind, where surface (warmer) water is "piled up" at one end of the lake and lower (colder) water is pushed downward
Ecosystem services: Benefits for human life that are derived from the basic functions of natural ecosystems
Ecosystem Stressor: A physical, chemical or biological process that causes a significant response on the (lake) ecosystem in some way; "stressor" is often used to indicate a process that disrupts the normal ecosystem functioning, and may affect the long-term sustainability of a particular ecosystem
Epilimnion: Upper layer of water in a lake, bounded by the thermocline below; this layer is generally well mixed (it is often

called the upper mixed layer) and warmer than the water below the thermocline

Eutrophication: A process that results when a water body receives an excessive amount of nutrients, usually phosphorus and/or nitrogen, that result in over-fertilization and productivity (growth) of plant species such as algae

Extirpated: Extinct in a given area

Fecundity: Ability to reproduce

Gradient: Rate of change of a quantity, or variable, such as temperature; while usually a gradient refers to a change over a spatial dimension (such as depth), it also can refer to a rate of change with time

Hypolimnion: Region of lake water below the thermocline; generally this water is colder and often has less dissolved oxygen than the overlying water

Hypoxia: A state in which the dissolved oxygen in the water column is reduced to such a level that it may adversely impact organisms that depend on oxygen to live

Legacy (contaminants): Contaminants previously deposited in sediments, usually by industry

Mass balance: A conceptual or mathematical statement that expresses the fundamental concept that mass is neither created nor destroyed; this is the basic starting point for building many water quality models, which are related to a particular system, or control volume of interest

Non-point source pollution: Air and water pollution from non-specific, diffuse sources.

Pelagic (region of the lake): Relating to open (deep) water areas

Salmonids: Top predator fish species (also valuable sport fish) such as trout and salmon

Shear stress: A frictional force acting along the direction of flow; a determining factor in calculating whether sediment will be eroded or not

Stratification (or stratified lake): A condition where the density changes with vertical position, with less dense (generally warmer) water closer to the surface, and more dense (generally cooler) water near the bottom – see Figure 5

Sustainability: The potential for long-term maintenance, in this case for ecosystem services.

Thermocline: Region of strong temperature variation with depth, generally forms in summer and separates the upper mixed layer of a lake (the epilimnion) from the lower, hypolimnion water – see Figure 7

Transmittal vector: Process by which an organism (invasive species) may be moved from one location to another

Turbidity: Cloudiness or "mudiness" in the water caused by suspended silt and other solids

Upwelling: A physical phenomenon caused by wind, where lower (colder) water is pushed upwards at one end of the lake

Veligers: Larval stage for zebra and quagga mussels

REFERENCES

Atkinson, J.F. 2002. Water resources issues of the Laurentian Great Lakes. In H. Rubin, P. Nachtnebel, J. Furst, and U. Shamir, editors. Water resources quality. Springer, Berlin, Germany.

Bails, J., A. Beeton, J. Bulkley, Jonathan, M. DePhillip, J. Gannon, M. Murray, H. Regier, and D. Scavia. 2005. Prescription for Great Lakes ecosystem protection and restoration: avoiding the tipping point of irreversible changes. Michigan Sea Grant, Ann Arbor, Michigan. (Nov. 2005).

Boyce, F.M., M.A. Donelan, P.F. Hamblin, C.R. Murthy, and T.J. Simons. 1989. Thermal structure and circulation in the Great Lakes. Atmosphere-Oceans 27(4):607-642.

Creed, R.P. The weevil-watermilfoil interaction at different spatial scales: what we know and what we need to know. Journal of Aquatic Plant Management 38:78-81.

Creed, R.P., Jr. 1998. A biogeographic perspective on Eurasian watermilfoil declines: Additional evidence for the role of herbivorous weevils in promoting declines? Journal of Aquatic Plant Management 36:16-22.

Creed, R.P. and S.P. Sheldon. 1994. Aquatic weevils (*Coleoptera, Curculionidae*) associated with northern watermilfoil (*Myriophyllum sibiricum*) in Alberta, Canada. Entomological News 105:98-102.

Crowder, L.B. 1984. Character displacement and habitat shift in a native cisco in southeastern Lake Michigan: evidence for competition? Copeia 1984(4):878-883.

Crowder, L.B., and F.P. Binkowski. 1983. Foraging behaviors and the interactions of alewife, *Alosa pseudoharengus*, and bloater, *Coregonus hoyi*. Environmental Biology of Fishes 8:105-113.

Depew, D.C., S.J. Guildford, and R.E.H. Smith. 2006. Nearshore–offshore comparison of chlorophyll a and phytoplankton production in the dreissenid-colonized eastern basin of Lake Erie. Canadian Journal of Fisheries and Aquatic Science 63(5):1115-1129.

DePinto, J.V., T.C. Young, and L.M. McIlroy. 1986. Impact of phosphorus control measures on water quality of the Great Lakes. Environmental Science & Technology 20(8):752 759.

DePinto, J.V. (U.S. co-chair), D. Lam (Canadian co-chair), M. Auer, N. Burns, S. Chapra, M. Charlton, D. Dolan, R. Kreis, T. Howell, and D. Scavia. 2006. Examination of the status of the goals of Annex 3 of the Great Lakes Water Quality Agreement. Report of the Annex 3 model review sub-group to the GLWQA Review Working Group D - Nutrients.

DePinto, J.V. and T.J. Stewart. 2006. Modeling the Lake Ontario ecosystem: next steps. White paper prepared for Lake Ontario Biological Monitoring Workshop, Kingston, Ontario (October 2006).

Edwards, W.J., J.D. Conroy, and D.A. Culver. 2005. Hypolimnetic oxygen depletion dynamics in the central basin of Lake Erie. Journal of Great Lakes Research 31 supplement 2:262-271.

Great Lakes Fishery Commission. 2000. Sea lamprey: a Great Lakes invader. GLFC Factsheet, Ann Arbor, Michigan, USA.

GLWQA [Great Lakes Water Quality Agreement]. 1978. Available at: http://www.epa.gov/glnpo/glwqa/.

Hecky, R.E., R.E.H. Smith, D.R. Barton, S.A. Guildford, W.D. Taylor, T.D. Howell, and M.N. Charlton. 2004. The nearshore shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Canadian Journal of Fisheries and Aquatic Science 61:1285-1293.

Jude, D.J. 2001. Round and tubenose gobies: 10 years with the latest Great LakespPhantom menace. Dreissena!: the digest of the national aquatic nuisance species clearinghouse. New York Sea Grant, Brockport, NY, USA.

Makarewicz, J.C. 2000. New York's north coast: a troubled coastline. Lake Ontario Embayment Initiative. Finger-Lakes-Lake Ontario Watershed Protection Alliance.

Makarewicz, J.C. and P. Bertram. 1991. Restoration of the Lake Erie ecosystem. Bioscience 41:216-223.

Makarewicz, J.C. and T. Howell. 2007. White paper, Lake Ontario Intensive Year – 2008: The Lake Ontario coastal zone - status and assessment. LOLA Workshop, International Joint Commission. Kingston, Ontario, Canada.

Mills, E.L., J.H. Leach, J.T. Carlton, and C.L. Secor. 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. Journal of Great Lakes Research 19(1):1-54.

Mills, E.L., J.R. Chrisman, B. Baldwin, R.W. Owens, R. O'Gorman, T. Howell, E.F. Roseman, and M.K. Raths. 1999. Changes in the Dreissenid community in the lower Great Lakes with emphasis on southern Lake Ontario. Journal of Great Lakes Research 25(1):187-197.

Mills, E.L., J.M. Casselman, R. Dermott, G. Fitzsimmons, G. Gal., K.T. Holeck, J.A. Hoyle, O.E. Jonannsson, B.F. Lantry, J.C. Makarewicz, E.S. Millard, I.F. Munawar, M. Munawar, R. O'Gorman, R.W. Owens, L.G. Rudstam, T. Schaner, and T.J. Stewart. 2003. Lake Ontario: food web dynamics in a changing ecosystem. Canadian Journal of Fisheries and Aquatic Science 60:471-490.

Nico, L., E. Maynard, P.J. Schofield, and M. Cannister. 2011. Cyprinus carpio. USGS Nonindigenous Aquatic Species Database, Gainesville, Florida, USA. Available from: http://nas.er.usgs.gov/queries/factsheet.aspx?speciesID=4 (Revision date: September 14, 2011).

Newman, R.M., and L.M. Maher. 1995. New records and distribution of aquatic insect herbivores of watermilfoils (*Haloragaceae: Myriophyllum spp.*) in Minnesota. Entomological News 106:6-12.

O'Neill, C.R. and D.B. MacNeill. 1991. The zebra mussel (Dreissena polymorpha) an unwelcome North American invader. New York Sea Grant, Coastal Resources Factsheet, Brockport, NY, USA.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. BioScience 50(1):53-65.

Thompson, D.Q., R.L. Stuckey, and E.B. Thompson. 1987. Spread, impact, and control of purple loosestrife (*Lythrum salicaria*) in North American wetlands. US Fish and Wildlife Service, Jamestown, North Dakota, USA.

Vermont Agency of Natural Resources. 1998. Water chestnut: water-nut family (*Trapaceae*). Vermont Invasive Exotic Plant Factsheet, Waterbury, Vermont, USA.

Transboundary Water Resources Management and the Potential for Integrated Water Resources Management (IWRM): Rhine River, Mekong River, and Zambezi River Case Studies

Jonathan W. Bulkley[1] and Christine J. Kirchhoff[2]

[1]School of Natural Resources and Environment, University of Michigan, USA; [2]School of Engineering, University of Connecticut, USA

Abstract

Integrated Water Resources Management (IWRM) is an evolving concept used to address the difficult issues associated with making efficient and effective use of the world's limited freshwater resources. IWRM differs by country due to geography, culture, and stage of development, but generally involves the management of all water resources taking into account other natural resource management, as well as social, economic, environmental and technical issues. A significant issue in water management is the need for cooperation among nations sharing transboundary waters that may have different usage requirements. We look at the history, progress, and challenges in implementing IWRM in the management of transboundary water resources in three case studies: the Rhine River (Europe), the Mekong River (Southeast Asia), and the Zambezi River (Southern Africa).

Learning Objectives

1. Understand Integrated Water Resource Management (IWRM) and its potential to facilitate the planning and management of transboundary water resources
2. Describe the current history and progress of implementing IWRM in three contrasting case studies
3. Identify the principal challenges related to IWRM, and strategies for mitigating those challenges, across the case studies

"The Provision of adequate fresh-water resources for people and ecosystems will be one of **the most critical and potentially contentious issues facing society and governments at all levels during the 21st century**" (AMS 2008).

INTRODUCING INTEGRATED WATER RESOURCES MANAGEMENT (IWRM)

Integrated Water Resources Management (IWRM) is evolving as a means to address the complex and critical issues associated with making the most effective and efficient use of water resources throughout the world. The concept of IWRM contrasts the traditional, fragmented approach to water resource management, where the water resources of an area are developed and implemented without full consideration of water demand as well as water supply. Full consideration of water as a resource requires integration between and among both the natural supply system as well the human user system (Adeyemo 2003). The concept of IWRM came from the Dublin Principles articulated in 1991, in anticipation of the 1992 United Nations Environment and Sustainability Conference in Rio, Brazil. The Dublin Principles are as follows:

1. Fresh water is a finite and valuable resource essential to sustain life, development, and the environment.
2. Water development and management should be based upon a participatory approach involving users, planners, and policy-makers at all levels.
3. Women play a central part in the provision, management, and safeguarding of water.
4. Water has an economic value in all of its competing uses and should be recognized as an economic good.

In 1992, the United Nations Rio Conference introduced IWRM as an agenda item. Subsequently, IWRM has evolved in different ways in different countries as a function of geography, culture, and stage of development (UN-Water 2008). As a consequence

of this evolution, there are several working definitions that have been developed to communicate the essence of IWRM and its concepts. Representative examples of definitions include the following (Davis 2007):

1. The World Bank: *A perspective that ensures that social, economic, environmental, and technical dimensions are taken into account in the management and development of water resources.*
2. The World Conservation Union (IUCN)*: [Several definitions exist] The integrated management of all water resources (i.e. surface water, ground water, marine waters, etc.) The integration of water with the management of other natural resources such as soil and native vegetation, including related management issues such as alien invasive species.*
3. Global Water Partnership (GWP)*: A process that promotes the coordinated development and management of water, land, and related resources to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.*

These three examples of IWRM represent global IWRM definitions and approaches. In 2002, the Johannesburg Summit on Sustainable Development incorporated water as one of the Summit's ten focal areas. The Framework for Action produced by the Summit established the two most important goals: (1) halve the number of people with no access to safe drinking water and improved sanitation by 2015; and (2) develop integrated water resource management and efficiency plans by 2005 (Varis et al. 2008).

In the United States, IWRM is perhaps less well known. Two examples of IWRM or IWRM-like definitions are (Davis 2007):

1. U.S. Environmental Protection Agency (US EPA): *A flexible framework for managing water resource quality and quantity within specified drainage areas or watersheds and includes stakeholder involvement and management actions supported by sound science and appropriate technology.*
2. U.S. Army Corps of Engineers (USACE): *The coordination of activities in pursuit of a set of common goals for water resources development and maintenance.*

The working definitions of IWRM cited above reflect the theory and concepts of IWRM as practiced both globally and in the United States. As touched on above, there is more active utilization of the IWRM approaches and concepts outside of the United States. Several factors contribute to this situation. For instance, two large U.S. federal government units have had responsibility for one or more aspects of water resource development for many years. The civilian section of the U.S. Army Corps of Engineers has been responsible for navigation and flood control of the nation's rivers since the 19th century, while the U.S. Bureau of Reclamation in the Department of Interior has held responsibility for the provision of water in the western region of the country (i.e., west of the 100th meridian) since early in the 20th century.

A number of organizations have been established to promote adoption of IWRM practices and approaches. One example is the Global Water Partnership (GWP), founded in 1996 by the Swedish International Development Agency (SIDA), the World Bank, and the United Nations Development Program (UNDP) to promote IWRM and to address the critical issues of sustainable water management (GWP 2009). The GWP's mission is to support countries in the sustainable management and development of their water resources through the implementation of IWRM (GWP 2009). To help share knowledge, the GWP has also developed a number of tools and resources, including an IWRM Toolbox (www.gwptoolbox.org/), designed to provide valuable insights and helpful information to professionals working in the IWRM Framework.

Transboundary Waters

In developed countries, many of us take water for granted. When we need it for personal use in our homes or places of work, it is provided. We may not know where our water comes from or where it goes after our use, or its potential use by other individuals downstream from our location. However, it is of critical importance to recognize four basic aspects of all water resources

that represent challenges. The first is the importance of the resource: water is an essential sustaining resource for life. Second, water is scarce. Water as a resource is not distributed equally across the landmasses of our world; in certain large regions, available water is scarce in relation to the water demands of the region. It follows that thirdly, water is not distributed evenly. Fourth, water is shared. Where water crosses national political boundaries, the issues of effective and sustainable water resource management become even more complicated (Box 1) (Frey 1993).

Transboundary waters are those waters—either surface water or ground water—that are shared by two or more nations. For example, there are 268 transboundary river basins worldwide; 250 rivers are shared between and among two or more nations; and over 50 rivers are shared by three or more nations (Draper 2007). For the purposes of our case study, in Europe, nine countries share the river Rhine; in Southeast Asia, the Mekong River is shared by six countries; and in Southern Africa, the Zambezi River is shared amongst eight countries. Given that approximately 40% of the world's population depends on these shared river basins for water, the need for effective cooperation among riparian countries for the planning and management of these shared waters is essential in the face of the growing demand for water and the potential adverse impacts in the river systems as a consequence of upstream usage (Draper 2007).

A transboundary riparian nation can be subject to multiple and complicating foreign policy factors that may impact the sharing of international waters. These factors include image (the concern of a nation for its international image); international law (the concern to abide by established legal rules); linkage (the perceived connection between water and other issues); reciprocity (a desire for mutual commitment and obligation); and sovereignty (the stress placed upon autonomy) (LeMarquand 1990).

Box 1. IWRM and Sustainable Water Resources

Historically, water resource development has often emphasized economic growth and benefits over important social and environmental elements. In recognition of this connection, the American Society of Civil Engineers (ASCE) and the UN Educational, Scientific, and Cultural Organization (UNESCO) derived sustainability criteria and guidelines for water resource systems. The sustainability guidelines are presented as six separate topics:

1. **Physical infrastructure**: The design, management and operation of the physical infrastructure supporting the development and use of water, e.g., design and manage systems to be effective, efficient, and robust in all respects; balance changes in demands and supplies over time and space.
2. **Environment and ecosystems**: E.g., ensure that water quality is considered along with water quantity when designing and operating water resource systems.
3. **Economics and finance**: Efficiency, survivability, and sustainability, e.g., fully consider all direct and indirect environmental costs over the full life cycles of the systems' projects.
4. **Institutions and society**: Meeting societal needs in equitable ways, e.g., implement fully democratic and participatory water planning and decision making processes, involving all stakeholders in the planning, execution, and management of the systems as much as possible
5. **Health and human welfare**: The provision of clean water and sanitation, e.g., guarantee a minimum water supply to all humans to maintain human health.
6. **Planning and technology**: Recognize that planning is multi-disciplinary in nature, and includes evaluation of all relevant options, including non-structural solutions and consideration of long-term effects of options and incorporation of conservation objectives into design criteria.

The working definition for sustainable water resource systems that emerged from the above effort is as follows: "Sustainable water resource systems are defined as supporting social objectives into the indefinite future without undermining the water resource system's hydrologic and ecological integrity" (ASCE Task Committee and UNESCO Working Group 1998).

IWRM and Transboundary Water Resources: Image and Reality

IWRM provides a framework for countries sharing transboundary waters to begin the process of planning, implementing, and eventually managing their shared resources on a sustainable basis. It includes the principles that water use in shared basins should be equitable and reasonable, and fulfill the obligation not to cause appreciable harm by taking into account all relevant factors and circumstances. Clearly, the process of bringing together two or more countries sharing transboundary waters is extraordinarily complex and challenging to all parties. It is clear that the each transboundary river basin is unique and each country has its own set of political, institutional, and legal frameworks as well as its unique water demand and use patterns, water use efficiencies, institutional, economic, and management capabilities (Varis et al. 2008). Accordingly, while IWRM offers an initial framework, the IWRM process that emerges has to be tailored to the individual realities in the basin itself.

IWRM is a useful starting point for transboundary water planning and management in light of the pressures that will face us now or in the near future. These include not only increasing population but increasing per capita water use, the availability of water in sufficient quantities and of adequate quality, sufficient water for agricultural production, increased cooling water to meet growing energy requirements, and appropriate collection, transport, and treatment of waste to protect and enhance public health. In addition to these challenges, there is another set of complex issues associated with maintaining environmental flows into rivers to support aquatic species, fishery resources, and hydropower production. A major challenge facing the water profession worldwide in the 21st century is how to develop and manage transboundary water sources in a sustainable and efficient way with full agreement and cooperation between the appropriate basin countries such that the result is a win-win situation for all parties (Varis et al. 2008).

IWRM Conceptual Frameworks and Concepts

IWRM is a framework for examining the nature/degree of management integration within a river basin; Cardwell et al. (2006) describe IWRM as a unified process directed toward a unified goal. This approach recognizes drivers for action such as competition for water throughout the basin plus complexity from stressors like climate change. Cardwell et al. (2006) also emphasize collaboration: basin countries must collaborate in order to achieve sustainable water resources use and benefit within the basin system.

IWRM is aligned with criteria for sustainable water resource systems and can take various forms (box 1). Davis (2007) articulates that IWRM is best practiced at the river basin or sub-basin scale. Water sharing is an important component, including sharing between multiple units of government and between two or more countries. A basic premise of IWRM is that sustainable water resources may be approached through integrative collaboration and multiple-objective, strategic and operational planning and implementation processes, rather than through single-sector focused planning and implementation with limited stakeholder participation. IWRM is also a stakeholder process, to promote coordinated activities in pursuit of common goals for multiple objectives, leading to the development of sustainable water resource systems. IWRM results in better water use in that it supports economic and social objectives while seeking to maintain environmental ecosystems. Drivers for IWRM include but are not limited to: water scarcity/conflicts; water quality/environmental degradation; financial crisis/matters; macro-economic reforms; political reforms; social issues; donor/lender pressures; internal/external agreements; and institutional synergy/pressures (Davis 2007).

The Global Environment Facility (GEF) aims to assist countries in developing a better understanding of their international water systems and how multiple sector activities have an impact on these ecosystems. GEF also assists groups of countries to build the capacity of existing or new institutions to utilize a more comprehensive approach for addressing transboundary water-related environmental concerns and implement measures that address priority transboundary environmental concerns (Gerlak 2007). It defines its role in international waters as a "catalyst to the implementation of a more comprehensive, ecosystem-based approach to managing international waters and their drainage basins as a means to achieving global environmental benefits" (Gerlak 2007). Gerlak (2007) points out that the greatest challenge is the creation of shared solutions to current problems. Increasingly GEF-led international water projects are incorporating the concept of IWRM, as most scholars and practitioners recognize integrated management as the best approach to resources management because it incorporates environmental, economic, and social considerations based on the principle of sustainability and involves broad stakeholder participation and capacity building.

Summing Up: Transboundary Water Resources and IWRM

Achieving effective IWRM is proving to be more difficult than initially envisioned. The approach is meant to facilitate integrating water priorities and related environmental issues into national economic development activities (World Water Development Report 3 2009). However, IWRM remains the best approach currently available to address issues that reach beyond national boundaries, and the even more complex problems of transboundary water sharing. Inter-regional cooperation built around sharing transboundary waters has the potential to both promote peace and build trust between cooperating countries (World Water Development Report 3 2009). Lastly, IWRM offers a framework for countries to jointly manage the potential impacts of climate change on shared water resources. This is an important advantage because developing countries are especially vulnerable to climate change, due to heavy dependence upon water resources, low capacity to adapt, poverty, and the multiple demands placed upon limited and potentially diminishing water resources. IWRM explicitly calls for consideration of the uncertainties arising from climate change and its impacts upon transboundary water resources (World Water Development Report 3 2009).

The following sections include three case studies of transboundary river basins: the Rhine, the Mekong, and the Zambezi. Each case study includes details about the shared resource, basin countries, and cooperative management structure. IWRM is discussed in each case according to the level of implementation in each basin.

IWRM Introduction Discussion Questions

1. What are the advantages of employing IWRM?
   a. Does your answer differ if you consider the context within which IWRM is applied (e.g., transboundary waters or waters governed by a single nation, developing or developed country)?
2. What are the shortcomings and/or difficulties of employing IWRM?
   a. Does your answer differ if you consider the context within which IWRM is applied (e.g., transboundary waters or waters governed by a single nation, developing or developed country)?
3. Does the water you use in your household originate from a transboundary water source? If so, what are the boundaries that it crosses prior to reaching you?
4. How might IWRM be useful for planning considering the possible adverse impacts of climate change on water supplies?

