

# Chapter 7: Status, Trends, and Future Projections of Inland Water Ecosystems in the US

## Chapter Lead

Mary E. Power, University of California, Berkeley

## Chapter Authors\*

Colden V. Baxter, Idaho State University

Alan P. Covich, University of Georgia

Walter K. Dodds, Kansas State University

Jacques C. Finlay, Department of Ecology, Evolution and Behavior, University of Minnesota

Nancy B. Grimm, Arizona State University

Alexander D. Huryn, University of Alabama, Department of Biological Sciences

Barbara L. Peckarsky, University of Wisconsin–Madison and Rocky Mountain Biological Laboratory

George R. Pess, George Pess Consulting LLC

Daniel E. Schindler, University of Washington

David L. Strayer, Cary Institute of Ecosystem Studies and University of Michigan, Graham Sustainability Institute

Michael J. Vanni, Miami University

Caryn C. Vaughn, University of Oklahoma

Kathleen C. Weathers, Cary Institute of Ecosystem Studies

## Graphics Lead

Mary E. Power, University of California, Berkeley

## Chapter Point of Contact

Tessa B. Francis, University of Washington

\*Authors listed in alphabetical order

## Date

February 23, 2026

1 **Chapter Contents**

2 Summary.....3

3 Background .....3

4 Key Message 7.1: Inland water ecosystems are in crisis—overdrawn, polluted,  
5 fragmented, and invaded .....6

6 Key Message 7.2: With further climatic change, inland water ecosystems and fresh  
7 water supplies will deteriorate more ..... 18

8 Key Message 7.3: Inland waters could be partially restored and managed to increase  
9 US resilience to climate change..... 21

10 Environmental Justice and Equity Highlights ..... 32

11 Emerging Issues .....33

12 References ..... 34

13

14

DRAFT

## 1 Summary

2 *Water is life. (translation of Lakota Mní wičhóni)*

3 Inland waters, lifeblood of Earth's continents, flow under and over land in a vast circulatory  
4 system of springs, streams, rivers, wetlands, ponds, lakes, groundwaters, and aquifers,  
5 driven by the sun as its beating heart. Inland waters of the US have been overdrawn,  
6 polluted, fragmented, and subjected to extinction of native species and invasion by non-  
7 native species. These threats will worsen with climate change and intensifying human  
8 pressures, making clean fresh water the most limiting resource for social–ecological  
9 systems in the US. Inland water ecosystems can partially heal if released or protected from  
10 these four harms, but because of current and future uncertainties, long-term monitoring  
11 programs to evaluate success and inform management or stewardship are vital.

12 This chapter reports status, trends, and projections for inland waters (fresh and saline) of  
13 the contiguous United States, Alaska, Hawai'i, and Puerto Rico. The coverage is not  
14 complete but highlights response to environmental change of key aquatic ecosystems over  
15 the last several decades. We conclude by presenting evidence that restoration guided by  
16 science can recover valued ecological functions and populations of native species,  
17 demonstrating the resilience of ecosystems when 'living space' is restored to nature.

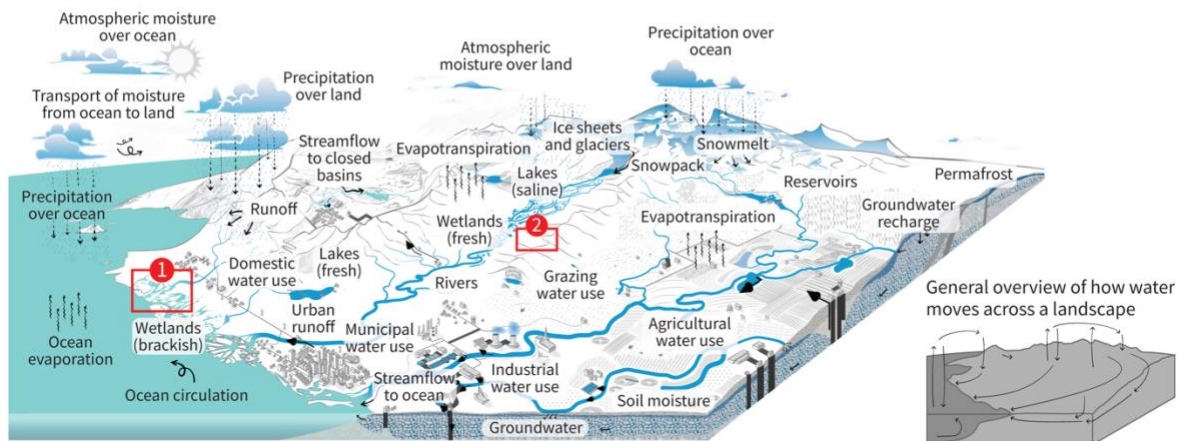
## 18 Background

19 Inland water ecosystems are inseparable from their landscapes and hydrologic contexts  
20 (Figure 7.1). The status of inland waters of the US is influenced by landscape connections  
21 at all scales (see KM 7.3). Precipitation falling on a watershed flows overland and via  
22 subsurface paths through the **critical zone**—the living skin of the Earth from the vegetation  
23 canopy down through soils and weathered bedrock—ending where fresh bedrock lacks  
24 enough porosity for water to be exchanged (1,2). The quality and quantity of water supply in  
25 each aquatic ecosystem depend on processes and conditions throughout its entire  
26 **watershed** (3) and **airshed** (4,5). Regional- to continental-scale habitats sustain migratory  
27 species, such as waterfowl and **anadromous** salmon, as well the human communities that  
28 depend on them (6–8). As components of Earth's hydrologic cycle, they exchange water  
29 with the atmosphere, biosphere, and lithosphere over global scales.

1 **Figure 7.1. Nested Scales of Landscape and Hydrologic Context for Inland Water**  
 2 **Ecosystems**

**Nested Scales of Landscape and Hydrologic Context for Inland Water Ecosystems**

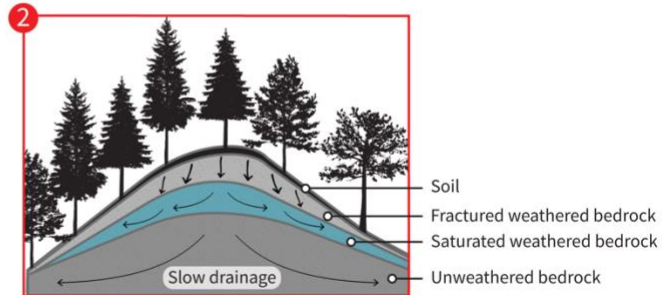
(a) Landscape overview of the water cycle



(b) Photo of wetlands in the Kvichak River watershed



(c) Overview of hydrology on a hill slope



3

4 **Nested scales of physicochemical contexts and processes structure ecology of inland**  
 5 **water ecosystems, which are inextricably linked to larger landscape and climatic**  
 6 **drivers.**

7 *Flowing waters sculpt all land surfaces into valleys separated by hillslopes. Surface waters*  
 8 *in valleys receive water, heat, sediments, dissolved chemicals, organic matter, and biota*  
 9 *via the **critical zones** of adjacent uplands within their **watersheds**, whose geology,*  
 10 *vegetation, and land affect surface water quantity and quality. “Portfolios” of watersheds*  
 11 *are linked by aerial, surface, and sub-surface flow paths, connections vital to migratory*  
 12 *species such as many salmonids and waterfowl. All these scales of inland waters are*  
 13 *nested within the global water cycle. (a) Adapted from USGS (9); (b) Aerial photograph of*  
 14 *Kvichak watershed, Alaska. Photo from EPA (10); (c) the critical zone, the skin of the Earth*  
 15 *where water is exchanged, extending vertically from the vegetation canopy down to the*  
 16 *bottom of the groundwater table, adapted from D. Rempe in Grant and Deitrich, 2017 (1).*

1 While covering only 4% of the land surface of the US, inland waters are home to a  
2 disproportionate number of the Nation's animal species and support complex webs of life  
3 (Figure 7.2). Intact inland water ecosystems that are rich in native species and sustained by  
4 natural landscape linkages and processes (11) can withstand and buffer against stresses  
5 and disturbances, benefiting humans. Native freshwater organisms, however, struggle to  
6 survive human pressures that will intensify as the climate warms (12), particularly in high-  
7 latitude (13–16), high-elevation (17), and arid regions (18–22).

8 **Figure 7.2. Inland Water Food Web**

**COPYRIGHTED MATERIAL**

Permission to reproduce pending.

9

10 **Inland water systems support an extraordinary richness of life.**

11 *Inland waters sustain a wealth of microbes, algae, fungi, plants, invertebrates, and*  
12 *vertebrates, many of which are ecologically linked to organisms in upland, subterranean,*  
13 *and often estuarine and coastal habitats. Adapted from Baxter et al. 2005 (23).*

14 Inland water ecosystems provide essential human benefits—clean water, pollutant and  
15 nutrient filtration, fisheries, flood mitigation, navigation, recreation, and cultural and  
16 spiritual connections. The market value of some of these benefits has been quantified,  
17 while others are difficult to assess or beyond price. Natural freshwater ecosystems are  
18 ultimately irreplaceable.

## 1 Key Message 7.1: Inland water ecosystems are in crisis— 2 overdrawn, polluted, fragmented, and invaded

3 *Across much of the US, surface and groundwaters are being withdrawn for use faster than*  
4 *they can be recharged (virtually certain). Many rivers, lakes, and aquifers are polluted by*  
5 *excessive nutrients, toxicants, and excessive fine sediment (virtually certain). Dams,*  
6 *levees, impermeable surfaces, and diversions have fragmented natural flows that sustain*  
7 *river, wetland, riparian, lake, and groundwater ecosystems, worsening impacts of floods*  
8 *and droughts (virtually certain). In many aquatic ecosystems, native species have been*  
9 *lost, while non-native species have become established (virtually certain). All of these*  
10 *harms pose grave threats to inland water ecosystems of the US.*

### 11 State of Knowledge 7.1

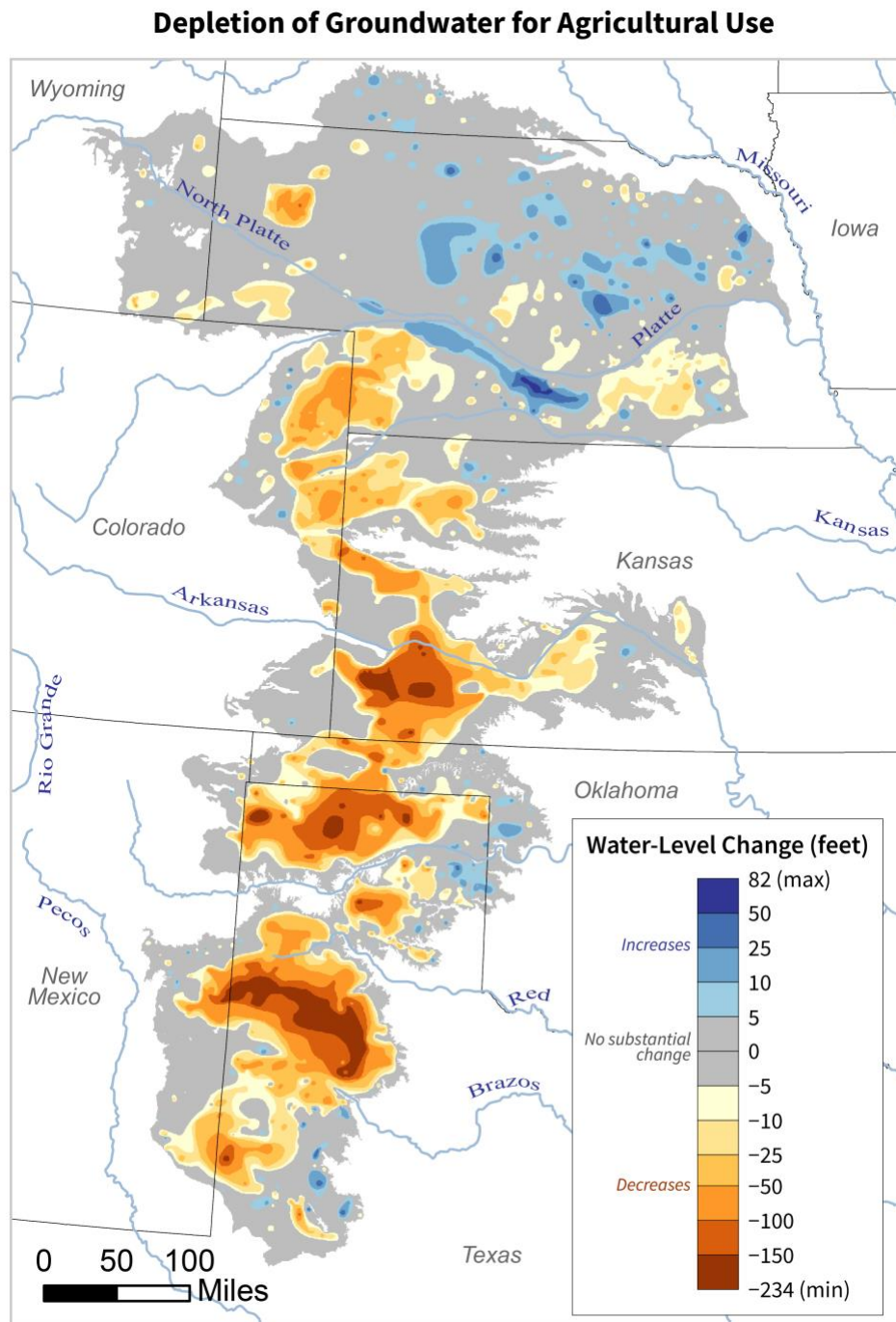
#### 12 The Growing Scarcity of Clean Fresh Water

13 Under prolonged, intensifying human impacts and climate change, inland waters of the US  
14 are depleted and degraded. Urban and agricultural development have altered flow paths  
15 linking inland surface water ecosystems to ground waters, affecting water quantity and  
16 degrading water quality and ecological resilience (Box 7.1). In many regions of the US,  
17 water supplies are **overdrafted** by agriculture (24), industry (where use has doubled since  
18 1995 (25)), and other human uses. Drying trends are seen in 540 intermittent streams with  
19 at least 30 years of gaging record in California, Arizona, New Mexico, Texas, Kansas, Idaho,  
20 and southern Florida (26). Only intermittent streams in Minnesota had fewer no-flow days,  
21 potentially because they were not frozen as long. In Utah, Arizona, California, and  
22 Colorado, severe overdraft has permanently reduced underground storage capacity via  
23 **inelastic subsidence** (collapse of subsurface spaces around sediment grains) (27–30).  
24 Freshwater depletion shrinks and degrades aquatic ecosystems, reducing access to clean,  
25 dependable fresh water that ultimately determines the fate of human communities. Loss of  
26 safe, reliable water supplies disproportionately affects certain historically marginalized  
27 human communities that rely on untreated or inadequately treated water and resources  
28 from inland waters (7,31,32).

#### 29 **Box 7.1. Depletion of the Ogallala Aquifer**

30 The vast Ogallala Aquifer sustains 25% of US crops (valued at \$35 billion per year) across  
31 eight states in the Central Plains (Figure 7.3). Between 1900 and 2008, the aquifer was  
32 drained of 89 trillion gallons, equivalent to two-thirds the volume of Lake Erie (33). This  
33 massive overdraft has depleted drinking water supplies for local communities (34); in many  
34 areas, crop irrigation and domestic uses relying on the aquifer are now difficult or  
35 impossible (35). The Ogallala sits within a larger High Plains Aquifer, where groundwater  
36 pumping has reduced or halted flow in many rivers and caused ecosystem shifts; for  
37 example, fish **assemblages** once dominated by species characteristic of larger rivers now  
38 resemble those typical of smaller streams (36).

1 **Figure 7.3. Depletion of the Ogallala Aquifer for Agricultural Use**



2

3 **Agricultural withdrawals from the Ogallala Aquifer have outpaced recharge from**  
 4 **precipitation.**

5 *Changes in water levels across the Ogallala Aquifer, which underlies parts of Colorado,*  
 6 *Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming and*

1 *countless watersheds. Withdrawals (90% for agricultural irrigation) far exceeded recharge*  
2 *from rain and snow. Shown are decreasing (red and orange) and increasing (blue) water*  
3 *levels between the period before the aquifer was tapped and 2015. Darker colors indicate*  
4 *greater changes. Gray indicates no substantial change. Adapted from Gowda et al. 2018*  
5 *and McGuire 2017 (37,38).*

6 [END BOX 7.1 HERE]

7 Decades of overdraft for agriculture have drained western and midwestern **aquifers**, deep  
8 underground reservoirs of often ancient water (Box 7.1). Groundwater levels have been  
9 lowered to less than 30% of their historic averages in Colorado Plateaus aquifers, the Rio  
10 Grande aquifer system, and the central and southern regions of the High Plains aquifer  
11 (39). In 221 watersheds in the Colorado, Columbia, and Missouri River Basins, streamflows  
12 have dropped over the past 35 years due to irrigation withdrawals (40). This leaves less  
13 water to feed desert streams, springs, and oases critical to imperiled native fish and  
14 invertebrates or to support fish, wildlife, and waterfowl that once abounded along  
15 mainstem rivers (41–43) (Box 7.3).

16 Although **irrigation efficiency** (“crop per drop”) has increased, withdrawals for irrigation  
17 have increased even more (40). Both factors reduce downstream water supply for nature  
18 (44,45). In the Laramie Basin of Wyoming, for example, wetlands that persist because of  
19 irrigation leakage contain the only remaining population of the endangered Wyoming toad  
20 (46) and serve as major breeding areas for migrating waterfowl (47). In southwest Idaho, an  
21 endangered hot spring snail has steadily lost habitat to irrigation pumping—interpreted as  
22 a harbinger of a similar fate for agriculture in this region (48). Increased irrigation and  
23 irrigation efficiency at the farm scale has reduced groundwater recharge at the watershed  
24 scale (49).

25 Increasing salinization trends threaten loss of freshwater species and potable water from  
26 many inland waters within this century (50–52). Heavily irrigated soils (e.g., in the Great  
27 Plains or the Salinas Valley of California) often become salinized as evaporation  
28 concentrates salts and other toxic minerals within the root zone (53–55). Along the  
29 Southern California and Florida coasts, overpumping allows seawater intrusion into fresh  
30 groundwater (50–52). Storm surge is salinizing fresh waters in southeastern coastal forests  
31 and farmlands (50–52). Agricultural lime and road salt for snow and ice control salinizes  
32 fresh waters in wetter regions of the US (56).

33 Naturally saline inland lakes, including Mono Lake and the Great Salt Lake, are also deficit  
34 in freshwater supply, rendering them too salty to support even salt-specialized native  
35 invertebrates (brine shrimp) that are essential to migrating birds (57) and also harvested  
36 commercially. The drying shoreline of the Great Salt Lake releases dust linked to cancer,  
37 cardiac arrhythmias, heart attacks, asthma, and bronchitis (57,58).

38 Even in water-rich regions of the US like the Southeast (Georgia, Alabama, Florida),  
39 increasing demands of municipal and agricultural users have led to depletion of

1 streamflow via over-tapped ground water (59–63) and interstate “water wars” (64).  
2 Freshwater ecosystems on tropical islands of the US are vulnerable to droughts if they have  
3 small watersheds and little sustained reserves from groundwater supply from porous  
4 limestone or volcanic rocks. Droughts have dried up headwater streams in Puerto Rico  
5 (65), Hawai’i (66,67), and Guam (68), reducing habitat for fish and crustaceans (69–71) and  
6 degrading fisheries and municipal drinking water supplies.

7 Only half of the 221 million acres of precolonial wetlands across the contiguous United  
8 States (CONUS) remain today, and their loss rate from 2009 to 2019 accelerated by 50%  
9 (72). In addition to human agriculture, development, and land conversion, drought and fire  
10 combine to severely damage wetland ecosystems (73,74). The Everglades had shrunk to  
11 nearly half its size by 2003 (75,76). Although the Everglades still supports diverse  
12 invertebrates, fish, and wildlife (77–80), the whole ecosystem is increasingly threatened by  
13 hurricanes and floods (76). Okefenokee Wildlife Refuge, the largest blackwater swamp in  
14 North America (81), is home to more than 400 native species of vertebrates, 200 species of  
15 birds, and 60 species of reptiles (82). The Okefenokee provides flood control, pollination  
16 services, carbon storage (83,84) and recreation for more than 800,000 people visitors each  
17 year. It now is threatened by increasing extreme droughts, wildfires (85,86), and changing  
18 land uses, such as mining (86,87).