RHINE RIVER CASE STUDY

Introduction

Originating in the Alps, the Rhine River watershed covers parts of nine countries—Switzerland, Austria, Italy, France, Germany, Belgium, the Netherlands, Liechtenstein, and Luxemburg—before it discharges to the North Sea. While it isn't the longest or largest river in the world, it is the most important commercial river in Europe (ICPR 2005). It has a drainage basin of 200,000 square kilometers and a length of 1,320 kilometers. The river flows at an annual average discharge of 2,200 cubic meters per second.

The basin is home to 58 million people, a third of whom rely on the river as a source of drinking water. Approximately 50% of the basin is used for agricultural production while 8% is used for settlements (Francesch 2002). Besides providing water for drinking and agricultural production, the Rhine also provides water for ecosystem services, navigation, power generation, industry, and recreation.

Point source pollution was a major source of pollution in the Rhine until the late 1980s. Attention has now turned to non-point source pollution reduction and to flood control as the primary issues of concern. The International Commission for the Protection of the Rhine (ICPR) is the organizational body established to facilitate cooperative, transboundary management of the Rhine River. To date, management efforts have been focused on singular issues rather than an integrative approach and IWRM as such is not well established in the basin. However, sustainability (one of the principles of IWRM) is encompassed in the sustainable development aims of the ICPR.

Rhine River Basin

The headwaters of the Rhine originate in the Swiss Alps (ICPR 2005; see Figure 1). Switzerland, France, Germany, and the Netherlands dominate the watershed, together contributing 92% of the Rhine River Basin area. The remaining five basin countries—Austria, Italy, Belgium, Liechtenstein, and Luxembourg—contribute the remaining 8% of the basin land area. The nine basin countries are prosperous and stable. The stability of the economic and political conditions in the Rhine basin countries creates a favorable situation for addressing environmental issues and for cooperation on management of the Rhine River. Table 1 summarizes the Rhine River Basin country profiles.

Basin stressors vary. Stressors in the headwaters and upper basin countries arise primarily from non-point source pollution while in the middle Rhine pollution from both point and non-point sources are problematic. Flooding is also an issue for the middle Rhine through the lower Rhine and delta. The Netherlands, situated at the Rhine delta and on the North Sea, is particularly prone to flooding given its location and that much of the land is below sea level. Table 2 provides a summary of the Rhine River Basin area and stressors.

The State of the Rhine in the Mid to Late 20th Century

The Rhine has long been used for navigation purposes because of its strong, steady flow (Figure 2). Because of this emphasis on navigation, Rhine River management was historically focused on improvements in the navigability of the river, including canalization and dredging. This historical focus also contributed to the Rhine's prominence in the region as a navigation throughway and, more recently, to enormous "hundred year floods" in 1983, 1988, 1993, and 1994 (Verweij 2000). The Rhine serves the world's third largest port by cargo tonnage at Rotterdam, the Netherlands, and the world's largest inland port at Duisburg, Germany (Verweij 2000).

Navigation and trade along the Rhine led to extensive industrial, urban, and agricultural development along the river, including chemical, mining, and pharmaceutical companies and steel manufacturing as well as large urban centers like Bonn, Cologne, Basel, Rotterdam, and many

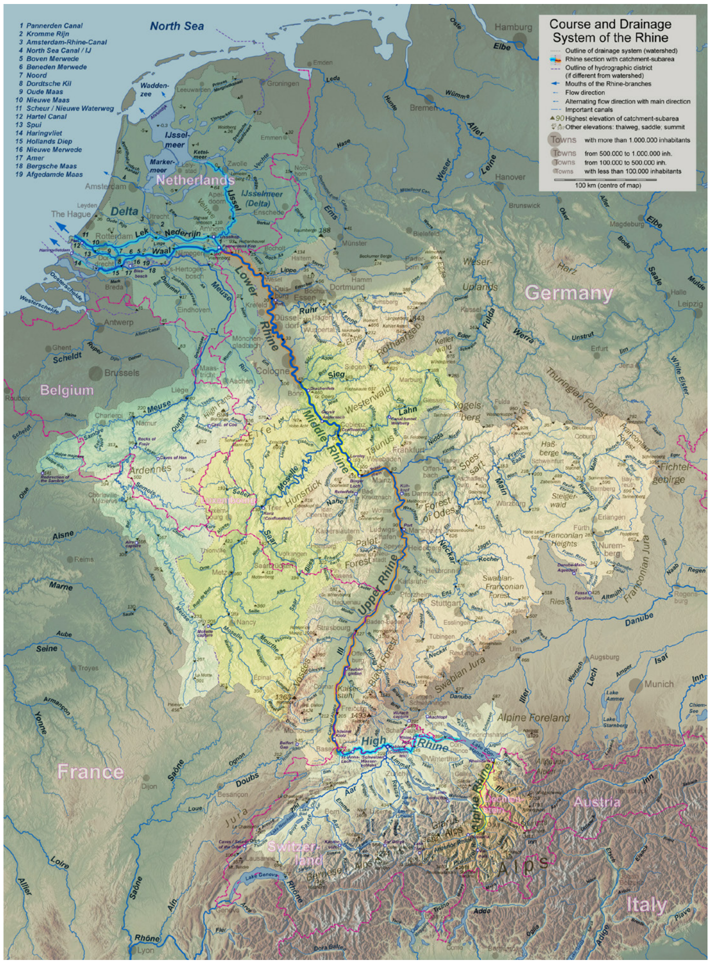


Figure 1. Rhine river basin
By WWasser (Own work) [CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Table 1. Rhine River Basin Country Profiles - Source: CIA World Fact Book; Waterwiki.net; Frijters and Leentvaar 2003).

COUNTRY	**SWITZERLAND**	**AUSTRIA**	**ITALY**	**FRANCE**	**GERMANY**	**BELGIUM**	**NETHERLANDS**	**LIECHTENSTEIN**	**LUXEMBOURG**
Type of Government	C	R	R	R	R	CM	CM	CM	CM
Total Population (millions)	7.4	8.2	58.1	60.9	82.4	10.4	16.6	0.03	0.49
Population Density (persons/km2)	181.4	99.2	197.6	114	230	344.3	395.8	221	186
Below Poverty Line (%)	n/a	5.9	n/a	6.2	11	15.2	10.5	n/a	n/a
Adult Literacy (%)	99	98	98.4	99	99	99	99	100	100
Women in Parliament (%)	25	34	11.5	12	32	35	37	12	17
Infant Mortality (#/1000)	4	4.5	5.6	3.4	4	4.5	4.8	4.5	4.6
GNP ($/capita)	41,000	38,400	30,400	33,200	34,200	27,570	38,500	25,000	80,500
Primary Economic Sector	B, I, S	B, I, S	I, S	I, S	I, S	B, I, S	I, S	I, S	I, S
Access to Clean Drinking Water (%)	100	100	100	100	100	100	100	100	100
Access to Sanitation (%)	100	100	100	100	100	100	100	100	100
Freshwater Resources (m3/ capita)	7,203	10,244	3,012	3,103	2,282	2,000	5,404	n/a	3,265
Emissions (metric tons/ capita)	7.3	11.3	9.9	9.3	12.3	14.4	13.3	7.6	24.9
Arable Land (%)	9.9	16.6	26.4	13.9	33.1	27.4	22	25	27.4

Symbols:
C = Confederation
R = Republic
CM = Constitutional Monarchy
B = Business
I = Industry
S = Services

Table 2. Rhine River Basin: Area, country position, basin and environmental stressors

COUNTRY	SWITZERLAND	FRANCE	GERMANY	NETHERLANDS
Basin Area Contribution (%)	18	13	55	6
Position in Basin	Headwaters	Upper	Middle	Delta
Basin stressors	Non-point source pollution	Non-point source pollution	Pollution control and flood protection	Flooding; upstream impacts
Country wide environmental stressors	AP, WP, AR, BL	AP, WP, AR	AP, WP, AR	AP, WP, AR

Symbols:
AP = air pollution
WP = water pollution
AR = acid rain
BL = biodiversity loss
Note: Austria, Italy, Belgium, Liechtenstein, and Luxembourg together comprise 8% of the basin area.

others (Saha 2008). This development, coupled with lax regulations, contributed to extensive degradation of the river, so much so that prior to the late 20th century, the Rhine River was known as the "open sewer of Europe" (Verweij 2000). In 1971, conditions worsened to an extreme, causing a 100 km stretch of the river to become devoid of oxygen (Verweij 2000), killing fish and other aquatic species and making visible the deplorable state of the river. Success at reducing river pollution over the last few decades has shifted attention to non-point source pollution reduction and flood management.

Early Efforts to Manage the Rhine

As previously mentioned, early efforts to manage the Rhine focused on navigation. The 1815 Peace Conference in Vienna, Austria established the Central Commission for the Navigation of the Rhine (CCNR), marking the first effort to cooperate on transboundary management of the river (Saha 2008). The CCNR is still active today, meeting twice a year to continue efforts to improve navigation and navigation safety protocols. The second transboundary management effort was the ineffective 1885 Salmon Treaty between Switzerland, Germany, the Netherlands, Luxembourg, and France (Verweij 2000; Cioc 2006). The Salmon Treaty was also notable for being the first attempt to protect the ecology of the Rhine.

The next serious effort to cooperate for protection of the Rhine was led by a Dutch delegation to the CCNR in 1946. The Dutch, motivated by their downstream location on the Rhine and the adverse impact of environmental degradation on the river delta, raised environmental concerns at the meeting (Ruchay 1995; Verweij 2000). Four years later, Switzerland, France, Germany, Luxembourg and the Netherlands formed the International Commission for the Protection of the Rhine (ICPR) (Saha 2008).

It took another 13 years for the ICPR to be recognized as an official body through the signing of the Bern Convention on the Protection of the Rhine in 1963 (Ruchay 1995; Oterdoom 2001). Thirteen more years would pass before the European Community would become a signatory to the Bern Convention (1976). The same year also marked the passage of the Chemical Convention and a year later (1977) the signing of the Chlorides Convention (Saha 2008). However, none of these early efforts resulted in significant improvements to the ecology of the Rhine (ICPR 2005).

In 1986, an accident at a facility owned by Sandoz AG in Basel, Switzerland dramatically changed the approach to managing the river (Verweij 2000). In the middle of the night on November 1, 1986, a fire erupted in a warehouse filled with chemicals. Firefighters battled the blaze with water that eventually washed into the river, turning the river red for 70 kilometers and killing fish and other organisms (Hull et al. 1986; Verweij 2000; EAWAG 2006). This accident made clear that current management efforts were ineffective and a new approach needed to be developed.

Accordingly, Switzerland, France, Germany, Luxembourg, the Netherlands, and representatives of the European Community signed a new Convention on the Protection of the Rhine in Bern in 1993. This new Convention for the protection of the Rhine entered into force in 2003 providing a revised framework for cooperation in the basin.

The International Commission for the Protection of the Rhine (ICPR) and the Rhine Action Program (RAP)

The ICPR is tasked with the following: (1) to monitor and report on the state of the Rhine; (2) to propose international policy solutions to ameliorate ecological problems in the river; and (3) to hold regular international consultations (about 80 per year) (Saha, 2008). Switzerland, France, Germany, Luxemburg, the Netherlands, and the European Community are members of the ICPR; Austria, Liechtenstein, and Belgium are "observers." Administrative offices of the ICPR are located in Koblenz, Germany (Saha 2008).

The ICPR is decentralized and operates by consensus. Decisions made by the ICPR are recommendations only and no sanctions are imposed on riparian countries in the event of non-compliance. These operating protocols were developed to promote trust and to ensure national sovereignty and individual responsibility at the lowest levels of government. Funding for the ICPR is through a regular budget cycle contributed by the riparian countries (Saha 2008).

Even though the ICPR was established in 1950, real progress on protection of the Rhine was stymied by legitimacy and credibility issues between riparian country scientists and civil servants, as well as a lack of trust that the ICPR could not overcome. However, the 1986 Sandoz accident changed the governance paradigm (Ruchay 1995; Verweij 2000). The accident raised awareness, called into question both the existing regulatory structures and the tepid efforts that had resulted in only modest improvements in river water quality, and provided an opportunity within the ICPR to build trust in responding to the crisis.

The Dutch minister and head of the Dutch ICPR delegation hired McKinsey, a private consulting firm, to develop an action program in consultation with the riparian countries, their scientists, and civil servants.

Figure 2. Rhine River at Boppard, Germany. Image by Isriya Paireepairit

This resulted in the drafting of the Rhine Action Plan (RAP) that called primarily for the return of salmon by 2000 and the reduction in point source pollution. In 1987, the ICPR member countries agreed to implement the Rhine Action Program (RAP) (Verweij 2000).

The ICPR assists the countries in implementing the RAP through facilitation of meetings, data acquisition and analysis, and the development of non-binding policy proposals. The non-binding agreements and decentralized approach have contributed to the ICPR's effectiveness as an international organization in the Rhine River Basin.

Transboundary Management: Organizations and Interactions

The European Union (EU), an economic and political union of 27 member states established by the Treaty of Maastricht in 1993, influences water management in the Rhine River Basin through its member states. Eight of the nine Rhine basin countries are members of the EU. The EU ensures that environmental legislation passed by the European Commission (the executive branch of the EU responsible for proposing legislation and implementing decisions) and agreed upon by the member states, is implemented.

The ICPR remains an important actor in the basin, working primarily in the area of pollution reduction and, more recently, flood control, while the CCNR continues to play a role in navigation. The ICPR has been instrumental in building trust among the riparian countries. However newly formed initiatives (such as the more recent efforts aimed at flood protection) still take time to mature, as differences in language, knowledge, and existing institutional structures must be overcome.

The location of countries along the river and the stressors associated with each location (Table 2) influence basin country priorities and their involvement in transboundary management. Historically, downstream countries have taken the initiative: for example, the Netherlands spearheaded the development of the RAP aimed at controlling pollution and returning salmon to the river. The Netherlands has also led recent efforts aimed at reducing flooding. Agricultural associations, drinking water associations, environmental groups and the public also provide input in various ways to the more formal transboundary management organizations. For example, a number of drinking water companies and environmental groups have been granted observer status in the ICPR.

Evaluating Transboundary Management Efforts: Successes

Since the passage of the RAP in 1987, point source discharges of toxic and other pollutants has decreased by 70% or more, with a subsequent increase in dissolved oxygen (Figure 3). Dioxins and DDT are no longer discharged and discharges of heavy metals and pesticides have been substantially reduced (Saha 2008). In addition, a new warning and monitoring system is in place to assist the riparian countries in detecting and responding to accidental releases of pollutants. As a result of the improvement in water quality, salmon returned to the river in the early 1990s.

New regulatory agreements have also been passed. In January 1998, the riparian ministers adopted the Convention for the Protection of the Rhine, which focuses on addressing next steps required to improve the ecological functioning of the Rhine. The 1998 Convention also targets reductions in non-point source pollution, removal of contaminated sediment, and an ecosystem approach for management of the watershed. Agreements such as the Rhine Action Program have stimulated the passage of water policies at the country level aimed at reducing pollution and more recently, the ecosystem-based approach for watershed management.

Since 1987, the ICPR has continued to provide a means for negotiating and establishing broad protection goals without prescribing the method for achieving these goals. This approach enables individual countries to govern more effectively. Additionally, in 1994, the ICPR was downsized to form a leaner, more agile management structure. Between 1950 and 1994, the ICPR had bourgeoned to 18 working groups, subgroups, and others, meeting along with the plenary sessions and meetings of the delegate heads. The downsizing reduced the number of permanent working groups to three, with two additional ad hoc groups. The revised

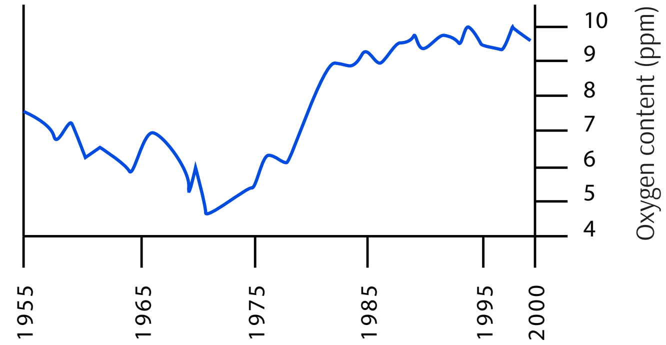


Figure 3. Improvement in dissolved oxygen level in the Rhine River (Adapted from ICPR 2005)

structure made for a more responsive, flexible and cost effective management regime (Ruchay 1995; Verweij 2000; Oterdoom 2001; ICPR 2005; Medema and Jeffrey 2008).

Evaluating Transboundary Management Efforts: Shortfalls

While point source pollution has decreased substantially, less success has been achieved in reducing non-point source pollution and its adverse impacts on the Rhine River. In addition to pollution from disperse sources, challenges remain regarding the treatment of contaminated sediment in the Rhine delta near the port of Rotterdam. Also, while salmon have returned to the river, the presence of large hydropower facilities impedes their progress upstream for spawning. Current management efforts are focused on non-point source pollution reduction.

Managing the river for improved navigation coupled with extensive urban development in the basin has resulted in increased flooding (Verweij 2000; Saha 2008). In response to the floods of 1993 and 1995, the Netherlands and Germany signed the Joint Declaration for the Cooperation Concerning Sustainable Protection against Floods. In 1998, the Action Plan on Flood Defense was approved at the 12th Conference of the Rhine Ministers. This Plan had four goals: to decrease the risk of flood damage; to decrease high water levels; to increase awareness of flood risk; and to improve flood warning. Current management efforts to control and protect against floods include structural measures such as higher embankments and new flood control barriers and, more recently, non-structural controls, such as dedicated inundation areas, awareness, and flood warning systems.

While transboundary cooperation has been successful in the area of pollution control, less success has been achieved in working towards Integrated Water Resource Management (IWRM). Transboundary management and cooperation was triggered by a series of problems or crises from the Sandoz accident, which precipitated increased point source pollution control, to more recent flood events that led to the 1998 Action Plan on Flood Defense. These management efforts have been focused on addressing particular concerns rather than reforming the overall approach to river and water management. The process of transboundary water management in the Rhine River Basin incorporates the sovereignty of the nine basin states, and operates through consensus and recommendations considered feasible and appropriate by member states.

Rhine River Case Study Discussion Questions

1. Prepare a conceptual map of the organizations involved in managing the Rhine River. Include with your map a brief description of each organization. How did the organizations and/or context change after the Sandoz accident?
2. How does the Rhine River case study illustrate management characteristics of IWRM? In what ways does the Rhine River case fall short of IWRM?
3. Why might IWRM be a good approach for the Rhine River?
4. What strategies might you use to implement IWRM in the Rhine River Basin? How might the Rhine River context help you implement IWRM? How might the Rhine River context impede implementation of IWRM?

MEKONG RIVER CASE STUDY

Introduction

The Mekong River is the longest river in Southeast Asia. It has a drainage basin of 795,000 square kilometers and a length of 4,800 kilometers, making it the twelfth longest river in the world (Jacobs 2002; ABD 2004; Mehtonen et al. 2008). The river flows at an annual average discharge of 15,000 cubic meters per second, ranking tenth among the world's largest rivers.

The Mekong River drains portions of six countries: China, Myanmar, Cambodia, Lao PDR, Vietnam, and Thailand. In Cambodia, the Mekong River splits into two rivers: the Tien and the smaller Bassac River (Mehtonen et al. 2008). As the river approaches the Vietnam delta region, the river further separates into many smaller rivers, where it is known as the River of Nine Dragons, before it discharges to the South China Sea (as shown in Figure 4).

The Mekong River Basin is divided into the Upper and Lower Mekong with China and Myanmar in the upper basin and Cambodia, Lao PDR, Thailand and Vietnam in the lower basin. The basin is home to 73 million people, a third of whom survive on a few dollars a day (Jacobs 2002; ABD 2004; Mehtonen et al. 2008). In addition, over 100 different ethnic groups live in the Lower Mekong River Basin, making it one of the most culturally diverse areas in the world.

The river provides many environmental, economic, and other benefits for the region, including fisheries, wetlands, transportation, trade, water supply, and tourism. The fisheries in the Mekong are among the most productive in the world, trailing only the Amazon (ABD 2004). The river also provides a source of energy through hydropower production. Lastly, the Mekong subregion is prized for its rich biodiversity.

There are a number of basin stressors including: flooding during the rainy season, land use change, watershed degradation, population growth, and the development of dams for hydropower (Jacobs 2002; ABD 2004).

There has been a long history of transboundary cooperative management of the Mekong River. The organization established to facilitate cooperative management of the Mekong is the Mekong River Commission (MRC). The agreement establishing the MRC includes principles of Integrated Water Resources Management (IWRM).

Mekong River Basin

Though the headwaters of the Mekong originate in China, China's Yunnan province, Lao PDR, Thailand, and Cambodia together dominate the watershed, accounting for 89% of the total basin area. The remaining two basin countries, Myanmar and Vietnam, contribute the remaining 11% of the basin land area. The six riparian countries have varying levels of wealth, population, literacy, and access to clean water and sanitation,

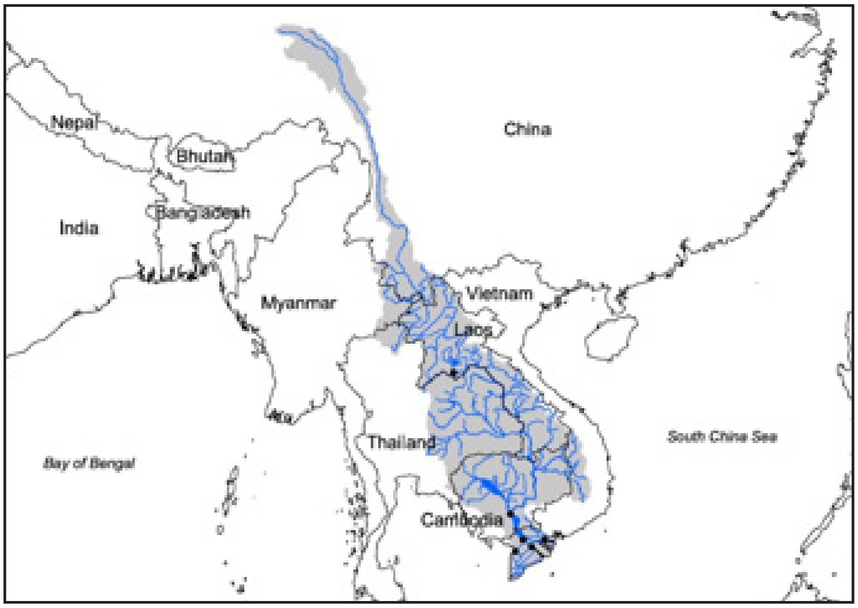


Figure 4. Mekong River Watershed
(Source EarthTrends: The Environmental Information Portal 2010)

Figure 5. The Mekong River Delta
(Source: NASA 1996)

however all six are classified as developing countries by the World Bank (World Bank 2009). At the time of writing, all six basin countries are stable politically. Table 3 summarizes the Mekong River Basin country profiles.