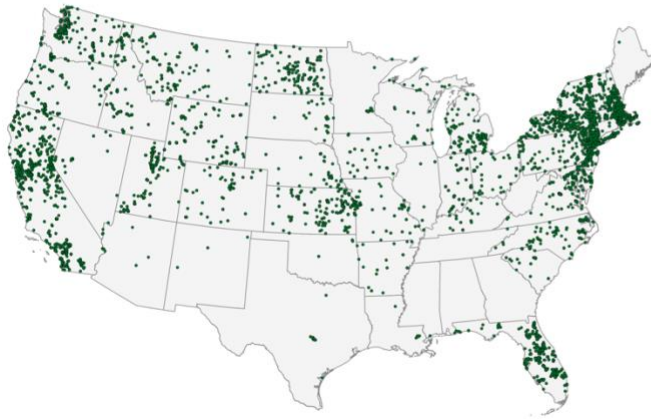
## 19 Pollution of Inland Waters

20 Inland waters are polluted with excessive nutrients (88), toxicants, fine sediments (89), and  
21 heat (Figure 7.3 and 7.4). Sewage and agricultural runoff increased nutrients in 49% of the  
22 981 lakes surveyed across CONUS (90), leading to eutrophication—blooms of algae and  
23 cyanobacteria in 49% of 981 lakes sampled across CONUS. Harmful algal and  
24 cyanobacterial blooms (HABS and cyano-HABs) smother the surfaces and choke water  
25 columns of lakes and rivers, harbor pest populations (e.g., mosquito larvae or fish  
26 parasites) (91), supplant beneficial, nutritious algae that fuel fish-bearing food webs (Figure  
27 7.4) (92–95). Blooms deplete dissolved oxygen, leading to fish kills and other problems.  
28 Massive nutrient loading into ground and surface waters of 39 million acres spanning  
29 Illinois, Indiana, Iowa, Missouri, and Ohio intensified after World War II, when midwestern  
30 prairies were converted to intensive corn and soybean cultivation (96). Today, this corn–  
31 soybean belt receives more than 4.5 million metric tonnes (MT) of chemical nitrogen  
32 fertilizer and nearly a million MT of nitrogen from manure per year (97). Drainage  
33 engineering shunts water rapidly off the land, resulting in the flow of dissolved nitrogen  
34 down the Mississippi River, which has devastated natural ecosystems in 6,000 square  
35 miles of the northern Gulf of Mexico (96,98,99). Excessive nitrate from midwestern  
36 agriculture also pollutes local water supplies and endangers local human health (see  
37 Chapter 13: Health and Well-Being).

## 1 **Figure 7.4. Harmful Algal Blooms in US Inland Waters**

### **Harmful Algal Blooms in US Inland Waters**

(a) Locations of harmful algal blooms, 2015–2026



(b) Harmful algal bloom at Binder Lake, Iowa



2

3 **Harmful bacterial blooms occur frequently and across all inland water types in the US,**  
 4 **posing risks to aquatic species and human health.**

5 *Harmful algal blooms (HABs) occur with high frequency across all inland waters across the*  
 6 *US, causing local environmental agencies to issue warnings about potential public health*  
 7 *impacts. (a) Map shows HABs as reported in state advisories and other local resources*  
 8 *between 2015–2026. Shown are reported advisories, water-body closures, blooms, and*  
 9 *warnings for lakes, ponds, reservoirs, and rivers (green symbols). Because reporting is*  
 10 *voluntary, this map underestimates the prevalence of HABs. (b) HABs can lead to fish kills,*  
 11 *as shown in this photo from Binder Lake in Iowa. (a) Figure original to The Nature Record;*  
 12 *(b) photo credit: Jennifer Graham, USGS.*

13 With increased nutrient pollution and warming of inland water, cyanobacterial blooms are  
 14 becoming more frequent and problematic (100). Although they have been foundational for  
 15 Earth's ecosystems for billions of years (and have oxygenated Earth's atmosphere), some  
 16 cyanobacteria release toxins like microcystin, detected in 50% of 981 lakes sampled  
 17 across CONUS in 2022, with levels exceeding those safe for swimming in 2% of these lakes  
 18 (90). Cyanotoxins have sickened or killed livestock (100), pets (101,102), and humans (103–  
 19 105). Cyano-HABs in western Lake Erie shut down the water supply of Toledo, Ohio, for  
 20 three days (106). While toxic cyanobacteria blooms have become more prevalent, it is not  
 21 clear what specific factors trigger them to produce toxins (107). This makes it hard to  
 22 assess hazard: Some nutrient-rich lakes have high biomass of nontoxic cyanobacteria,  
 23 while other lower-nutrient lakes can produce toxic blooms (108–110).

24 While too much phosphorus loading pollutes inland waters (90,111) at an estimated US  
 25 cost of \$4.3 billion per year (112), loss of phosphorus from land is also deeply concerning.

1 Earth's supplies of phosphorus—an essential nutrient—are limited, and losses to runoff  
2 can limit terrestrial production. Analysis of daily concentrations and fluxes in 430 rivers  
3 across CONUS showed that while phosphorus concentrations in urban rivers generally  
4 decreased from 1980 to 2019, concentrations in most agricultural rivers increased (112),  
5 and the total estimated to be lost from the land in runoff increased 6.5% per decade over  
6 the past 40 years, possibly because of increased river discharge (112).

7 Inland waters are also contaminated with **toxicants**, including petroleum products or by-  
8 products, microplastics, pesticides (113), dioxins and other persistent organic pollutants,  
9 and excreted pharmaceuticals near cities and concentrated animal feeding operations  
10 (114). **Endocrine disruptors** from pesticides or pharmaceuticals (115) distort hormonal  
11 balances that regulate development. Atrazine, an agricultural herbicide that feminizes  
12 male frogs (116), has been detected in 41% of 981 lakes surveyed in 2022 across CONUS  
13 (90). Other pharmaceutical pollutants alter crayfish behavior, aquatic insect life cycles,  
14 and algal production (114). Ongoing releases of antibiotics (used to increase growth rates  
15 in concentrated animal feeding operations (117) and intensive fish aquaculture (118,119))  
16 can select for antibiotic-resistant pathogens in surface or groundwaters, potentially  
17 contaminating water supplies used by humans as well as nearshore marine environments.

18 Many pollutants including pharmaceuticals, organic toxins, and heavy metals  
19 **bioaccumulate** in bodies of organisms that are unable to shed or excrete them (114,120).  
20 Some of these—such as PFAS, or “forever chemicals” (121–123); mercury; and PCBs  
21 (polychlorinated biphenyls)—also **biomagnify** up food chains (124), so long-lived top  
22 predators like large fish or osprey have chemical burdens many orders of magnitude  
23 greater than those of their prey's prey, or organisms lower in food webs (125). PCBs were  
24 found in the tissue of every fish sampled by EPA scientists in 2022, supporting an estimate  
25 that 58,747 lakes across CONUS have contaminated fish (90).

26 A pollutant left by car tires on roads, 6PPD-quinone, has proven highly toxic to coho and  
27 other salmon (126). Microplastics, now pervasive in the environment and in human bodies,  
28 are ingested by several important taxa of freshwater invertebrates. Their impacts remain  
29 poorly understood (127–129), although they have recently been found to be more  
30 concentrated in plaque that is associated with damaged human hearts or circulatory  
31 systems (130). Disposal mine wastes, injected fracking compounds, and heavy-metal  
32 drilling fluids (131,132) are contaminating groundwater, polluting human water supplies,  
33 and potentially exterminating many microbes and endemic invertebrates before they have  
34 even been discovered and described (133,134). Pollution can travel upslope as well;  
35 recently discovered airborne pathways can carry pathogens and toxins like hydrogen  
36 sulfide from contaminated fresh waters (e.g., the heavily polluted Tijuana River) to humans  
37 hundreds of miles away (135–137).

38 Fine sediments unleashed by erosive land uses and intense storms allow toxic chemicals  
39 like ammonia to build up (138), while phosphorus and toxins adhere to fine sediment  
40 particles and are retained in riverbeds, worsening pollution (139). Excessive fine sediment

1 deposits smother salmon eggs (89,140,141) and impair growth and survival of rearing  
2 juvenile salmonids (142) as well as juveniles of freshwater mussels that live buried in  
3 stream sediments (143,144) and many other invertebrates that nourish stream-dwelling  
4 fishes and riparian birds (89).

#### 5 Fragmentation of Inland Water Ecosystems

6 Human impacts—impermeable surfaces (pavement and roofs), ditches, denuded  
7 shorelines, drainage engineering, culverts, canals, levees, and dams—fragment inland  
8 water flow paths and habitats over a range of scales. If precipitation can sink into the  
9 ground, water is stored in soil and fractured bedrock, replenishing aquifers and  
10 groundwater, and is slowly released to sustain either surface waters or terrestrial  
11 vegetation during dry periods (Figure 7.1c). Slow subsurface flow paths reduce peak flows  
12 during floods and prolong flows during drought (145). Groundwater discharge into surface  
13 waters during warm seasons provides critical cool refuges for coldwater species (146). In  
14 contrast, when roofs, pavements, or other impermeable surfaces block natural hydrologic  
15 flow paths, precipitation flows quickly into channels, generating more erosion and  
16 producing “flashier” (more rapid, larger, but less sustained) peak flows (145,147). Overland  
17 flows also deliver more raw pollution to waterways because they short-circuit the  
18 purification and microbial detoxification and **denitrification** (conversion of nitrate to  
19 nitrogen gas) that occurs during contact with soils (148–150). Agricultural drainage tiles,  
20 compacted and overgrazed soils, wetland ditching, floodplain diking, and other land  
21 modifications to reduce subsurface residence times of water also worsen the extreme  
22 flooding and droughts projected and now observed under hydroclimatic change (151,152)  
23 (see Ch. 10: Climate Change).

24 **Riparian** corridors along channels or lakeshores have been fragmented by extirpation or  
25 damage of their vegetation. Wooded riparian corridors shade and cool channels (153), as  
26 well as filter and retain sediments, nutrients, and toxicants that would otherwise pollute  
27 surface waters. Their rooted banks, where undercut, provide excellent cover for fish and  
28 other aquatic vertebrates, as well as perches for birds, adult dragonflies and damselflies,  
29 spiders, lizards, amphibians, and bats that prey on aquatic insect emergence that  
30 concentrates along shorelines (Figure 7.2) (23,154–157). In general, riparian zones harbor  
31 more plant and animal species than adjacent aquatic or upland terrestrial habitats (158).  
32 They also serve as migration corridors for valued birds and mammals (159). Two-thirds to  
33 three-quarters of historic riparian forest in CONUS has been lost to agriculture, livestock  
34 grazing, groundwater pumping, and urbanization (160). However, a survey of riparian buffer  
35 zones for 42,363 catchments across 63 ecoregions of CONUS showed a small increase  
36 from 1972 to 2003, possibly due to natural recovery and protection or restoration efforts  
37 (161).

38 **Levees** block natural lateral migrations of rivers that once created and revitalized diverse  
39 and productive **floodplain** habitats (162–164) and also have unintended consequences.  
40 River floodplains and their diverse array of side channels, off-channel water bodies, and

1 wetlands have supported humans for millennia, dissipating floodwaters, storing and  
 2 detoxifying groundwater, regenerating soil fertility, retaining sediments that would  
 3 otherwise fill mainstream reservoirs (165), and supporting abundant productive  
 4 populations of fish, water fowl, and other vertebrates on scenic waterscapes. But an  
 5 estimated 30% of floodplain area in CONUS and 83% of the Mississippi River's historical  
 6 floodplain has been lost (Box 7.3) (152). Lateral habitats also matter in smaller streams. In  
 7 Puerto Rico, dams result in loss of side-channel and headwater habitats by restricting  
 8 upstream migration of native freshwater species and increasing sediment accumulation  
 9 and decreasing storage for municipal water supplies and recreation (69).

10 Finally, river channel networks are fragmented by tens of thousands of flow-regulating  
 11 dams (Figure 7.5). These have artificially stabilized and sometimes reversed (for summer  
 12 agriculture in the arid West) normal seasonal flow and thermal regimes to which native  
 13 organisms have adapted (166–168). Two million dams and culverts block upstream fish  
 14 movements, devastating migratory fish populations, including both Pacific and Atlantic  
 15 salmon, which historically abounded in rivers draining to both US coasts (169,170). The  
 16 great ecological harms of these dams are, happily, revealed by the amazing recovery of  
 17 river ecosystems, salmon, and other native species when dams are removed (see KM 7.3).

18 **Figure 7.5. Fragmentation of Freshwater Systems and Flows**

### Fragmentation of Freshwater Systems and Flows

(a) Large and Medium Dams



(b) Watersheds



	Number of Dams			Number of Dams	
	Large	Medium		Large	Medium
Pacific Northwest	68	925	Mississippi	441	24,974
California	70	944	Souris-Red-Rainy	14	377
Great Basin	5	405	Great Lakes	22	1,767
Colorado	26	910	North Atlantic	90	6,351
Rio Grande	18	453	South Atlantic-Gulf	99	9,194
Texas-Gulf	79	3,113	Hawai'i	0	32

19

1 **Rivers and floodplains have been fragmented by water levees and dams across the**  
2 **US.**

3 *Tens of thousands of dams fragment the rivers and streams of the United States. These*  
4 *maps show (a) the distribution and abundance of almost 52,000 medium and large dams*  
5 *across the US, including Hawai'i, and (b) the major geographic regions and river systems in*  
6 *the US, with total counts of dams by region. Dams shown are at least 7.6 m high with more*  
7 *than 18,500 m<sup>3</sup> of storage, or at least 1.8 m high with more than 61,700 m<sup>3</sup> of storage. Large*  
8 *dams (black circles) retain more than 100 million m<sup>3</sup> of water in reservoirs, while medium*  
9 *dams (gray circles) store less than that. No dams meeting these criteria exist in Alaska.*  
10 *Figure original to The Nature Record.*

11 At regional scales, a portfolio of linked river, wetland, and lake ecosystems can stabilize  
12 delivery of ecosystem goods and services, much as a diverse portfolio of stocks and bonds  
13 can stabilize investments (171). For example, the Alaska Bristol Bay sockeye fishery as a  
14 whole maintained stable high catches despite a precipitous drop in the number of fish  
15 returning to one key river because this loss was offset by newly increased production from  
16 other rivers of the region (172–174). Within rivers, salmon production from different  
17 tributaries varies asynchronously as well, further stabilizing fish returns at the watershed  
18 scale (175,176). If this habitat complexity (and the population diversity it supports) is  
19 degraded (for example, by mining), Bristol Bay salmon populations will become more  
20 vulnerable to crashes, as are salmon throughout their ranges at lower latitudes (177).

21 Regional- to continental-scale inland water habitats are essential for supporting other  
22 migrations that require unbroken river corridors (e.g., alewives and river herring in Maine,  
23 catadromous eels east of the Rocky Mountains) or adequate aquatic habitat along North  
24 America's four continental flyways for hundreds of bird species (including cranes, geese,  
25 ducks, and many songbirds) that migrate annually between northern summer breeding  
26 grounds and southern overwintering habitats (178).

27 **Loss of Native Biota and Introduction of Non-Native Species**

28 Human activities have caused population declines of native animals, plants, and other  
29 species throughout inland waters of the United States, so that thousands of species are  
30 now imperiled or extinct. Some valued native species (e.g. fishes, freshwater mussels)  
31 have been overharvested by humans; more are being lost to habitat degradation. As  
32 freshwater habitats are being destroyed, non-native species are being introduced, many of  
33 which infect, outcompete, or prey on native species. As of 2023, 188 non-native species  
34 have been introduced to the Great Lakes, and some have harmed native species by  
35 outcompeting or preying on them or harboring pathogens (179,180). Declines in a native  
36 deep water crustacean, *Diporeia*, followed invasions of Lake Michigan by non-native zebra  
37 and quagga mussels and appear to have transformed the lake bed from a food source to a  
38 food sink for fish and other consumers (181,182). Native inland water biota throughout  
39 CONUS are handicapped if exotic species are better adapted to human-manipulated flow  
40 and temperatures, as occurs in western rivers invaded by bullfrogs, warmwater fishes

1 (183), and other species introduced from the Midwest. Facing non-native species  
2 introductions, habitat degradation, and overharvesting, freshwater animals have higher  
3 rates and risk of extinction than populations from any other terrestrial or marine  
4 ecosystem. More than 10% of North American freshwater mussel (*Unionoida*) and snail  
5 species are thought to have gone extinct **globally** since 1800 (184,185). Of the surviving  
6 species, 55–72% of North American snails, freshwater mussels, and crayfishes and 33–  
7 43% of fish, mayfly, and stonefly species from inland waters are as or more imperiled than  
8 the spotted owl and the polar bear (186), with danger of extinction expected in coming  
9 decades. Only 7% and 17% of North American birds and mammals, respectively, are in  
10 similar peril (187).

11 Since European colonization, many populations of native invertebrates and fishes that  
12 don't face extinction have nevertheless increased or decreased in abundance, some more  
13 than threefold over a few decades, particularly in developed parts of the country.  
14 Throughout CONUS, Hawai'i, Puerto Rico, American Sāmoa, and Guam, populations of  
15 algae, vascular plants, aquatic insects, crustaceans, mollusks, worms, and fishes have  
16 changed in abundance due to nutrient loading, non-native species introduction, dams and  
17 hydrologic alterations, climate change, land-use change in the watershed or riparian zone,  
18 water withdrawals, floods, droughts, pesticides, and harvest (188–192). Aquatic insects  
19 used as indicators of high water quality (mayflies, stoneflies, caddisflies, damselflies and  
20 dragonflies) have tended to decline (193,194). Weather surveillance radar shows that  
21 mayfly (*Hexagenia*) abundance has decreased over 50% over the western Lake Erie Basin  
22 and Upper Mississippi River (195). As larvae, these insects feed fish, and as emerging  
23 adults, they feed birds and bats. Breeding success in spotted flycatchers and flying  
24 performance in bank swallows were positively correlated with aquatic insect availability  
25 because they are rich in polyunsaturated fatty acids (196,197). Amphibians are also  
26 declining globally, including in the US (198,199). Some suffer from disappearance of  
27 habitats, like ephemeral ponds (200,201). Other amphibians confront threats and stressors  
28 from water, land, and air. For example, yellow-legged frogs (*Rana muscosa*) declined in  
29 alpine lakes of the California Sierra Nevada due to predation from non-native golden trout  
30 (202), airborne pesticides from lowland agriculture (203), and disease (204).

31 The 57 species of turtles (freshwater or terrestrial) in CONUS constitute 18% of global  
32 turtle species. Diversity is highest in Southeast, peaking in the Mobile River Basin with  
33 more than 18 species and 24 more in the surrounding region. Almost 40% of US turtle  
34 species are threatened (205), mainly by habitat loss and degradation but also due to some  
35 commercial collection for the international pet and consumption trade (206). Turtles' long  
36 life spans require long-term studies to adequately document declines.

37 Some population losses have had large economic consequences. For example, the Great  
38 Lakes, which once supported large fisheries worth millions of dollars per year, have now  
39 lost or are close to losing several native fish stocks (blue pike, several whitefish species,  
40 lake sturgeon) (207,208). Collapse of coastal salmon populations have eliminated more  
41 than 10,000 jobs that once kept more than 1,000 fishing boats in port and has cost the

1 California economy over a billion dollars per year (209). Likewise, US freshwater mussels  
2 supported fisheries for shells and pearls that were worth \$10 billion (2017 dollars)  
3 (210,211). We do not know enough about the ecological or economic consequences of  
4 most losses and declines of native species, however, to estimate the cumulative economic  
5 losses of their declines.

6 At the same time, invasive species are introduced via human activities, including boat  
7 transfers between watersheds (212–214), releases of shipping ballast water (215,216),  
8 aquarium releases (217–219), escapes from aquaculture (220,221), construction of canals  
9 (222,223), and movement of contaminated recreational gear (224,225), as well as  
10 deliberate stocking of non-native species thought to be desirable by agency scientists or  
11 members of the public (226–228). These activities have brought hundreds of non-native  
12 species into US inland waters, and the numbers are increasing (180,229–233). This rate of  
13 new species invasions is expected to continue without effective management actions  
14 (232,234,235).

15 Non-native species now dominate many inland waters in the US, changing their ecological  
16 functioning and value to people. Proliferations of non-native water hyacinth, Eurasian  
17 water-milfoil, and hydrilla block canals, clog recreational waters, and damage fish habitats  
18 in thousands of lakes, reservoirs, and rivers throughout the United States (236–238).  
19 Invasion of predatory Asian swamp eels (*Monopterus albus/javanensis*) in Taylor Slough of  
20 the Everglades National Park decreased the average fish and crayfish species richness by  
21 25%; there was also a 68% decline in the small fish and decapod biomass, followed by an  
22 80% decrease in nesting wading birds (239,240).

23 Introduced fishes such as Asian carp almost always outcompete native fishes for food and  
24 habitat and carry harmful pathogens, impacting both commercial and recreational  
25 fisheries and decreasing water quality by consuming aquatic vegetation and stirring up  
26 sediment (241–244). The quagga mussel has transformed chemical cycles and food webs  
27 throughout the Great Lakes, reducing growth rates and landings of lake whitefish, the  
28 region's most valuable commercial fish (245–248). Imported diseases such as viral  
29 hemorrhagic septicemia and whirling disease have devastated salmonids and other  
30 valuable fish populations throughout the country (249–251). The costs of these harms are  
31 hard to estimate precisely but are probably in the range of billions of dollars per year—as  
32 costly as natural hazards such as storms, wildfires, and floods (252–254).

### 33 Ecosystem Consequences of Changes in Species Distribution and Abundance

34 Changes in populations of inland-water species can strongly affect their ecosystems (255).  
35 For example, after once-abundant mussels in the Kiamichi River in Oklahoma declined by  
36 60% due to a series of droughts and poor management of an upstream reservoir, the  
37 nitrogen and phosphorus they had formerly filtered, stored, and recycled into the food web  
38 built up to decrease water quality in the river (256). Declines of aquatic stoneflies that feed  
39 on tree leaves in streams slowed organic-matter decomposition, nutrient recycling, and  
40 productivity in their streams (257). The introduction of the non-native spiny water flea

1 reduced water clarity and the food supplies to sports fish in and around the Great Lakes  
2 (258,259). Non-native bivalves (zebra and quagga mussels, the basket clam *Corbicula*, the  
3 newly arrived golden mussel) and other species also clog industrial and agricultural water  
4 systems and canals and foul ship and boat hulls, with costs estimated at tens of millions of  
5 dollars per year in the United States (260,261).

6 The spread of chytrid fungi has devastated frog populations. Where their litter- and algae-  
7 grazing tadpoles were lost, litter decomposition decreased, **benthic algae** bloomed, and  
8 biogeochemical cycling and food webs shifted (262,263).

9 Losses of large fish species, including apex predators, are particularly concerning. Large  
10 fish link aquatic open water and nearshore lake food webs (264,265), as well as river,  
11 terrestrial, and marine habitats (31,175,176,266), via their movements, migrations, and  
12 changes in foraging and habitat use over their life cycles. Overharvests of once-abundant  
13 fishes have often altered ecosystem function (267). Migratory salmon swim marine  
14 nutrients hundreds to thousands of miles up rivers (175,264,268). Their carcasses feed  
15 scavenging vultures, eagles, raccoons, and bears and nourish riparian terrestrial  
16 ecosystems (269). Restoration, management, and conservation efforts have had some  
17 success due to advances in data, methods, and collaborations (see KM 7.3). Overall,  
18 however, these efforts are not keeping pace with aggregate human impacts. Areas that now  
19 support richer assemblages of native species (undeveloped areas, parks, and reserves) are  
20 under increasing threat from direct human impacts and indirect impacts from climate and  
21 invasive species.

## 22 Description of Evidence Base

23 It is *virtually certain*, based on multidecadal in situ and satellite groundwater monitoring  
24 across CONUS and extensive modelling, that across much of the US, surface and  
25 groundwaters are being withdrawn for use faster than they can be recharged. It is *virtually*  
26 *certain*, based on multi-decadal in situ and satellite water quality monitoring across  
27 CONUS and extensive field observations, that many rivers, lakes, and aquifers in the US are  
28 polluted by excessive nutrients, toxicants, and excessive fine sediment—although trends  
29 are less documented in Alaska). That dams, levees, impermeable surfaces, and diversions  
30 have fragmented natural flows that sustain river, wetland, riparian, lake, and groundwater  
31 ecosystems, worsening impacts of floods and droughts and disrupting species life  
32 histories and migrations, is *virtually certain* based on decades of ecological field studies  
33 and monitoring, including of major bird and fish migrations and comprehensive aerial and  
34 ground-based observations of ecosystem impacts on inland waters. In many aquatic  
35 ecosystems, the loss of native species and establishment of non-native species is *very well*  
36 *established*, based on studies and observations in many aquatic ecosystems across the  
37 US. While extinctions and non-native introductions with harmful impacts are documented  
38 throughout CONUS, Alaska, Hawai'i, Guam, and Puerto Rico, field monitoring and  
39 taxonomic training have not been sufficient to detect all such changes in biogeographical  
40 distributions.

## 1 Key Message 7.2: With further climatic change, inland water 2 ecosystems and fresh water supplies will deteriorate more

3 *As climate change continues to alter the hydrologic system in the US, inland water habitats,*  
4 *native plants and animal populations, and the quality and quantity of ground- and surface-*  
5 *water supplies are expected to degrade further (established but incomplete). Both inland*  
6 *water systems and the human societies that depend on them are expected to experience*  
7 *new diseases and abrupt changes in habitats and landscapes (virtually certain). These*  
8 *changes are expected to accelerate and become increasingly difficult to reverse under*  
9 *further climate change (established but incomplete).*

### 10 State of Knowledge 7.2

#### 11 Warming Impacts on Quantity and Quality of Inland Waters

12 Rain and snowfall patterns and intensity are changing over the US and will continue to do  
13 so into the future (270) (Figure 7.6). Variable precipitation and rising temperatures are  
14 intensifying droughts—which have been longer and hotter over the last 22 years (271),  
15 reducing snowpack (272,273), and increasing heavy downpours (274). Observed rising  
16 frequency of short-duration (hourly to daily) extreme rainfall events are responsible for  
17 more than a hundred deaths per year in the US (275), as they can lead to flash floods that  
18 occur with little warning (see Ch 10: Climate Change). Intense floods also damage  
19 infrastructure and pollute water supplies (276,277), harming aquatic biota and public  
20 health (278). In 2025, a flood killed more than 135 people in the Texas Hill Country, and  
21 other deaths occurred in North Carolina, New Mexico, Virginia, and New Jersey (279).

22 Hydroclimatic change will not only affect the quality and quantity of water available to  
23 sustain natural ecosystems or satisfy rising human demands, but will also shift its  
24 seasonal delivery (163,177,280). Warming-related snow deficits in Western US mountain  
25 rivers (272,273,281) reduce late-summer streamflow (282), which is critical to recharging  
26 the groundwater table needed by rivers to buffer low flow and high temperatures (283–286).  
27 This is particularly true for the western mountain regions of US and Alaska, where changes  
28 in snowmelt delivery and loss of storage in snowpacks, glaciers, and permafrost are well  
29 documented (53,163,177,280,282,287–293).

#### 30 Effects of Climate Warming on Impacts of Pollution

31 Warming will exacerbate almost every factor harming inland water species and  
32 ecosystems. Warm water holds less dissolved oxygen, stressing fish and many aquatic  
33 invertebrates and making them more vulnerable to toxicants. Changes in streamflow and  
34 temperature can stress riparian vegetation, reducing shading and bank stabilization of  
35 stream channels (289). Warming also increases solubility of toxic metals and other  
36 toxicants so these are more easily transferred into organisms and the water column from  
37 lake sediments (294). Warming and low oxygen also releases phosphorus from sediments

1 (295) so it can circulate up to the **surface waters** to fuel algal blooms (296). Increasing  
2 strength of storms and winds under climate change (297) are expected to deliver more  
3 nutrients to fuel increasing eutrophication (298,299). In agricultural watersheds, warmer,  
4 wetter conditions and more intense storms will increase delivery of nutrients, pesticides,  
5 and eroded soil to rivers and lakes (299). In many agricultural watersheds, most annual  
6 nutrient flux through streams occurs during a few days with large storms (300,301). Across  
7 climate scenarios, nutrient loading to rivers within the continental US is expected to  
8 increase on average by nearly 20% by the end of the century, compared to historical  
9 loading (between 1997–2005), particularly in the Northeast and the Corn Belt (298).

10 Warmer waters also tend to favor cyanobacteria, including toxin-producing species (302–  
11 306). Increases in seasonal surface temperatures in western Lake Erie are associated with  
12 a 30% increase since 1995 in the seasonal growth rate, the number of bloom days, and the  
13 duration of the bloom season of *Microcystis* (93), the liver-toxic cyanobacteria that shut  
14 down Toledo’s water supply for more than 2 days in 2014 (307).

## 15 Warming and Species Interactions

### 16 *Native and Non-Native Species*

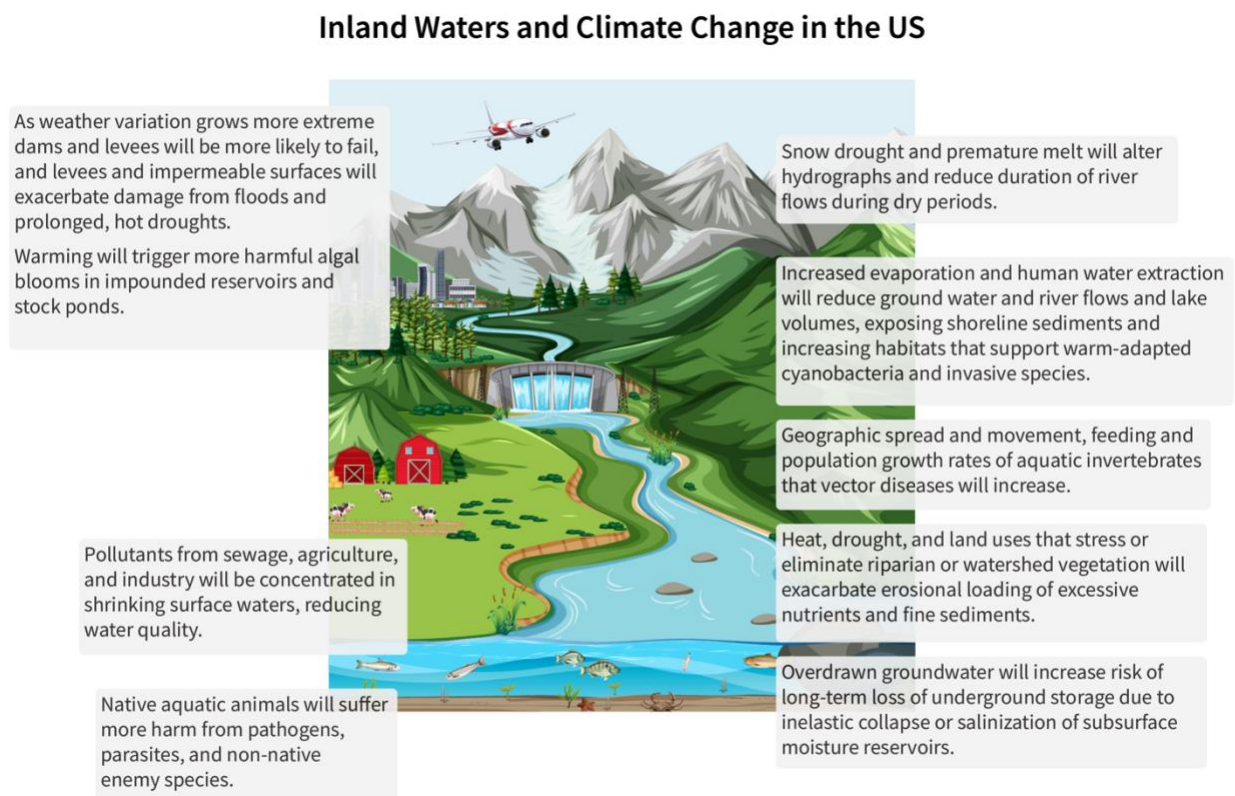
17 As climate change proceeds, aquatic systems may be particularly vulnerable to invasion  
18 (308,309). If environmental conditions, like higher temperatures or low current velocities,  
19 are hospitable for non-native introduced species, long experience has shown that they are  
20 likely to establish, and often out-perform resident native species (310). A meta-analysis of  
21 157 non-native species and 204 native species showed that aquatic native animals were  
22 particularly vulnerable, as many performed more poorly in warming environments than  
23 non-native invaders (308). Non-native freshwater species overall had broader  
24 environmental tolerances (and correspondingly larger geographical ranges) than native  
25 species (309). Warming as well as artificial flow regulation of western rivers has greatly  
26 disadvantaged native fishes (168) and frogs (311,312) in interactions with non-native  
27 species from the US Midwest or Southeast. For example, native coldwater steelhead  
28 (salmonids) are less able to compete with juveniles (313) or avoid predation from adults  
29 (314) of the warmwater non-native piscivorous pikeminnow introduced into coastal  
30 California rivers.

### 31 *Hosts, Pathogens, and Parasites*

32 Impacts of pathogens and parasites are increasing as inland waters of CONUS warm  
33 (315,316), plausibly due northward spread of parasites, pathogens, or their vectors or  
34 intermediate hosts; weakening of host resistance; acceleration of parasite life cycles or  
35 pathogen population growth relative to slower-growing vertebrates; increases in the  
36 number of parasite pathogens or parasite generations per year with extended growing  
37 seasons; and faster transmission through host populations (particularly if aquatic habitats  
38 shrink or become more stagnant) (315). Although outcomes and mechanisms vary among  
39 species and environmental contexts, warming leads to more adverse outcomes for animal

1 hosts in a number of cases, including red sore disease in largemouth bass (317),  
 2 ectoparasitic copepods in river-breeding frogs (318), and blackspot disease in steelhead  
 3 trout (319). Chytrid infections (which are devastating amphibians worldwide) in  
 4 populations of native western river-breeding frogs may be a counter-example—an  
 5 extensive survey of specimens from Oregon through California showed that the frequency  
 6 of detected infections declined with maximum air temperature (263).

## 7 **Figure 7.6. Inland Waters and Climate Change in the US**



8

9 **Warming will exacerbate harms already underway because of past and current human**  
 10 **activities.**

11 *Examples of how warming will exacerbate harms caused by past and current human*  
 12 *activities. Figure original to The Nature Record.*

## 13 **Description of Evidence Base**

14 Predicted increases in warming and extreme hydrologic variation have become a reality,  
 15 with a robust evidence base of long-term monitoring studies at large and small spatial  
 16 scales showing impacts on water quantity and quality, including drought and flood regimes  
 17 across nearly every region in the US regardless of moisture regime. A solid base of evidence  
 18 shows that warming and reduced water supplies (due to natural or anthropogenic drought)  
 19 are negatively impacting many inland water species, particularly those adapted to colder

1 habitats with high water quality. Expected future degradation from climate change is  
2 assessed to be *established but incomplete* because it is not known whether valued native  
3 species have sufficient genetic variation or developmental plasticity to adapt to new  
4 hydroclimatic regimes; knowledge of the environmental or genetic factors that control  
5 traits (toxicity, virulence, vulnerability) of ecological importance is far from complete. Many  
6 observational and some experimental studies across a broad range of vertebrates and  
7 invertebrates show cases in which warming increases the spread and virulence of  
8 pathogens and parasites and weakens host defenses, with some exceptions. Replacement  
9 of native plants and animals by the spread of non-natives better adapted to warmer  
10 climates has been widely observed across the US, and there is now a robust evidence base  
11 over geography, time, and taxonomy indicating that these adverse ecological changes,  
12 many of them abrupt, are *virtually certain* to affect most inland water ecosystems in the  
13 US. Interactive impacts of multiple stressors (toxins, salinity, heat, eutrophication,  
14 pathogens) in the natural environment are known in a few cases, but how most will play out  
15 in warming, dwindling inland water ecosystems remains unknown. The lack of knowledge  
16 about whether humans will reduce their impacts and restore conditions under which native  
17 aquatic species can adapt to increasing climate stress makes our assessment of future  
18 degradation *established but incomplete*.

### 19 Key Message 7.3: Inland waters could be partially restored and 20 managed to increase US resilience to climate change

21 *Inland water habitats and biota are capable of surprising recovery if released from*  
22 *chronically damaging human impacts, although recovery times vary greatly among*  
23 *ecosystems (well established). Measures that could, if widely applied, recover important*  
24 *ecological and human benefits in inland waters of the US, and make them more resilient to*  
25 *further hydroclimatic change, include: (1) controlling nutrient loading (very well*  
26 *established) and supporting aquatic food webs with thriving native predators (established*  
27 *but incomplete), (2) reconnecting the natural hydrologic flow paths that link inland waters*  
28 *to their watersheds and connect them at regional scales (very well established), (3)*  
29 *restoring natural or semi-natural seasonal hydrologic regimes (well established), (4)*  
30 *building and maintaining barriers to invasive species (established but incomplete), and (5)*  
31 *establishing long-term monitoring programs to evaluate success and the need for*  
32 *stewardship in response to changing ecosystem states and environmental conditions*  
33 *(virtually certain).*

### 34 State of Knowledge 7.3

#### 35 Resilience of Inland Water Ecosystems and Biota

36 Collapse of natural inland water ecosystems is not inevitable. If seasonally or periodically  
37 flushed by natural or managed flows, rivers (41,320) and wetlands (11) are remarkably  
38 resilient, as are inland water biota (321,322). Riverine taxa, particularly western species,  
39 have behaviors (321,322) and life histories (323–325) adapted to highly variable hydrologic

1 regimes. Insects with aquatic larvae that alternate with aerial adults (326) or fishes with  
2 both marine and freshwater life history stages (327) are better able to rebuild populations  
3 after environmental disruption or stresses have ended. Pacific salmon provide a clear  
4 example. Because they spend part of their lives in the ocean and some returning spawners  
5 stray into non-natal rivers, they have, over their evolution, endured volcanic eruptions and  
6 the breakup of huge ice dams (325,328). Population variability in spawners' return times  
7 allow some individuals to survive unpredictable year-to-year variation in river flows  
8 (327,328). Some turtle, amphibian, and fish species can go into quiescent states, under  
9 lakebed or shorelines, to weather stressful months (329,330). Even species that evolved in  
10 more stable habitats like large lakes have resistant life stages that can long endure  
11 unfavorable environmental periods, sometimes for decades or centuries (331,332).

## 12 Vulnerability to Prolonged Stress and Habitat Loss

13 Despite their ability to tolerate environmental change, many inland water populations  
14 (particularly vertebrates) can't endure prolonged stress (e.g., from dewatered, artificially  
15 stabilized, or seasonally mistimed flow or thermal regimes (166,167,333)), particularly  
16 when compounded by habitat loss to pollution, diking and draining of wetlands (Figure 7.2),  
17 loss of riparian corridors (334), or massively engineered levees (324,335), dams (336,337),  
18 diversions, and culverts (338). The severity and decade-to-century long legacies of these  
19 harms in the US make the natural ecosystem recoveries seen when inland waters are  
20 relieved of these pressures all the more remarkable.

## 21 Restoring Food Webs and Water Quality of Inland Waters

22 Inland waters, particularly clear low-nutrient lakes, provide clear, drinkable or swimmable  
23 water and can sustain vibrant populations of native fishes and other vertebrates of cultural  
24 and economic value. Such lakes are maintained by restricted nutrient loading, and  
25 sometimes periodic flushing of their waters. When such habitats are overloaded with  
26 nutrients (from sewage or agrochemicals, destruction of wetlands and native watershed  
27 vegetation, erosion, overdrafts of water that reduce depth and increase wind mixing—see  
28 KM 7.1), they can be tipped into green-water (**eutrophic**) states (Box 7.2) (339).

29 Remediations have been suggested and attempted via **biomanipulation**: measures to  
30 promote consumers and predators (much longer-lived than fast-growing algae and  
31 microbes) could sustain or recover clear water states by sequestering nutrients (Box 7.2)  
32 (94,340,341). Evidence for this “top down” control of inland water quality has been mixed  
33 (342), however, and results in the same habitat can vary between years under different  
34 hydroclimatic conditions. A consensus is emerging that consumers, predators, and  
35 terrestrial wildlife of inland waters should be recovered and sustained for their own value,  
36 but that water quality must be managed by controlling pollutants from watersheds.

### 37 **Box 7.2. Recovery of Lake Washington**

38 Lake Washington, in Washington State, is surrounded by the rapidly growing Greater Seattle  
39 Metropolitan area where human density has increased rapidly over the last century, one of

1 the most rapidly growing urban centers in the US. Water quality was heavily degraded and  
 2 characterized by nuisance blue-green algae during the early 20th century as the city was  
 3 expanding rapidly but with limited management of sewage-derived nutrients (particularly  
 4 phosphorus) (343). Nutrient management and sewage diversion out of the watershed  
 5 reduced phosphorus inputs to the lake, leading to improved water quality and reductions in  
 6 nuisance algae within a decade (Figure 7.7) (343).

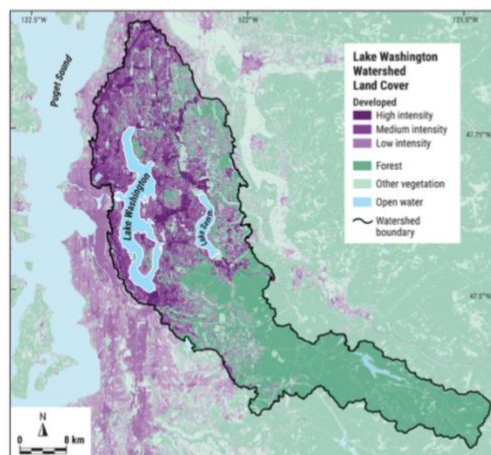
7 At the same time, there were important changes in the lake food web. Longfin smelt  
 8 (*Spirinchus thaleichthys*) became established in the lake, owing to a combination of flood  
 9 control measures on the Cedar River, which flows into the lake and is spawning ground for  
 10 the smelt. The increasing population of longfin smelt predominantly preyed upon a small,  
 11 shrimp-like crustacean in the lake, *Neomysis mercedis*. *Neomysis*, in turn, is a keystone  
 12 predator on *Daphnia* (the water flea). Through this chain of food web interactions, the  
 13 increase in longfin smelt led to the establishment and eventual dominance of *Daphnia*  
 14 in the zooplankton community. Because of its high grazing rates on algae, *Daphnia* further  
 15 clarified the lake by reducing algae abundance, leading to increases in transparency from  
 16 two meters to over six meters.

17 Excellent water quality has persisted to the present because of the stability of *Daphnia*  
 18 grazers and continued effective nutrient management in the watershed despite an increase  
 19 of more than 30% in human density since 2000 (344). Lake Washington remains a classic  
 20 example showing that excellent water quality can be maintained by nutrient management  
 21 and aquatic food webs despite intense urbanization.