Basin stressors vary. In the upper basin, hydropower development and channelization along with concomitant aquatic ecosystem impacts and soil erosion are the dominant stressors. Downstream, potential impacts from hydropower development in the upper basin are of concern, and may already be altering river flows and aquatic systems (from the dams already constructed). Deforestation poses another significant problem in the lower basin. The fluctuations between flooding and drought are the primary stressors for Cambodia and Vietnam, respectively. Cambodia faces the greatest risk from flooding, given its location in the delta region of the Mekong along with Vietnam (Figure 5) and upstream flooding of Tonle Sap that occurs because of the rainy season flow reversal of the Tonle Sap River (Figure 6). Table 4 provides a summary of the Mekong River Basin area and stressors.

Because these are developing countries, the regional and national focus has been on economic development in the region, including developing transportation, electrical, and other infrastructure conducive to growing economies. This focus on development has concentrated attention on developing water resources to support economic growth and infrastructure development over and above possible social and environmental impacts and concerns. But, for example, if Lao PDR were to move aggressively towards energy development of tributaries to the Mekong, these new hydropower developments would have the potential to further impact river flows and aquatic ecosystems in the lower basin as well. However riparian countries, particularly in the Lower Mekong, have still developed a framework for transboundary cooperation in water resources management.

The State of the Mekong

The Mekong River provides water for drinking, sustaining important fisheries, hydropower energy production, navigation, agriculture, and ecosystem services, among other uses. A primary characteristic of the hydrologic dynamic of the Mekong is the strong natural seasonal variation in flow. The flood pulse, normally arriving in September through October, helps to maintain a functioning ecosystem, stimulate fisheries, and maintain salinity gradients (Sneddon and Fox 2006). But this seasonal variation also contributes to problems with flooding during high flows and with salinity issues in low flow periods. Wet season flows often exceed 20,000 cubic meters per second while in the dry season flows are on the order of 2,000 cubic meters per second (Jacobs 2002).

The fisheries in the Mekong and its tributaries supply ~60% of the protein intake of basin residents (Jacobs 2002). Fisheries in the delta region produce ~240,000-400,000 tons of fish each year (Sneddon and Fox 2006); the value of the fisheries alone is estimated to be about $1.2 billion (U.S.) per year (Jacobs 2002; Sneddon and Fox 2006). The fisheries and other natural resources support approximately 85% of the population living in the basin through subsistence and commercial fishing, rice production, and agriculture (Jacobs 2002).

Environmental degradation due to the impacts of pollution, logging and mining, population pressures, and agriculture are significant issues in the Mekong basin. Environmental degradation has led to decreased water quality in parts of the basin and also contributed to declining fisheries. These impacts are expected to increase as the population (which has doubled in the basin over the last 30 years) continues to increase (Jacobs 2002; UNITAR 2004; Hirsch 2006). Flooding (e.g., Cambodia) and water scarcity (e.g., Thailand) are also of concern. Floods in 2000, 2001, and 2003 caused an estimated $1 billion (US) in damage. As with environmental degradation, the threat from too much or too little water will be more problematic as populations and development increase. In addition, climate change has the potential to produce additional adverse impacts upon the region's water resources.

Lastly, regional economic development and the concomitant need for energy to drive development are spurring change in the basin (Jacobs 2002; Hirsch 2006). In the last decade, basin countries have proposed more than 100 new dams on the Mekong (Figure 7). The proposed dams will provide much needed energy for the region and help supply water for irrigation and

Table 3. Mekong River Basin country profiles

	CHINA, YUNNAN PROVINCE	MYANMAR	LAO PDR	VIET NAM	THAILAND	CAMBODIA
Type of Government	C	MJ	C	C	CM	CM/D
Total Population (millions)	42.4	51.1	5.4	78.9	62.9	13.3
Population Density (persons/km2)	109	70	25	253	126	192
Below Poverty Line (%)	4.6	14	39	37	13	36
Adult Literacy (%)	98	91	71	97	99	79
Women in Parliament (%)	22	n/a	21	27	6.6	5.5
Infant Mortality (#/1000)	32	47	90	30	25	95
GNP ($/capita)	565	n/a	260	390	2,000	260
Primary Economic Sector	A	A	A	I, S	I, S	A
Access to Clean Drinking Water (%)	75	70	58	56	80	30
Access to Sanitation (%)	38	70	46	73	96	18
Freshwater Resources (m3/capita)	>10,000	28,500	63,200	11,400	6,800	39,600
Emissions (metric tons/capita)	2.5	0.18	0.07	0.6	3.2	0.06

Symbols:

C = Communist
MJ = Military Junta
CM = Constitutional Monarchy
CM/D = Constitutional Monarchy/Democracy

A = Agricultural
I = Industry
S = Services

other uses. China is building a series of dams on the upper Mekong, and has completed six mega-dams. An additional fourteen dams are under construction or being planned (International Rivers 2013).Plans to build dams in Lao PDR, Thailand, and Cambodia are also under consideration. For example, Lao PDR has some 30 dams planned for installation to provide hydropower to serve the country's growing power needs as well as those of Thailand, Cambodia, and Vietnam. These dams are supported by basin countries that need power for development, as well as by basin countries with hydropower potential and limited national income, and by countries and companies that supply the money, parts, and labor for construction of hydropower facilities and associated infrastructure (Casey 2007; Imhof 2007; Lawrence and Middleton 2007; Salidjanova 2007).

The potential ecological impacts of the proposed dams

Table 4. Mekong River Basin: Area, country position, basin and environmental stressors. (Adapted from MRC 2005)

COUNTRY	**CHINA, YUNNAN PROVINCE**	**MYANMAR**	**LAO PDR**	**VIET NAM**	**THAILAND**	**CAMBODIA**
Basin Area Contribution (%)	21	3	25	8	23	20
Position in Basin	Headwaters	Upper	Lower	Lower	Lower	Delta
Basin stressors	Hydropower development, soil erosion	Soil erosion	Hydropower development, deforestation	Deforestation, drought	Deforestation	Flooding, drought
Country wide environmental stressors	AP, WP, SE	D, UP, BL, SE	D, BL, UO	D, BL	D, BL, AP, WP, LS, SE, WS	AP, WP

Symbols:
AP = air pollution
WP = water pollution
SE = soil erosion
D = deforestation
UP = urban pollution
BL = biodiversity loss
UO = unexploded ordinance
LS = land subsidence
WS = water scarcity

are not well understood. A change in the Mekong hydrograph could negatively affect fisheries, endangered species habitat, and agricultural productivity. Existing dams are already blamed for decreasing yields in fisheries but the long-term impacts are unknown. The effect of additional dams that would further impede fish migration routes and inundate spawning is of serious concern to scientists studying dam impacts in the region (Pearce 2004; Imhof 2007; Lawrence and Middleton 2007; Salidjanova 2007). These concerns include the potential disruption of the flood pulse for Lake Tonle Sap in Cambodia and for the delta itself (Salidjanova 2007). The flood is critical because every monsoon season the river reverses flow and fills Tonle Sap. When the dry season returns, the flow again changes and water from the lake contributes as flow into the Mekong (as shown in Figure 6). This process is believed to provide the necessary nutrients and habitat for fisheries nurseries to survive and thrive—fisheries supporting millions.

The flood pulse is also critical for the delta. Seasonally inundated areas of the delta provide the necessary environment for reproduction utilized by 90% of all Mekong species (Sneddon and Fox 2006).

Dam proponents point to the possibility of reducing salinity issues in the delta with installation of dams along the main stem, which would ensure a greater dry season flow. Dam opponents counter with the negative impact of displacing tens of thousands of rural villagers from the affected areas. Existing dams are estimated to have already displaced tens of thousands of people. However, at present, environmental and social costs are less of a concern in the region than pressures for increased development. In addition to dams for hydropower, damming for large irrigation projects is also under consideration. One such project has been proposed by Thailand to divert water for irrigation.

In addition to dams, China is also working to remove rapids and canalize portions of the Mekong to improve trade navigation. The canalization project would open a river trade route between China and neighboring Vietnam. At present, the environmental and ecological impacts upon the Mekong River from the canalization project are not well understood.

Managing the Mekong: A Brief History

Transboundary cooperation in the management of the lower basin began in 1957 with a United Nations-led effort to promote international river basin planning (Jacobs 2002; Hirsch 2006; Mehtonen et al. 2008). This effort resulted in the establishment of the Committee of Coordination and Investigation of the Lower Mekong River Basin, involving Cambodia, Laos, Thailand, and South Vietnam, called the Mekong Committee (MC). This committee initiated one of the first efforts to study the social, economic, and organizational aspects of a project prior to construction. This approach echoes the principles of IWRM as we understand them today. Cambodia's civil war and the subsequent regime of the Khmer Rouge reduced the effective activities of the MC. In 1978, a new arrangement between Lao PDR, Thailand, and Vietnam was formed, the Interim Mekong Committee, or IMC (MRC 2000; ABD 2004; Mehtonen et al. 2008).

The IMC remained active until April 1995, when the Agreement on the cooperation for the sustainable development of the Mekong River Basin was signed by all four lower basin countries: Cambodia, Lao PDR, Thailand, and Vietnam. This Agreement formed the new Mekong River Commission (MRC), the principal organization with responsibility for transboundary cooperative management of the Lower Mekong River (MRC 2000; Jacobs 2002; Mehtonen et al. 2008). The Mekong Agreement focuses on the sustainable and comprehensive management of the river including, in principle, environmental and social impacts. This approach echoes the tenets of Integrated Water Resource Management (Mehtonen et al. 2008).

In 1992, all six riparian countries entered into the Greater Mekong Subregional Economic Cooperation Program (GMS Program), ostensibly to strengthen environmental protections, institutions, and sustainable development mechanisms. This program was initiated by the United

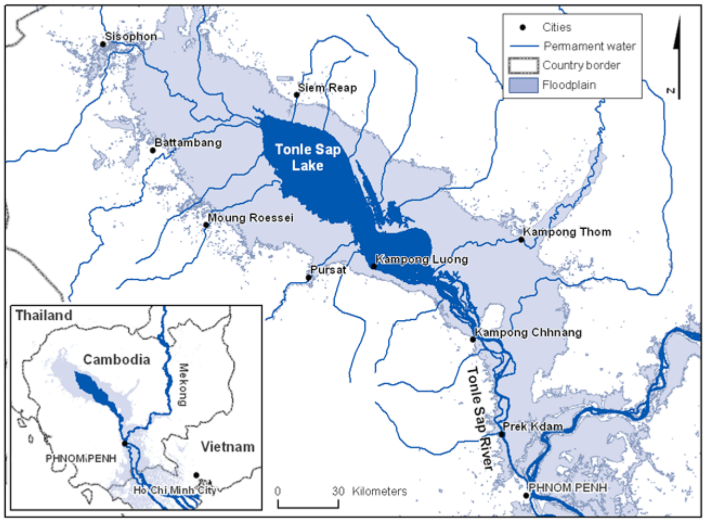


Figure 6. Tonle Sap flow reversal during monsoon season Mkummu [GFDL (www.gnu.org/copyleft/fdl.html), CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/) from Wikimedia Commons

Figure 7. Dam development on the Mekong (Image used with permission - © TERRA www.terraper.org - see Lawrence, S. and C. Middleton 2007)

Nations Economic and Social Commission for Asia and the Pacific. While environmental issues are listed in the GMS, activities have primarily focused on cooperation for economic and infrastructure development (Mehtonen et al. 2008). The Golden Triangle was established in 1993 between Thailand, Lao PDR, Myanmar, and China with a goal "to facilitate common use and development of the Mekong" (Jacobs 2002). Its focus has been on developing transportation and trade routes.

The Association of Southeast Asian Nations (ASEAN) was established in 1967 by Indonesia, Malaysia, the Philippines, Singapore, and Thailand to bridge the development gap and accelerate economic and trade integration. Today, all of the Mekong basin countries except China are members of ASEAN. In 1996, ASEAN began the Mekong Basin Development Cooperation initiative to enhance economic and sustainable development of the Mekong basin (Mehtonen et al. 2008). In 2002, ASEAN created a new Working Group on Water Resources Management focused on IWRM (Mehtonen et al. 2008) but it remains to be seen how much traction the environment and social issues will have as development projects proceed in the basin. Other development-focused management initiatives exist in the Mekong River Basin, but, as seen above, less emphasis is placed on environmental and social concerns.

The Mekong River Commission

In April 1995, the four lower basin riparian countries signed the Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, in Thailand. By signing the Agreement, these countries agreed to develop, conserve, and use the river cooperatively in a sustainable manner (MRC 2000; Jacobs 2002). This Agreement created the Mekong River Commission (MRC) as the primary agent for cooperative river basin management (Figure 8). The MRC is a policy-making body and its policies are binding on the four member countries. However because China and Myanmar are not signatories of the Agreement, this framework is limited to the lower Mekong Basin.

The MRC consists of a Council, a Joint Committee (JC), and a Secretariat. One member at the ministerial and cabinet level from each member country sits on the Council while the JC consists of one member from each country at the department head level (MRC 2000). The Secretariat provides technical and administrative assistance to the Council and JC and is located in Phenom Penh, Cambodia. The MRC is funded by the member countries and donors (90%).

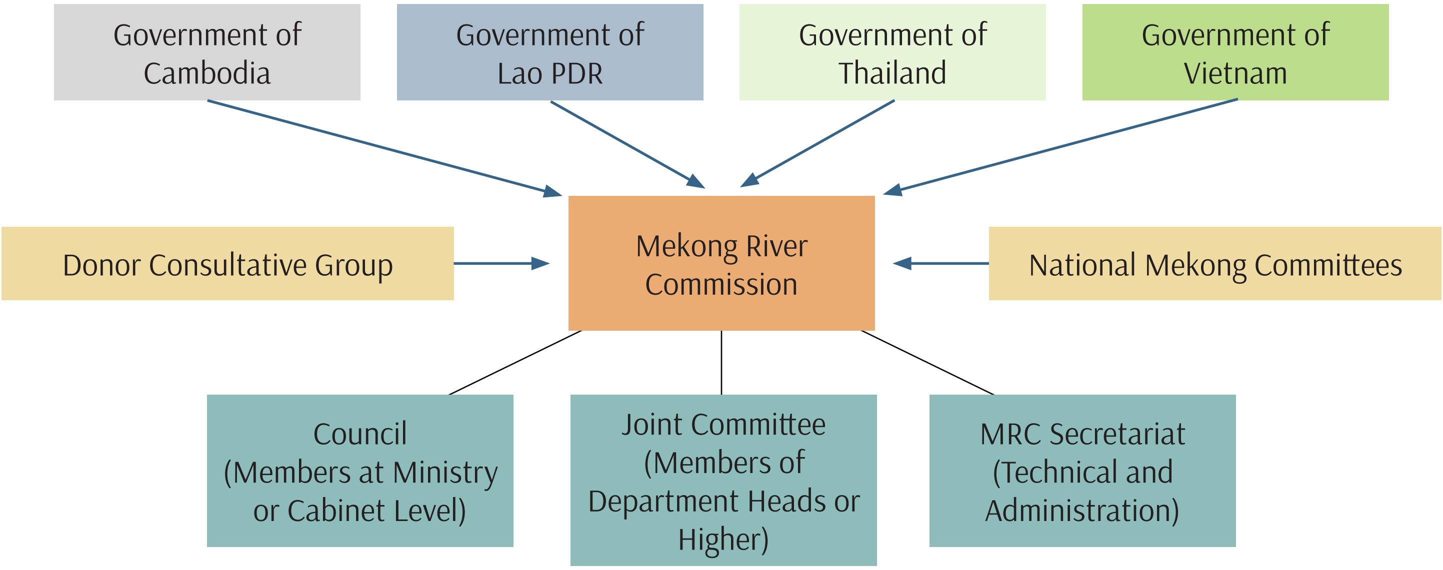


Figure 8. Mekong River Commission governance structure

Transboundary Management: Organizations and Interactions

The Mekong River Commission influences water management in the lower Mekong Basin countries through the prior consultation and notification provisions of the Agreement along with other binding decisions. The MRC has fostered regional cooperation for water resources development but has emphasized national and regional level interactions over local or community level interactions. Member states differ in terms of human, economic, and technical capacity for development. These differences can be a barrier to interaction and cooperation. MRC member countries and the other riparian countries are also involved in bilateral and multi-lateral cooperative efforts.

The Asian Development Bank, the World Bank, and other donors influence water management in the Basin by funding or not funding projects, and by requiring or not requiring environmental or social impact analysis and mitigation. The GMS Program, aimed at economic development, and the ASEAN Working Group on Water Resources Management also influence water management in the region. Like the MRC, these organizations promote dialogue at the regional or national level.

The location, varied interests, and characteristics of the individual riparian nations (Figure 4, Tables 3 and 4) influence each country's priorities and involvement in the transboundary management of the Mekong. Cambodia, the second most downstream country, emphasizes the maintenance of the seasonal high and low flows to protect Tonle Sap Lake and other flood plain ecosystems. Further downstream, Vietnam considers sufficient low flows as the most significant river issue. Upstream, projects that divert flow from the main stem and tributaries to support irrigated agriculture are priorities for Thailand. China and Lao PDR, on the other hand, are focused on hydropower development, and China is also focused on opening a trade route to Southeast Asia by making key portions of the Mekong navigable for shipping. These varied interests and motivations, as well as the sheer number of proposed projects, heightens the need to cooperatively plan and manage the Mekong River Basin in order to understand the potential impacts of development projects on river flows and ecosystems.

The role and involvement of NGOs in water resources management is increasingly important. For instance, the World Conservation Union (IUCN) and the Global Water Partnership (GWP) are active in the region. The IUCN has focused on increasing dialogue between local, national, and regional groups, while GWP has promoted IWRM through various water forums (Mehtonen et al. 2008).

Evaluating Management Efforts: Successes

The existence of a number of international agreements and management organizations in the Mekong River Basin is a testament to the recognition that cooperation is needed. Agreements and cooperative frameworks such as the MRC provide a forum for dialogue, albeit a dialogue that has historically focused on the regional and national level at the expense of the local and community levels. However, recent calls by NGOs and donor organizations for enhancing participation may increase communication at lower levels (Sneddon and Fox 2006). Cooperative efforts like the MRC have led to the development of data and improved understanding of the ecological and physical underpinnings of the Mekong River system. Cooperation has also led to the development of a flood forecasting and warning system (Jacobs 2002).

Instability in the region forestalled development of massive dams in the 1960s and 1970s. The delay meant that rapid dam building in the Lower Mekong River without consideration for subsequent environmental and social impacts (as happened in other parts of the world) did not take place in this region. This delay has also allowed new governance frameworks and approaches, like IWRM and those emphasizing sustainable development, to take hold. Dam projects now consider (at least to some extent) environmental and social impacts.

China and Myanmar have been dialogue members of the MRC since 1996. While the arrangement brings these upper basin countries into the discussion, it does not bind them to any decisions or agreements passed by the MRC (Mehtonen et al. 2008). The MRC is increasingly reaching out to China particularly in the area of scientific cooperation. China is also taking a greater interest in regional development, which may translate to greater cooperation in management of the Mekong (Jacobs 2002).

Evaluating Management Efforts: Impediments

Ineffective water use planning, insufficient data and data sharing, poor intra-nation institutional coordination, incomplete understanding of the Mekong River system, lack of skilled personnel, poor communication, and weak policy, regulatory frameworks, and enforcement mechanisms, are the primary constraints limiting sustainable management of the Mekong River Basin.

The MRC as an institution also has significant issues, particularly with participation versus non-participation, members' differing priorities, and limitations to its authority. Additionally, China and Myanmar are not full participants; participation in the MRC is regarded by these two countries as a possible constraint to further development. Differential rates of regional development also create differential incentives and disincentives for participating or for refusing to participate in the MRC (UNITAR 2004; Hirsch 2006). For example, China, a non-participant, and Thailand, a participant, are developing more quickly than other countries in the region. While the MRC does have policy-making authority that binds participating countries, it does not currently have the ability to set a basin-wide agenda, nor do countries relinquish their sovereignty simply by participating in the MRC. Myanmar is a non-participant for other reasons, including internal political struggles and an abundant water supply. The MRC is further hampered by its small size and limited resources and by extreme poverty in the basin. Donor funding (which provides 90% of the MRC budget) impedes the sense of riparian country ownership in the MRC and its governance mechanisms. The MRC has also seen its authority undermined: for example, China established a separate cooperative network among the four upper basin countries to facilitate development of a navigation channel on the upper Mekong. This network completely bypasses the MRC and thus undercuts MRC's authority to govern the basin. Lastly, the MRC is not regarded as a forum for local or community concerns but rather only representing national concerns.

In addition to these issues, the pressure in the basin countries to increase development has suppressed efforts to promote environmental concerns to a certain degree. Critics argue that the overriding emphasis on river basin development by the MRC and other regional organizations has meant that development has proceeded in practice without a commitment to the environment and social issues (Sneddon and Fox 2006). Thailand is an exception, given the development of a strong environmental movement within the country that has elevated environmental issues onto the agenda. Cambodia is also beginning to develop an environmental movement.

The 1995 Mekong Agreement (which formed the MRC) lays out strict policies for maintaining minimum flows during the dry season but does not include provisions for maintaining high flows during the wet season (Sneddon and Fox 2006). This hamstrings the MRC regarding any control over main stem development projects that might alter the flood-pulse. Even a functioning basin organization does not guarantee comprehensive cooperation between riparian countries to enable implementation of IWRM principles (Mehtonen et al. 2008). While sustainable development is a foundational principle of the MRC Agreement and IWRM, neither sustainable development nor IWRM has gotten much traction in the basin.

Mekong River Case Study Discussion Questions

1. Prepare a conceptual map of the organizations involved in managing the Mekong River. Include with your map a brief description of each organization. What does your map indicate about how the Mekong is managed? How does this compare to the management of the Rhine?
2. Think back to the Rhine River Case Study. How are the ICPR and MRC similar? How are they different? How might these similarities and differences influence their success managing transboundary water resources in the basin?

3. How does the Mekong River Case Study illustrate management characteristics of IWRM? In what ways does the Mekong River case fall short of IWRM?
4. Why might IWRM be a good approach in the Mekong River?
5. What strategies might you use to implement IWRM in the Mekong River Basin? How might the Mekong River context help you implement IWRM? How might the Mekong River context impede implementation of IWRM?

ZAMBEZI RIVER CASE STUDY

Introduction

The Zambezi River Basin is home to about 40 million people in Southern Africa, who rely on the river for drinking water, fisheries, irrigation, hydropower production, mining and industry, ecosystem maintenance, and other uses. With a drainage area of 1.385 million square kilometers and a length of 3,000 kilometers (Chenje 2003; Wirkus and Boge 2006; Phiri 2007), the Zambezi River flows at an annual discharge of 3,600 cubic meters per second (Lamoree and Nilsson 2000; Wirkus and Boge 2006). The Basin supports a vast amount of terrestrial biodiversity and the richest and most diverse flora in Africa (Chenje 2003). The watershed covers portions of eight countries–Zambia, Angola, Namibia, Botswana, Zimbabwe, Malawi, Tanzania, and Mozambique–before it discharges to the Indian Ocean (Figures 9 and 10).