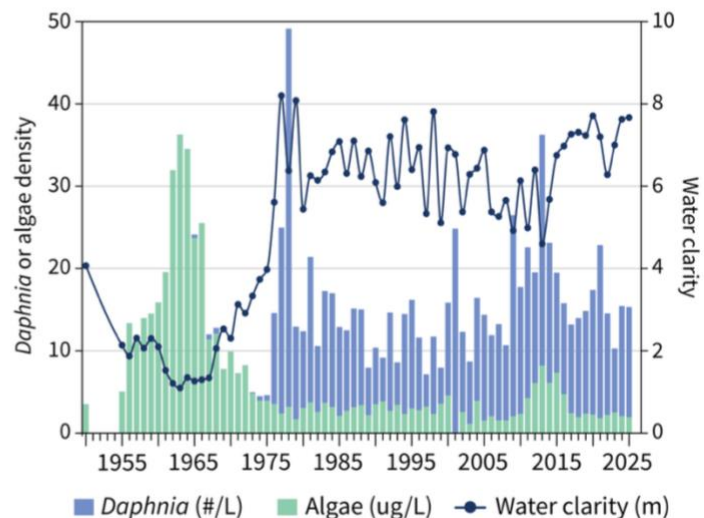
22 **Figure 7.7. Urban Development and Lake Ecosystem Responses in the Lake**  
 23 **Washington Watershed**

### Urban Development and Lake Ecosystem Responses in the Lake Washington Watershed

(a) Land-cover



(b) Lake ecosystem responses



24

1 **Active human management efforts and corresponding ecosystem responses have**  
2 **improved water clarity in Lake Washington.**

3 *(a) Land-cover map of Lake Washington watershed in 2021 showing intense urban*  
4 *development in close proximity to the lake. The human population increased by 34%*  
5 *between 2000 and 2020. (b) Long-term trends in lake water clarity (black line; measured as*  
6 *the Secchi depth, i.e., the depth at which a black and white disk lowered from the water's*  
7 *surface disappears from sight), the amount of algae in the water (green bars; measured as*  
8 *the chlorophyll concentration), and the abundance of efficient phytoplankton grazers in the*  
9 *zooplankton community (blue bars; annual summer Daphnia densities). (a) Reprinted from*  
10 *Nidzgorski and DeGasperi 2025 (344). (b) Figure original to The Nature Record; data from*  
11 *Edmondson 1984 and Nidzgorski and DeGasperi 2025 (343,344) and D.E. Schindler,*  
12 *unpublished.*

13 [END BOX 7.2 HERE]

14 Legacy nutrients that have accumulated within watersheds and aquatic ecosystems  
15 complicate restoration of eutrophic waters. Nutrients and pollutants that have  
16 accumulated in soils of watersheds can leach into inland waters for decades or even  
17 centuries, masking the benefit of reducing or curtailing new nutrient inputs (e.g., from  
18 fertilizers) (301,345,346). Similarly, accumulation of nutrients (particularly phosphorus) in  
19 lake sediments can delay recovery from eutrophication if these nutrients are released into  
20 overlying waters by wind mixing or hypoxia (347). Lakes vary greatly in their legacies,  
21 landscape context, and **morphometry** (ratio of lake width to depth and other aspects of  
22 basin shape), so will differ in their rate recover from eutrophication, which may take  
23 decades, even if introduction of anthropogenic nutrients is curtailed (348). By far the best  
24 measure is to prevent excessive nutrient loading to lakes in the first place. But another  
25 means would be reconnection of these waters to upland flowpaths and storage elements  
26 that could be powerful tools for water quality management.

27 The role of legacy damage to inland waters or watersheds requires understanding local  
28 landscape history and site-specific natural channel-forming processes. This research,  
29 however, proves cost effective as it can explain or predict when active restoration  
30 measures will fail or require sustained expensive maintenance. For example, extensive tree  
31 planting was ineffectual for reducing stream bank erosion and retaining fine sediment and  
32 nutrients in watersheds feeding excessive silt and phosphorus into the Chesapeake Bay  
33 (349,350). Nutrient and sediment retention improved substantially, however, when deep  
34 legacy sediments from 18th–19th-century upland deforestation and long-vanished early  
35 American mill ponds were removed (349,351–353). Within a few years of unburial, historic  
36 freshwater marshes (critical habitat for the severely endangered Muhlenberg turtle)  
37 reformed via connection to long-buried groundwater springs (353,354).

## 1 Reconnecting Formerly Fragmented Inland Waters

2 While conspicuous dams, diversions, and levees fragment formerly connected inland  
3 water networks, pavements, roofs, and other impermeable surfaces are even more  
4 ubiquitous agents of this harm. Lack of recognition of vital linkages of surface to  
5 subsurface waters has long hindered water management, particularly in the arid west  
6 (355,356). Reconnecting precipitation to subsurface storage and slow release would  
7 improve ecological and societal resilience through current and anticipated drought and  
8 deluge events. Prolonged water contact with the soils and weathered bedrock also reduces  
9 nutrient and toxicant pollution. For example, small (1.6 ft deep, 17 ft diameter) soil-filled  
10 bioretention cells, built to detain water in traffic calming circles, reduced concentrations of  
11 6PPD-quinone (the toxin from car tires so lethal to salmonids) by ten-fold in urban road  
12 runoff (150).

13 These benefits play out on larger scales in floodplains recovered by levee setbacks,  
14 removals, or creative design—it was long ago pointed out that if low structures need to stay  
15 in floodplains and survive inundation, they can be encircled by ring levees (357). Such  
16 approaches create or conserve wetlands for **denitrification** (converting nitrate to harmless  
17 atmospheric nitrogen gas) (358) and for enhancing natural landscapes, fisheries, wildlife,  
18 and waterfowl populations. Wetlands generating these benefits can “time share” with  
19 certain land uses (farming, grazing) that reap the soil fertility and plant production of  
20 wetlands for farming or grazing during low flows, or employ them as methods to enhance  
21 “conjunctive” water storage or reroute floods. For example, the Yolo Bypass, a floodplain  
22 created to divert floodwaters around Sacramento, California, significantly enhances the  
23 growth of outmigrating juvenile salmon and therefore their chances of returning from the  
24 sea (359,360).

25 Mosquito production is a potential concern in wetland restoration. In Indiana (361),  
26 however, mosquito populations or complaints about bites dropped after wetland  
27 restoration, possibly because healthy wetlands support abundant mosquito predators  
28 (e.g., odonates, fish, amphibians), whereas puddles that remain after wetlands are drained  
29 can produce more of these short-lived pests and vectors. If habitats are sufficiently  
30 inundated, predators control disease-vectoring mosquitoes by both eating them and  
31 inhibiting their larval feeding so that smaller, weaker, less fecund adults emerge—this is  
32 possibly a factor for why mosquito-transmitted West Nile cases increase during drought  
33 (362). An international meta-analysis advised that reconstructed wetlands should be  
34 carefully managed when necessary to favor predators over mosquitos (363).

35 New or recovered floodplains quickly attract and sustain abundant populations—for  
36 example, of migratory birds in the Mississippi River Basin (Box 7.3) (164) and the recovered  
37 Cosumnes River floodplain in California (41,364,365) and of salmonids in the Yolo  
38 floodplain (360,366)—while recharging groundwater, dissipating flood waters, and  
39 enhancing soil and water quality (366).

1 Finally, rapid ecological recovery and benefits have followed the more than 2,025 dam  
2 removals that occurred across CONUS from 1912–2022 (367). Only a few years after  
3 removal of dams on the Elwha River in Washington state, riparian and river habitats had  
4 recovered natural features and thriving runs of native salmonids (368–371). Similarly, within  
5 one to two years of the removal of four major dams on the Klamath River in Oregon and  
6 California, thousands of Chinook salmon are accessing newly reopened habitat—some  
7 reaching more than 360 river miles from the ocean into the Upper Klamath Basin for the  
8 first time in over a century (372). Dam removals from the Penobscot River of Maine were  
9 followed within a year by the restoration of hundreds of thousands, then millions of  
10 migratory river herring (373), a key forage fish for the largest run of Atlantic salmon left in  
11 the US as well as four commercially important ground fish that gather at river mouths in the  
12 Gulf of Maine to prey on them (374,375). Endangered shortnose sturgeon reached habitat  
13 in the Penobscot River that had been blocked by dams for more than a century (376).

#### 14 Restoring Natural Flow Regimes

15 Humans have frequently imposed unnatural flow regimes on rivers that devastate native  
16 organisms and populations, but some harms have been alleviated with relatively minor  
17 adjustments to flows, where crucial bottlenecks in the life histories of species needing  
18 particular conservation protection are known. Mussel larvae in Kentucky (377) and eggs  
19 and tadpoles of native frogs in California (333) were wiped out by large flow releases from  
20 dams at times of year when flows in unregulated rivers were normally low. Adjustments of  
21 the timing of flow releases promote persistence of such species (333). Reinstating key  
22 elements of natural seasonal flow regimes (286) that sustain native populations and  
23 natural ecosystem functions sometimes necessitate only small additional releases of  
24 water. In the Eel, a California river under Mediterranean seasonality, only one bed-scouring  
25 flood per year is needed to rejuvenate salmon-supporting early summer food webs (320)  
26 and greatly reduce invasive bullfrog tadpoles. In Putah Creek in Northern California,  
27 dominance by native fishes was reestablished and expanded spatially by pulsed reservoir  
28 releases and elevated flows at biologically important times of year, with only a small  
29 increase in water delivery required (168). Attention to flows appropriate for key life history  
30 events of other taxa has supported regeneration of native riparian trees (167,378,379).

#### 31 **Box 7.3. The Mississippi River**

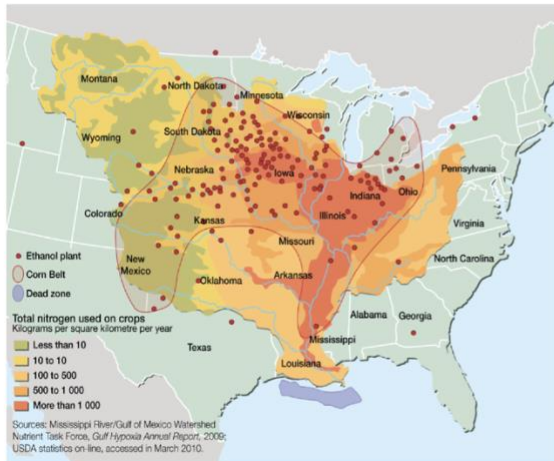
32 The Mississippi River has been heavily engineered for shipping and polluted by agriculture.  
33 Most of the Mississippi watershed is under intensive agriculture and receives hundreds of  
34 millions of pounds, annually, of herbicides (380) and of pesticides (381), and more than 2  
35 billion pounds of commercial nitrogen fertilizers (Figure 7.8) (382). Only one tributary of the  
36 Upper Mississippi River—the 44,000 km<sup>2</sup> Minnesota River—retains sufficient natural area in  
37 its 44,000 km<sup>2</sup> watershed to assess how wetland cover influences nitrogen retention within  
38 intensively managed agricultural watersheds (358). Analyses of these sub-basins suggest  
39 that 5–10% cover of wetland in a watershed can reduce nitrate (NO<sub>3</sub>) runoff to the  
40 Mississippi River by about 50% (358,383), a finding supported by subsequent studies,  
41 including some at large scales (384). These studies suggest that a surprisingly small

- 1 reallocation of farmlands to wetlands at critical landscape locations could alleviate a large  
 2 portion of the pollution problem, while also providing other benefits such as decreased  
 3 stream erosion and increased fish, wildlife, and waterfowl habitat.

4 **Figure 7.8. The Mississippi River Drainage Network**

**The Mississippi River Drainage Network**

(a) Agriculture in the Mississippi River Basin



**COPYRIGHTED MATERIAL**

Permission to reproduce pending.

5

6 **Agriculture along the Mississippi River adds nitrogen resulting in oxygen-poor waters**  
 7 **downstream, but increasing wetland cover can reduce nitrate levels.**

8 *The 2,340 mile long Mississippi River drains 1.25 million square miles and 41% of the area*  
 9 *and 31 of the 48 states in the contiguous US, including a vast area of agricultural land. (a)*  
 10 *The Mississippi River drainage system encompasses nearly all of the US corn belt (red*  
 11 *outline). Intensive agricultural production is supported by the addition of nitrogen, at levels*  
 12 *ranging from less than 10 kilograms per square kilometer per year (kg/km<sup>2</sup> per year; green*  
 13 *shading) to more than 1,000 kg/km<sup>2</sup> per year (red shading). Accumulation of nitrogen in*  
 14 *surface waters has created a “dead zone” of oxygen-poor waters at the mouth of the*  
 15 *Mississippi (see Ch. 6: Marine Ecosystems). (b) Increasing the proportion of the watershed*  
 16 *comprised of wetlands can reduce nitrate levels in receiving waters (permission pending).*  
 17 *(a) Cartographer: Riccardo Pravettoni, UNEP/GRID-*  
 18 *Arendal; <https://www.grida.no/resources/6227>.*

19 Restoration of Mississippi wetlands also shows the surprising resilience of its natural  
 20 floodplain ecosystems. Until the late 19th and early 20th centuries, wetlands and their off-  
 21 mainstem water bodies along the Mississippi were clearwater, scenic habitats that  
 22 supported more than 120 fish species, huge numbers (and rich harvests) of diverse  
 23 waterfowl, furbearing mammals, turtles, fishes, and mussels. Levee construction reduced  
 24 the seasonally inundated floodplain along the Mississippi by about 90% (27.2 million acres

1 out of 30.5 million acres of floodplain) (385). But The Nature Conservancy's Emiquon  
2 Reserve—a large floodplain restoration along the Illinois River near its confluence that is  
3 now approaching its 20th year—shows that both nutrient retention capacity and the rich  
4 biota of central Mississippi wetlands and floodplains have surprising resilience (Figure 7.9).

5 Six hundred generations of Native American tribes, including the Peoria, Potawatomi,  
6 Kickapoo, Sauk and Fox, and Myaamia, trace some of their history to this region. After they  
7 were displaced, European-American settlers fished and hunted the forested and grassed  
8 floodplains as a commons (386). Floodplains, forests, fish, birds, and wildlife disappeared  
9 after wetlands were privatized; floodplain lakes were ditched, drained, and converted to  
10 corn production; and the Mississippi was engineered for navigation. In 1924, two floodplain  
11 lakes had been disconnected from the Illinois River near its confluence with the Mississippi  
12 and reduced to ditches in agricultural farmlands. In 2007, the restoration project led by The  
13 Nature Conservancy reconnected these lakes to the mainstem, carefully engineering and  
14 monitoring sediment and water delivery from the river. This restored 11 square miles (more  
15 than 6,000 acres) of former floodplain lakes and wetlands where hundreds of thousands of  
16 migratory birds and populations of 30 native fish species now thrive (41,365). The  
17 recovered floodplain enriches the lives of approximately 20,000 visitors annually and is  
18 blessed each year by descendants of tribes who once lived there.

19 **Figure 7.9. Restoration of the Emiquon Preserve in the Illinois River Valley**

### Restoration of the Emiquon Preserve in the Illinois River Valley



20

21 **A restoration project along the Illinois River demonstrates the resilience of wetlands**  
22 **and floodplains.**

23 *The Emiquon floodplain was restored from agricultural production to an ecological*  
24 *preserve. In both panels, the Illinois River is at the right, with upstream at the top. The*

Do not cite, quote, or distribute.

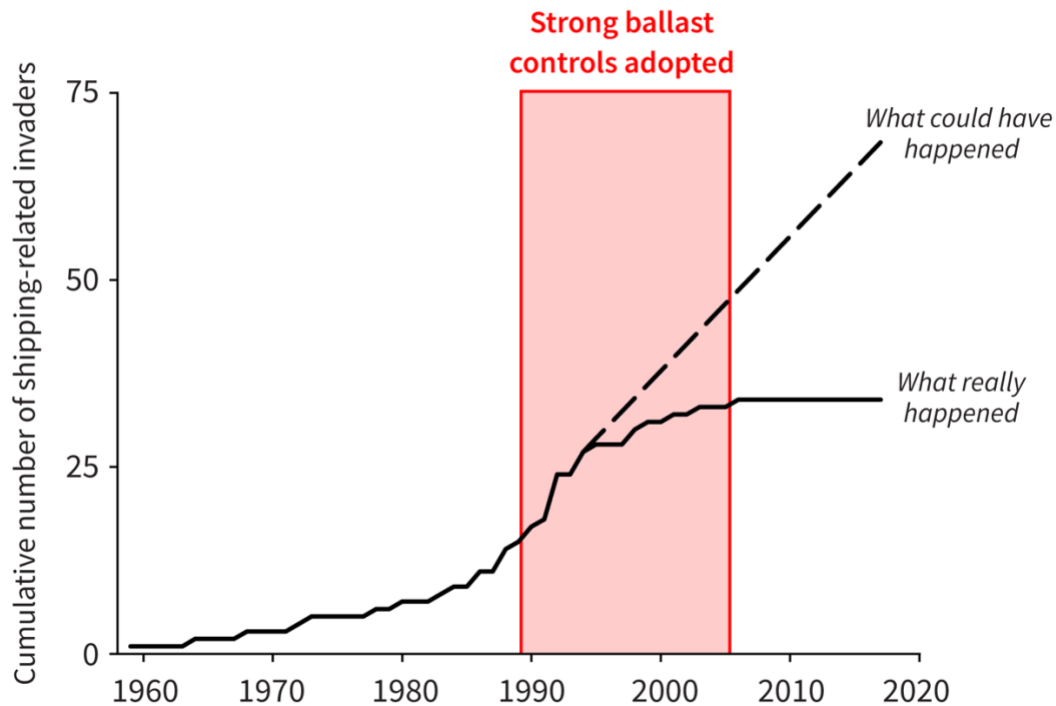
1 *distance across the floodplain, from the tree-lined bluff at the left to the eastern bluff, is 3.4*  
2 *miles (5.5 km). The river is 600 feet (183 m) wide. (left) The Emiquon Floodplain Preserve in*  
3 *June 2006, while it was still being farmed (note the white farm buildings in the upper left).*  
4 *Some water had begun to collect in Thompson Lake. (right) The restored floodplain (which*  
5 *is greater than 6,000 acres, or 2,400 ha) in June 2010. The farm buildings were replaced*  
6 *with a visitors' kiosk, paths, parking, and a launching ramp. Flag Lake is immediately left of*  
7 *the channel, covered with submergent and emergent vegetation. Thompson Lake is deeper,*  
8 *mostly open water, with fringing wetland vegetation. (left) Google Earth (June 2, 2006).*  
9 *Emiquon Preserve. 40°21'03"N 90°05'05"W, USDA/FPAC/GEO. <https://earth.google.com/>*  
10 *[Accessed February 11, 2026]. (right) Google Earth (June 23, 2010). Emiquon Preserve.*  
11 *40°21'03"N 90°05'05"W, USDA/FPAC/GEO. <https://earth.google.com/> [Accessed February*  
12 *11, 2026].*

13 [END BOX 7.3 HERE]

#### 14 Opportunities to Manage Non-Native Species

15 Reconnecting formerly isolated habitats may unleash invasions by non-native species  
16 (387), but there are preventative measures. For example, a 60-year record suggested that  
17 ballast controls have been effective against invasion by non-native species to the Great  
18 Lakes. The opening of the St. Lawrence Seaway in 1959 allowed ocean-going ships to come  
19 into the Great Lakes. The ballast water of these ships brought in many non-native species  
20 (Figure 7.10). In the 1980s, several species with especially large economic and ecological  
21 effects appeared (e.g., zebra and quagga mussels, round goby), and the states and  
22 provinces around the Great Lakes decided that they could no longer tolerate such high  
23 rates of invasion into the valuable Great Lakes ecosystems. Beginning about 1989, they  
24 imposed a series of regulations that stopped ships entering the Great Lakes from releasing  
25 untreated ballast water. In response, shipping-related invasions dropped almost to zero  
26 (Figure 7.10) (216), even though large numbers of ships continued to come into the Great  
27 Lakes.

28 Invaders arriving via the pet and horticulture trade, aquaculture, canals, and recreation  
29 could be stopped by other means (388). These measures would obviate post-  
30 establishment control programs with higher economic and ecological costs and lower  
31 chances of success (389).

1 **Figure 7.10. Preventing Great Lakes Invasions****Preventing Great Lakes Invasions**

2

3 **Ballast controls reduce the arrival rate of non-native species in the Great Lakes.**

4 *Strong ballast-water controls imposed by the Great Lakes states and provinces between*  
 5 *1989 and 2005 (red bar) effectively curtailed shipping-related invasions into the Great*  
 6 *Lakes. The “what could have happened” line (dashed line) is a conservative linear*  
 7 *extrapolation of the observed data (black line), which was increasing exponentially until the*  
 8 *introduction of these controls. The difference between the two lines suggests that at least*  
 9 *dozens of new invasions were prevented between 1995 and 2017 and continue to be*  
 10 *prevented. Adapted from Strayer 2024 (187).*

11 **Long-Term Monitoring Is Essential**

12 Monitoring before and after projects (or other changes to environments) is crucially  
 13 important but usually insufficient or not done at all (390). It is very challenging to match  
 14 observation schedules to timelines of ecologically significant changes, which can be faster  
 15 (e.g. non-native species introductions, toxic spills) or slower (release of legacy pollutants  
 16 from watersheds) than monitoring observations (391). Over the last few decades, however,  
 17 several US agencies have developed and maintained invaluable multidecadal monitoring  
 18 programs, recording time series that document trends in quantity and quality of inland  
 19 waters: these programs include the United States Geological Survey’s Stream Gaging

1 Network that tracks changes in US streamflow (26,392), the Environmental Protection  
2 Agency’s National Aquatic Resource Surveys (393), and two of its programs: the National  
3 Lakes Assessment (90), which tracks trends in lake water quality and harmful algal blooms,  
4 and the National Rivers and Streams Assessments (138). The National Atmospheric  
5 Deposition/National Trends Network documented significant reductions in acid rain and its  
6 precursors from 1986 to 2016 (394), which had previously devastated freshwater biota of  
7 lakes of the US Northeast (395). These programs have shown that over the last century,  
8 some water quality and quantity problems have worsened, while others have improved. For  
9 example, over 50 years after passage of the Clean Water Act, reduction of domestic and  
10 industrial point source pollution, and phasing out of leaded gasoline, water quality in many  
11 rivers and streams in the US has improved, with decreases in fecal bacteria (which  
12 continued to decrease from the 1980s to 2015) (396) and lead in the Nation’s waters from  
13 1974 to 1981 (although salt, nitrate, chloride, cadmium, and arsenic have increased)  
14 (52,397). Rivers no longer catch on fire as some did prior to regulation (398), and local  
15 “dead zones” below sewage treatment facilities have recovered (125). The National  
16 Atmospheric Deposition Program National Trends Network has documented some  
17 improvements in acid precipitation, particularly in the northeastern US from 1985 to 2002  
18 (399). These trends show that if the political will exists to improve water quality, it can be  
19 done.

## 20 Description of Evidence Base

21 Many native aquatic species are resilient and can recover rapidly, particularly in rivers, after  
22 inland waters are degraded. In the Pacific Northwest, California, Maine, and Illinois, large-  
23 scale habitat recovery following levee breaches or dam removals on major rivers, or  
24 setbacks that allow floodplain recovery, have allowed surprisingly rapid recovery of  
25 populations of valued migratory aquatic vertebrates (salmonids, alewives, waterfowl) as  
26 well as resident species. Thriving ecosystems have persisted for 20 years since a large  
27 floodplain was restored in Illinois. This resilience of inland water ecosystems and species,  
28 when released from harmful human impacts or engineered constraints, is *well established*.  
29 However, determining whether recoveries are proceeding as intended under changing  
30 environmental conditions would require more examples, on meaningful ecological scales,  
31 that are monitored both before and after intervention.

32 Recovery of inland water systems via controlling nutrient loading is *very well established*  
33 based on long-term recovery of a number of well-studied lakes across the US, including  
34 multi-decadal intensive study and monitoring of large urban lakes (343,344). However,  
35 certain inland waters eutrophied by legacy nutrients may require more time or different  
36 measures (349–353) for recovery than frequently flushed ecosystems. For example,  
37 nutrients in deep lake sediments (301,345,346) or in watershed soils (300,400) may remain  
38 problematic long after contemporary sources of pollution have been controlled.  
39 Furthermore, pollutants can be resuspended by wind-driven stirring or borne in via erosion  
40 during rain events, prolonging their negative impacts.

1 Manipulation of fish and other consumers in the food chain as a successful approach to  
2 recovery, by suppressing algal populations, is assessed to be *established but incomplete*  
3 because these efforts have met with mixed results over decades. While food-web  
4 responses are always context-dependent, measures that reduce invertebrate-feeding fish  
5 achieve the most consistent benefits for water quality.

6 Reconnecting natural water flow paths is *very well established* as a successful recovery  
7 strategy, based on experimental results at small scales (e.g., within urban environments)—  
8 where slowing the paths of precipitation to surface waters by increasing permeability of  
9 Earth's surface reduces flooding and contaminant transport—and on large-scale  
10 restoration projects (e.g., of wetlands along major river corridors) that demonstrate  
11 benefits for migrating fish and waterfowl populations throughout the US  
12 (41,164,359,360,364,365). Harmful impacts of non-native species on native species are  
13 exacerbated under unnatural environmental conditions (of flow, temperature, or water  
14 chemistry (333), and several long-term field studies have shown that native species will  
15 recover where key components of natural environmental regimes are restored (168). Also,  
16 some large-scale measures to reduce non-native species introductions have curtailed their  
17 spread, though there are a limited number of examples of long-term control over large  
18 ecosystem scales (187,216).

19 Overall trends and feedbacks in improvement or degradation of inland waters and their  
20 biota under changing environments will play out over decades, sometimes with long lags  
21 between actions and consequences. Based on multi-decadal monitoring programs across  
22 all inland water types and across the US, it is *virtually certain* that monitoring programs  
23 provide vital support for forecasting responses of inland water ecosystems to change and  
24 informing management options (11,394,401).

## 25 Major Uncertainties and Research Gaps

26 The social and ecological benefits restored by large-scale, well-documented cases  
27 encourage the expansion of passive restoration (such as removal of engineering control  
28 structures and reallocation of water during critical periods) of other inland water  
29 landscapes. For restorations of heavily modified systems near critical human  
30 infrastructure, some active management (e.g. flow or sediment regulation structures) may  
31 be needed, with careful real-time monitoring to assess impacts of management decisions.  
32 Outcomes remain contingent, however, on site-dependent legacies (natural and human-  
33 caused) and on future climate impacts.

## 34 Environmental Justice and Equity Highlights

35 Native American Tribes have led or been key players in dam removals on major rivers  
36 including the Klamath and the Penobscot, Ottawa, and Elwha rivers (402–405). Removal of  
37 smaller water diversions throughout the US has restored access for local indigenous  
38 populations to fishing and shell fishing, key elements of their cultural heritage (406,407).

1 Water systems serving communities with more Black and Latino residents have higher  
2 concentrations of harmful PFAS and are nearer sources (like airports, military bases,  
3 landfills) of these "forever chemicals" (408). Negative impacts of climate change on Native  
4 Alaskans (409,410) include thermakarst melt that endangers homes, livelihoods, and lives  
5 of Native Alaskans, and are now widely recognized as mediated through large-scale  
6 degradation or destruction of freshwater resources and ecosystems.

## 7 Emerging Issues

8 Understanding the critical zone (1), the skin of the Earth where water is exchanged, from  
9 the vegetation canopy down to the bottom of the groundwater table, must advance to  
10 support better management of extreme variability in precipitation (drought vs deluge) that  
11 has begun under warming and will worsen.

12 Below are some key questions that remain to be answered:

13 How do interactions of geology, topography, vegetation, soils and microbiomes, and land  
14 use affect the storage, chemical evolution, and release regimes of ground to surface water,  
15 and how will these interactions evolve under different future scenarios? Practical  
16 applications require that we understand how long (temporally and spatially) subsurface  
17 waters must reside and travel to recover the quality and quantity required for natural  
18 ecosystems and vital human uses.

19 How do cocktails of toxicants and other solutes interact and evolve in open environments  
20 (for example under exposure to UV). What are their impacts on organisms over time and  
21 space?

22 What causes or triggers toxicity in cyanobacteria of inland waters?

23 What are the bottlenecks and opportunities that confront inland water species through  
24 their life histories (particularly for migratory fishes, birds, crustacea)? Site-based, spatially  
25 explicit knowledge is required for recovery.

26 How much genetic diversity or developmental plasticity remains in native populations and  
27 how much environmental change can organisms and populations tolerate? Should  
28 assisted migration or species replacements be considered?

29 What is the appropriate role, if any, for gene editing or synthetic biology in recovery,  
30 conservation, and management of inland waters? Will planning, regulation, and  
31 management of synthetic organisms that are released into the wild be sufficient to prevent  
32 or contain damages (411) like, or worse than, those caused by non-native species?

## 1 References

- 2 1. Grant GE, Dietrich WE. The frontier beneath our feet. *Water Resour Res.* 2017  
3 Apr;53(4):2605–9. <https://doi.org/10.1002/2017WR020835>
- 4 2. White T, Brantley S, Banwart S, Chorover J, Dietrich W, Derry L, et al. The Role of Critical  
5 Zone Observatories in Critical Zone Science. In: *Developments in Earth Surface*  
6 *Processes* [Internet]. Elsevier; 2015 [2026 Jan 25]. p. 15–78.  
7 <https://doi.org/10.1016/B978-0-444-63369-9.00002-1>
- 8 3. Soininen J, Bartels P, Heino J, Luoto M, Hillebrand H. Toward More Integrated Ecosystem  
9 Research in Aquatic and Terrestrial Environments. *BioScience.* 2015 Feb 1;65(2):174–  
10 82. <https://doi.org/10.1093/biosci/biu216>
- 11 4. Brahney J, Weathers KC, Reche I. Dust and Fog Effects on Inland Waters. In:  
12 *Encyclopedia of Inland Waters* [Internet]. Elsevier; 2022 [2026 Jan 9]. p. 639–56.  
13 <https://doi.org/10.1016/B978-0-12-819166-8.00069-4>
- 14 5. Canham CD, Pace ML, Weathers KC, McNeil EW, Bedford BL, Murphy L, et al. Nitrogen  
15 deposition and lake nitrogen concentrations: a regional analysis of terrestrial controls  
16 and aquatic linkages. *Ecosphere.* 2012;3(7):art66. [https://doi.org/10.1890/ES12-  
17 00090.1](https://doi.org/10.1890/ES12-00090.1)
- 18 6. Hilborn R, Quinn TP, Schindler DE, Rogers DE. Biocomplexity and fisheries sustainability.  
19 *Proc Natl Acad Sci U S A.* 2003 May;100(11):6564–8.  
20 <https://doi.org/10.1073/pnas.1037274100>
- 21 7. Matsaw SL. Teachings from the Land of my Ancestors: Knowing Places as a Gatherer,  
22 Hunter, Fisher and Ecologist. In: Pontius JB, Mueller MP, Greenwood D, editors. *Place-*  
23 *based Learning for the Plate: Hunting, Foraging and Fishing for Food* [Internet]. Cham:  
24 Springer International Publishing; 2020 [2026 Jan 9]. p. 73–85.  
25 [https://doi.org/10.1007/978-3-030-42814-3\\_6](https://doi.org/10.1007/978-3-030-42814-3_6)
- 26 8. Reed R, Norgaard KM. Salmon Feeds Our People: Challenging Dams on the Klamath  
27 River. In: Reed, Ron and Kari Marie Norgaard “Salmon Feeds Our People: Challenging  
28 Dams on the Klamath River” pp 7-16 in Walker Painemilla, K, Rylands, A B, Woofter, A,  
29 & Hughes, C eds *Indigenous People and Conservation: From Rights to Resource*  
30 *Management Conservation International: Arlington VA, 2010.* 2010. p. 7–16.
- 31 9. Water Data For The Nation Blog [Internet]. 2023 [2026 Jan 29]. A New Take on the Water  
32 Cycle. <https://waterdata.usgs.gov/blog/water-cycle-release/>
- 33 10. US EPA R 10. About Bristol Bay [Internet]. 2013 [2026 Jan 29].  
34 <https://www.epa.gov/bristolbay/about-bristol-bay>

- 1 11. Moreno-Mateos D, Power ME, Comín FA, Yockteng R. Structural and Functional Loss in  
2 Restored Wetland Ecosystems. Loreau M, editor. PLoS Biol. 2012 Jan  
3 24;10(1):e1001247. <https://doi.org/10.1371/journal.pbio.1001247>
- 4 12. Orfinger AB, Houghton DC, Robinson JL. Editorial: Aquatic insect ecology in a  
5 changing world. Front Ecol Evol. 2023 Sep 18;11:1282196.  
6 <https://doi.org/10.3389/fevo.2023.1282196>
- 7 13. Huryn AD. Rust never sleeps: Climate change, permafrost thaw, and the rapid  
8 environmental degradation of wilderness river ecosystems. 2025;
- 9 14. Sullivan PF, Dial RJ, Cooper DJ, Diamond C, Tino CJ, Gregory DD, et al. Wild, scenic,  
10 and toxic: Recent degradation of an iconic Arctic watershed with permafrost thaw.  
11 Proc Natl Acad Sci. 2025 Sep 16;122(37):e2425644122.  
12 <https://doi.org/10.1073/pnas.2425644122>
- 13 15. Kendrick MR, Huryn AD, Bowden WB, Deegan LA, Findlay RH, Hershey AE, et al.  
14 Linking permafrost thaw to shifting biogeochemistry and food web resources in an  
15 arctic river. Glob Change Biol. 2018 Dec;24(12):5738–50.  
16 <https://doi.org/10.1111/gcb.14448>
- 17 16. O'Donnell JA, Carey MP, Koch JC, Baughman C, Hill K, Zimmerman CE, et al. Metal  
18 mobilization from thawing permafrost to aquatic ecosystems is driving rusting of  
19 Arctic streams. Commun Earth Environ. 2024 May 20;5(1):268.  
20 <https://doi.org/10.1038/s43247-024-01446-z>
- 21 17. Niedrist GH, Füreder L. Disproportional vulnerability of mountain aquatic  
22 invertebrates to climate change effects. Arct Antarct Alp Res. 2023 Dec  
23 31;55(1):2181298. <https://doi.org/10.1080/15230430.2023.2181298>
- 24 18. Carpenter SR, Fisher SG, Grimm NB, Kitchell JF. Global change and fresh-water  
25 ecosystems. Annu Rev Ecol Syst. 1992;23:119–39.
- 26 19. Jaeger KL, Olden JD, Pelland NA. Climate change poised to threaten hydrologic  
27 connectivity and endemic fishes in dryland streams. Proc Natl Acad Sci U S A. 2014  
28 Sep 23;111(38):13894–9. <https://doi.org/10.1073/pnas.1320890111>
- 29 20. Wang J, Grimm NB, Lawler SP, Dong X. Changing climate and reorganized species  
30 interactions modify community responses to climate variability. Proc Natl Acad Sci.  
31 2023 Sep 26;120(39):e2218501120.  
32 [https://doi.org/10.1073/PNAS.2218501120/SUPPL\\_FILE/PNAS.2218501120.SAPP.PDF](https://doi.org/10.1073/PNAS.2218501120/SUPPL_FILE/PNAS.2218501120.SAPP.PDF)
- 33 21. Grimm NB, Fisher SG. Responses of Arid-Land Streams to Changing Climate. In: Firth  
34 P, Fisher SG, editors. Global Climate Change and Freshwater Ecosystems. New York,  
35 NY: Springer; 1992. p. 211–33. [https://doi.org/10.1007/978-1-4612-2814-1\\_10](https://doi.org/10.1007/978-1-4612-2814-1_10)

- 1 22. Dodds WK, Gido K, Whiles MR, Fritz KM, Matthews WJ. Life on the Edge: The Ecology of  
2 Great Plains Prairie Streams. *BioScience*. 2004 Mar 1;54(3):205–16.  
3 [https://doi.org/10.1641/0006-3568\(2004\)054%255B0205:LOTETE%255D2.0.CO;2](https://doi.org/10.1641/0006-3568(2004)054%255B0205:LOTETE%255D2.0.CO;2)
- 4 23. Baxter CV, Fausch KD, Carl Saunders W. Tangled webs: reciprocal flows of invertebrate  
5 prey link streams and riparian zones. *Freshw Biol*. 2005 Feb;50(2):201–20.  
6 <https://doi.org/10.1111/j.1365-2427.2004.01328.x>
- 7 24. Yang Y, Tilman D, Jin Z, Smith P, Barrett CB, Zhu YG, et al. Climate change exacerbates  
8 the environmental impacts of agriculture. *Science*. 2024 Sep 6;385(6713):eadn3747.  
9 <https://doi.org/10.1126/science.adn3747>
- 10 25. Wang Y, Ma F, Wang H, Tzachor A, Jiang M, Fang K, et al. Doubling of the global  
11 freshwater footprint of material production over two decades. *Nat Sustain* [Internet].  
12 2025 Oct 30 [2025 Oct 30]; <https://doi.org/10.1038/s41893-025-01661-2>
- 13 26. Zipper SC, Hammond JC, Shanafield M, Zimmer M, Datry T, Jones CN, et al. Pervasive  
14 changes in stream intermittency across the United States. *Environ Res Lett*. 2021 Aug  
15 1;16(8):084033. <https://doi.org/10.1088/1748-9326/ac14ec>
- 16 27. Li J, Smith R, Grote K. Analyzing spatio-temporal mechanisms of land subsidence in  
17 the Parowan Valley, Utah, USA. *Hydrogeol J*. 2023 Mar;31(2):293–311.  
18 <https://doi.org/10.1007/s10040-022-02583-5>
- 19 28. Peng M, Lu Z, Zhao C, Motagh M, Bai L, Conway BD, et al. Mapping land subsidence  
20 and aquifer system properties of the Willcox Basin, Arizona, from InSAR observations  
21 and independent component analysis. *Remote Sens Environ*. 2022 Mar;271:112894.  
22 <https://doi.org/10.1016/j.rse.2022.112894>
- 23 29. Smith RG, Knight R, Chen J, Reeves JA, Zebker HA, Farr T, et al. Estimating the  
24 permanent loss of groundwater storage in the southern San Joaquin Valley, California.  
25 *Water Resour Res*. 2017 Mar;53(3):2133–48.  
26 <https://doi.org/10.1002/2016WR019861>
- 27 30. Vajedian S, Smith R, Schreüder WA, Maurer J. Aquifer system deformation in the San  
28 Luis Valley: A new framework for modeling subsidence in agricultural regions. *J Hydrol*.  
29 2024 Oct;642:131876. <https://doi.org/10.1016/j.jhydrol.2024.131876>
- 30 31. Allan JD, Abell R, Hogan Z, Revenga C, Taylor BW, Welcomme RL, et al. Overfishing of  
31 Inland Waters. *BioScience*. 2005;55(12):1041. [https://doi.org/10.1641/0006-  
32 3568\(2005\)055%255B1041:OOIW%255D2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055%255B1041:OOIW%255D2.0.CO;2)
- 33 32. Reid AJ, Eckert LE, Lane JF, Young N, Hinch SG, Darimont CT, et al. “Two-Eyed Seeing”:  
34 An Indigenous framework to transform fisheries research and management. *Fish Fish*.  
35 2021;22(2):243–61. <https://doi.org/10.1111/faf.12516>

- 1 33. USGS Scientific Investigations Report 2013–5079: Groundwater Depletion in the  
2 United States (1900–2008) [Internet]. [2026 Jan 29].  
3 <https://pubs.usgs.gov/sir/2013/5079/>
- 4 34. Sanderson M, Miller-Klugesherz J, Griggs B, Weeks J, Guynup S. Farmers are depleting  
5 the Ogallala Aquifer because the government pays them to do it [Internet]. 2020 [2025  
6 Oct 13]. <https://doi.org/10.64628/AAI.jyntnv647>
- 7 35. Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, et al.  
8 Impacts, Risks, and Adaptation in the United States: The Fourth National Climate  
9 Assessment, Volume II [Internet]. U.S. Global Change Research Program; 2018 [2025  
10 Nov 17]. <https://doi.org/10.7930/NCA4.2018>
- 11 36. Perkin JS, Gido KB, Falke JA, Fausch KD, Crockett H, Johnson ER, et al. Groundwater  
12 declines are linked to changes in Great Plains stream fish assemblages. *Proc Natl*  
13 *Acad Sci*. 2017 Jul 11;114(28):7373–8. <https://doi.org/10.1073/pnas.1618936114>
- 14 37. McGuire VL. Water-level and recoverable water in storage changes, High Plains  
15 aquifer, predevelopment to 2015 and 2013–15 [Internet]. Scientific Investigations  
16 Report. U.S. Geological Survey; 2017 [2026 Jan 29]. Report No.: 2017–5040.  
17 <https://doi.org/10.3133/sir20175040>
- 18 38. Gowda PH, Steiner J, Olson C, Boggess M, Farrigan T, Grusak MA. Chapter 10 :  
19 Agriculture and Rural Communities. Impacts, Risks, and Adaptation in the United  
20 States: The Fourth National Climate Assessment, Volume II [Internet]. U.S. Global  
21 Change Research Program; 2018 [2026 Jan 29].  
22 <https://doi.org/10.7930/NCA4.2018.CH10>
- 23 39. Gorski G, Stets EG, Scholl MA, Degnan JR, Mullaney JR, Galanter AE, et al. Water  
24 supply in the conterminous United States, Alaska, Hawaii, and Puerto Rico, water  
25 years 2010–20 [Internet]. Version 1.0: January 15, 2025; Version 1.1: January 17, 2025.  
26 Reston, VA; 2025 p. 76. (Professional Paper). Report No.: 1894B.  
27 <https://doi.org/10.3133/pp1894B>
- 28 40. Ketchum D, Hoylman ZH, Huntington J, Brinkerhoff D, Jencso KG. Irrigation  
29 intensification impacts sustainability of streamflow in the Western United States.  
30 *Commun Earth Environ*. 2023 Dec 15;4(1):479. [https://doi.org/10.1038/s43247-023-  
31 01152-2](https://doi.org/10.1038/s43247-023-01152-2)
- 32 41. Lemke MJ, Walk JW, Lemke AM, Sparks RE, Blodgett KD. Introduction: The ecology of a  
33 river floodplain and the Emiquon preserve. *Hydrobiologia*. 2017 Dec;804(1):1–17.  
34 <https://doi.org/10.1007/s10750-017-3335-8>