Once the recent Zambezi Watercourse Commission (ZAMCOM) Agreement (signed in 2004) is ratified by six of the eight basin states, the Commission will be officially established. Thus far, the Agreement has been signed by seven of the eight basin states but only four out of the seven signatories have ratified the Agreement through formal parliamentary adoption. The new organization will facilitate transboundary, cooperative management of the Zambezi River. Integrated Water Resource Management principles are embodied in the nascent ZAMCOM Agreement and in the IWRM strategy for the basin.

The Zambezi River Basin

The headwaters of the Zambezi originate in Zambia. Together, Zambia, Zimbabwe, Angola, Malawi and Mozambique dominate the watershed, contributing 95% of the Zambezi River Basin area. The remaining three basin countries—Botswana, Namibia, and Tanzania—contribute the remaining 5% of the basin land area.
The eight basin countries have varying levels of wealth,

Figure 9. The Zambezi River Basin
(Used with permission from Dr. Amy Burnicki, 2008. University of Wisconsin, Department of Geography)

population, literacy, and access to clean water and sanitation, however all eight are classified as developing countries by the World Bank (World Bank 2009). A summary is included in Table 5.

Basin stressors vary, however many of the basin countries struggle with water scarcity, drought, rapid population growth (averaging 2.9% per year in the basin), poverty, water pollution, and lack of information about available water resources. Poverty is an environmental stressor due to overexploitation of the environment for survival, resulting in degraded and less productive land and water resources (Chenje 2003). Table 6 provides a summary of the Zambezi River Basin area and stressors.

With the exception of Zimbabwe, there is a stable political framework within each of the riparian basin countries. Because these are developing countries, the regional and national focus has been on economic development in the basin including developing the transportation, electrical, and other infrastructure conducive to support growing economies. This focus on development has concentrated attention on developing water resources to stimulate economic growth and infrastructure development over and above possible social and environmental impacts and concerns. However, despite this development focus, the riparian countries in the Zambezi Basin, have developed a framework for transboundary cooperation in the management of the water resources of the Zambezi River.

The State of the Zambezi

Of the approximately 40 million people living in the Zambezi River Basin, the majority live in Malawi, Zimbabwe, and Zambia (Wirkus and Boge 2006). This population living in the Basin represents about 20% of the total population in the Southern African Development Community (SADC), making the Zambezi an important river in the region (Chenje 2003). Basin residents rely on the river for drinking water, fisheries, irrigation, hydropower production, mining and industry, ecosystem maintenance, to name a few uses. The Zambezi River also attracts tourists from around the globe, who visit Victoria Falls and the wildlife that the river supports along its banks. Tourism supports local economies along the river and brings much needed foreign currency into the basin countries. Though the river is an important natural resource, protecting and managing the sustainable use and development of the Zambezi is an ongoing challenge.

Figure 10. The Zambezi river and its floodplain, seen from the international space station. (Source: NASA)

Table 5. Zambezi River Basin Country Profiles (Source: Population Reference Bureau (2009); CIA Fact Book)

	ANGOLA	BOTSWANA	MALAWI	MOZAMBIQUE	NAMIBIA	TANZANIA	ZAMBIA	ZIMBABWE
Type of Government	R	PR	D	R	R	R	R	PD
Total Population (millions)	16.3	1.8	13.1	20.4	2.1	38.7	11.5	13.3
Population Density (persons/ km2)	13	3	110	25	3	41	15	34
Below Poverty Line (%)	70	30.3	53	70	34.9	36	86	68
Adult Literacy (%)	73	89	76	63	93	92	89	98
Women in Parliament (%)	16	7	15	30	26	21	12	10
Infant Mortality (#/1000)	141	56	96	108	55	78	100	60
GNP ($/capita)	5,600	16,400	800	800	5,200	1,300	1,300	200
Primary Economic Sector	I, S, A	I, S, A	I, S, A	I, S, A	I, S, A	I, S, A	I, S, A	I, S, A
Emissions (metric tons/capita)	0.5	2.3	0.1	0.1	1.2	0.1	0.2	0.9
Arable Land (%)	2.65	0.65	20.7	5.43	0.99	4.23	6.99	8.24

Symbols:

R = Republic
PR = Parliamentary Republic
D = Democracy
PD = Parliamentary Democracy

I = Industry
S = Services
A = Agricultural

Eight basin countries share the Zambezi Basin watershed; however, their national interests in the river differ. For example, Zambia and Zimbabwe have the lion's share of the watershed within their borders and participate in bilateral management of the river through the Zambezi River Authority, sharing the Kariba Dam and Victoria Falls. Zambia has sufficient water resources but Zimbabwe suffers from water scarcity. For this reason, Zimbabwe plans to divert water from the Zambezi to Bulawayo (its second largest city) to provide municipal and irrigation water to a region chronically short of water. The pipeline would extend for about 225 miles (450 kilometers) and require major energy inputs to overcome both distance and an increase in elevation of about 3,000 feet (1000 meters) to reach the Bulawayo municipality (Wirkus and Boge 2006). Namibia also has pressing needs for water for new irrigation projects (Wirkus and Boge 2006). One proposed solution is to build infrastructure necessary to transfer Zambezi River water to the Okavango River (Turton 2008). In addition, Botswana sees the Zambezi as a source of water for its capital city, Gaborone.

Table 6. Zambezi River Basin: Area, country position, basin, and environmental stressors

COUNTRY	ANGOLA	BOTSWANA	MALAWI	MOZAMBIQUE	NAMIBIA	TANZANIA	ZAMBIA	ZIMBABWE
Basin Area Contribution (%)	14	1.5	12	12	1.5	2	41	16
Position in Basin	Upper	Upper	Lower	Delta	Upper	Lower	Headwaters; upper	Middle
Basin stressors	Poverty	Water scarcity	Poverty	Drought; floods; poverty	Drought; floods; poverty	Drought	Pollution; poverty	Pollution; poverty
Country wide environmental stressors	SE, DS, DF, BL, WS, P	DS, WS	DF, WP, P	DS, WP, D, F, P	WS, DS, D	DF, DS, D, F	AP, AR, WP, DF, SE, DS, P	DF, SE, AP, WP, D, P

Symbols:

SE = soil erosion
DS = desertification
DF = deforestation
BL = biodiversity loss
WS = water scarcity
P = poverty
WP = water pollution
D = drought
F = flooding
AP = air pollution
AR = acid rain

The increasing demand for water is a crucial concern as a consequence of population growth, increasing irrigation to increase food production, and the reality of climate change. The population in the Zambezi River Basin is increasing at the rate of 2.9% per year. More than 40% of the current population is under 14 years of age. It is anticipated that the population will continue to expand until at least the year 2015. Rainfall is the primary source of freshwater renewal in the Basin. Global warming and climate change are already apparent in much of Southern Africa including the Zambezi River Basin. Air temperatures are increasing; rainfall is decreasing; and the frequency of drought conditions are increasing. Water rich countries like Angola, Mozambique, and Zambia are less reliant on surface water for irrigation but Namibia and Botswana receive scant rainfall and are reliant on groundwater, an unsustainable practice as groundwater resources in the area are essentially non-renewable (Chenje 2003; Scholes and Biggs 2004). Table 7 summarizes the water resources available for each of the eight basin countries.

Seasonal rainfall variation is also an issue as it can lead to flooding, particularly in downstream countries like Mozambique. These floods were once cyclical but damming of the river has made the floods unpredictable and difficult to manage, and the flooding issue remains contentious. In water scarce countries, drought is always a concern, exacerbated by the risks and uncertainties associated with climate change. As indicated by Table 7, two countries, Malawi and Zimbabwe, are already under water stress. Climate change is expected to cause increased water stress in these areas and others, as rainfall continues to decrease and evaporation rates increase with rising temperatures. Continued population growth will also lead to increasing water stress (Chenje 2003).

Even in areas with plentiful water resources, access to clean drinking water and sanitation remains a persistent and significant challenge in Southern Africa, particularly in rural and impoverished urban areas. Lack of access to clean water contributes to illness and death particularly among children and those with compromised immune

Table 7. *Water resources in the Zambezi Basin (Source: Scholes and Biggs 2004)*

BASIN COUNTRIES	**RENEWABLE WATER RESOURCES**			
	TOTAL (KM^3/AC)	**WITHDRAWALS (KM^3/AC)**	**WITHDRAWALS % OF TOTAL**	**WATER 2001 (M^3/ PERSON)**
Angola	184.0	0.4	0.19%	13,620
Botswana	14.4	0.1	0.97%	8,471
Malawi	17.3	0.6	3.65%	1,641[a]
Mozambique	216.1	0.6	0.29%	11,960
Namibia	17.9	0.3	1.51%	10,022
Tanzania	91.0	2.0	2.20%	2,642
Zambia	105.2	1.7	1.65%	10,233
Zimbabwe	20.0	2.6	13.05%	1,560[a]

[a] Indicates water stress (1,700 m^3/person)

Table 8. *Clean water and sanitation in the Zambezi River Basin (Source: Scholes and Biggs 2004)*

BASIN COUNTRIES	**DRINKING WATER ACCESS**		**SANITATION**	
	% URBAN	**% RURAL**	**% URBAN**	**% RURAL**
Angola	34	40	70	30
Botswana	100	90	88	43
Malawi	95	44	96	70
Mozambique	81	41	68	26
Namibia	100	67	96	17
Tanzania	90	57	99	86
Zambia	88	48	99	64
Zimbabwe	100	73	71	57

systems (Scholes and Biggs 2004). Table 8 summarizes the percentage of access to clean drinking water and sanitation for rural and urban populations in the eight Basin countries. Reduction of the number of people without access to water and sanitation is of critical importance, and is an example of one of the many issues competing for time, attention, and money in the region.

Several large dams have already been constructed on the Zambezi to generate much needed electrical power for basin states. The two largest dams are the Kariba Dam, located between Zimbabwe and Zambia, and the Cahora Bassa Dam in Mozambique (Wirkus and Boge 2006). A number of other new dams are under discussion. One proposed dam to be located at Batoka Gorge would generate 1600 megawatts, while another new dam at Devil's Gorge would generate 1240 megawatts. The need for electricity and the availability of external funding means that hydropower projects are likely to be built along the Zambezi in the coming years. Eight additional dam sites along the Zambezi's main stem have been identified. However, resistance to building additional large dams is growing because of environmental costs and, more recently, concerns regarding loss of water from reservoirs through evaporation. In-country diversions of water from the Zambezi River are limited by the costs involved and out-of-basin diversions are the least likely, because of the very large financial costs involved as well as the significant political complexities.

Pollution in the surface water and groundwater of the Zambezi Basin is a result of mining, industrial, agricultural activities as well as the discharge of human wastes without adequate treatment. The deterioration of lakes, streams, and rivers has been a consequence of these pollutant loadings, resulting in major negative water quality impacts on the surface waters. The in-stream manifestations of these negative impacts include eutrophication (excessive nutrients causing algal blooms), increased dissolved and suspended solids, increased nitrates, and toxic contaminants from mining operations. Non-native invasive species introductions have also impacted the Zambezi River: for example, the introduction of the water hyacinth, a floating plant that covers the water surface and disrupts the normal functions of aquatic ecosystems, has had negative impacts. Conversely, the introduction of the Lake Tanganika sardine, known locally as the Kapenta, has had positive consequences: it has become a major source of protein for the population within the Zambezi Basin. However, the survival of the Kapenta is threatened by overfishing of this important food source. Another threat facing the region has arisen from the fact that nearly 74% of the energy needs within the Zambezi Basin are provided by burning of biomass or fuel wood. This use of fuel wood for cooking and lighting has resulted in deforestation and the subsequent erosion of soil that is carried to the basin's surface waters by rainfall and subsequent runoff.

Managing the Zambezi River Basin

Most of the basin countries have adopted environmental standards and regulations. However, persistent problems include lack of enforcement of existing regulations, weak institutional and legal structures, and inadequate economic, human, and technical capacity (Chenje 2003). Fully effective transboundary water management of shared water resources remains a continuing challenge for Southern Africa, particularly in the Zambezi River Basin. The lack of adequate institutional structures both within each country and at the basin level has long impeded progress on transboundary water management of the Zambezi River, though the tide may be turning. The earliest effort in transboundary management resides with the Zambezi River Authority (ZRA), a bilateral organization involving Zambia and Zimbabwe. The ZRA is focused on the joint operation of the Kariba Dam and has responsibility for water allocations to both countries and their respective electricity companies (Wirkus and Boge 2006). Other responsibilities include: data collection, monitoring, and planning for new dams.

The United Nations Environment Program (UNEP) has played a role in energizing cooperative transboundary management of the Zambezi River. In 1987, the governments of Botswana, Mozambique, Tanzania, Zambia, and Zimbabwe adopted the Agreement on the Action Plan for the Environmentally Sound Management of the Common Zambezi River System (ZACPLAN) (Lamoree and Nilsson, 2000; Wirkus and Boge, 2006); Angola, Malawi, and Namibia joined in the early 1990s. ZACPLAN details some 19 Zambezi Action Projects (ZACPROs), including plans for water resource assessments, water project planning, a monitoring system, a database, and an integrated water resources development plan. The implementing agency for ZACPLAN is the Zambezi Watercourse Commission (ZAMCOM). The agreement for establishing ZAMCOM was signed in 2004 by seven of the eight basin states (Turton 2008); Zambia announced its readiness to join the Commission in May 2013, but have not yet signed the Agreement (ZAMCOM 2013). The principle sticking point is that Zambia contains the bulk of the watershed drainage area for the basin. As such Zambia does not wish to give control to other basin countries over waters it feels belongs to Zambians. Though seven of the eight basin states have signed the Agreement, in order for the Agreement to take effect six of the eight basin states must ratify the Agreement. This occurred in 2011, seven years after the initial signing of the Agreement (ZAMCOM 2012).

In moving to establish ZAMCOM, seven of the eight basin countries have demonstrated their commitment to adhere to the principles of equitable, reasonable, and sustainable use and efficient management of the water resources of the Zambezi River, inter-generational equity, prevention of harm, and cooperation (Wirkus and Boge 2006). These principles are key to the tenants of IWRM (Wirkus and Boge 2006). ZAMCOM's functions include: (1) data collection and dissemination; (2) support, coordination, and harmonizing management and development of the Zambezi; (3) advising member states; (4) fostering awareness; (5) cooperation with the Southern African Development Community (SADC) and other organizations; and, (6) promoting and supporting the harmonization of national water policies and legislation (Wirkus and Boge 2006). The Agreement uses the Revised SADC Protocol of 2000 as the basis of the agreement. The Protocol provides a legal framework for governance of the shared watercourse (Turton 2008).

The SADC encompasses all of Southern Africa from the Democratic Republic of Congo to South Africa and Madagascar. This supra-regional organization was established for the purpose of integration, harmonization, and sustainable development for the region. But SADC's charge is not simply economic; rather SADC is also concerned with the sustainable use and management of natural resources including water. SADC's Water Division has been instrumental in facilitating the development of institutions for more sustainable water resource management of the 15 shared rivers in Southern Africa, including the Zambezi River (Tumbare 2005). SADC has also been instrumental in trying to harmonize national level water policies and in spearheading the development and adoption of several regional water protocols governing shared watercourses. Principal among these is the Revised Protocol on Shared Watercourses (Chenje 2003).

Transboundary Management: Organizations and Interactions

The Zambezi River Authority exercises authority over operation of the Kariba Dam. This powerful organization exerts influence on the Zambian and Zimbabwean governments through its knowledge and expertise of the hydrology of the river and potential future dam sites. The ZRA has also played a significant role in the ZACPRO6 project to create a basin-wide integrated water resource management plan. ZRA oversaw the effort and was instrumental in achieving progress on an otherwise slow-moving effort (Wirkus and Boge 2006). Oversight for ZACPRO6 will be in the hands of ZAMCOM.

Donors and NGOs also play a role in the basin. The Swedish International Development Cooperation Agency (SIDA) provides financial support for the ZRA's Environmental Monitoring Program; similarly, the French Global Environmental Facility (FGEF) provides money to the ZRA for the Pollution Monitoring and Management Program (Wirkus and Boge, 2006). Donors are also largely responsible for supporting ZACPLAN: the ZACPLAN meetings were 100% donor funded (Wirkus and Boge, 2006). Furthermore, SIDA, the Norwegian Agency for Development Cooperation (NORAD), and the Danish International Development Agency (DANIDA) are the principle funders for the ZACPRO6 effort concerned with developing an integrated water resource management plan for the Zambezi River basin. UNEP played a pivotal part in the establishment of ZACPLAN along with the World Bank and the United Nations Development Program (UNDP). Regional stakeholders have been participating in annual stakeholder dialogues.

Evaluating Transboundary Management Efforts: Successes

The ZRA is seen as a successful bilateral management effort between Zambia and Zimbabwe primarily because of the many shared interests, organizational strength, autonomy, and clear mandate (Wirkus and Boge 2006). At the basin-scale, the adoption of the SADC Water Protocol and Revised Protocol for Shared Watercourses are regarded as great achievements. The 2000 Revised Protocol marked SADC's first legally binding framework program. Adoption of that protocol set the stage for further cooperative effort and led to the commitment to establish ZAMCOM. The ZAMCOM Agreement took years of negotiation, implying basin states take the process very seriously (Turton 2008).

ZAMCOM requires notification and consultation of member states for any river main stem development project and includes provisions for dispute resolution. These provisions mean basin states have a framework for cooperatively managing the Zambezi. Another achievement was the creation of a database for the basin states containing information about water resources and existing and planned projects. The Zambezi River Basin Information System and Database was recently completed, no small feat given each individual state's resistance to supplying information. Eventually, these impediments were overcome and the database was finalized. Efforts are currently underway to implement the Integrated Water Resource Management Strategy for the basin developed under the auspices of ZACPRO 6.4.

Evaluating Transboundary Management Efforts: Shortfalls

Unfortunately, national sovereignty, competing water demands, human and financial resources, lack of knowledge, and political power differentials have made instituting sustainable water resource planning and management difficult on the Zambezi (Swatuk 2005). National interests and national sovereignty often stymie cooperation; but, eventually, progress is made. Evidence suggests that over the long-term, water scarcity in basin countries will create strong incentives to support cooperative management and investment in water resources (Turton 2008). Also, even with SADC in play, governance remains a key constraint to the achievement of sustainable water resource management in the Zambezi Basin (Scholes and Biggs 2004). Other impediments to sustainable water resource management include: poor data collection, management, and dissemination systems, inadequate training, and weak stakeholder participation (Phiri 2007). Heavy donor involvement and support of the ZACPLAN and ZAMCOM process has hampered national and regional collaboration due to coordination problems among the donors. Lastly, strong water sector involvement has had the effect of limiting input from other ministries, making integrated water resources management more difficult within and between basin countries.

<u>Zambezi River Case Study Discussion Questions</u>

1. Prepare a conceptual map of the organizations involved in managing the Zambezi River. Include with your map a brief description of each organization. Compare your map of the Zambezi River Basin management organizations to the maps you drew for the Rhine and the Mekong. What similarities and differences in the management structure do you notice across the three river basins?
2. Think back to the Rhine and Mekong River Case Studies. How does the proposed ZAMCOM differ from the ICPR and MRC? How is the proposed ZAMCOM similar to the ICPR and MRC?
3. How does the Zambezi River Case Study illustrate management characteristics of IWRM? In what ways does the Zambezi River Case fall short of IWRM?
4. What strategies might you use to facilitate successful implementation of IWRM in the Zambezi River Basin? In your answer consider strategies at the regional level (e.g., SADC), national level (e.g., Zambia, GWP, SIDA, etc.), and local level (e.g., NGO, water department, community organization, etc.)

DISCUSSION

Integrated Water Resources Management (IWRM) is a process that promotes the coordinated development, management, and sustainable use of water, land, and related resources to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP 2009). The three cases presented above—the Rhine River, the Mekong River, and the Zambezi River—illustrate the challenges associated with implementing IWRM in three international transboundary contexts. IWRM process is weakest in the Rhine and strongest in the Zambezi. This uneven application of IWRM illustrates and underscores the challenges of applying this approach.

Gerlak (2007) provides a summary of the challenges faced when implementing IWRM and how to mitigate those challenges in a broader context. She summarizes important lessons learned in Global Environmental Facility (GEF) projects in transboundary waters as follows (Gerlak 2007):

1. Creating a shared vision;
2. Involving the public and the private sectors;
3. Coordinating program activities;
4. Building governance institutions and capacity;
5. Improving the ecosystem;
6. Difficult to transform data into information necessary to inform decision makers;
7. Participating agencies must commit to the priorities outlined in the Strategic Action Plan;
8. Need strong analysis that is technically sound, thorough, and comprehensive;
9. IWRM failures observed from inadequate

incorporation of stakeholders;

10. IWRM failures occur if the root causes of transboundary problems are not identified;
11. Broad public participation in the IWRM process can help build regulatory success and legitimacy;
12. Tools for effective public participation in IWRM processes are in the highest demand.

GEF and the Environmental Law Institute have developed a collection of training materials to deliver a series of regional workshops on public participation in international water management. These training materials describe how to conduct a Transboundary Diagnostic Analysis (TDA) and how to develop a Strategic Action Program (SAP). The purpose of the TDA is to: (a) analyze major threats within a river basin; (b) create and disseminate scientific knowledge; (c) examine the root causes of conflict and/or degradation; and, (d) reveal social issues. The TDA serves as the basis for creating the Strategic Action Plan (SAP). The SAP integrates actions to address the findings of the TDA and may include policy, institutional, and/or legal reforms at both the national and multinational levels. The implementation of the SAP integrates the regional priorities into national development plans. Lessons learned through application of the TDA and SAP approach are as follows:

1. Collaborating nations should create inter-ministerial technical teams whose task it is to assemble information on water-related environmental problems in their part of a particular basin or ecosystem;
2. Deficiencies observed in communication and coordination results in reduced effectiveness of GEF program;
3. Need for inter-ministerial coordination, particularly from the finance minister in GEF-led projects;
4. Early projects lack of effort in building capacity on a system-wide basis in terms of strengthening governmental organizational frameworks and processes;
5. Primary emphasis on creation of institutional mechanisms and diagnosis of the problem and less emphasis on activities to correct the problem(s); 20-30 year time period is needed to observe and document environmental improvements in large ecosystems.

While difficult to achieve, IWRM is still a worthwhile framework. As we face increasing pressures on water resources, we must change our management approaches. IWRM is one such approach and is necessary if we are to achieve sustainable water management.

REFERENCES

ADB (Asian Development Bank). 2004. Greater Mekong subregion: atlas of the environment. Asian Development Bank, Manila, Philippines.

Adeyemo, E.A. 2003. effective water governance through the paradigm of TWRM. 29th WEDC (Water, Engineering and Development Centre and the National Water Resources Institute, Nigeria) International Conference, Nigeria.

AMS (American Meteorological Society) Policy Statement. May 12, 2008. Available at http://www.ametsoc.org/policy/2008waterresources_amsstatement.html.

ASCE (American Society of Civil Engineers) & UNESCO. 1998. Task Committee on Sustainability Criteria, Water resource Planning and Management Division, ASCE and Working Group, UNESCO/IHP IV Project M-4.3, ASCE.

Cardwell, H., R. Cole, L. Cartwright, and L. Martin. 2006. Integrated water resources management: definitions and conceptual musings. The Journal of Contemporary Water Research and Education 135:8-18.