- 1 42. Sparks RE, Bayley PB, Kohler SL, Osborne LL. Disturbance and recovery of large  
2 floodplain rivers. *Environ Manage.* 1990 Sep;14(5):699–709.  
3 <https://doi.org/10.1007/BF02394719>
- 4 43. Banks R, Springer P. A Century of Population Trends of Waterfowl in Western North  
5 America. *Stud Avian Biol* [Internet]. 1994 Jan 1;15(1).  
6 <https://digitalcommons.usf.edu/sab/vol15/iss1/12>
- 7 44. Grafton RQ, Williams J, Perry CJ, Molle F, Ringler C, Steduto P, et al. The paradox of  
8 irrigation efficiency. *Science.* 2018 Aug 24;361(6404):748–50.  
9 <https://doi.org/10.1126/science.aat9314>
- 10 45. Morrisett CN, Van Kirk RW, Bernier LO, Holt AL, Perel CB, Null SE. The irrigation  
11 efficiency trap: rational farm-scale decisions can lead to poor hydrologic outcomes at  
12 the basin scale. *Front Environ Sci.* 2023 Aug 28;11:1188139.  
13 <https://doi.org/10.3389/fenvs.2023.1188139>
- 14 46. Parker JM, Anderson SH. Habitat Use and Movements of Repatriated Wyoming Toads. *J*  
15 *Wildl Manag.* 2003 Apr;67(2):439. <https://doi.org/10.2307/3802784>
- 16 47. Prenzlów DM, Lovvorn JR. Design and Results of a Waterfowl Breeding Population  
17 Survey for Wyoming. *J Wildl Manag.* 1997 Jul;61(3):758.  
18 <https://doi.org/10.2307/3802182>
- 19 48. Myler CD, Mladenka GC, Minshall GW. TREND ANALYSIS SHOWS DECLINE OF AN  
20 ENDANGERED THERMOPHILIC SPRINGSNAIL (PYRGULOPSIS BRUNEAUENSIS) IN  
21 SOUTHWESTERN IDAHO. *West North Am Nat.* 2007 Apr;67(2):199–205.  
22 [https://doi.org/10.3398/1527-0904\(2007\)67%255B199:TASDOA%255D2.0.CO;2](https://doi.org/10.3398/1527-0904(2007)67%255B199:TASDOA%255D2.0.CO;2)
- 23 49. Sowby RB, Hansen NC, Hopkins EG. The Conflicting Legacy of U.S. Irrigation [Internet].  
24 Preprints; 2024 [2025 Dec 30]. <https://doi.org/10.22541/au.172252404.43757270/v2>
- 25 50. Hintz WD, Fay L, Relyea RA. Road salts, human safety, and the rising salinity of our  
26 fresh waters. *Front Ecol Environ.* 2022 Feb;20(1):22–30.  
27 <https://doi.org/10.1002/fee.2433>
- 28 51. Dugan HA, Bartlett SL, Burke SM, Doubek JP, Krivak-Tetley FE, Skaff NK, et al. Salting  
29 our freshwater lakes. *Proc Natl Acad Sci.* 2017 Apr 25;114(17):4453–8.  
30 <https://doi.org/10.1073/pnas.1620211114>
- 31 52. Kaushal SS, Likens GE, Pace ML, Reimer JE, Maas CM, Galella JG, et al. Freshwater  
32 salinization syndrome: from emerging global problem to managing risks.  
33 *Biogeochemistry.* 2021 Jun;154(2):255–92. [https://doi.org/10.1007/s10533-021-](https://doi.org/10.1007/s10533-021-00784-w)  
34 [00784-w](https://doi.org/10.1007/s10533-021-00784-w)

- 1 53. Power ME, Chandra S, Gleick P, Dietrich WE. Anticipating responses to climate change  
2 and planning for resilience in California’s freshwater ecosystems. *Proc Natl Acad Sci*.  
3 2024 Aug 6;121(32):e2310075121. <https://doi.org/10.1073/pnas.2310075121>
- 4 54. Presser TS. “The Kesterson effect.” *Environ Manage*. 1994 May;18(3):437–54.  
5 <https://doi.org/10.1007/BF02393872>
- 6 55. Schoups G, Hopmans JW, Young CA, Vrugt JA, Wallender WW, Tanji KK, et al.  
7 Sustainability of irrigated agriculture in the San Joaquin Valley, California. *Proc Natl*  
8 *Acad Sci*. 2005 Oct 25;102(43):15352–6. <https://doi.org/10.1073/pnas.0507723102>
- 9 56. Dugan HA, Skaff NK, Doubek JP, Bartlett SL, Burke SM, Krivak-Tetley FE, et al. Lakes at  
10 Risk of Chloride Contamination. *Environ Sci Technol*. 2020 Jun 2;54(11):6639–50.  
11 <https://doi.org/10.1021/acs.est.9b07718>
- 12 57. Wurtsbaugh WA, Miller C, Null SE, DeRose RJ, Wilcock P, Hahnenberger M, et al.  
13 Decline of the world’s saline lakes. *Nat Geosci*. 2017 Nov;10(11):816–21.  
14 <https://doi.org/10.1038/ngeo3052>
- 15 58. Bowen L. Will We Save the Great Salt Lake? | The Nature Conservancy. 2025;  
16 <https://www.nature.org/en-us/about-us/where-we-work/united-states/utah>
- 17 59. Schlef KE, Steinschneider S, Brown CM. Spatiotemporal impacts of climate and  
18 demand on water supply in the Apalachicola-Chattahoochee-Flint Basin. *J Water*  
19 *Resour Plan Manag*. 2018;144: e05017020.
- 20 60. Rugel K. Stakeholders reach consensus in troubled waters: Apalachicola-  
21 Chattahoochee-flint river basin, southeastern USA. *Case Stud Environ*.  
22 2020;4(1):p.1112837.
- 23 61. McNabb DE, Swenson CR. Water crises in the South and Southcentral regions. In:  
24 America’s Water Crises: The Impact of Drought and Climate Change. Springer Nature  
25 Switzerland; 2023. p. 257–78.
- 26 62. Diem JE, Bonsu PO. Recent variability and trends and projected changes in  
27 precipitation in the southeastern United States: a focus on the Apalachicola-  
28 Chattahoochee-Flint River Basin. *Theor Appl Climatol*. 2024;155:3147–62.
- 29 63. Karki R, Kalin L, Srivastava P, Rowles K, Masters M, Bartels W lin. Stakeholder-driven  
30 assessment of watershed management strategies for agriculture and ecological  
31 sustainability: A case study in the lower Apalachicola-Chattahoochee-Flint (ACF)  
32 River Basin. *J Environ Manage*. 2025 Jan;373:123628.  
33 <https://doi.org/10.1016/j.jenvman.2024.123628>
- 34 64. Manganiello C. Watering Georgia: The State of Water and Agriculture in Georgia  
35 [Internet]. Georgia Water Coalition; 2017 [2025 Nov 23].

- 1 [https://chattahoochee.org/wp-](https://chattahoochee.org/wp-content/uploads/2018/07/GWC_WateringGeorgia_Report.pdf)  
2 [content/uploads/2018/07/GWC\\_WateringGeorgia\\_Report.pdf](https://chattahoochee.org/wp-content/uploads/2018/07/GWC_WateringGeorgia_Report.pdf)
- 3 65. Gutiérrez-Fonseca PE, Ramírez A, Pringle CM, Torres PJ, McDowell WH, Covich A, et al.  
4 When the rainforest dries: Drought effects on a montane tropical stream ecosystem in  
5 Puerto Rico. *Freshw Sci.* 2020 Jun;39(2):197–212. <https://doi.org/10.1086/708808>
- 6 66. Clilverd HM, Tsang YP, Infante DM, Lynch AJ, Strauch AM. Long-term streamflow trends  
7 in Hawai'i and implications for native stream fauna. *Hydrol Process.* 2019;33(5):699–  
8 719. <https://doi.org/10.1002/hyp.13356>
- 9 67. Frauendorf TC, MacKenzie RA, Tingley III RW, Frazier AG, Riney MH, El-Sabaawi RW.  
10 Evaluating ecosystem effects of climate change on tropical island streams using high  
11 spatial and temporal resolution sampling regimes. *Glob Change Biol.*  
12 2019;25(4):1344–57. <https://doi.org/10.1111/gcb.14584>
- 13 68. Gingerich S, Johnson A, Rosa S, Marineau M, Wright S, Hay LE, et al. Water resources  
14 on Guam—Potential impacts of and adaptive response to climate change [Internet].  
15 Reston, VA; 2019 p. 55. (Scientific Investigations Report). Report No.: 2019–5095.  
16 <https://doi.org/10.3133/sir20195095>
- 17 69. Covich AP, Crawl TA, Heartsill-Scalley T. Effects of drought and hurricane disturbances  
18 on headwater distributions of palaemonid river shrimp (*Macrobrachium* spp.) in the  
19 Luquillo Mountains, Puerto Rico. *J North Am Benthol Soc.* 2006 Mar;25(1):99–107.  
20 [https://doi.org/10.1899/0887-3593\(2006\)25%255B99:EODAH%255D2.0.CO;2](https://doi.org/10.1899/0887-3593(2006)25%255B99:EODAH%255D2.0.CO;2)
- 21 70. Tingley RW, Infante DM, MacKenzie RA, Strauch AM, Foulk PB, Roth B. Climate-driven  
22 differences in flow regimes alter tropical freshwater ecosystems with consequences  
23 for an endemic shrimp. *Front Ecol Evol* [Internet]. 2024 Feb 27 [2026 Jan 5];12.  
24 <https://doi.org/10.3389/fevo.2024.1182021>
- 25 71. Kwak T, Engman A, Fischer J, Lilyestrom C. Drivers of Caribbean freshwater  
26 ecosystems and fisheries. In 2016. p. 219–32.
- 27 72. Lang MW, Ingebritsen JC, Griffin RK. Status and Trends of Wetlands in the  
28 Conterminous United States 2009 to 2019. Washington D.C.: U.S. Department of  
29 Interior, Fish and Wildlife Service; 2024 p. 43.
- 30 73. Cooper SD, Klose K, Herbst DB, White J, Drenner SM, Eliason EJ. Wildfire and drying  
31 legacies and stream invertebrate assemblages. *Freshw Sci.* 2021 Dec 1;40(4):659–80.  
32 <https://doi.org/10.1086/717416>
- 33 74. Damasceno-Junior GA, Pereira ADMM, Saharjo BH, Archibald S, Zhang B, Bilbao B, et  
34 al. Flood-Fire Interplays in Wetlands: The Rising of an Actionable Field of Study.  
35 *Wetlands.* 2025 Dec;45(8):122. <https://doi.org/10.1007/s13157-025-02005-8>

- 1 75. Perry W. Elements of South Florida's Comprehensive Everglades Restoration Plan.  
2 Ecotoxicology. 2004 Apr;13(3):185–93.  
3 <https://doi.org/10.1023/B:ECTX.0000023564.10311.4a>
- 4 76. Aumen NG, Havens KE, Best GR, Berry L. Predicting Ecological Responses of the  
5 Florida Everglades to Possible Future Climate Scenarios: Introduction. Environ  
6 Manage. 2015 Apr;55(4):741–8. <https://doi.org/10.1007/s00267-014-0439-z>
- 7 77. Lockwood JL, Ross MS, Sah JP. Smoke on the water: the interplay of fire and water flow  
8 on Everglades restoration. Front Ecol Environ. 2003;1(9):462–8.  
9 [https://doi.org/10.1890/1540-9295\(2003\)001%255B0462:SOTWTI%255D2.0.CO;2](https://doi.org/10.1890/1540-9295(2003)001%255B0462:SOTWTI%255D2.0.CO;2)
- 10 78. Batzer DP. The Seemingly Intractable Ecological Responses of Invertebrates in North  
11 American Wetlands: A Review. Wetlands. 2013 Feb;33(1):1–15.  
12 <https://doi.org/10.1007/s13157-012-0360-2>
- 13 79. Batzer D, Boix D, editors. Invertebrates in Freshwater Wetlands [Internet]. Cham:  
14 Springer International Publishing; 2016 [2026 Jan 9]. [https://doi.org/10.1007/978-3-](https://doi.org/10.1007/978-3-319-24978-0)  
15 [319-24978-0](https://doi.org/10.1007/978-3-319-24978-0)
- 16 80. Fish D, Tesh RB, Guzman H, Travassos Da Rosa APA, Balta V, Underwood J, et al.  
17 Emergence potential of mosquito-borne arboviruses from the Florida Everglades.  
18 Moreira LA, editor. PLOS ONE. 2021 Nov 22;16(11):e0259419.  
19 <https://doi.org/10.1371/journal.pone.0259419>
- 20 81. Batzer DP, Golladay SW, Day F. Southeastern swamp complexes. In: Batzer DP,  
21 Baldwin AH, editors. Wetland habitats of North America: ecology and conservation  
22 concerns. Berkeley: University of California Press; 2012. p. 217–30. (Stephen Bechtel  
23 Fund imprint in ecology and the environment).
- 24 82. Gibbons W. New Georgia Encyclopedia. 2020 [2026 Jan 9]. Natural History of the  
25 Okefenokee Swamp. [https://www.georgiaencyclopedia.org/articles/geography-](https://www.georgiaencyclopedia.org/articles/geography-environment/natural-history-of-the-okefenokee-swamp/)  
26 [environment/natural-history-of-the-okefenokee-swamp/](https://www.georgiaencyclopedia.org/articles/geography-environment/natural-history-of-the-okefenokee-swamp/)
- 27 83. Ingraham MW, Foster SG. The value of ecosystem services provided by the U.S.  
28 National Wildlife Refuge System in the contiguous U.S. Ecol Econ. 2008 Nov  
29 1;67(4):608–18. <https://doi.org/10.1016/j.ecolecon.2008.01.012>
- 30 84. Patton D, Bergstrom JC, Moore R, Covich AP. Economic value of carbon storage in U.S.  
31 National Wildlife Refuge wetland ecosystems. Ecosyst Serv. 2015 Dec;16:94–104.  
32 <https://doi.org/10.1016/j.ecoser.2015.10.017>
- 33 85. Beganyi SR, Batzer DP. Wildfire induced changes in aquatic invertebrate communities  
34 and mercury bioaccumulation in the Okefenokee Swamp. Hydrobiologia. 2011  
35 Jul;669(1):237–47. <https://doi.org/10.1007/s10750-011-0694-4>

- 1 86. Loftin CS, Guyette MQ, Wetzel PR. Evaluation of Vegetation-Fire Dynamics in the  
2 Okefenokee National Wildlife Refuge, Georgia, USA, with Bayesian Belief Networks.  
3 Wetlands. 2018 Aug;38(4):819–34. <https://doi.org/10.1007/s13157-018-1033-6>
- 4 87. Falkenstein LG. Modeling of Surficial and Groundwater Hydrology in Southeastern  
5 Georgia Including the Okefenokee Swamp. [Master’s Thesis]. [Athens, GA]: University  
6 of Georgia; 2023.
- 7 88. Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, et al. Eutrophication  
8 of U.S. Freshwaters: Analysis of Potential Economic Damages. Environ Sci Technol.  
9 2009 Jan 1;43(1):12–9. <https://doi.org/10.1021/es801217q>
- 10 89. Waters TF. Sediment in streams: sources, biological effects, and control. Bethesda,  
11 Maryland, USA.: American Fisheries Society,; 1995.
- 12 90. EPA U. National Lakes Assessment Report | US EPA [Internet]. 2024 [2026 Jan 9].  
13 <https://nationallakesassessment.epa.gov/webreport>
- 14 91. Schloesser DW. Distribution and abundance of freshwater polychaetes, *Manayunkia*  
15 *speciosa* (Polychaeta), in the Great Lakes with a 70-year case history for western Lake  
16 Erie. J Gt Lakes Res. 2013 Jun;39(2):308–16. <https://doi.org/10.1016/j.jglr.2013.03.006>
- 17 92. Power ME, Bouma-Gregson K, Higgins P, Carlson SM. The Thirsty Eel: Summer and  
18 Winter Flow Thresholds that Tilt the Eel River of Northwestern California from Salmon-  
19 Supporting to Cyanobacterially Degraded States. Copeia. 2015 Mar;103(1):200–11.  
20 <https://doi.org/10.1643/CE-14-086>
- 21 93. Gobler CJ, Burkholder JM, Davis TW, Harke MJ, Johengen T, Stow CA, et al. The dual  
22 role of nitrogen supply in controlling the growth and toxicity of cyanobacterial blooms.  
23 Harmful Algae. 2016 Apr;54:87–97. <https://doi.org/10.1016/j.hal.2016.01.010>
- 24 94. Vadeboncoeur Y, Power ME. Attached Algae: The Cryptic Base of Inverted Trophic  
25 Pyramids in Freshwaters. Annu Rev Ecol Evol Syst. 2017 Nov 2;48(1):255–79.  
26 <https://doi.org/10.1146/annurev-ecolsys-121415-032340>
- 27 95. Bouma-Gregson K, Power ME, Bormans M. Rise and fall of toxic benthic freshwater  
28 cyanobacteria (*Anabaena* spp.) in the Eel river: Buoyancy and dispersal. Harmful  
29 Algae. 2017 Jun;66:79–87. <https://doi.org/10.1016/j.hal.2017.05.007>
- 30 96. Glibert PM. From hogs to HABs: impacts of industrial farming in the US on nitrogen  
31 and phosphorus and greenhouse gas pollution. Biogeochemistry. 2020  
32 Sep;150(2):139–80. <https://doi.org/10.1007/s10533-020-00691-6>
- 33 97. Foley J. It’s time to rethink America’s corn system. Sci Am. 2013;(March 5).

- 1 98. Rabalais NN, Turner RE, Díaz RJ, Justić D. Global change and eutrophication of coastal  
2 waters. *ICES J Mar Sci.* 2009;66(7):1528–37. <https://doi.org/10.1093/icesjms/fsp047>
- 3 99. Rabalais NN, Turner RE. Gulf of Mexico Hypoxia: Past, Present, and Future. *Limnol*  
4 *Oceanogr Bull.* 2019;28(4):117–24. <https://doi.org/10.1002/lob.10351>
- 5 100. Moreira C, Vasconcelos V, Antunes A. Cyanobacterial Blooms: Current Knowledge and  
6 New Perspectives. *Earth.* 2022 Feb 3;3(1):127–35.  
7 <https://doi.org/10.3390/earth3010010>
- 8 101. Hill H. Dog Deaths in Humboldt and Mendocino County Water Bodies Possibly Related  
9 to Cyanobacterial Toxicity [Internet]. Eureka, CA: REHS, Humboldt County Division of  
10 Environmental Health and the California Animal Health and Food Safety Laboratory;  
11 2010 [2025 Nov 21].  
12 [https://www.waterboards.ca.gov/water\\_issues/programs/bluegreen\\_algae/docs/work](https://www.waterboards.ca.gov/water_issues/programs/bluegreen_algae/docs/work)  
13 [group110805/harriethill.pdf](https://www.waterboards.ca.gov/water_issues/programs/bluegreen_algae/docs/work)
- 14 102. Blue Green Algae Work Group of. Cyanobacteria in California Recreational Water  
15 Bodies: Providing Voluntary Guidance about Harmful Algal Blooms, Their Monitoring,  
16 and Public Notification [Internet]. Eureka, CA: State Water Resources Control Board  
17 (SWRCB), the California Department of Public Health (CDPH), and Office of  
18 Environmental Health and Hazard Assessment (OEHHA); 2010 [2025 Nov 21].  
19 [https://www.waterboards.ca.gov/water\\_issues/programs/bluegreen\\_algae/docs/work](https://www.waterboards.ca.gov/water_issues/programs/bluegreen_algae/docs/work)  
20 [group110805/bgadetailedfactsheet.pdf](https://www.waterboards.ca.gov/water_issues/programs/bluegreen_algae/docs/work)
- 21 103. Jochimsen EM, Carmichael WW, An JS, Cardo DM, Cookson ST, Holmes CE, et al. Liver  
22 failure and death after exposure to microcystins at a hemodialysis center in Brazil. *N*  
23 *Engl J Med.* 1998 Mar 26;338(13):873–8.  
24 <https://doi.org/10.1056/NEJM199803263381304>
- 25 104. Carmichael WW, Azevedo SM, An JS, Molica RJ, Jochimsen EM, Lau S, et al. Human  
26 fatalities from cyanobacteria: chemical and biological evidence for cyanotoxins.  
27 *Environ Health Perspect.* 2001 Jul;109(7):663–8.  
28 <https://doi.org/10.1289/ehp.01109663>
- 29 105. Garamszegi SP, Banack SA, Duque LL, Metcalf JS, Stommel EW, Cox PA, et al.  
30 Detection of  $\beta$ -N-methylamino-L-alanine in postmortem olfactory bulbs of Alzheimer’s  
31 disease patients using UHPLC-MS/MS: An autopsy case-series study. *Toxicol Rep.*  
32 2023;10:87–96. <https://doi.org/10.1016/j.toxrep.2023.01.002>
- 33 106. Matson PG, Boyer GL, Bridgeman TB, Bullerjahn GS, Kane DD, McKay RML, et al.  
34 Physical drivers facilitating a toxigenic cyanobacterial bloom in a major Great Lakes  
35 tributary. *Limnol Oceanogr.* 2020;65(12):2866–82. <https://doi.org/10.1002/lno.11558>