Casey, M. 2007. Dams may damage Mekong River, Groups Say. National Geographic News. Available from: http://news.nationalgeographic.com/news/2007/11/071114-AP-thailand-threatened.html.

Chenje, M. 2003. Hydropolitics and the quest of the Zambezi River Basin Organization. Pages 189-208 in M. Nakayama. International waters in Southern Africa. United Nations University Press, Tokyo, Japan.

CIA (Central Intelligence Agency). 2008. The World Factbook. Available from https://www.cia.gov/library/publications/the-world-factbook/.

Cioc, M. 2006. The Rhine: an eco-biography, 1815-2000. University of Washington Press, Seattle, Washington, USA.

Davis, M.D. 2007. Integrated water resource management and water sharing. The Journal of Water Resource Planning and Management 133:427-445.

Draper, S.E. 2007. Introduction to transboundary water sharing. The Journal of Water Resource Planning and Management 133:377-381.

Earth Trends – Environmental Information Portal 2010: Watersheds of the World: Asia and Oceania – Mekong Watershed. Creative Commons: http://earthtrends.wri.org/text/water-resources/map-364.html.

EAWAG. 2006. Rhine running red, fish dead - 20th anniversary of the Sandoz blaze. Swiss Federal Institute of Aquatic Science and Technology. Available from http://www.novaquatis.eawag.ch/media/2006/20061101/index_EN.

Francesch, M. 2002. Europe's Rhine River delta and China's Pearl River delta: issues and lessons for Integrated Water Resources

Management. Asian Journal of Public Administration 24:23-56.

Frijters, I.D. and J. Leentvaar. 2003. Rhine case study. Paris: UNESCO, 42pp.

Frey, F.W. 1993. The political context of conflict and cooperation over international river basins. International Water Resources Association 15:223-230.

Gerlak, A.K. 2007. International water systems. Water Policy 9:55-72.

Grabs, W., editor. 1997. Impacts of climate change on hydrological regimes and water resources management in the Rhine. International Commission for the Hydrology of the Rhine Basin. Available at http://www.chr-khr.org/files/RapportI-16.pdf.

GWP (Global Water Partnership). 2009. Available from http://www.gwptoolbox.org/ (accessed August 2009).

Hirsch, P. 2006. Water governance reform and catchment management in the Mekong region. The Journal of Environment & Development 15:184-201.

Hull, J., D. Kirk, and E. Wallace. 1986. Environment a proud river runs red. Time Magazine. Available from http://www.time.com/time/magazine/article/0,9171,962910,00.html.

ICPR (International Commission for the Protection of the Rhine). 2005. No frontiers for the Rhine: inventory 2004 in the Rhine river basin. Dr. A. Schulte-Wulwer-Leidig and D.M. Saha, editors. Koblenz, Germany.

Imhof, A. 2007. The Mekong: diverse, magnificent, threatened. World Rivers Review 22(2):2.

International Rivers. 2013. Lancang River dams: threatening the flow of the lower Mekong. Available from http://www.internationalrivers.org/files/attached-files/ir_lacang_dams_2013_5.pdf.

Jacobs, J.W. 2002. The Mekong River Commission: transboundary water resources planning and regional security. The Geographic Journal 168:354-364.

Lamoree, G. and A. Nilsson. 2000. A process approach to the establishment of international river basin management in Southern Africa. Physics and Chemistry of the Earth 25:315-323.

Lawrence, S. and C. Middleton. 2007. Mainstream dams threaten the mother of all rivers. World Rivers Review 22(2):6-9.

LeMarquand, D. 1990. International Development of the Senegal River. International Water Resources Association 18:54-68.

Medema, W., and P. Jeffrey. 2008. Factors that mediate implementation of Integrated Water Resources Management: Evidence from the Rhine basin. CAIWA conference proceedings. Available from: http://www.newater.uni-osnabrueck.de/caiwa/data/papers%20session/E3/conference_paper_CAIWA_Wietske%20Medema%20&%20Paul%20Jeffrey[1].pdf.

Mehtonen, K., M. Keskinen, and O. Varis. 2008. The Mekong: IWRM and Institutions. Pages 207-226 in O. Varis, C. Tortajada and A.K. Biswas, editors. Management of transboundary rivers and lakes. Springer, Berlin, Germany.

MRC. 2000. Mekong River Commission Secretariat Database and Information System, MRC. Available from http://www.mrcmekong.org/.

MRC. 2005. Overview of the hydrology of the Mekong Basin. Mekong River Commission, Vientiane, Lao PDR.

NASA. 1996. Image available from http://eol.jsc.nasa.gov/sseop/EFS/photoinfo.pl?PHOTO=STS075-721-47.

Oterdoom, H. 2001. From use and protection to sustainable development: the Rhine River, a case study. International Commission for the Protection of the Rhine, Koblenz, Germany.

Pearce, F. 2004. Where have all the fish gone? Independent. Available from http://www.independent.co.uk/news/world/asia/where-have-all-the-fish-gone-560635.html.

Phiri, Z. 2007. Rapid assessment of Water Resources in the Zambezi River Basin. Stakeholder Dialogue Conference - Preparing an IWRM Strategy for the Zambezi Basin. Victoria Falls, ZACPRO 6.2.

Ruchay, D. 1995. Living with water: Rhine river basin management. Water, Science and Technology 31:27-32.

Saha, D.M. 2008. Presentation at the International Commission for the Protection of the Rhine given for the NeWater Summer School. ICPR Headquarters, Koblenz, Germany.

Salidjanova, N. 2007. Chinese damming of Mekong and negative repercussions for Tonle Sap. Available from http://www1.american.edu/ted/ice/mekong-china.htm.

Scholes, R.J. and R. Biggs 2004. Ecosystem services in Southern Africa: a regional assessment. Council for Scientific and Industrial Research, Pretoria, South Africa.

Sneddon, C. and C. Fox, 2006. Rethinking transboundary waters: a critical hydropolitics of the Mekong basin. Political Geography 25:181-202.

Swatuk, L. 2005. Political challenges in implementing IWRM in Southern Africa. Physics and Chemistry of the Earth 30:872-880.

Task Committee on Sustainability Criteria, Water resource Planning and Management Division, ASCE and Working Group, UNESCO/IHP IV Project M-4.3, ASCE (American Society of Civil Engineers) & UNESCO 1998.

Tumbare, M.J. 2005. Management of shared watercourses in Southern Africa. Water Management 158:151-156.

Turton, A. 2008. The Southern Africa hydropolitical complex. Pages 21-29 in O. Varis, C. Tortajada and A.K. Biswas, editors. Management of transboundary rivers and lakes. Springer, Berlin, Germany.

UNEP/DEWA/GRID-Europe. 1998-2008. Europe publication “Freshwater in Europe”. Available at http://www.grid.unep.ch/product/ publication/freshwater_europe.php.

UNITAR (United Nations Institute for Training and Research) 2004. Training workshop on wetlands, biodiversity and water: New tools for ecosystem management. Hiroshima Office for Asia and the Pacific, Series on Biodiversity, Kushiro, Japan.

UN-Water, 2008. Status Report on IWRM and Water Efficiency Plans for CSD16. Prepared for the 16th Session of the Commission on Sustainable development in May 2008.

Varis, O., C. Tortajada and A.K. Biswas, 2008. Management of transboundary rivers and lakes. Springer, Berlin, Germany.

Verweij, M. 2000. Transboundary environmental problems and cultural theory: the protection of the Rhine and the Great Lakes. Palgrave MacMillan, UK.

WaterWiki.net. Provided and maintained by UNDP and UN-Water. Available at: http://waterwiki.net/index.php/Water_Conflict_and_Cooperation/Rhine_River_Basin.

Wirkus, L. and V. Boge. 2006. Transboundary water management on Africa's international rivers and lakes: current state and experiences. Transboundary water management in Africa: Challenges for development and cooperation. W. Scheumann and S. Neubert. German Development Institute, Bonn, Switzerland.

World Bank. 2009. Data and Statistics. Available at: http://data.worldbank.org/indicator/all.

World Water Development Report 3. 2009. Water in a changing world, United Nations.

ZAMCOM (Zambezi Watercourse Commission). 2012. Press release: Zambezi Watercourse Commision holds historic meeting. Available from http://www.zambezicommission.org/index.php?option=com_content&view=article&id=14:zambezi-watercourse-commission-holds-historic-meeting&catid=14:press-releases&Itemid=118.

ZAMCOM (Zambezi Watercourse Commission). 2013. Press Release. Available from http://www.zambezicommission.org/index.php?option=com_content&view=article&id=42:press-release&catid=14&Itemid=118.

How the West Was Watered: A Case Study of the Colorado River

Erin C. Betley[1]

[1]Center for Biodiversity and Conservation, American Museum of Natural History, USA

Abstract

This case study is divided into two parts to explore the Colorado River and the tradeoffs involved in managing the river. In Part I, background information on the river basin is presented within the social, political, and environmental context of the system's complex management framework. In Part II, the class is tasked with completing a brief stakeholder analysis for the river that allows them to explore the tradeoffs involved in managing the Colorado River. Finally, students are asked to use their understanding of the river and its stakeholders to explore how the West will be watered.

Case Study Subject and Goals

Through a case history format, this case study aims to provide undergraduate level students with a solid understanding of the geography, history, and environmental and political context of the Colorado River system. Students will consider how growth in human population, agriculture, and hydrological development impact the river and its ecosystems. They will understand how water rights and allocations affect various stakeholders in terms of tradeoffs. Finally, the case study will promote reflection and discussion on the issues of water conservation, water management and rights, impacts of water use and climate change on freshwater ecosystems, and science and policy.

PART I

EIGHT THINGS TO KNOW ABOUT THE COLORADO RIVER AND BIODIVERSITY

1. Currently, almost all of the water in the Colorado River is diverted for use by farms and cities; none reached the sea before a tiny fraction of water pulsed to the Sea of Cortez in May 2014 as a result of a historic agreement between the United States (U.S.) and Mexico.
2. Climate change is reducing the supply of Colorado River water.
3. Urban growth is increasing the demand for Colorado River water.
4. Agricultural use of water is favored by a complex system of water allocations originally devised in 1922 and modified by international treaties, court cases, and federal laws and policies.
5. River management is the result of complex negotiations between the U.S. and Mexico, among seven U.S. states, and among stakeholders representing agricultural users, municipal users, native tribes and environmental groups.
6. The reduction of flow in the river has greatly reduced the extent and quality of riparian, wetland, and estuarine habitats. Invasive species have also altered these habitats and several native species are at risk of extinction.
7. Little water is currently allocated to support natural ecosystems.
8. Because approximately 90% of the Colorado River's water is diverted before it reaches the border, most of the economic benefits of water use are within the U.S. and most of the environmental consequences occur in Mexico.

The Mighty Colorado

The dominant river of the American southwest, the Colorado River cuts a wide swath through not only vast deserts and arid plains, but also through the lives of many people and species. It is a dynamic body of water, with headwaters in the snowpack of Colorado's Rocky Mountain National Park, outlet in the Gulf of California, and over 2,250 kilometers in between draining water from Wyoming, Utah, Colorado, New Mexico, Nevada, California, Arizona, and Mexico (Figure 1). Its mighty force carved out the Grand Canyon, nourished life in great deserts, and fed an expansive delta. In the last 100 years, the river has become tightly regulated and is used so completely that it now flows only rarely all the way to the sea.

For thousands of years, Native Americans have lived along the river and used its waters. Remains of elaborate canal systems indicate that many of these tribes had sophisticated water management practices to irrigate fields of crops, while other tribes relied extensively on the river's ecosystems for hunting and gathering. Many of these tribes, including the Mohave, Hopi, Ute, and Navajo, continue to use the river's water. The Cucupá have continuously fished, hunted, and gathered in the river's Delta region for millennia.

Spanish explorers provided the first written documentation of the river in the 16th century, with expeditions originating from the mouth of the river. In the first few decades of the 19th century, explorers from the eastern United States began to travel along the river. Parts of its course were not mapped until 1869, in two expeditions lead by John Wesley Powell. The flooding regime of the river and its turbulent waters made navigation difficult, but early settlers used skiffs and steamboats to transfer people and supplies. With the construction of two massive dams, the Hoover and Glen Canyon Dams, in the 20th century the river became navigable, fueling a population and development boom.

The more recent history of the Colorado River tracks the story of one of the fastest growing regions in the United States. The river's water has fueled development and growth through irrigation, hydroelectric power, and water supplies for the burgeoning cities of Denver, Phoenix, Tucson, Las Vegas, San Diego, and Los Angeles among others both in and outside of the river's basin. Over 40 million people in the U.S. and Mexico use Colorado River water every day, for everything from municipal to industrial uses. Water from the river plays an integral part in keeping over two million hectares of farmland in production in the U.S. and hundreds of thousands of hectares in Mexico (USBR 2012). In addition to irrigated agriculture, the regional economy is also built upon livestock grazing, mining, forestry, manufacturing, oil and gas production, recreation, and tourism, all supported by the water of the Colorado River.

Figure 1. Colorado River Basin
By Shannon1 [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

The massive river infrastructure that delivers water to surrounding communities includes hydroelectric dams along with 12 major reservoirs on the river and its tributaries (see Figures 1 and 2) (Christensen et al. 2004). The two largest reservoirs, Lake Powell behind Glen Canyon Dam and Lake Mead behind Hoover Dam, comprise 85% of the river system's storage capacity and, combined, can store about four years of annual river flow (Christensen et al. 2004).

In transforming the river, humans have altered the spectacular natural ecology and hydrological features of the Colorado River, initially named "Rio Colorado" or "the Red River" by Spanish explorers for its reddish-brown, silty quality (USBR 2004). With the construction of dams and reservoirs, most notably the Glen Canyon Dam which trapped sediments that settled into the bottom of Lake Powell, the river has become tightly managed, with its flows regulated and clearer, more blue-green than red. The reduction of flow in the river has greatly reduced the extent and quality of riparian, wetland, and estuarine habitats—they are shadows of what they were 100 years ago—and the river's unique biodiversity has been significantly impacted. Invasive species have also altered these habitats and several native species are at risk of extinction. Part II of this case study explores many of the ecological consequences of changes in the river.

The Most Complicated Water System in the World: Management and River Policies

At the dawn of the 20th century, explorers had mapped the Colorado River, and as the promise of gold and fortune beckoned, populations in the American West expanded in extent and numbers. In 1902, with the settling of the West underway, the U.S. Bureau of Reclamation was instated to undertake the planning, construction, and implementation of numerous water diversion and storage projects in the western United States to promote this growth. In the 1910s and 20s, basin states began initial negotiations about the allocation of Colorado River water. In 1922, the Colorado River Compact was signed among seven U.S. basin states—a document that to this day allocates every drop of water in the river. Additional layers of interstate and international agreements, prior appropriation allocations, and federally reserved water rights for Native Tribes now comprise a "Law of the River," making the Colorado River the "most complicated water system in the world" (Gertner 2007; USBR 2011) (see Appendix 1.)

The Colorado River Compact divides waters of the river in the U.S. into two basins (the Upper Basin in Colorado, Wyoming, Utah, and New Mexico, and the Lower Basin in California, Nevada, Arizona). A treaty signed in 1944 by the United States and Mexico allocates some Colorado River water to Mexico. Using the volume of the "acre-foot" (one acre covered one foot deep in water or enough water to supply two households for a year, also equivalent to 1,230 million cubic meters), the Compact states that the Colorado's waters are to be divided between the Upper and Lower Basins, assigning 7.5 million acre-feet (maf) per year to each, while at the same time requiring that the Upper Basin deliver to the Lower Basin 75 maf over a moving ten year average. These two requirements in the Compact create one of the fundamental controversies of the Colorado River: when total flows over a 10-year period are less than what was contemplated in the Compact, which Basin must bear the shortage? Furthermore, within each basin, how will multiple states manage a potential water shortage? Meanwhile, the Treaty guarantees Mexico 1.5 maf per year, with the exception of years of "extraordinary drought" - a term not yet defined - when deliveries might be proportionally reduced to all other states.

The river's infrastructure supports the terms of the Compact (Figure 2). For example, Lake Powell's purpose is to store flows to ensure the Upper Basin's annual delivery requirement to the Lower Basin. Lake Mead stores water released from Lake Powell and regulates water deliveries for Lower Basin water users and Mexico. Water deliveries to users depend on water availability in reservoirs: Upper Basin deliveries depend on water in Upper Basin reservoirs and Lower Basin deliveries depend on water levels in Lake Mead. It is critical to note that during ideal conditions, the river's reservoirs store more than four times the river's annual flow, so the river's annual hydrology can be very different from the state of its reservoirs. Therefore, water users may start to experience shortages long after a dry period begins, but shortages may continue long after normal or wet conditions return.

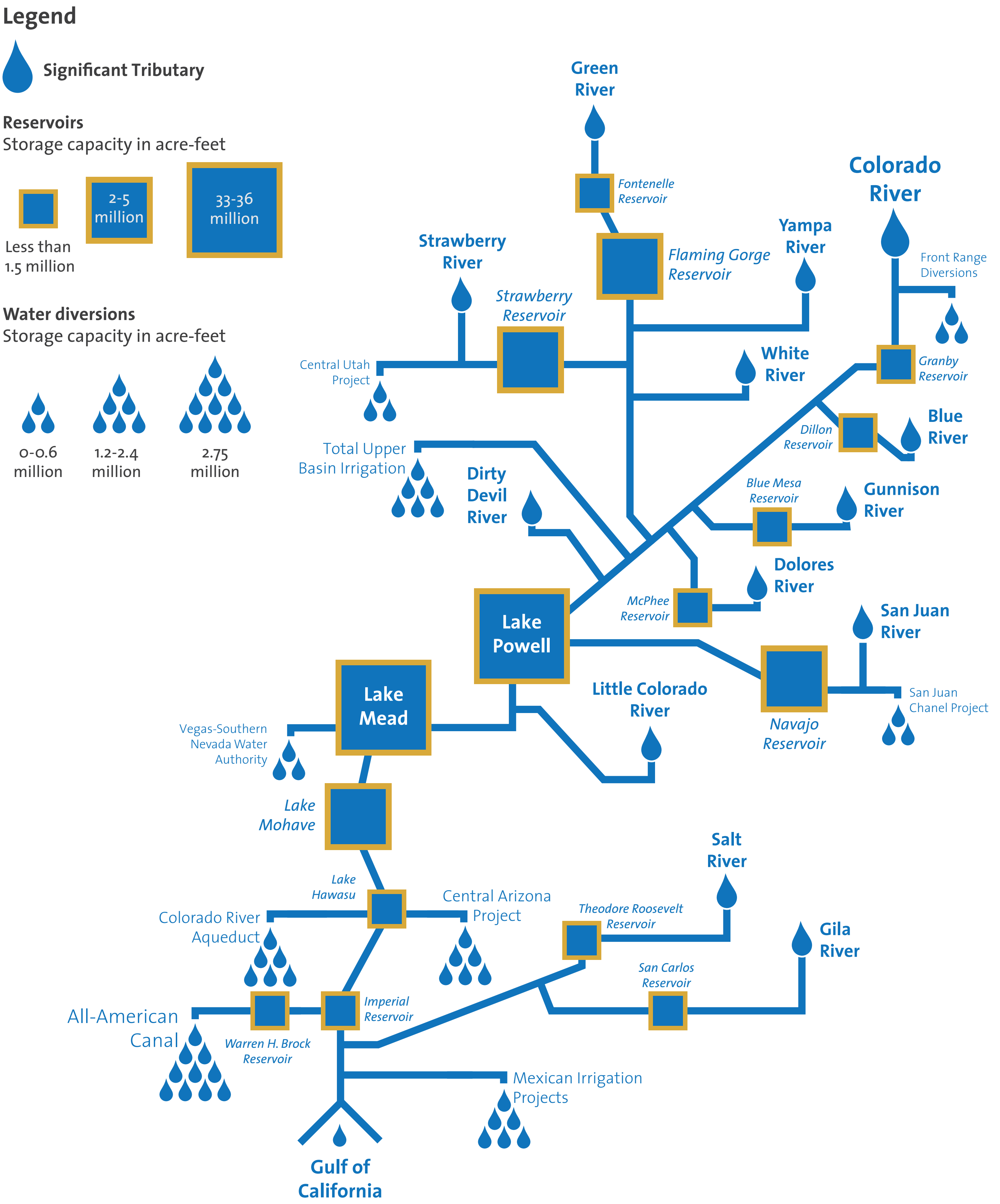


Figure 2: Infrastructure of the Colorado River (adapted from HCN Publisher, Ed Martston). Illustration by Nadav Gazit

A cast of main players orchestrates the tight river regulation (see Appendix 1), led by the U.S. Bureau of Reclamation, which builds and oversees the management of the Colorado River's water storage and delivery infrastructure, including Lake Mead and Lake Powell. It is important to note the international nature of this river: Colorado River management has been primarily a domestic issue for the U.S., while Mexico is significantly impacted by critical upstream policy and management decisions.

Status of Colorado River Allocations

While the legal framework that allocates Colorado River water is firmly established, the flows in the river itself vary, given the amount of melted snowpack in the headwaters. This variability can be extreme—the historic record shows that annual flows can range from four maf to 24 maf. This variation, in turn, is at the root of past and future concerns about how water is managed. For instance, streamflow measurements from 1886-1921 at Lees Ferry in Arizona at the dividing line between the Basins (24 kilometers below Glen Canyon Dam at the entrance to Grand Canyon National Park) were used to frame the terms of the Compact. However, recent research has shown that these were some of the wettest years for the Colorado River in the last century (Figure 3, Box 1), while recent years have matched the more typical drier periods in the known history of the river (Vano et al. 2014).

The disparity in river levels has resulted in conflicts over how to allocate scarce resources. For the majority of the last 40 years, the river has run dry before reaching the once expansive delta into the Gulf of California (Flessa et al. 2013), a phenomenon that has been replicated in many of the world's major rivers, including the Nile, Yellow, and Indus (Gleick 2003).