- 1 107. Bouma-Gregson K, Olm MR, Probst AJ, Anantharaman K, Power ME, Banfield JF.  
2 Impacts of microbial assemblage and environmental conditions on the distribution of  
3 anatoxin-a producing cyanobacteria within a river network. *ISME J.* 2019 Jun  
4 1;13(6):1618–34. <https://doi.org/10.1038/s41396-019-0374-3>
- 5 108. Reint KL, Harris TD, North RL, Almela P, Berger SA, Bizic M, et al. Blooms also like it  
6 cold. *Limnol Oceanogr Lett.* 2023 Aug;8(4):546–64. <https://doi.org/10.1002/lo2.10316>
- 7 109. Cottingham KL, Ewing HA, Greer ML, Carey CC, Weathers KC. Cyanobacteria as  
8 biological drivers of lake nitrogen and phosphorus cycling. *Ecosphere.* 2015  
9 Jan;6(1):1–19. <https://doi.org/10.1890/ES14-00174.1>
- 10 110. Ewing HA, Weathers KC, Cottingham KL, Leavitt PR, Greer ML, Carey CC, et al. “New”  
11 cyanobacterial blooms are not new: two centuries of lake production are related to ice  
12 cover and land use. *Ecosphere.* 2020;11(6):e03170. <https://doi.org/10.1002/ecs2.3170>
- 13 111. Schindler DW. Evolution of Phosphorus Limitation in Lakes: Natural mechanisms  
14 compensate for deficiencies of nitrogen and carbon in eutrophied lakes. *Science.*  
15 1977 Jan 21;195(4275):260–2. <https://doi.org/10.1126/science.195.4275.260>
- 16 112. Zhi W, Baniecki H, Liu J, Boyer E, Shen C, Shenk G, et al. Increasing phosphorus loss  
17 despite widespread concentration decline in US rivers. *Proc Natl Acad Sci.* 2024 Nov  
18 26;121(48):e2402028121. <https://doi.org/10.1073/pnas.2402028121>
- 19 113. Weston DP, Holmes RW, You J, Lydy MJ. Aquatic toxicity due to residential use of  
20 pyrethroid insecticides. *Environ Sci Technol.* 2005 Dec 15;39(24):9778–84.  
21 <https://doi.org/10.1021/es0506354>
- 22 114. Richmond EK, Rosi EJ, Walters DM, Fick J, Hamilton SK, Brodin T, et al. A diverse suite  
23 of pharmaceuticals contaminates stream and riparian food webs. *Nat Commun.* 2018  
24 Nov 6;9(1):4491. <https://doi.org/10.1038/s41467-018-06822-w>
- 25 115. Snyder SA, Westerhoff P, Yoon Y, Sedlak DL. Pharmaceuticals, Personal Care  
26 Products, and Endocrine Disruptors in Water: Implications for the Water Industry.  
27 *Environ Eng Sci.* 2003 Sep;20(5):449–69.  
28 <https://doi.org/10.1089/109287503768335931>
- 29 116. Hayes TB, Collins A, Lee M, Mendoza M, Noriega N, Stuart AA, et al. Hermaphroditic,  
30 demasculinized frogs after exposure to the herbicide atrazine at low ecologically  
31 relevant doses. *Proc Natl Acad Sci.* 2002 Apr 16;99(8):5476–80.  
32 <https://doi.org/10.1073/pnas.082121499>
- 33 117. Andersson DI, Hughes D. Microbiological effects of sublethal levels of antibiotics. *Nat*  
34 *Rev Microbiol.* 2014 Jul;12(7):465–78. <https://doi.org/10.1038/nrmicro3270>

- 1 118. Mohammed EAH, Kovács B, Kuunya R, Mustafa EOA, Abbo ASH, Pál K. Antibiotic  
2 Resistance in Aquaculture: Challenges, Trends Analysis, and Alternative Approaches.  
3 Antibiotics. 2025 Jun 11;14(6):598. <https://doi.org/10.3390/antibiotics14060598>
- 4 119. Okeke ES, Chukwudozie KI, Nyaruaba R, Ita RE, Oladipo A, Ejeromedoghene O, et al.  
5 Antibiotic resistance in aquaculture and aquatic organisms: a review of current  
6 nanotechnology applications for sustainable management. Environ Sci Pollut Res.  
7 2022 Oct;29(46):69241–74. <https://doi.org/10.1007/s11356-022-22319-y>
- 8 120. Tsui MTK, Blum JD, Finlay JC, Balogh SJ, Nollet YH, Palen WJ, et al. Variation in  
9 Terrestrial and Aquatic Sources of Methylmercury in Stream Predators as Revealed by  
10 Stable Mercury Isotopes. Environ Sci Technol. 2014 Sep 2;48(17):10128–35.  
11 <https://doi.org/10.1021/es500517s>
- 12 121. Cookson ES, Detwiler RL. Global patterns and temporal trends of perfluoroalkyl  
13 substances in municipal wastewater: A meta-analysis. Water Res. 2022 Aug  
14 1;221:118784. <https://doi.org/10.1016/j.watres.2022.118784>
- 15 122. Jones DK, Quinlin KA, Wigren MA, Choi YJ, Sepúlveda MS, Lee LS, et al. Acute Toxicity  
16 of Eight Aqueous Film-Forming Foams to 14 Aquatic Species. Environ Sci Technol.  
17 2022 May 17;56(10):6078–90. <https://doi.org/10.1021/acs.est.1c03776>
- 18 123. Fu Q, Meyer C, Patrick M, Kosfeld V, Rüdél H, Koschorreck J, et al. Comprehensive  
19 screening of polar emerging organic contaminants including PFASs and evaluation of  
20 the trophic transfer behavior in a freshwater food web. Water Res. 2022 Jun  
21 30;218:118514. <https://doi.org/10.1016/j.watres.2022.118514>
- 22 124. Chen CY, Stemberger RS, Kamman NC, Mayes BM, Folt CL. Patterns of Hg  
23 Bioaccumulation and Transfer in Aquatic Food Webs Across Multi-lake Studies in the  
24 Northeast US. Ecotoxicology. 2005 Mar 1;14(1):135–47.  
25 <https://doi.org/10.1007/s10646-004-6265-y>
- 26 125. Dodds WK, Whiles MR. Responses to Stress, Toxic Chemicals, and Other Pollutants in  
27 Aquatic Ecosystems. In: Freshwater Ecology [Internet]. Elsevier; 2020 [2025 Nov 21].  
28 p. 453–502. <https://doi.org/10.1016/B978-0-12-813255-5.00016-8>
- 29 126. Greer JB, Dalsky EM, Lane RF, Hansen JD. Tire-Derived Transformation Product 6PPD-  
30 Quinone Induces Mortality and Transcriptionally Disrupts Vascular Permeability  
31 Pathways in Developing Coho Salmon. Environ Sci Technol. 2023 Aug 1;57(30):10940–  
32 50. <https://doi.org/10.1021/acs.est.3c01040>
- 33 127. Au SY, Lee CM, Weinstein JE, van den Hurk P, Klaine SJ. Trophic transfer of  
34 microplastics in aquatic ecosystems: Identifying critical research needs. Integr  
35 Environ Assess Manag. 2017 May 1;13(3):505–9. <https://doi.org/10.1002/ieam.1907>

- 1 128. Scherer C, Brennholt N, Reifferscheid G, Wagner M. Feeding type and development  
2 drive the ingestion of microplastics by freshwater invertebrates. *Sci Rep.* 2017 Dec  
3 5;7(1):17006. <https://doi.org/10.1038/s41598-017-17191-7>
- 4 129. Ogonowski M, Wagner M, Rogell B, Haave M, Lusher A. Microplastics could be  
5 marginally more hazardous than natural suspended solids – A meta-analysis.  
6 *Ecotoxicol Environ Saf.* 2023 Oct;264:115406.  
7 <https://doi.org/10.1016/j.ecoenv.2023.115406>
- 8 130. Marfella R, Prattichizzo F, Sardu C, Fulgenzi G, Graciotti L, Spadoni T, et al.  
9 Microplastics and Nanoplastics in Atheromas and Cardiovascular Events. *N Engl J*  
10 *Med.* 2024 Mar 7;390(10):900–10. <https://doi.org/10.1056/NEJMoa2309822>
- 11 131. Shrestha N, Chilkoor G, Wilder J, Gadhamshetty V, Stone JJ. Potential water resource  
12 impacts of hydraulic fracturing from unconventional oil production in the Bakken  
13 shale. *Water Res.* 2017 Jan 1;108:1–24. <https://doi.org/10.1016/j.watres.2016.11.006>
- 14 132. Torres L, Yadav OP, Khan E. A review on risk assessment techniques for hydraulic  
15 fracturing water and produced water management implemented in onshore  
16 unconventional oil and gas production. *Sci Total Environ.* 2016 Jan 1;539:478–93.  
17 <https://doi.org/10.1016/j.scitotenv.2015.09.030>
- 18 133. Gibert J, Culver DC. Assessing and conserving groundwater biodiversity: an  
19 introduction. *Freshw Biol.* 2009 Apr;54(4):639–48. <https://doi.org/10.1111/j.1365-2427.2009.02202.x>
- 21 134. Danielopol DL. Groundwater Fauna Associated with Riverine Aquifers. *J North Am*  
22 *Benthol Soc.* 1989 Mar;8(1):18–35. <https://doi.org/10.2307/1467399>
- 23 135. Pendergraft MA, Belda-Ferre P, Petras D, Morris CK, Mitts BA, Aron AT, et al. Bacterial  
24 and Chemical Evidence of Coastal Water Pollution from the Tijuana River in Sea Spray  
25 Aerosol. *Environ Sci Technol.* 2023 Mar 14;57(10):4071–81.  
26 <https://doi.org/10.1021/acs.est.2c02312>
- 27 136. Dueker ME, O’Mullan GD, Martínez JM, Juhl AR, Weathers KC, Dueker ME, et al.  
28 Onshore Wind Speed Modulates Microbial Aerosols along an Urban Waterfront.  
29 *Atmosphere* [Internet]. 2017 Nov 8 [2026 Jan 9];8(11).  
30 <https://doi.org/10.3390/atmos8110215>
- 31 137. Rico B, Barsanti K, Porter W, Stigler Granados P, Prather K. Heavily Polluted Tijuana  
32 River Drives Regional Air Quality Crisis [Internet]. *Chemistry*; 2024 [2025 Nov 14].  
33 <https://doi.org/10.26434/chemrxiv-2024-mjgbr>
- 34 138. US EPA. National Rivers and Streams Assessment Report: The Third Collaborative  
35 Study [Internet]. Office of Research and Development; 2024 [2026 Jan 10]. Report No.:  
36 EPA 841-R-22-004. <https://riverstreamassessment.epa.gov/webreport>

- 1 139. Evans-White MA, Haggard BE, Scott JT. A Review of Stream Nutrient Criteria  
2 Development in the United States. *J Environ Qual*. 2013 Jul;42(4):1002–14.  
3 <https://doi.org/10.2134/jeq2012.0491>
- 4 140. Miller RR, Williams JD, Williams JE. Extinctions of North American fishes during the  
5 past century. *Fisheries*. 1989;15:22–38.
- 6 141. Bisson PA, Quinn TP, Reeves GH, Gregory SV. Best management practices, cumulative  
7 effects, and long-term trends in fish abundance in Pacific Northwest river systems. i.  
8 In: *Watershed management: balancing sustainability and environmental change* R  
9 Naiman, editor. New York, New York, USA.: Springer-Verlag; 1992. p. 189–232.
- 10 142. Suttle KB, Power ME, Levine JM, McNeely C. HOW FINE SEDIMENT IN RIVERBEDS  
11 IMPAIRS GROWTH AND SURVIVAL OF JUVENILE SALMONIDS. *Ecol Appl*. 2004  
12 Aug;14(4):969–74. <https://doi.org/10.1890/03-5190>
- 13 143. Geist J, Auerswald K. Physicochemical stream bed characteristics and recruitment of  
14 the freshwater pearl mussel (*Margaritifera margaritifera*). *Freshw Biol*. 2007;52:2299-  
15 2316. <https://doi.org/doi:10.1111/j.1365-2427.2007.01812.x>
- 16 144. Roley SS, Tank JL. Pore water physicochemical constraints on the endangered  
17 clubshell mussel (*Pleurobema clava*). *Can J Fish Aquat Sci*. 2016;73(12):1712–22.  
18 <https://doi.org/doi.org/10.1139/cjfas-2015-0442>
- 19 145. Dunne T, Leopold LB. *Water in Environmental Planning*. San Francisco: W.H. Freeman  
20 and Co.; 1978.
- 21 146. Mejia FH, Ouellet V, Briggs MA, Carlson SM, Casas-Mulet R, Chapman M, et al. Closing  
22 the gap between science and management of cold-water refuges in rivers and  
23 streams. *Glob Change Biol*. 2023 Oct;29(19):5482–508.  
24 <https://doi.org/10.1111/gcb.16844>
- 25 147. Dralle DN, Rossi G, Georgakakos P, Hahm WJ, Rempe DM, Blanchard M, et al. The  
26 salmonid and the subsurface: Hillslope storage capacity determines the quality and  
27 distribution of fish habitat. *Ecosphere*. 2023 Feb;14(2):e4436.  
28 <https://doi.org/10.1002/ecs2.4436>
- 29 148. Morse CC, Huryn AD, Cronan C. Impervious Surface Area as a Predictor of the Effects  
30 of Urbanization on Stream Insect Communities in Maine, U.S.A. 2003;
- 31 149. Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL, et al. Emissions  
32 pathways, climate change, and impacts on California. *Proc Natl Acad Sci*. 2004 Aug  
33 24;101(34):12422–7. <https://doi.org/10.1073/pnas.0404500101>
- 34 150. Rodgers TFM, Wang Y, Humes C, Jeronimo M, Johannessen C, Spraakman S, et al.  
35 Bioretention Cells Provide a 10-Fold Reduction in 6PPD-Quinone Mass Loadings to

- 1 Receiving Waters: Evidence from a Field Experiment and Modeling. Environ Sci  
2 Technol Lett. 2023 Jul 11;10(7):582–8. <https://doi.org/10.1021/acs.estlett.3c00203>
- 3 151. Stevenson S, Coats S, Touma D, Cole J, Lehner F, Fasullo J, et al. Twenty-first century  
4 hydroclimate: A continually changing baseline, with more frequent extremes. Proc  
5 Natl Acad Sci. 2022 Mar 22;119(12):e2108124119.  
6 <https://doi.org/10.1073/pnas.2108124119>
- 7 152. Knox RL, Morrison RR, Wohl EE. A river ran through it: Floodplains as America’s newest  
8 relict landform. Sci Adv. 2022;
- 9 153. Spanjer AR, Gendaszek AS, Wulfskuhle EJ, Black RW, Jaeger KL. Assessing climate  
10 change impacts on Pacific salmon and trout using bioenergetics and spatiotemporal  
11 explicit river temperature predictions under varying riparian conditions. PLOS ONE.  
12 2022 May 20;17(5):e0266871. <https://doi.org/10.1371/journal.pone.0266871>
- 13 154. Jackson BK, Stock SL, Harris LS, Szewczak JM, Schofield LN, Desrosiers MA. River food  
14 chains lead to riparian bats and birds in two mid-order rivers. Ecosphere. 2020  
15 Jun;11(6):e03148. <https://doi.org/10.1002/ecs2.3148>
- 16 155. Nakano S, Murakami M. Dynamic interdependence between terrestrial and aquatic  
17 food webs. Proc Natl Acad Sci U S A. 2009 Apr 27;98(1):166–70.
- 18 156. Sabo JL, Power ME. River–Watershed Exchange: Effects of Riverine Subsidies on  
19 Riparian Lizards and Their Terrestrial Prey. Ecology. 2002;83(7):1860–9.  
20 [https://doi.org/10.1890/0012-9658\(2002\)083%255B1860:RWEEOR%255D2.0.CO;2](https://doi.org/10.1890/0012-9658(2002)083%255B1860:RWEEOR%255D2.0.CO;2)
- 21 157. Power ME, Rainey WE, Parker MS, Sabo JL, Smyth A, Khandwala S, et al. River-to-  
22 Watershed Subsidies in an Old-Growth Conifer Forest. In: Polis GA, Power ME, Huxel  
23 GR, editors. Food Webs at the Landscape Level. University of Chicago Press; 2004.
- 24 158. Sabo JL, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, et al. RIPARIAN ZONES  
25 INCREASE REGIONAL SPECIES RICHNESS BY HARBORING DIFFERENT, NOT MORE,  
26 SPECIES. Ecology. 2005 Jan;86(1):56–62. <https://doi.org/10.1890/04-0668>
- 27 159. Skagen SK, Kelly JF, Finch DM, Krueper DJ, Melcher CP. GEOGRAPHY OF SPRING  
28 LANDBIRD MIGRATION THROUGH RIPARIAN HABITATS IN SOUTHWESTERN NORTH  
29 AMERICA. 2005;
- 30 160. Swift BL. STATUS OF RIPARIAN ECOSYSTEMS IN THE UNITED STATES1. JAWRA J Am  
31 Water Resour Assoc. 1984 Apr;20(2):223–8. [https://doi.org/10.1111/j.1752-  
32 1688.1984.tb04675.x](https://doi.org/10.1111/j.1752-1688.1984.tb04675.x)
- 33 161. Jones KB, Slonecker ET, Nash MS, Neale AC, Wade TG, Hamann S. Riparian habitat  
34 changes across the continental United States (1972–2003) and potential implications

- 1 for sustaining ecosystem services. *Landsc Ecol.* 2010 Oct;25(8):1261–75.  
2 <https://doi.org/10.1007/s10980-010-9510-1>
- 3 162. Sparks RE. Need for Ecosystem Management of Large Rivers and Their Floodplains.  
4 *BioScience.* 1995 Mar;45(3):168–82. <https://doi.org/10.2307/1312556>
- 5 163. Beechie TJ, Sear D a., Olden JD, Pess GR, Buffington JM, Moir H, et al. Process-based  
6 principles for restoring river ecosystems. *Biosci* 603 Pp20. 2010;60(3):209–22.
- 7 164. Bellmore JR, Baxter CV, Martens K, Connolly PJ. The floodplain food web mosaic: a  
8 study of its importance to salmon and steelhead with implications for their recovery.  
9 *Ecol Appl.* 2013 Jan;23(1):189–207. <https://doi.org/10.1890/12-0806.1>
- 10 165. Morris GL. Classification of Management Alternatives to Combat Reservoir  
11 Sedimentation. *Water* [Internet]. 2020 Mar 18 [2026 Jan 5];12(3).  
12 <https://doi.org/10.3390/w12030861>
- 13 166. Ward JV, Stanford JA. Thermal responses in the evolutionary ecology of aquatic  
14 insects. *Ann Rev Entomol.* 1982;27:97–117.
- 15 167. Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, et al. The Natural Flow  
16 Regime. *BioScience.* 1997 Dec;47(11):769–84. <https://doi.org/10.2307/1313099>
- 17 168. Kiernan JD, Moyle PB, Crain PK. Restoring native fish assemblages to a regulated  
18 California stream using the natural flow regime concept. *Ecol Appl.* 2012  
19 Jul;22(5):1472–82. <https://doi.org/10.1890/11-0480.1>
- 20 169. National Research Council. Atlantic Salmon in Maine [Internet]. Washington, D.C.:  
21 National Academies Press; 2004 [2026 Jan 9]. <https://doi.org/10.17226/10892>
- 22 170. Quinn T. The Behavior and Ecology of Pacific Salmon and Trout [Internet]. Second.  
23 University of Washington Press; 2018 [2025 Oct 13]. 562 p.  
24 [https://uwapress.uw.edu/book/9780295743332/the-behavior-and-ecology-of-pacific-](https://uwapress.uw.edu/book/9780295743332/the-behavior-and-ecology-of-pacific-salmon-and-trout/)  
25 [salmon-and-trout/](https://uwapress.uw.edu/book/9780295743332/the-behavior-and-ecology-of-pacific-salmon-and-trout/)
- 26 171. Schindler DE, Hilborn R, Chasco B, Boatright CP, Quinn TP, Rogers LA, et al.  
27 Population diversity and the portfolio effect in an exploited species. *Nature.* 2010  
28 Jun;465(7298):609–12. <https://doi.org/10.1038/nature09060>
- 29 172. Moore JW, McClure M, Rogers LA, Schindler DE. Synchronization and portfolio  
30 performance of threatened salmon. *Conserv Lett.* 2010 Sep;3(5):340–8.  
31 <https://doi.org/10.1111/j.1755-263X.2010.00119.x>
- 32 173. Carlson SM, Satterthwaite WH. Weakened portfolio effect in a collapsed salmon  
33 population complex. Fleming IA, editor. *Can J Fish Aquat Sci.* 2011 Sep;68(9):1579–89.  
34 <https://doi.org/10.1139/f2011-084>