The Upper Basin states currently consume between 4.1 and 4.6 maf per year of their Compact entitlement of 7.5 maf. However, the Bureau of Reclamation concluded more than a decade ago that based on historic records of Colorado River hydrology, only 6.0 maf per year (including reservoir evaporation) is actually available to Upper Basin States in light of their obligation to deliver 75 maf over a ten year rolling average to the Lower Basin States plus half of the 1.5 maf per year delivery obligation to Mexico. Meanwhile, the Lower Basin has reached full use of its allocation, and even exceeded its allocation for several years in the 1990s – using excess water from the Upper Basin allocation to meet this demand. Two critical factors have been at play in the Lower Basin in recent years: a "use it or lose it" system of water rights and increasing urban demand, especially in areas that are outside the river basin. The initial formation of the Law of the River occurred when populations were low and during the era of manifest destiny, when agriculture was seen as the best way to provide livelihoods in the desert and settle the region, and rights were allocated to support farms. Despite brisk population growth in urban centers and concurrent increases in water demand,

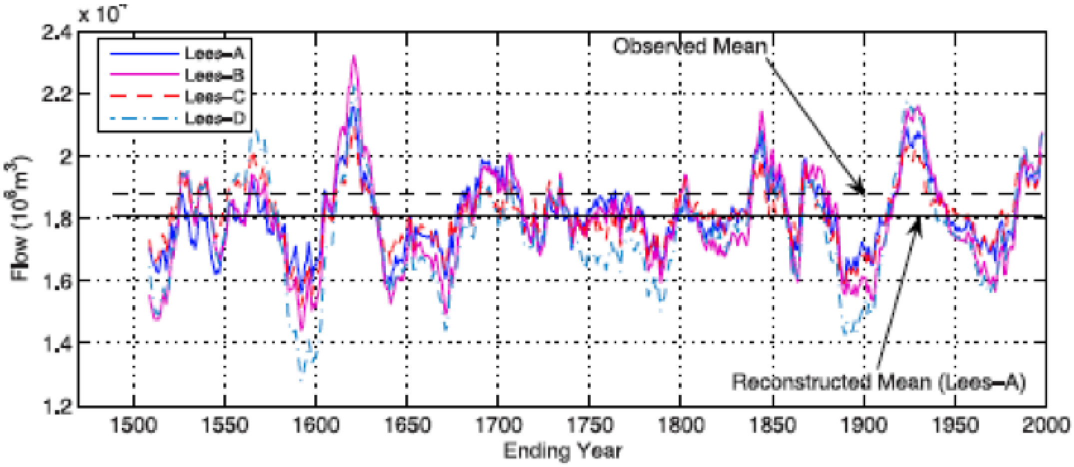


Figure 3: Time-series plot of the annual flow volume (in millions of acre-feet) for the Colorado River at Lees Ferry (Woodhouse et al. 2006).

agricultural water users still hold the vast majority of the Lower Basin's water rights and consume 70% of all the water in the basin (Morrison et al. 1996; Gertner 2007; Kuhn 2012; USBR 2012).

In Mexico, the region affected by the Colorado River is the area along the California and Arizona borders. The region includes urbanized areas such as the Mexicali-Calexico and the San Diego-Tijuana areas, but also major agricultural areas such as the Imperial and Mexicali valleys and important environmental features along the river corridor and its Delta.

A wide variety of crops are raised throughout the entire river basin, from hay in the Colorado Plateau to fruits and vegetables on the U.S./Mexico border. This irrigated agriculture is valued in the billions of dollars, and significant crops include vegetables and winter lettuce. The majority of water used in agriculture irrigates intermediate crops (those not directly consumed by humans, but by livestock) such as alfalfa and sudan grass that generate lower economic returns and is often exported.

Rapid population growth in the cities of the southwestern U.S. and Mexico has created new urban demands. For example, Las Vegas, one of the fastest growing cities in the U.S. in recent years with over two million people in the driest valley of the nation's driest state, gets 90% of its water from Lake Mead (notably, the city gets most of its electricity from the Hoover Dam) and has been using its full allocation for more than a decade. To provide water for an increasing population, Las Vegas' water providers have implemented aggressive water conservation policies and are pursuing development of groundwater extraction projects elsewhere in Nevada. Significantly, the majority of urban water use is outdoors, where water is used for landscaping, irrigating lawns, and filling swimming pools.

It is crucial to note that these water allocations for human uses do not take into account the needs of

Box 1. Drought, Climate Change, and the River

Recent research has examined the complex hydrological regime of the Colorado River and the implications of continued drought and climate change. River modeling by federal agencies and water managers is done using historical datasets on river parameters with the assumption that future flows will mimic those of the previous century. However, researchers are discovering that the years of data that formed the basis of the Colorado River Compact were among the wettest compared to the rest of the 20th century. Some scientists warn that this fundamental assumption may over-estimate the average stream flow by as much as 20% (Dettman 2004), and recent studies have projected a decrease in the natural water supply (USBR 2012). Furthermore, these particular years may have been the wettest in more than one thousand years. Data supporting this assertion has come from numerous tree-ring studies that reconstruct precipitation and river flow in the basin over time (Woodhouse et al. 2006; Woodhouse et al. 2010).

Since 1999/2000, the Southwest has been in the midst of a multi-year drought and the Colorado River had some of the lowest flows since stream flow gauges were installed. It is notable that this recent drought pales in comparison to some of the most severe droughts that have been documented in the southwest over the past 1,500 years—the most severe of which lasted 50 years (Woodhouse et al 2010). The water shortages occurring today may not be an aberration, but a return to a historical norm.

Furthermore, climate change is of particular concern for the Colorado River basin due to the sensitivity of the Rocky Mountain snowpack accumulation that feeds runoff, and will only exacerbate the problem of drought. Numerous studies have assessed the hydrologic and water resources impacts in the river basin, using a range of climate change scenarios including those recently set forth by the Intergovernmental Panel on Climate Change (2013). Many of these studies suggest vulnerability of the river to changes in precipitation and temperature-related effects, such as increased evapotranspiration, which could result in reduced stream flows of between five and 35% in the coming decades and depleted reservoirs (Christensen et al. 2004; Christensen and Leittenmeier 2006; McCabe and Wolock 2007; Rajagopalan et al. 2009; Woodhouse et al. 2010, USBR 2012, Vano et al. 2014).

biodiversity. In recent decades, stakeholders have begun to recognize the importance of freshwater flows for native species and riparian habitats and how Colorado River water allocations have negatively impacted biodiversity. Laws such as the Endangered Species Act were created to protect threatened and endangered species, and government and state agencies have worked to conserve some key habitat, through initiatives such as the Grand Canyon Protection Act of 1992. Numerous groups have emerged to advocate for nature as a stakeholder, including the Nature Conservancy, Sonoran Institute, ProNatura, Environmental Defense Fund, and Defenders of Wildlife. While in most cases, "nature" is not a recognized user of water in the system, especially in the context of the Law of the River and river allocation schemes, freshwater needs for biodiversity constitutes a critical demand on the river's water.

The River Allocation Dilemma

Due to natural flow variability, the 1922 Compact allocated more water than is actually available in the river (Box 1). As Upper Basin water users plan new projects to extract water from the river that belongs to them under the terms of the Compact, and as climate change promises to decrease flows in the river, the specter of a "Compact Call" is raised. If the Upper Basin states fail to deliver enough water, Lower Basin states may try to legally force Upper Basin states, through provisions in the Compact, to reduce consumption - a politically charged situation (Gertner 2007). While the specter of a Compact Call has not been raised since, water levels in Lake Powell and Lake Mead have dropped to levels just above limits that would trigger declaration of a water shortage. In 2007, spurred by a multi-year drought, declining reservoirs, and growing water demands, the seven Colorado River basin states in the U.S. took steps to begin to address the situation by signing a historic agreement that established additional guidelines in the instance of a water shortage in the Lower Basin (USBR 2007). The complex agreement specifies that if levels in Lake Mead drop below a set level, Arizona and Nevada will have to curtail their use of water, while California's allotment of 4.4 maf will be upheld, due to the terms of a series of Supreme Court cases dealing with disputes between California and Arizona over Colorado River water.

The dilemma is exacerbated by the fact that the allocation system gives little incentive to reduce water use as water is heavily subsidized and users tend to adopt "use it or lose it" policies that perpetuate rights secured on a first-come, first-served basis. New cities must purchase existing rights from agricultural districts that may be reluctant to trade these precious senior rights. New water users reliant on the basin's groundwater confront dropping water tables. Unless there is a limit to extraction, each new well puts further pressure on a declining resource.

PART II

"You could not step twice into the same river" - Heraclitus

WHAT ARE THE TRADEOFFS?

The water regulation regime of the Colorado River means tradeoffs for stakeholders. How do these tradeoffs impact others upstream and downstream?

Class Activity: Brainstorm a list of stakeholders in the Colorado River and their primary concerns. Then, read through the tradeoffs below and identify two key stakeholders who are affected by each tradeoff. How are they affected, and what are possible strategies for mitigating these impacts?

Optional activity: Use the Stakeholder Analysis NCEP module to identify key stakeholders and their concerns (available at ncep.amnh.org)

Water rights and the accommodation of new demands

The issue of water rights is central to the historical and current context of management of the Colorado River. As indicated in Appendix 1, the 'Law of the River' tightly controls how water is allocated amongst stakeholders. Within this allocation scheme, there are few options for securing additional Colorado River water. Las Vegas, for example, relies on banking, trading, reusing, and buying water rights to sustain its growth.

As noted above, agriculture is the main recipient of Colorado River water, but there is a growing need for

municipal and industrial uses of water. The key water rights issue for the Colorado River is that rights were appropriated under the principles of prior appropriation (which means first in time, first in right, so that the oldest rights have priority over newer rights, and when there is not enough water to satisfy all rights, the newer rights will be cut off first). Agricultural districts were well established before many cities applied for water rights, creating a situation where cities are more vulnerable to shortages than farmlands. Colorado River water rights are permanent and cannot be renegotiated, and while they can be sold, there are restrictions on interstate trading. In addition, an individual farmer cannot sell water to an external user without the approval of their irrigation district, and districts are often wary of selling a resource whose value only increases over time. Despite these restrictions, water for growing urban populations is so valuable that cities throughout the Colorado River basin have purchased rights to Colorado River water from farms, a practice often criticized as "buy and dry" for the impact it has on the rural, selling communities. Some more innovative deals have been struck, such as those where cities pay farmers a contracted rate for the right to use the water during shortage years when the city would experience a water shortage due to the junior status of its rights. This "dry year lease" allows farming to continue in most years.

Out-of-basin transfers, where water is moved through massive pipelines, constitute a tradeoff as well, since water moves out of the system and is not returned to the Colorado River's streamflow. Water slated for use in homes and farms around Phoenix and Tucson, Arizona, travels along the 540-kilometer Central Arizona Project canal (built in 1985) from Lake Havasu through the Sonoran Desert. Other massive infrastructures are the 390-kilometer Colorado River Aqueduct in Southern California, the 112-kilometer San Diego Aqueduct, and the 200-kilometer Coachella Canal in California. The 136-kilometer All-American Canal provides water for the Imperial Valley of Southern California, a productive agricultural region that was once desert. Colorado's Front Range, including Denver, imports Colorado River water through mountain tunnels across the continental divide.

Furthermore, one of the most complex management issues facing the Colorado River is the legal definition, quantification, and allocation of Native American water rights claims. When the United States reserves public land for Native Americans, it implicitly reserves sufficient water to satisfy the purposes for which the land was reserved. This practice is known as the federal reserved rights doctrine, based on a 1908 U.S. Supreme Court case that confers senior water rights to Native American users in states that may be already using their full allocation of Colorado River water. Many of the unsettled rights involve large quantities of water, potentially impacting water uses around the basin and as well as long-term planning for the basin (Morrison et al. 1996; USDOJ 2014).

Salinity and water quality

The Colorado River system is naturally very saline—natural springs that feed the river's flow add more than half of the river's salt load. Many factors directly influence salinity in the basin: stream flow, reservoir storage, water resource development, salinity control methods (such as properly draining irrigation fields), climatic conditions, and natural runoff. Almost seven billion kilograms of salt are carried past the U.S. Geological Survey gauge below Hoover Dam each year. The flow of the river dilutes this salt, and depending upon the quantity of flow, salinity can be relatively dilute or concentrated, though salinity is cumulative and generally increases downstream, so salinity levels are highest in water being delivered to Mexico (USBRUC 2013).

Salinity levels are directly influenced by salt loading (as salt is carried from land into the river) and consumption of water flowing in the river system. While salt loading can come from natural runoff and runoff from human activities such as logging, mining, and urbanization, irrigated agriculture is the largest user of water in the Colorado River basin and a major contributor to the salinity of the system. Agriculture increases salinity by consuming water through evapotranspiration and by leaching salts from saline soils, a process where salt is extracted from soils by dissolving in water (Box 2). Municipal and industrial use increases salinity through the consumption of the water. The combined effects of instream, nonconsumptive water use and off stream consumption have had a significant impact on the river's

salinity. The basin wide drought since 1999 has also had an influence on the present high levels of salinity of the Colorado River (USBRUC 2013).

A significant negative impact of the salt concentration is economic. The last estimate of salinity damages in the Lower Basin alone was almost $300 million per year, primarily due to reduced agricultural crop yields, corrosion, and plugging of pipes and water fixtures (USBRUC 2013).

Salinity control projects have been implemented for decades, and salinity has been dramatically reduced since its 1970s highs. Much of the current salinity control in the river basin focuses on managing and minimizing salt loading into the river, primarily due to increased irrigation efficiency (Butler 2001). To achieve this goal, a variety of salinity control methods are used. Saline springs and seeps are collected for disposal by evaporation, industrial use, or deep-well injection. Other methods include both on-farm and off-farm delivery system and irrigation improvements, which reduce the loss of water and reduce salt pickup by improving irrigation practices, controlling soil erosion, protecting riparian areas, and by lining canals and ditches (USBR 2014a).

Salinity is not the only water quality concern in the Colorado River basin. Other issues of concern include reservoir eutrophication and algal impacts; natural bromide in the water and formation of potentially toxic or carcinogenic compounds with chlorination or ozonation during water treatment; selenium and trace elements from irrigation return flows and their impacts on endangered species; contaminants such as ammonium perchlorate and pharmaceuticals into Lake Mead; and ammonium, trace elements, and radiologicals from uranium mine tailings along the river (USBRUC 2013).

Box 2. The Story of the Salton Sea: No Easy Answers

The Salton Sea is California's largest lake, located just north of the productive agricultural area known as the Imperial Valley, part of the Imperial Irrigation District. However, the saline Salton Sea is no ordinary lake, owing to its complex history. The area is part of the Salton Sink that has intermittently held prehistoric lakes from spillover from the Colorado River. Prior to the turn of the 20th century, the area that is now the sea was a dry area where salt mining occurred. The present lake was created when heavy flow caused the Colorado River to breach a dyke in 1905 and then flood the area. Water flowed into the basin for two years before river flow was controlled—the lack of any drainage created a massive saline lake that is now saltier than the oceans (Salton Sea Authority 2014).

Today, the lake is replenished by agricultural runoff from nearby irrigated farmland in the Imperial and Coachella Valleys. Over the past century, the Salton Sea has become the "crown jewel of avian biodiversity" with over 400 bird species relying on its critical position along the Pacific Flyway. However, the Salton Sea is continuing to get saltier, which combined with other threats such as increasing nutrient levels from runoff and fluctuating surface levels, affects many species such as fishes and micro-organisms that support the diverse bird populations in the Salton Sea National Wildlife Refuge. To add to the dilemma, political roadblock is fast approaching, due to terms of an existing agreement among several agencies that manage Colorado River water. The agreement decrees that water transfers from the Imperial Irrigation District to San Diego and the Coachella Valley must begin in 2018. Human health consequences also loom, as the increasingly exposed lakebed produces dust that threatens air quality—a phenomenon that will increase when water transfers commence. In recent years, stakeholders including the Salton Sea Authority, US Bureau of Reclamation, California Resources Agency, and California Department of Water Resources, among others, have created various restoration plans for the sea. These plans range from the Salton Sea Restoration program, a $9 billion plan to restore a smaller but more manageable Salton Sea that includes habitat for birds and fish, to lower cost efforts to save an even smaller portion of the sea, financed by on site renewable energy projects (California Department of Water Resources 2014; Salton Sea Authority 2014). Given the high cost of the plans, progress has been slow to date and confined to small habitat restoration projects, while at the same time, costs of inaction continue to accumulate, to the tune of billions of dollars in health care costs, and reduced property values and agricultural productivity (Cohen 2014).

Riparian habitats and species

Riparian ecosystems are among the most diverse, dynamic, and complex biophysical habitats on the terrestrial Earth. Moreover, these ecosystems attenuate flooding, maintain elevated water tables, improve water quality, and thus provide valuable human and ecological services. Riparian corridors are also critical habitat for desert flora and fauna, providing oases of species richness and high productivity in otherwise dry environments. They are critical routes for migratory birds passing through desert regions on their way to nesting or wintering grounds. The integrity of riparian landscapes is maintained by disturbances. Because of its ecotonal nature and position in the landscape, riparian vegetation experiences disturbances associated with both aquatic systems (e.g., flooding generated by spring snowmelt and channel widening) and uplands (e.g., fire and wind throw) (All 2006).

Riparian zones in the western U.S. and Mexico have undergone remarkable changes over the past century through water diversion, groundwater decline, flow regulation, channelization, and dams that reduce flows and eliminate the normal pulse flood regime of dry-region rivers. The impact of these changes on riparian habitats has been exacerbated by spread of opportunistic invasive species. One such invasive is the salt-tolerant shrub saltcedar (*Tamarix ramosissima*), which along with a native salt-tolerant shrub arrowweed (*Pluchia sericea*), has largely replaced native cottonwood (*Populus fremontii*) and willow trees (*Salix gooddingii*) on the lower Colorado River. Loss of these native trees that depend on timed, seasonal flooding for germination, has degraded the habitat value of the riparian zone for wildlife (especially birds that use rivers as migration routes and nesting sites) and programs to restore native trees are underway (DiTomosa 1998; Stromberg 2001; Nagler et al. 2004). While intensive salt-cedar eradication removal programs use mechanical, chemical, and biological control agents, research indicates that a restoration of the natural flood pulse regime of the river may assist with regenerating native vegetation. Studies support the hypothesis that restoration of a pulse flood regime will regenerate native riparian vegetation despite the presence of a dominant invasive species, and suggest that natural resource managers and river operations specialists should examine the potential for providing beneficial floods on arid-zone rivers as a means of reestablishing native vegetation (Nagler et al. 2005; Tiegs et al. 2005; Glenn et al. 2013).

The Grand Canyon ecosystem was drastically altered by the Glen Canyon Dam: natural flash floods that would previously scour the canyon and deposit fertile sediment from tributaries originating in the Colorado Plateau no longer occur. Given the research indicating the restoration potential of pulse floods, managers began a program of experimental releases of man-made floods from Glen Canyon Dam in 1996, in efforts to mimic the natural flooding behavior of the river prior to the 1963 construction of the dam. Notably, these releases change the rate of water deliveries from Lake Powell to Lake Mead downstream, but not the total volume. The flows are part of an adaptive management strategy, building on the results from each test, intended to deposit sand up and onto eroded Grand Canyon sandbars and beaches, restore vegetation, and create habitat for endangered fishes as required by the Endangered Species Act. Scientists have conducted experiments during and following the floods to assess the impact of high water flows on key species and habitats in Grand Canyon National Park. These experiments have yielded mixed preliminary results, with increase in sandbar area and volume in some portions of the river and some erosion in others. Scientists are now testing more frequent high flow pulses to prevent erosion (USBR 2013).

Since the construction of the Glen Canyon Dam, the Grand Canyon ecosystem has also been characterized by cooler and clearer water, since the once warm water of the river now sits for long periods in Lake Powell. All of these changes have affected the native biota, such as the federally endangered humpback chub (*Gila cypha*) and razorback sucker (*Xyrauchen texanus*). The Colorado River contains one of the most unique collections of fish fauna in North America – with as many as three quarters of its approximately 32 freshwater species recognized as endemic (Minckley et al 1986; Minckley and Deacon 1991). More than 50 species of non-native species have been introduced into the upper parts of the river alone, where they compete with native fishes in areas where their ranges overlap (Upper Colorado River Endangered Species Recovery Program 2014).

Water managers have begun to understand how changes to the river have affected native species and protection and restoration initiatives are underway, including several major federal recovery and mitigation programs. Since 1988, the Upper Colorado River Endangered Fish Recovery System has worked to recover endangered Colorado River basin fishes. The Lower Colorado Multiple Species Conservation Program is a coordinated long-term effort to conserve and work towards recovery of endangered species and protect and maintain wildlife habitat in the Lower Basin. This is one of the largest conservation plans ever attempted. Both recovery efforts involve multiple stakeholders, from federal and state agencies to environmental groups and other private organizations. The driving legislation behind these initiatives is the Endangered Species Act, which calls for agencies to provide for the survival and recovery of threatened and endangered species through conservation and management initiatives, such as designating critical habitat and creating recovery and habitat conservation plans (USBR 2014b; Upper Colorado River Endangered Species Recovery Program 2014).

While the network of dams along the river has ecological consequences, they provide necessary services for many residents both in and out of the basin. The hydroelectric power facilities along the river and its tributaries generate approximately 12 billion kilowatt-hours annually that is used both inside and outside the basin, and the revenues from the dams underwrite programs ranging from salinity control to fish habitat restoration (Tillman and Anning 2014).

As highlighted in the next section, the river's management has significantly affected the riparian habitats and species in Mexico (some of the largest patches of riparian habitat remaining in the entire Colorado River basin), especially in the Colorado River Delta. However, as evidenced by numerous verdicts in U.S. courts, the U.S. federal government's claims of responsibility for species protection ends at the border, so even the Endangered Species Act does not require that programs such as the Lower Colorado Multiple Species Conservation Program incorporate the Delta into its planning process.

Colorado River Delta

Some of the most pronounced tradeoffs in the way the river is regulated are the consequences for the Colorado River Delta. Before its damming and diversion, the Colorado River emptied virtually its entire flow into the Gulf of California, also known as the Sea of Cortez (Dettman et al. 2004). These massive freshwater flows created a landscape of wetlands and forests that the famed conservationist Aldo Leopold described as "a hundred green lagoons" when he visited in 1922. Since that time, major impoundments caused first by Hoover Dam (Lake Mead filled from 1935-1957) and then by Glen Canyon Dam (Lake Powell filled from 1964-1981) desiccated the Delta. Except for a few limited occasions, no water flowed beyond Morelos Dam at the border in Mexico from 1960 until 1980 as these reservoirs filled (Pitt et al. 2000; Zamora-Arroyo et al. 2008). Even during wet years, water was simply captured behind the dams rather than transmitted to the Delta and the sea (Glenn et al. 2001) (see Figure 4 for water levels at the international border.) Since the river no longer reached the ocean in most years due to upstream withdrawals, key riparian, wetland, and intertidal habitats that normally sustain bird populations, fisheries, and coastal fishing communities were compromised (Gleick 2003). The balance between freshwater flows and saltwater intrusion was also altered, further affecting riparian species.

Residents in the Delta region are primarily fishermen, farmers, and workers employed in service industries for these professions. Agricultural irrigation currently dominates the water usage agenda in northern Mexico, and the Colorado River provides water to hundreds of thousands hectares of irrigated farmland (Glenn at al. 2013). Most fishing income in the past was derived from the shrimp industry; however, this industry has been decimated in recent years both by overfishing and lack of the fresh water influx that shrimp are dependent upon. Fishing is dependent on habitat quality and the intensity of fishing effort, whereas farming relies strongly on availability of irrigation water. Human vulnerability to fluctuations in ecosystem productivity in these areas is pronounced for the Gulf fisheries (All 2006).

Increased public interest in environmental issues over the years has substantially boosted attention to the Delta from governments, non-governmental organizations and environmental groups on both sides of the border. Scientists are working to understand and reconstruct the relationship between Colorado River freshwater flows and the health of the estuary. Aragon-Noriega and Calderon-Aguilera (2000) show a statistically significant positive correlation between river flow and the relative abundance of postlarvae of the shrimp Litopenaeus stylirostris in the years 1993–1997. Rowell et al. (2005) used oxygen isotopes in fish otoliths to determine that Colorado River flow is important in providing brackish water nursery habitat for the Gulf corvina (*Cynoscion othonopterus*), a commercially valuable and endemic fish in the upper Gulf of California. The results also supported the hypothesis that declines in commercial landings of Gulf corvina can be partially attributed to reduced river flow and that increased flow would increase nursery habitat and likely benefit recruitment.

Notably, the Colorado River Delta in Mexico has shown resilience and has revegetated somewhat following 20 years of water flows from the U.S. Lake Powell, the last major impoundment built on the river, filled in 1980. Since then, flood flows in the main channel of the river, released by managers in the United States when flows exceed available storage capacity and uses, have occurred in El Niño cycles, and have returned native trees and other vegetation to the riparian corridor, as the pulses led to the germination of willow and cottonwood seeds. In addition, environmental organizations working in the Delta began to purchase water from local farmers to irrigate nascent restoration sites, indicating the significant restoration potential for the Delta should some freshwater flows be regularly restored. The native riparian vegetation provides a migration route for endangered southwestern willow flycatchers (*Empidonax traillii*) and other migratory birds moving north from Mexico for summer nesting. The Delta is an important stopover point on the Pacific Flyway with 55% of the total bird species in North America breeding, wintering, and/or migrating through the area (Zamora-Arroyo et al. 2008). Many studies report that these flows have improved the ecology of the intertidal zone and the marine zone in the Upper Gulf of California (Glenn et al. 1996; Pitt et al. 2000; Nagler et al. 2005; Glenn et al. 2007).

More recently, a historic agreement, five years in the making, between the U.S and Mexico resulted in the release of the largest pulse of water into the Delta in decades, to be followed by a smaller permanent annual flow to sustain the ecosystem. The initial two-month long flood, enough water to reach the Gulf of California according to sophisticated models, was designed to simulate a natural spring flood, trigger germination of

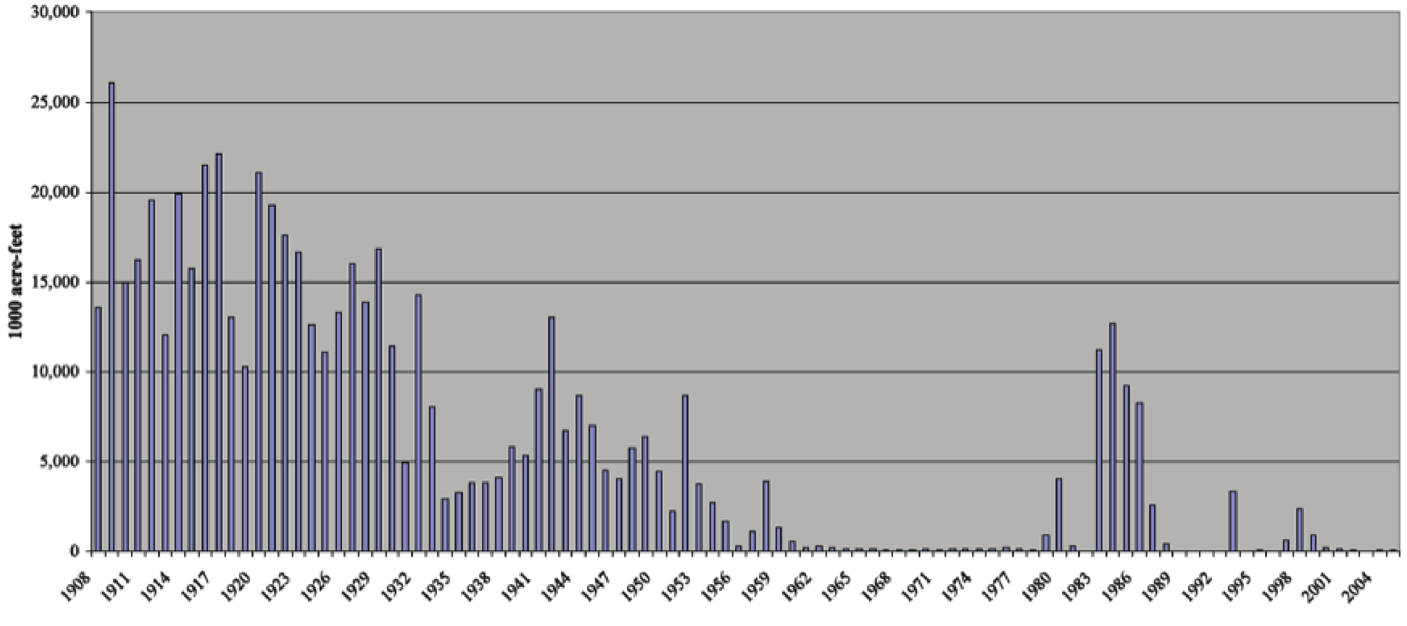


Figure 4: Colorado River Annual Flow Volume Below Major Dams and Diversions, 1908-2005 (Wheeler et al. 2007).

native seeds, and create new wetlands, while the annual flow is designed to maintain this new growth (Glenn et al. 2013). The pulse flow, about one percent of the river's historical flow, was released from the Morelos Dam on March 23, 2014. According to the terms of the agreement, scientists will carefully assess the hydrological, ecological, and operational consequences of the new water deliveries by stakeholders, and continue to write the story of the Colorado River Delta (Water Education Foundation 2014; Witze 2014).

Groundwater

Surface water is derived from precipitation and can be diverted. Groundwater, however, accumulates from precipitation, irrigation, or river seepage that is absorbed into the ground and is collected in underground aquifers over thousands of years. Groundwater – both renewable and nonrenewable - can then be accessed through wells and is also a major contributor to surface water flows. In addition to supplying surface water, the Colorado River provides groundwater to surrounding areas.

In the arid West, only a small portion of groundwater can be recharged through precipitation. Continuous withdrawals can cause water tables to drop, aquifers to collapse, and lands to sink, resulting in loss of valuable water storage resources. In addition, groundwater pollution can be more severe than surface water pollution, as the normal cleansing mechanisms at work in surface waters are not present in ancient aquifers threatened by agricultural runoff, dumping of wastewater, and industrial and hazardous waste. Salinity, in particular, is one of the most devastating forms of groundwater pollution in the Colorado River basin, derived from salt percolating down from agricultural fields (Morrison et al. 1996).

Groundwater in the Lower Basin is already over drafted above natural recharge levels, which has direct impacts on levels of groundwater surfacing in the Colorado River Delta region. This is compounded by the already overdrawn Mexicali aquifer, which provides water for Mexican farmers. In some areas where water from the Colorado River is imported, groundwater is heavily used, but not always regulated. Any solution to these conflicts is complicated by the fact that the problem of groundwater management is after-the-fact: unregulated water is often over-appropriated before overdraft consequences are evident. Any action therefore will require individual stakeholders to give up water rights, so any attempts to regulate groundwater would be expected to face opposition from agricultural interests fearing pumping restrictions and local water districts opposing oversight (Morrison et al. 1996). A recent study, using satellite data to track groundwater depletion in the Colorado River basin from 2004 to 2013, found such significant losses in the basin during these drought years (equivalent to two full Lake Meads) that the depletion may threaten the long term ability to meet future allocations of surface water (Castle et al. 2014). Startlingly, the study found that groundwater was filling the gap between demands and the annual renewable surface water supply, and given its decline, this groundwater supply is nonrenewable, indicating that the available stock of freshwater in the basin is in significant decline.

HOW WILL THE WEST BE WATERED?

This case study has given an overview of the complex social, political, and environmental framework that follows the Colorado River along its course.

Class Activity: Given this information and your own creativity – break into groups and brainstorm ways that the West will be watered in the future. How does climate change affect this process? What other factors may come into play in the future? Specific discussion points are given below.

The realities of increasing demands on finite water resources mean challenges ahead for the southwestern U.S. and there are no easy answers. The modern history of the Colorado River has been marked by the principle of building more infrastructure to sustain economic growth, but is transitioning to an era of increasing institutional flexibility such as the use of markets to transfer water to accommodate new water needs including those of freshwater ecosystems. However, the challenges ahead may require a more comprehensive approach. Possibilities lie in new policies, cooperation, technologies, and tired and true conservation.

Agricultural and urban conservation initiatives

The powerful U.S. Bureau of Reclamation has shifted from dam–building to resource management. The agency recently released a report on the supply of and demand for Colorado River water that explored various options for meeting future demands, ranging from increasing supply and reducing demand (through reuse and conservation measures), to modifying operations to reduce evaporation, to transferring and banking water throughout the system (USBR 2012). Despite the inherent uncertainties in projecting climate change and population growth, this report makes clear that the West is urgently facing a water crisis. The report projects that by 2060, river supplies will fall short of demand by about 3.2 million acre-feet—more than five times the amount of water annually consumed by Los Angeles (Figure 5).

There are significant opportunities for water conservation in the biggest water-consuming sector of agriculture. Morrison et al. (1996) estimate that improvements in irrigation efficiency or shifts in cropping patterns can free significant amounts of water for ecological or other purposes. For Arizona, the authors estimate that upgrading half of all irrigated cotton and major vegetable and citrus crops to drip or other micro-irrigation techniques, and upgrading half of irrigated alfalfa, wheat, and barley crops to more efficient irrigation methods could save on the order of 445,000 acre-feet of water per year. Combined with other conservation approaches, an approximately 1.24 maf could be saved per year, comparable to the groundwater overdraft in Arizona. However, the benefit of water conservation is not always clear-cut: some water used for agriculture drains back to the river and is used by others downstream, though repeated withdrawal of water for agriculture and return drainage can increase the river's salinity downstream.

Urban conservation will also be part of the way the West will be watered. Successful efforts to curb domestic water use permanently will include a combination of economic incentives, efficiency standards and regulations, voluntary retrofits of appliances for example, and public outreach that together promote the use of water-saving technologies and behaviors. Since outdoor water use accounts for the majority of domestic water use, technologies and behavior change also need to apply to landscaping and other outdoor water uses. These initiatives, however, are dependent upon a stabilized rate of population growth—a complex challenge that requires urban planning and growth management tools.

Any water conservation measures in the home, business, and agriculture are complicated by the "use it or lose it" structure of the Colorado River allocation scheme—though stakeholders are now working collaboratively to make adjustments to this system, within the confines of the Law of the River, through tools like economic incentives and properly designed water pricing and tax structures. As an example of an innovative approach to modifying the rigid allocation structure, the four largest cities (Los Angeles, Denver, Phoenix, and Las Vegas) that depend on the Colorado River for their drinking water started piloting an innovative conservation plan that pays farmers, industries, and municipalities to reduce their water use. Called the Colorado River System Conservation Program, the $11 million fund is designed to keep the levels of Lake Mead and Lake Powell high enough to avoid a declaration of water shortage, which would trigger politically sensitive reductions in water deliveries. Las Vegas for example, has many incentives to participate, given its dependence on Lake Mead. Lake levels have dropped close to the top of the city's uppermost water intake pipe, and while the city has been constructing a third intake tunnel deeper in the reservoir since 2008, the clock is running out on the other two intake pipes that may be high and dry in coming years (Postel 2014).

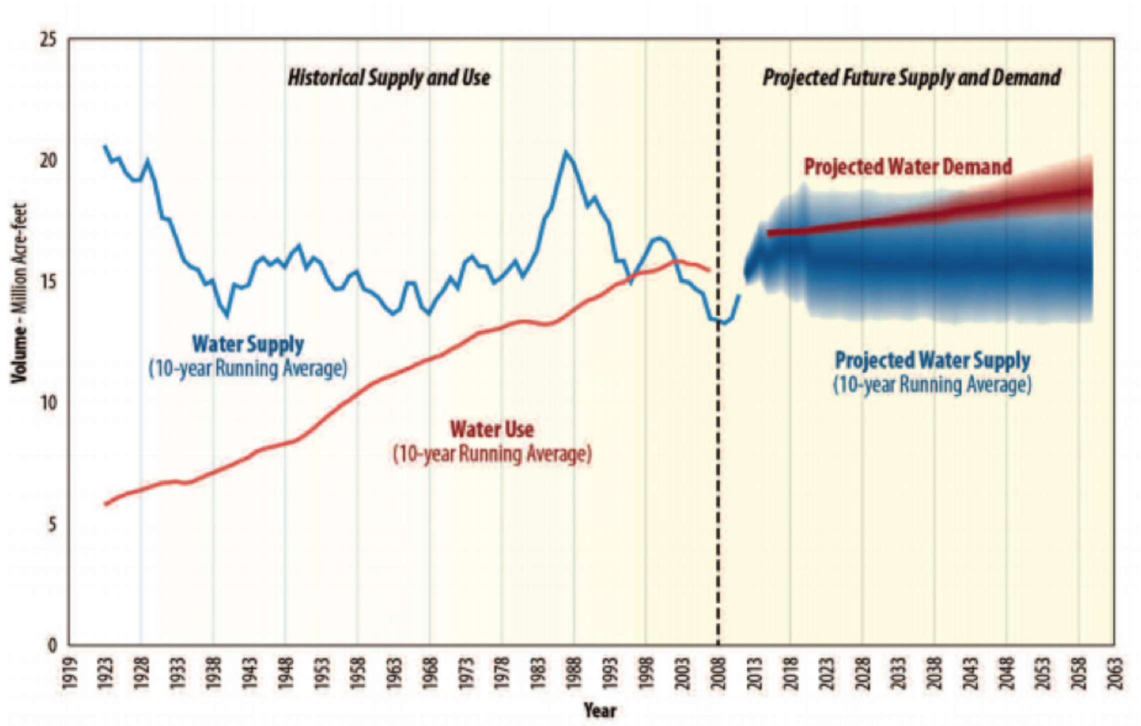
Discussion Question 1:

Are these conservation efforts feasible? What other conservation opportunities may be available? Where would conservation efforts have the most impact? How can stakeholders and managers promote water conservation?

Market-based re-allocation

Most of today's new water demands are met through

Historical Supply and Use[1] and Projected Future Colorado River Basin Water Supply and Demand



[1] Water use and demand include Mexico's allotment and losses such as those due to reservoir evaporation, native vegetation, and operational inefficiencies.

Figure 5: The range of projected future water supply and demand in the Colorado River basin, modeled on various management scenarios in the coming years, shows future imbalances and an uncertain future water supply (USBR 2012).

re-allocation of existing rights through market mechanisms, in other words, the selling and buying of water. Some transactions have transferred the water rights themselves, while most of today's transactions are based on long-term leases of water, allowing the holder of the water right to continue to own that property. In some cases, water can be "banked" or stored for use in another year in one of the Colorado River system's large reservoirs. In the Lower Basin, banked water is "taxed" by 5%, which creates a system benefit: more water is in storage for all consumptive users.

Voluntary water transfers can move water from low valued uses, such as alfalfa farming to higher valued uses, such as drinking water, yet this is contingent upon stakeholder agreement as part of the Law of the River.

Technological solutions and augmentation

A cutting edge water management project using reclaimed water for municipal purposes is operating in Orange County, California. The Orange County Water District has reduced their dependence on groundwater and imported water (including from the Colorado River) by diverting highly treated wastewater that is currently discharged into the ocean to groundwater basins for reuse. Before it is distributed, the treated water undergoes an advanced treatment process that includes

Discussion Question 2:

How do we supply these "new" demands from urban areas and for biodiversity needs? What are the consequences of moving water from agricultural use to urban use? What should be done for farmworkers, agribusinesses, and county tax revenues? Does it make sense to take agriculture out of production in order to water lawns and fill swimming pools? Given your understanding of the Law of the River, what re-allocation schemes are feasible? Now, imagine that the law could be changed. What changes regarding allocations and water rights should be made? How would these changes impact other stakeholders?

two membrane filtration systems - microfiltration and reverse osmosis, and treatment by ultraviolet light and hydrogen peroxide. Once purified, the water is sent to spreading basins to seep into the ground, like rain, blending with groundwater that is then withdrawn for drinking water and other purposes. The Orange County Water District has decades of experience reusing purified wastewater that is injected into wells to serve as a saltwater intrusion barrier to prevent coastal wells from being contaminated with seawater. The reclaimed water project has been operational since 2008 and produces enough water to meet the daily needs of 600,000 residents in Orange County (Groundwater Replenishment System 2014). Innovative approaches such as the Groundwater Replenishment System, which is slated for expansion in the coming years to meet the needs of 250,000 more residents, will be increasingly necessary as water stress increases.

In the face of persistent drought in the basin, the seven Colorado River basin states in the U.S. have begun to study opportunities to augment water supply in the region, looking at everything from desalination of brackish and ocean water, to weather modification such as cloud seeding to increase precipitation, to the importation of freshwater in bags through ocean routes, to the construction of pipelines to import water from other regions of the continent (Southern Nevada Water Authority 2008, USBR 2012). These augmentation projects have varying associated legal, political, and environmental issues—they may not necessarily be inexpensive or easy to implement, but some of them show promise and will continue to be pursued as water supplies tighten in coming years. For example, in Yuma, Arizona, the U.S. Bureau of Reclamation constructed a desalting plant designed to remove minerals from nearby agricultural runoff. Construction of the plant was completed in 1992, but due to both complications from a plant flood and the surplus supply conditions, it has only been sporadically operational. Given the recent drought and increasing demands, interest in the augmentation potential of the plant has increased (USBR 2014c). However, it is important to note that the runoff that would be processed is what sustains the nearby Cienega de Santa Clara wetland in Sonora, Mexico, in the Colorado River Delta. In this scenario, water that may be "saved" through desalination would constitute a tradeoff in terms of reduced flows into critical wetlands that provide habitat for endangered and threatened species.

Discussion Question 3:

How feasible are these technological solutions and augmentation strategies? What are the costs and benefits of these approaches? How does water conservation fit as an augmentation strategy? How might water managers make decisions about different strategies and what political considerations would come to play?

Policy and science

Much of the Law of the River—the Compact, the federal and state statutes, interstate compacts, court decisions, and other operating criteria and administrative decisions that define the river's overall governance —was established in the past and it is clear that the situation has changed dramatically in the intervening years. Volumes of new scientific information have been made available since then: the scientific knowledge base of Colorado River hydrology and climate rivals, and may exceed, comparable knowledge bases for any of the world's river systems. It is time to re-evaluate the body of policy concerning the river. Multiple stakeholders have called for a comprehensive study and policy review that is informed by science and planning principles and marked by collaboration and cooperation between US and Mexico, states, and stakeholders at all levels (National Research Council 2007).

Tradeoffs and river management

As outlined in Part II, the management of the Colorado River results in complex tradeoffs. The river is a managed river and will remain so. The question is what it will be managed for and how to do it right in the years to come.

Currently, it's well managed for agriculture and power generation, managed adequately for cities, and badly managed for nature and biodiversity. As demands rise and supplies tighten, stakeholders will need to revisit questions about how the river is managed.

Discussion Question 4:

How does policy adjust to changing realities and new scientific information? Scientific discovery tends to occur faster than policy change – how can stakeholders keep abreast of change? Students can discuss the revised estimation of water yield since the Compact, the recognition of the value of biodiversity since the construction of major Colorado River infrastructure, or the emerging understanding of the impact of climate change on the river and its users. Imagine if the Law of the River could be re-evaluated and re-negotiated. What aspects might be changed? How would this impact other areas of the basin and other stakeholders?

Discussion Question 5:

Are all the many uses of the Colorado River compatible? If not, what should the priorities be and why? Are there fair ways to move water from one use to another? Which stakeholders have the power to make these changes?

Binational cooperation

In general, the history of the management of the Colorado River has been primarily U.S. based, to the detriment of Mexico in terms of water quality and habitat quality, especially in the Delta. Most of the economic benefits of Colorado River management have been north of the border while most of the environmental costs have been south of the border. The International Boundary and Water Commission, an arm of the U.S. State Department, governs the relationship between the U.S. and Mexico on the Colorado River. Border water controversies cover a wide range of environmental and economic issues, including habitat and biodiversity conservation, water quality and water to support agricultural and economic development. In the past, the U.S. and Mexico might try to address those issues separately or through limited bi-national programs, but as border cities and economies have grown more interdependent, so has the need to find solutions that satisfy constituencies on both sides of the border. A solution to a problem on one side of the border likely will have repercussions, sometimes negative, on the other side. It is clear that bi-national cooperation will be essential for restoration of habitat in key riparian areas and the Colorado River Delta.

The historic agreement to provide a pulse and annual flows to the Delta is an example of how cooperation can result in a win-win. In order to "free up" water from the tight allocation system to flow to the Delta, representatives from the U.S and Mexico crafted an agreement whereby in exchange for flows into the Delta that come from Mexico's 1.5 maf allocation, the U.S is providing financing for the leak-prone water supply system in the Mexicali Valley. The water saved through these improvements, combined with water committed from Mexico's existing allocation, and water purchased by environmental organizations working in the Delta, is a down payment on a restored Delta (Jenkins 2014).

Discussion Question 6:

Imagine if the river were completely within the U.S. Would the Delta be better protected or restored? Discuss the Colorado River as an example of the difficulties and possibilities of cross-border environmental policy. How can nations avoid zero-sum outcomes with regard to water management? Are there are interests on both sides of the border that can be served through a collaborative approach to river management?

Facing the Challenge of the 21St Century

Every drop of Colorado River water is already appropriated, and its value will only increase. The river's complex regulatory framework, rooted in almost 100 years of legal and social history, and constantly under revision, is what makes this system so extraordinarily complex. As demands mount and tradeoffs grow even more complex, sound water policy will require innovative thinking, consensus building, and an integrated planning process.

The complex story of how the West was and will be watered is directly related to the past and future of the West itself. While the history and ecology of the Colorado River basin make it unique, the system also illustrates many of the challenges faced by water managers all over the world. How do we minimize the environmental impact of dams, pollution, and overuse? How do we balance the needs of all the species that inhabit the basin and depend upon its freshwater resources? Because the Colorado is so well studied and carefully monitored, the lessons learned by its managers are widely applicable to other river systems – and clarify the tradeoffs that water management involves.

QUESTIONS FOR FURTHER DISCUSSION

1. Reflect on the title of this case study, "How the West Was Watered." Which stakeholders were watered? Which stakeholders were de-watered?
2. Compare the discussion in Part II to the 150 different proposals for balancing the water budget of the Colorado River considered by the U.S. Bureau of Reclamation in their report "Colorado River Basin Water Supply and Demand Study" (USBR 2012). Do you agree with the report conclusions about the most promising proposals? Then read "Colorado River Drought Forces Painful Reckoning for States", published in January 2014 by The New York Times (http://www.nytimes.com/2014/01/06/us/colorado-river-drought-forces-a-painful-reckoning-for-states.html) and discuss the future of water in the Southwest. How will supplies continue to meet demand? Discuss the complicated issues of water conservation versus supply augmentation. Topics can include issues such as desalination, transfer of water rights and banking of water in reservoirs.
3. Read "Drought – and neighbors – press Las Vegas to conserve water", published in April 2014 by The LA Times (http://www.latimes.com/nation/la-na-las-vegas-drought-20140421-story.html#page=1). Given the precarious situation for this city that is entirely dependent on the dropping water levels of Lake Mead, how is the state of water resources in the city affecting planning for and development of the region? Can this challenge be overcome by linking land-use planning to water planning? How might this linkage work?
4. Research the story of how Tucson was able to break the historical rise in per capita water via a combination of water pricing, city ordinances, use of xeriscaping, and other conservation strategies combined with public awareness campaigns.
5. Read Box 2 above. Who are the main stakeholders in the restoration of the Salton Sea? For example, what is the close relationship between agriculture and the lake? If farmers are transferring their water rights to urban areas, how will the Salton Sea be affected? Research the concerns of those supporting and opposing the restoration, including conservationists (http://www.latimes.com/opinion/op-ed/la-oe-0918-morrison-salton-sea-krantz-20140918-column.html#page=1), farmers (http://news.nationalgeographic.com/news/2014/02/140218-salton-sea-imperial-valley-qsa-water-conservation/) and taxpayers (http://www.cvindependent.com/index.php/en-US/news/environment/item/1297-saving-the-sea-the-government-takes-baby-steps-to-preserve-the-salton-sea).
6. Read "Exporting the Colorado River to Asia, through hay" published January 2014 by National Geographic (http://news.nationalgeographic.com/news/2014/01/140123-colorado-river-water-alfalfa-hay-farming-export-asia/). What is virtual water? How is the river water used to produce hay in the Yuma and Imperial Valleys an additional tradeoff to be considered in managing the Colorado River, especially it comes to the issues of water rights and new markets for river water?
7. Read "New Hope for the Delta," published in January 2014 by High Country News (https://www.hcn.org/issues/45.18/new-hope-for-the-delta/print_view), and discuss the deal making that lead to the historic 2014 release of water into the Colorado River Delta. A photo essay by High Country News documents the historic flood pulse in rich detail (https://www.hcn.org/articles/colorado-river-delta/), and the story made international news (http://www.latimes.com/nation/la-na-ff-colorado-river-delta-20140323-story.html and http://www.dailymail.co.uk/news/article-2750254/Dramatic-

photographs-capture-mighty-Colorado-River-kissing-sea-time-50-years-coast-Mexico-dams-intentionally-unleashed.html)

8. How has the 'Law of the River' affected the native people of the Colorado River Delta? Read and discuss "In the Colorado River Delta, waters – and prospects – are drying up" (http://www.latimes.com/news/nationworld/world/la-me-newcolorado25-2008may25,0,1536281.story) and "Grabbing the Colorado from "the People of the River" (http://newswatch.nationalgeographic.com/2012/12/19/grabbing-the-colorado-from-the-people-of-the-river/).

APPENDIX 1: LAW OF THE RIVER, ALLOCATION REGIME, AND MAJOR PLAYERS

Law of the River

The Colorado River has been subjected to extensive negotiations and litigation. As a result, a complex set of federal laws, compacts, court decisions, treaties, state laws and other agreements has been developed, known as the "Law of the River". Principal documents forming the Law of the River are:

- Colorado River Compact of 1922
- Boulder Canyon Project Act of 1928
- Mexican Treaty of 1944
- Upper Colorado River Basin Compact of 1948
- Colorado River Storage Project Act of 1956
- 1963 US Supreme Court decision, Arizona v. California
- Colorado River Basin Project Act of 1968
- 1970 Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs
- Minute 242 of the 1973 International Boundary and Water Commission
- Colorado River Basin Salinity Control Act of 1974
- Grand Canyon Protection Act of 1992
- 2001 Colorado River Interim Surplus Guidelines
- 2007 Colorado River Interim Shortage Guidelines
- Minute 319 of the 2012 International Boundary and Water Commission

Allocation Regime (USBRUC 2005)

Water quantity
Colorado River water was apportioned by the Colorado River Compact of 1922, the Boulder Canyon Project Act of 1928, the Water Treaty of 1944, the Upper Colorado River Basin Compact of 1948, and the United States Supreme Court (Arizona v. California et al. 1963). The Colorado River Compact divided the Colorado River Basin between the Upper and Lower Basins at Lees Ferry (just below the confluence of the Paria River), apportioning to each use of 7.5 maf annually. In addition to this apportionment, the Lower Basin was given the right to increase its beneficial consumptive use by one maf per year. The compact also contains provisions governing exportation of Colorado River water. The Water Treaty of 1944 obligates the United States to deliver to Mexico 1.5 maf of Colorado River water annually, absent treaty surplus or shortage conditions.

Upper Colorado use
The Upper Colorado River Basin Compact of 1948 divided and apportioned the water apportioned to the Upper Colorado River Basin by the Colorado River Compact, allocating to **Arizona** 50,000 acre-feet annually, with the remaining water allocated to Upper Colorado River Basin States as follows:

- **Colorado** 51.75%
- **New Mexico** 11.25%
- **Utah** 23%
- **Wyoming** 14%

Lower Colorado use
States of the Lower Colorado River Basin did not agree to a compact for the apportionment of waters in the Lower Colorado River Basin; in the absence of such a compact Congress, through Secretarial contracts authorized by the Boulder Canyon Project Act, allocated water from the mainstem of the Colorado River below Lees Ferry among California, Nevada, and Arizona, and the Gila River between Arizona and New Mexico. This apportionment was upheld by the Supreme Court, in 1963, in the case of Arizona v. California. As confirmed by the US Supreme Court in 1963, from the mainstem of the Colorado River (i.e., The Lower Basin):

- **Nevada** was apportioned 300,000 acre-feet annually and 4% of surplus water available;

- **Arizona** was apportioned 2,800,000 acre-feet annually and 46% of surplus water available; and
- **California** was apportioned 4,400,000 acre-feet annually and 50% of surplus water available.

Mexico

The Water Treaty of 1944 obligates the United States to deliver to Mexico 1.5 maf of Colorado River water annually, absent treaty surplus or shortage conditions.

Major Players In Colorado River Management

- US Federal Government
    - US Bureau of Reclamation
    - US Army Corps of Engineers
    - Bureau of Indian Affairs
    - National Park Service
    - US Fish and Wildlife Service
    - International Boundary and Water Commission
    - Western Area Power Administration

- Government of Mexico (national, state, and local)
- State and City Governments (Upper and Lower Basin) in US
    - *Upper Basin*
        - Upper Colorado River Commission
        - Colorado River Water Conservation District
        - Utah Division of Water Resources
        - Wyoming Water Development Commission
        - New Mexico Environmental Department
    - *Lower Basin*
        - Arizona Department of Water Resources
        - Central Arizona Water Conservation District
        - California Department of Water Resources
        - Colorado River Board of California
        - Nevada Division of Water Resources
        - Colorado River Commission of Nevada
        - Southern Nevada Water Authority
        - Colorado River Salinity Control Forum
        - Colorado River Basin Ten Tribes Partnership

GLOSSARY

Acre-foot: A common water industry unit of measurement. An acre-foot is 325,851 gallons, or the amount of water needed to cover one acre with water one foot deep. An acre-foot serves annual needs of two typical California families.

Aquifer: Underground formation of water-bearing permeable rock, sand, or soil; an aquifer stores groundwater.

Allocation: Systematic distribution of water rights in this case.

Augmentation: Increasing stream flow through various means to "develop" water beyond what is supplied in normal river operations.

Alluviation: The process of sediment or gravel accumulating in a flowing water body.

Biodiversity: The variety of life on Earth at all its levels, from genes to ecosystems, and the ecological and evolutionary processes that sustain it.

Brackish: Mixed salt and fresh water, less salty than seawater.

Compact Call: If the Upper Basin states are unable to deliver the quantity of water required by the Colorado River Compact, Lower Basin states may legally force Upper Basin states, through provisions in the Compact, to reduce consumption - a politically charged situation

Desalting: Removing salt from water by evaporation, distillation, reverse osmosis, nanofiltration, etc.

Ecosystem: A community of organisms and its environment, functioning as an ecological unit.

Ecotone: Transition area between two adjacent ecological communities usually exhibiting competition between organisms common to both.

Endemic: Exclusively native to the biota of a specific place.

Erosion: Wearing away of the earth's surface by running water, wind, ice, or other geological agents.

Eutrophication: Over-enrichment of a body of water with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration.

Evapotranspiration: Process of transferring moisture from the earth to the atmosphere by evaporation of water and transpiration from plants.

Groundwater: Water beneath the Earth's surface, supplying rivers, springs, and wells.

Headwaters: Source or upper part of a stream or river.

Hydrological: Pertaining to water, its properties and movement through the Earth's land and atmosphere.

Invasive Species: A species that spreads widely and causes ecological or economic harm.

Irrigation: Applying water to crops, lawns or other plants using pumps, pipes, hoses, sprinklers, etc.

Isotope: Different forms of atoms of the same element.

Lower Basin: Portion of Colorado River below Lees Ferry in Arizona.

Native: A species that is indigenous to a region: the species lives there or has lived there historically, but was not introduced there from elsewhere.

Otolith: A bone-like structure found in the inner ear of many species of fish that allows scientists to estimate age.

Riparian: Relating to or living or located on the bank of a natural watercourse (as a river) or sometimes of a lake or a tidewater.

Runoff: Water that drains or flows off the surface of the land.

Salinity: The amount of salt in water.

Saltwater intrusion: When saltwater moves into the freshwater zone of an aquifer, making the water unfit for drinking.

Snowpack: Layers of ice and snow accumulated on the ground that persists through winter and melts in the spring and summer.

Stakeholder: Any individual, group or organization having a valid interest in a field or matter.

Trihalomethanes: Produced when water is disinfected with chlorine and the chlorine reacts with naturally occurring organic matter found in most freshwaters.

Upper Basin: Portion of Colorado River above Lees Ferry in Arizona.

Water Rights: The legal right to use water from a water course or body of water.

Xeriscaping: Planting native and drought-tolerant plants, shrubs, and groundcover that require relatively low amounts of water.

LITERATURE CITED

All, J.D. 2006. Colorado river floods, droughts, and shrimp in the upper Gulf of California, Mexico. Environmental Management 37(1):111-125.

Aragon-Noriega, E. and L. Calderon-Aguilera. 2000. Does damming of the Colorado River affect the nursery area of blue shrimp Litopenaeus stylirostris (Decapada: Penaeidae) in the Upper Gulf of California? Revista de Biologia Tropical 48:867-871.

Butler, D.L. 2001. Effects of piping irrigation laterals on selenium and salt loads, Montros Arroyo Basin, Western Colorado. U.S. Geological Survey Water Resources Investigations Report 01-4204, 14p.

California Department of Water Resources. 2014. Salton Sea Ecosystem Restoration Program. Available from: http://www.water.ca.gov/saltonsea/.

Castle, S.L., B.F. Thomas, R.T. Reager, M. Rodell, S.C. Swenson, and J.F. Famigletti. 2014. Groundwater depletion during drought threatens future water security of the Colorado River Basin. Geophysical Research Letters 41(16): 5904-5911.

Christensen, N. and D.P. Lettenmaier. 2006. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. Hydrological Earth System. Science 3:1–44.

Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettemaier, and R.N. Palmer. 2004. The effects of climate change on the hydrology and water resources of the Colorado River Basin. Climatic Change 62:337-363.

Cohen, M. 2014. Hazard's Toll: The Cost of Inaction at the Salton Sea. Pacific Institute. Available from: http://pacinst.org/publication/hazards-toll/.

Colorado River Basin Salinity Control Program. 2005. Water quality standards for salinity. Available from: http://www.crb.ca.gov/Salinity/2005/2005%20Triennial%20Review.pdf.

Dettman, D.L., K.W. Flessa, P.D. Roopnarine, B. Schone, and D.H. Goodwin. 2004. The use of oxygen isotope variation in shells of estuarine mollusks as a quantitative record of seasonal and annual Colorado River discharge. Geochimica et Cosmochimica Acta 68(6):1253–1263.

DiTomaso, J. 1998. Impact, biology, and ecology of saltcedar (Tamarix spp.) in the southwestern United States. Weed Technology 12:326–336.

Flessa, K.W. et al. 2013. Flooding the Colorado River Delta: A landscape-scape scale experiment. Eos, Transactions, American Geophysical Union 94: 485-496.

Fradkin, P. 1996. A river no more: the Colorado River and the West. University of California Press, Berkeley, California, USA.

Franks, C. and J. Simes. 2002. The mighty Colorado. California Biodiversity News 9(1) Available from: http://biodiversity.ca.gov/newsletter/v9n1/colorado.html.

Gertner, J. 2007. The future is drying up. New York Times. October 21. Available from: http://www.nytimes.com/2007/10/21/magazine/21water-t.html?pagewanted=all.

Gleick, P.H. 2003. Global freshwater resources: soft-path solutions for the 21st century. Science 302:1524-1528.

Glenn E., C. Lee, R. Felger and S. Zengel. 1996. Effects of water management on the wetlands of the Colorado River delta, Mexico. Conservation Biology 10:1175–1186.

Glenn, E.P., F. Zamora-Arroyo, P.L. Nagler, M.Briggs, W. Shaw and K.W. Flessa. 2001. Ecology and conservation biology of the Colorado River Delta, Mexico. Journal of Arid Environments 49:5–15.

Glenn, E.P., K.W. Flessa, and J. Pitt. 2013. Restoration potential of aquatic ecosystems of the Colorado River Delta, Mexico: Introduction to special issue on "Wetlands of the Colorado Delta." Ecological Engineering 59:1-6.

Groundwater Replenishment System. 2014. Groundwater replenishment system overview. Available from: http://www.gwrsystem.com/.

Hinojosa-Huerta, O., P.L. Nagler, Y. Carrillo-Guererro, and E. P. Glenn. 2013. Effect of drought on birds and riparian vegetation in the Colorado River Delta, Mexico. Ecological Engineering 51:275-281.

Intergovernmental Panel on Climate Change. 2013. Climate change 2013: the physical science basis. Cambridge University Press, New York, USA. Available from: http://www.ipcc.ch/report/ar5/wg1/.

Jacobs, J. 2011. The sustainability of water resources in the Colorado River Basin. The Bridge 41(4): 6-12.

Jenkins, M. 2013. New Hope for the Delta. High Country News. Available from: https://www.hcn.org/issues/45.18/new-hope-for-the-delta.

Kenney, D., S. Bates, A. Bensard, and J. Berggren. 2011. The Colorado River and the Inevitability of Institutional Change. Public Land and Resources Law Review 32: 103-152. Available from: http://scholarship.law.umt.edu/cgi/viewcontent.cgi?article=1025&context=plrlr.

Kuhn, E. 2012. Risk management strategies for the Upper Colorado River Basin. Available from: http://www.crwcd.org/media/uploads/Kuhn_on_Risk_Mgt_Strategies_of_the_UCRB.pdf.

McCabe, G.J., and D.M. Wolock. 2007. Warming may create substantial water supply shortages in the Colorado River basin. Geophysical Research Letters 34:L22708.

Minckley, W.L., D.A. Hendrickson, and C.E. Bond. 1986. Geography

of western North American freshwater fishes: description and relationships to intracontinental tectonism. Pages 516–613 in C.H. Hocutt and E.O. Wiley, editors. Zoogeography of North American freshwater fishes. John Wiley and Sons, Inc., New York, USA.

Minckley, W.L. and J.E. Deacon. 1991. Battle against extinction. In Native fish management in the American West. University of Arizona Press, Tucson, Arizona, USA.

Morrison, J.I., S. Postel, and P.H. Gleick. 1996. The sustainable use of water in the lower Colorado River Basin. Available from: http://pacinst.org/publication/sustainable-water-lower-crb./

Nagler, P.L., E.P. Glenn, T.L. Thompson, A. Huete. 2004. Leaf area index and normalized difference vegetation index as predictors of canopy characteristics and light interception by riparian species on the Lower Colorado River. Agricultural and Forest Meteorology 125:1–17.

Nagler, P.L., O. Hinojosa-Huerta, E.P. Glenn, J. Garcua-Hernandez, R. Romo, C. Curtis, A. Huete, and S.G. Nelson. 2005. Regeneration of native trees in the presence of invasive saltcedar in the Colorado River Delta, Mexico. Conservation Biology 19(6):1842-1852.

National Research Council of the National Academies, Committee on the Scientific Bases of Colorado River Basin Water Management. 2007. Colorado River Basin water management: evaluating and adjusting to hydroclimatic variability. National Academies Press, Washington D.C., USA. Available from: http://www.nap.edu/catalog.php?record_id=11857.

Pitt, J., D. Luecke, M. Cohen, E. Glenn and C. Valdes-Casillas. 2000. Two nations, one river: managing ecosystem conservation in the Colorado River delta. Natural Resources Journal 40:819–864.

Postel, S. 2014. An innovative conservation fund for the Colorado River. National Geographic Newswatch. Available from: http://newswatch.nationalgeographic.com/2014/05/06/an-innovative-conservation-fund-proposed-for-colorado-river/.

Rajagopalan, B., K. Nowak, J. Prairie, M. Hoerling, B. Hardin, J. Barsugli, A. Ray, and B. Udall. 2009. Water supply risk on the Colorado River: Can management mitigate? Water Resources Research 45:W08201.

Reisner, M. 1986. Cadillac desert: the American West and its disappearing water. Penguin Books, New York, USA.

Rodriguez, C.R., K.W. Flessa, and D.L. Dettman. 2001. Effects of upstream diversion of Colorado River water on the estuarine bivalve mollusks Mulinia coloradoensis. Conservation Biology 15(1):249-258.

Rowell, K., K.W. Flessa, D.L. Dettman, and M. Román. 2005. The importance of Colorado River flow to nursery habitats of the Gulf corvine (Cynoscion othonopterus). Canadian Journal of Fisheries and Aquatic Science 62:2874–2885.

Salton Sea Authority. 2014. The Salton Sea. Available from: http://saltonsea.ca.gov/.

Solokoff, L. 2007. Future looks uncertain, costly for Salton Sea. California Planning and Development Report. Available from: http://findarticles.com/p/articles/mi_m0BYL/is_9_22/ai_n25012529.

Southern Nevada Water Authority. 2008. Colorado River Augmentation Study. Available from: http://www.snwa.com/html/wr_colrvr_augmentation.html and https://www.usbr.gov/lc/region/programs/crbstudy/longtermaugmentationrpt.pdf.

Stromberg, J. 2001. Restoration of riparian vegetation in the southwestern United States: importance of flow regimes and fluvial dynamism. Journal of Arid Environments 49:17–34.

Tiegs, S.D., J.F. O'Leary, M.M. Pohl, and C.L. Munill. 2005. Flood disturbance and riparian species diversity on the Colorado River Delta. Biodiversity and Conservation 14:1175–1194.

Tillman, F.D, and Anning, D.W., 2014, Updated estimates of long-term average dissolved-solids loading in streams and rivers of the Upper Colorado River Basin: U.S. Geological Survey Open-File Report 2014-1148. Available from: http://pubs.usgs.gov/of/2014/1148/pdf/ofr2014-1148.pdf.

Upper Colorado River Endangered Fish Recovery Program. 2014. Upper Colorado River Endangered Fish Recovery Program. Available from: http://www.coloradoriverrecovery.org/

USBR (United States Bureau of Reclamation). 2004. Hoover Dam Learning Packet. Available from: http://www.usbr.gov/lc/hooverdam/educate/edpack0.html.

USBR (United States Bureau of Reclamation). 2007. Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. Available from: http://www.usbr.gov/lc/region/programs/strategies.html.

USBR (United States Bureau of Reclamation). 2011. Law of the River. Available from: http://www.usbr.gov/lc/region/g1000/lawofrvr.html.

USBR (United States Bureau of Reclamation). 2012. Colorado River Basin Water Supply and Demand Study. Available from: http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Executive%20Summary/CRBS_Executive_Summary_FINAL.pdf.

USBR (United States Bureau of Reclamation). 2013. Glen Canyon Dam 2013 High Flow Experimental Release. Available from: http://www.usbr.gov/uc/rm/gcdHFE/2013/.

USBR (United States Bureau of Reclamation). 2014a. Colorado River Basin Salinity Control program. Available from: http://www.usbr.gov/uc/progact/salinity/index.html.

USBR (United States Bureau of Reclamation). 2014b. Lower Colorado River Multi-Species Conservation Program. Available from: http://www.lcrmscp.gov/.

URBR (United States Bureau of Reclamation). 2014c. Yuma Desalting Plant. From: http://www.usbr.gov/lc/yuma/facilities/ydp/yao_ydp.html.

USBRUC (United States Bureau of Reclamation Upper Colorado). 2013. Quality of Water: Colorado River Basin Progress Report No. 24. Available from: http://www.usbr.gov/uc/progact/salinity/pdfs/PR24final.pdf.

USDOJ (United States Department of Justice). 2014. Federal reserved water rights and state law claims. Available from: http://www.justice.gov/enrd/3245.htm.

Valdés-Casillas, C., E.P. Glenn, O. Hinojosa-Huerta, Y. Carillo-Guerrero, J. García-Hernández, F. Zamora-Arroyo, M. Muñoz-Viveros, M. Briggs, C. Lee, E. Chavarría-Correa, J. Riley, D. Baumgartner, and C. Condon. 1998. Wetland management and restoration in the Colorado River delta: the first steps. Special publication of the CECARENA-ITESM Campus Guaymas and NAWCC. México.

Vano, J.A. et al. 2014. Understanding uncertainties in future Colorado River stream flow. Bulletin of the American Meteorological Society 95:59-78.

Water Education Foundation. 2014. Colorado River Project: Summer 2014 River Report. Available from: http://www.watereducation.org/river-report.

Wheeler, K.G., J. Pitt, T.M. Magee, and D.F Luecke. 2007. Alternatives for restoring the Colorado River Delta. Natural Resources Journal 47(4):44.

Witze, E. 2014. Water returns to arid Colorado River delta. Nature 507:286-287.

Woodhouse, C.A., S.T. Gray, and D.M. Meko. 2006. Updated streamflow reconstructions for the Upper Colorado River Basin, Water Resources Research (42/W05415):1-16.

Woodhouse, C.A., D.M. Meko, G. M. MacDonald, D.W. Stahle, and E.R. Cooke. 2010. A 1,200 year perspective of 21st century drought in southwestern North America. Proceedings of the National Academy of Sciences 107(50): 21283-21288.

Zamora-Arroyo, F., O. Hinojosa-Huerta, E. Santiago, E. Brott, and P. Culp. 2008. Collaboration in Mexico: renewed hope for the Colorado River Delta. Nevada Law Journal 8(3):871-889.

ACKNOWLEDGEMENTS

NCEP gratefully acknowledges the support of the following organizations and institutions:

The John D. and Catherine T. MacArthur Foundation
California State University-Chico
Kerala Agricultural University
Metropolitan Community College-Blue River
United States Geological Survey
University at Buffalo
University of Michigan

We welcome your comments and feedback. To write to NCEP or for more information,
contact the Network of Conservation Educators and Practitioners at:
American Museum of Natural History
Center for Biodiversity and Conservation
79th Street at Central Park West
New York, New York 10024
ncep@amnh.org

Lessons in Conservation is available electronically at ncep.amnh.org/linc

American Museum of Natural History
Center for Biodiversity and Conservation
Network of Conservation Educators & Practitioners