- 1 174. Griffiths JR, Schindler DE, Armstrong JB, Scheuerell MD, Whited DC, Clark RA, et al.  
2 Performance of salmon fishery portfolios across western North America. Angeler D,  
3 editor. *J Appl Ecol*. 2014 Dec;51(6):1554–63. <https://doi.org/10.1111/1365-2664.12341>
- 4 175. Wipfli MS, Baxter CV. Linking Ecosystems, Food Webs, and Fish Production: Subsidies  
5 in Salmonid Watersheds. *Fisheries*. 2010 Aug 1;35(8):373–87.  
6 <https://doi.org/10.1577/1548-8446-35.8.373>
- 7 176. Rossi GJ, Bellmore JR, Armstrong JB, Jeffres C, Naman SM, Carlson SM, et al.  
8 Foodscapes for salmon and other mobile consumers in river networks. *BioScience*.  
9 2024 Oct 16;74(9):586–600. <https://doi.org/10.1093/biosci/biae064>
- 10 177. Munsch SH, Greene CM, Mantua NJ, Satterthwaite WH. One hundred-seventy years of  
11 stressors erode salmon fishery climate resilience in California’s warming landscape.  
12 *Glob Change Biol*. 2022 Apr;28(7):2183–201. <https://doi.org/10.1111/gcb.16029>
- 13 178. Malone KM, Webb EB, Mengel DC, Kearns LJ, McKellar AE, Matteson SW, et al.  
14 Wetland management practices and secretive marsh bird habitat in the Mississippi  
15 Flyway: a review. *J Wildl Manag*. 2023 Sep;87(7):e22451.  
16 <https://doi.org/10.1002/jwmg.22451>
- 17 179. Lower E, Sturtevant R, Iott S, Martinez F, Rutherford E, Mason DM, et al. The Great  
18 Lakes’ most unwanted: Characterizing the impacts of the top ten Great Lakes aquatic  
19 invasive species. *J Gt Lakes Res*. 2024 Aug;50(4):102365.  
20 <https://doi.org/10.1016/j.jglr.2024.102365>
- 21 180. Sturtevant RA, Mason DM, Rutherford ES, Elgin A, Lower E, Martinez F. Recent history  
22 of nonindigenous species in the Laurentian Great Lakes; An update to Mills et al.,  
23 1993 (25 years later). *J Gt Lakes Res*. 2019 Dec;45(6):1011–35.  
24 <https://doi.org/10.1016/j.jglr.2019.09.002>
- 25 181. Nalepa TF, Fanslow DL, Lang GA. Transformation of the offshore benthic community in  
26 Lake Michigan: recent shift from the native amphipod *Diporeia* spp. to the invasive  
27 mussel *Dreissena rostriformis bugensis*. *Freshw Biol*. 2009 Mar;54(3):466–79.  
28 <https://doi.org/10.1111/j.1365-2427.2008.02123.x>
- 29 182. Nalepa TF, Fanslow DL, Foley Iii AJ, Lang GA, Eadie BJ, Quigley MA. Continued  
30 disappearance of the benthic amphipod *Diporeia* spp. in Lake Michigan: is there  
31 evidence for food limitation? *Can J Fish Aquat Sci*. 2006 Apr 1;63(4):872–90.  
32 <https://doi.org/10.1139/f05-262>
- 33 183. Marchetti MP, Moyle PB, Levine R. Alien Fishes in California Watersheds:  
34 Characteristics of Successful and Failed Invaders. *Ecol Appl*. 2004;14(2):587–96.  
35 <https://doi.org/10.1890/02-5301>

- 1 184. Haag WR, Williams JD. Biodiversity on the brink: an assessment of conservation  
2 strategies for North American freshwater mussels. *Hydrobiologia*. 2014  
3 Sep;735(1):45–60. <https://doi.org/10.1007/s10750-013-1524-7>
- 4 185. NatureServe Explorer [Internet]. 2025 [2025 Dec 1]. <https://explorer.natureserve.org/>
- 5 186. NatureServe. Biodiversity in Focus: United States Edition. Arlington, VA: NatureServe;  
6 2023.
- 7 187. Strayer DL. Beyond the sea: the hidden life in lakes, streams, and wetlands. Johns  
8 Hopkins University Press; 2024. 215 p.
- 9 188. Griffiths THD, Griffiths JJ. Mosquitoes Transported by Airplanes: Staining Method Used  
10 in Determining Their Importation. *Public Health Rep* 1896-1970. 1931;46(47):2775.  
11 <https://doi.org/10.2307/4580253>
- 12 189. Barmantlo SH, Schrama M, De Snoo GR, Van Bodegom PM, Van Nieuwenhuijzen A,  
13 Vijver MG. Experimental evidence for neonicotinoid driven decline in aquatic emerging  
14 insects. *Proc Natl Acad Sci*. 2021 Nov 2;118(44):e2105692118.  
15 <https://doi.org/10.1073/pnas.2105692118>
- 16 190. King RS, Scoggins M, Porras A. Stream biodiversity is disproportionately lost to  
17 urbanization when flow permanence declines: evidence from southwestern North  
18 America. *Freshw Sci*. 2016 Mar 1;35(1):340–52. <https://doi.org/10.1086/684943>
- 19 191. Maguire TJ, Mundle SOC. Citizen Science Data Show Temperature-Driven Declines in  
20 Riverine Sentinel Invertebrates. *Environ Sci Technol Lett*. 2020 May 12;7(5):303–7.  
21 <https://doi.org/10.1021/acs.estlett.0c00206>
- 22 192. Nessel MP, Konnovitch T, Romero GQ, González AL. Decline of insects and arachnids  
23 driven by nutrient enrichment: A meta-analysis. *Ecology*. 2023 Feb;104(2):e3897.  
24 <https://doi.org/10.1002/ecy.3897>
- 25 193. Sánchez-Bayo F, Wyckhuys KAG. Worldwide decline of the entomofauna: A review of  
26 its drivers. *Biol Conserv*. 2019 Apr;232:8–27.  
27 <https://doi.org/10.1016/j.biocon.2019.01.020>
- 28 194. Houghton DC, DeWalt RE. The caddis aren't alright: modeling Trichoptera richness in  
29 streams of the northcentral United States reveals substantial species losses. *Front*  
30 *Ecol Evol*. 2023 Aug 9;11:1163922. <https://doi.org/10.3389/fevo.2023.1163922>
- 31 195. Stepanian PM, Entekin SA, Wainwright CE, Mirkovic D, Tank JL, Kelly JF. Declines in an  
32 abundant aquatic insect, the burrowing mayfly, across major North American  
33 waterways. *Proc Natl Acad Sci*. 2020 Feb 11;117(6):2987–92.  
34 <https://doi.org/10.1073/pnas.1913598117>

- 1 196. Eden CF, Broughton RK, Donato B, Hewson CM, Isaksson C, Sharp SP. Cross-system  
2 transfer of fatty acids from aquatic insects supports terrestrial insectivore condition  
3 and reproductive success. *Oecologia*. 2025 Dec;207(12):191.  
4 <https://doi.org/10.1007/s00442-025-05827-9>
- 5 197. Twining CW, Shipley JR, Winkler DW. Aquatic insects rich in omega-3 fatty acids drive  
6 breeding success in a widespread bird. *Ecol Lett*. 2018;21(12):1812–20.  
7 <https://doi.org/10.1111/ele.13156>
- 8 198. Beebee TJC, Griffiths RA. The amphibian decline crisis: A watershed for conservation  
9 biology? *Biol Conserv*. 2005 Oct;125(3):271–85.  
10 <https://doi.org/10.1016/j.biocon.2005.04.009>
- 11 199. Luedtke JA, Chanson J, Neam K, Hobin L, Maciel AO, Catenazzi A, et al. Ongoing  
12 declines for the world’s amphibians in the face of emerging threats. *Nature*. 2023 Oct  
13 12;622(7982):308–14. <https://doi.org/10.1038/s41586-023-06578-4>
- 14 200. DuBose TP, Moore CE, Silknetter S, Benson AL, Alexander T, O’Malley G, et al.  
15 Mismatch between conservation status and climate change sensitivity leaves some  
16 anurans in the United States unprotected. *Biol Conserv*. 2023 Jan;277:109866.  
17 <https://doi.org/10.1016/j.biocon.2022.109866>
- 18 201. Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, et al. Emerging threats  
19 and persistent conservation challenges for freshwater biodiversity. *Biol Rev*.  
20 2019;94(3):849–73. <https://doi.org/10.1111/brv.12480>
- 21 202. Vredenburg VT. Reversing introduced species effects: Experimental removal of  
22 introduced fish leads to rapid recovery of a declining frog. *Proc Natl Acad Sci*. 2004  
23 May 18;101(20):7646–50. <https://doi.org/10.1073/pnas.0402321101>
- 24 203. Davidson C, Knapp RA. MULTIPLE STRESSORS AND AMPHIBIAN DECLINES: DUAL  
25 IMPACTS OF PESTICIDES AND FISH ON YELLOW-LEGGED FROGS. *Ecol Appl*. 2007  
26 Mar;17(2):587–97. <https://doi.org/10.1890/06-0181>
- 27 204. Smith TC, Knapp RA, Briggs CJ. Declines and extinctions of mountain yellow-legged  
28 frogs have small effects on benthic macroinvertebrate communities. *Ecosphere*. 2016  
29 Jun;7(6):e01327. <https://doi.org/10.1002/ecs2.1327>
- 30 205. Rhodin AGJ, Stanford CB, Dijk PPV, Eisemberg C, Luiselli L, Mittermeier RA, et al.  
31 Global Conservation Status of Turtles and Tortoises (Order Testudines). *Chelonian*  
32 *Conserv Biol*. 2018 Dec 18;17(2):135. <https://doi.org/10.2744/CCB-1348.1>
- 33 206. Easter T, Trautmann J, Gore M, Carter N. Media portrayal of the illegal trade in wildlife:  
34 The case of turtles in the US and implications for conservation. *People Nat*. 2023  
35 Apr;5(2):758–73. <https://doi.org/10.1002/pan3.10448>

- 1 207. Brenden TO, Brown RW, Ebener MP, Reid KB. Great Lakes Commercial Fisheries:  
2 Historical Overview and Prognoses for the Future. In: Taylor WW, Lynch AJ, Leonard NJ,  
3 editors. Great Lakes Fisheries Policy and Management: A Binational Perspective  
4 [Internet]. Michigan State University Press; 2012 [2025 Dec 1]. p. 339–97.  
5 <https://doi.org/10.14321/j.ctt7ztc19>
- 6 208. Great Lakes Fishery Commission. Commercial fish production in the Great Lakes  
7 1867–2020 [online database] [Internet]. Ann Arbor, Michigan; 2022 [2026 Jan 12].  
8 <https://www.glfrc.org/great-lakes-databases.php>
- 9 209. NOAA. Past fishing and development makes California salmon more vulnerable to  
10 climate change [Internet]. 2022. [https://www.fisheries.noaa.gov/feature-story/past-](https://www.fisheries.noaa.gov/feature-story/past-fishing-and-development-makes-california-salmon-more-vulnerable-climate-change)  
11 [fishing-and-development-makes-california-salmon-more-vulnerable-climate-change](https://www.fisheries.noaa.gov/feature-story/past-fishing-and-development-makes-california-salmon-more-vulnerable-climate-change)
- 12 210. Claassen C. Washboards, pigtoes, and muckets: historic musseling In the Mississippi  
13 watershed. *Hist Archeol*. 1994;28:1–145.
- 14 211. Strayer DL. What are Freshwater Mussels Worth? *Freshw Mollusk Biol Conserv*. 2017  
15 Oct 1;20(2):103. <https://doi.org/10.31931/fmbc.v20i2.2017.103-113>
- 16 212. Johnson LE, Ricciardi A, Carlton JT. OVERLAND DISPERSAL OF AQUATIC INVASIVE  
17 SPECIES: A RISK ASSESSMENT OF TRANSIENT RECREATIONAL BOATING. *Ecol Appl*.  
18 2001 Dec;11(6):1789–99. [https://doi.org/10.1890/1051-](https://doi.org/10.1890/1051-0761(2001)011%255B1789:ODOAIS%255D2.0.CO;2)  
19 [0761\(2001\)011%255B1789:ODOAIS%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(2001)011%255B1789:ODOAIS%255D2.0.CO;2)
- 20 213. Rothlisberger JD, Chadderton WL, McNulty J, Lodge DM. Aquatic Invasive Species  
21 Transport via Trailered Boats: What is Being Moved, Who is Moving it, and What Can Be  
22 Done. *Fisheries*. 2010 Mar 1;35(3):121–32. [https://doi.org/10.1577/1548-8446-](https://doi.org/10.1577/1548-8446-35.3.121)  
23 [35.3.121](https://doi.org/10.1577/1548-8446-35.3.121)
- 24 214. Kelly NE, Wantola K, Weisz E, Yan ND. Recreational boats as a vector of secondary  
25 spread for aquatic invasive species and native crustacean zooplankton. *Biol*  
26 *Invasions*. 2013 Mar;15(3):509–19. <https://doi.org/10.1007/s10530-012-0303-0>
- 27 215. Ricciardi A. Patterns of invasion in the Laurentian Great Lakes in relation to changes in  
28 vector activity. *Divers Distrib*. 2006;12(4):425–33. [https://doi.org/10.1111/j.1366-](https://doi.org/10.1111/j.1366-9516.2006.00262.x)  
29 [9516.2006.00262.x](https://doi.org/10.1111/j.1366-9516.2006.00262.x)
- 30 216. Ricciardi A, Maclsaac HJ. Vector control reduces the rate of species invasion in the  
31 world’s largest freshwater ecosystem. *Conserv Lett*. 2022 Mar;15(2):e12866.  
32 <https://doi.org/10.1111/conl.12866>
- 33 217. Padilla DK, Williams SL. Beyond ballast water: aquarium and ornamental trades as  
34 sources of invasive species in aquatic ecosystems. *Front Ecol Environ*. 2004;2(3):131–  
35 8. [https://doi.org/10.1890/1540-9295\(2004\)002%255B0131:BBWAAO%255D2.0.CO;2](https://doi.org/10.1890/1540-9295(2004)002%255B0131:BBWAAO%255D2.0.CO;2)

- 1 218. Rixon CAM, Duggan IC, Bergeron NMN, Ricciardi A, Macisaac HJ. Invasion risks posed  
2 by the aquarium trade and live fish markets on the Laurentian Great Lakes. *Biodivers*  
3 *Conserv.* 2005 Jun;14(6):1365–81. <https://doi.org/10.1007/s10531-004-9663-9>
- 4 219. Strecker AL, Campbell PM, Olden JD. The Aquarium Trade as an Invasion Pathway in  
5 the Pacific Northwest. *Fisheries.* 2011 Feb 1;36(2):74–85.  
6 <https://doi.org/10.1577/03632415.2011.10389070>
- 7 220. Chapman DC, Hoff MH, editors. *Invasive Asian Carps in North America* [Internet].  
8 American Fisheries Society; 2011 [2026 Jan 9].  
9 <https://doi.org/10.47886/9781934874233>
- 10 221. Oficialdegui FJ, Soto I, Balzani P, Cuthbert RN, Haubrock PJ, Kourantidou M, et al. Non-  
11 Native Species in Aquaculture: Burgeoning Production and Environmental  
12 Sustainability Risks. *Rev Aquac.* 2025 Jun;17(3):e70037.  
13 <https://doi.org/10.1111/raq.70037>
- 14 222. Mills EL, Chrisman JR, Holeck DT. The role of canals in the spread of nonindigenous  
15 species in North America. In: Claudi R, Leach JH, editors. *Nonindigenous freshwater*  
16 *organisms: vectors, biology, and impacts.* Boca Raton: Lewis Publishers; 2000. p. 347–  
17 80.
- 18 223. Marsden JE, Ladago BJ. The Champlain Canal as a non-indigenous species corridor. *J*  
19 *Gt Lakes Res.* 2017 Dec;43(6):1173–80. <https://doi.org/10.1016/j.jglr.2017.08.005>
- 20 224. Gates KK, Guy CS, Zale AV, Horton TB. Adherence of *Myxobolus cerebralis* Myxospores  
21 to Waders: Implications for Disease Dissemination. *North Am J Fish Manag.* 2008 Oct  
22 1;28(5):1453–8. <https://doi.org/10.1577/M08-025.1>
- 23 225. Bothwell ML, Lynch DR, Wright H, Deniseger J. On the Boots of Fishermen: The History  
24 of Didymo Blooms on Vancouver Island, British Columbia. *Fisheries.* 2009 Aug  
25 1;34(8):382–8. <https://doi.org/10.1577/1548-8446-34.8.382>
- 26 226. Johnson BM, Arlinghaus R, Martinez PJ. Are We Doing All We Can to Stem the Tide of  
27 Illegal Fish Stocking? *Fisheries.* 2009 Aug 1;34(8):389–94.  
28 <https://doi.org/10.1577/1548-8446-34.8.389>
- 29 227. Mandrak NE, Cudmore B. The fall of Native Fishes and the rise of Non-native Fishes in  
30 the Great Lakes Basin. *Aquat Ecosyst Health Manag.* 2010 Aug 31;13(3):255–68.  
31 <https://doi.org/10.1080/14634988.2010.507150>
- 32 228. Bernery C, Bellard C, Courchamp F, Brosse S, Gozlan RE, Jarić I, et al. Freshwater Fish  
33 Invasions: A Comprehensive Review. *Annu Rev Ecol Evol Syst.* 2022 Nov 2;53(Volume  
34 53, 2022):427–56. <https://doi.org/10.1146/annurev-ecolsys-032522-015551>

- 1 229. Mills EL, Strayer DL, Scheuerell MD, Carlton JT. Exotic Species in the Hudson River  
2 Basin: A History of Invasions and Introductions. *Estuaries*. 1996 Dec;19(4):814.  
3 <https://doi.org/10.2307/1352299>
- 4 230. Mills EL, Leach JH, Carlton JT, Secor CL. Exotic Species in the Great Lakes: A History of  
5 Biotic Crises and Anthropogenic Introductions. *J Gt Lakes Res*. 1993 Jan 1;19(1):1–54.  
6 [https://doi.org/10.1016/S0380-1330\(93\)71197-1](https://doi.org/10.1016/S0380-1330(93)71197-1)
- 7 231. Marsden JE, Hauser M. Exotic species in Lake Champlain. *J Gt Lakes Res*. 2009  
8 Jun;35(2):250–65. <https://doi.org/10.1016/j.jglr.2009.01.006>
- 9 232. Seebens H, Meyerson LA, Richardson DM, Lenzner B, Tricarico E, Courchamp F, et al.  
10 Biological invasions: a global assessment of geographic distributions, long-term  
11 trends, and data gaps. *Biol Rev*. 2025 Dec;100(6):2542–83.  
12 <https://doi.org/10.1111/brv.70058>
- 13 233. Jackson MC, Grey J. Accelerating rates of freshwater invasions in the catchment of the  
14 River Thames. *Biol Invasions*. 2013 May;15(5):945–51. [https://doi.org/10.1007/s10530-  
15 012-0343-5](https://doi.org/10.1007/s10530-012-0343-5)
- 16 234. Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, et al. No  
17 saturation in the accumulation of alien species worldwide. *Nat Commun*. 2017 Feb  
18 15;8(1):14435. <https://doi.org/10.1038/ncomms14435>
- 19 235. Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, et al.  
20 Projecting the continental accumulation of alien species through to 2050. *Glob*  
21 *Change Biol*. 2021 Mar;27(5):970–82. <https://doi.org/10.1111/gcb.15333>
- 22 236. Gallardo B, Clavero M, Sánchez MI, Vilà M. Global ecological impacts of invasive  
23 species in aquatic ecosystems. *Glob Change Biol*. 2016;22(1):151–63.  
24 <https://doi.org/10.1111/gcb.13004>
- 25 237. Macêdo RL, Haubrock PJ, Klippel G, Fernandez RD, Leroy B, Angulo E, et al. The  
26 economic costs of invasive aquatic plants: A global perspective on ecology and  
27 management gaps. *Sci Total Environ*. 2024 Jan 15;908:168217.  
28 <https://doi.org/10.1016/j.scitotenv.2023.168217>
- 29 238. U.S. Geological Survey. Nonindigenous Aquatic Species [Internet]. [2025 Nov 21].  
30 <https://nas.er.usgs.gov/queries/FactSheetList.aspx>
- 31 239. Pintar MR, Strickland ND, Kline JL, Cook MI, Dorn NJ. Asian swamp eels  
32 (*Synbranchidae*, *Monopterus*) in Florida: distribution, spread, and range of hydrologic  
33 tolerance over twenty-seven years (1997–2023). *Aquat Invasions*. 2024 May  
34 13;19(2):233–58. <https://doi.org/10.3391/ai.2024.19.2.124660>

- 1 240. Pintar MR, Dorn NJ. Invasive swamp eels reduce aquatic animal diversity and  
2 disproportionately reduce prey for nesting wading birds. *Sci Rep.* 2025 May  
3 23;15(1):17975. <https://doi.org/10.1038/s41598-025-02887-y>
- 4 241. Government of Canada PS and PC. Biological synopsis of grass carp  
5 (*Ctenopharyngodon idella*) / by Becky Cudmore and Nicholas E. Mandrak. : Fs97-  
6 4/2705E-PDF - Government of Canada Publications - Canada.ca [Internet]. 2002  
7 [2025 Dec 1]. <https://publications.gc.ca/site/eng/9.562403/publication.html>
- 8 242. Strayer DL. Alien species in fresh waters: ecological effects, interactions with other  
9 stressors, and prospects for the future. *Freshw Biol.* 2010 Jan 1;55(s1):152–74.  
10 <https://doi.org/10.1111/j.1365-2427.2009.02380.x>
- 11 243. Vilizzi L, Tarkan AS, Copp GH. Experimental Evidence from Causal Criteria Analysis for  
12 the Effects of Common Carp *Cyprinus carpio* on Freshwater Ecosystems: A Global  
13 Perspective. *Rev Fish Sci Aquac.* 2015 Jul 3;23(3):253–90.  
14 <https://doi.org/10.1080/23308249.2015.1051214>
- 15 244. Hochstrasser JM, Collins SF. Assessing the direct and indirect effects of bigheaded  
16 carp (*Hypophthalmichthys* spp.) on freshwater food webs: A meta-analysis. *Freshw*  
17 *Biol.* 2024;69(10):1399–407. <https://doi.org/10.1111/fwb.14314>
- 18 245. Madenjian CP, Bunnell DB, Warner DM, Pothoven SA, Fahnenstiel GL, Nalepa TF, et al.  
19 Changes in the Lake Michigan food web following dreissenid mussel invasions: A  
20 synthesis. *J Gt Lakes Res.* 2015 Jan 1;41:217–31.  
21 <https://doi.org/10.1016/j.jglr.2015.08.009>
- 22 246. Cunningham KE, Dunlop ES. Declines in lake whitefish larval densities after dreissenid  
23 mussel establishment in Lake Huron. *J Gt Lakes Res.* 2023 Apr 1;49(2):491–505.  
24 <https://doi.org/10.1016/j.jglr.2022.12.015>
- 25 247. Karatayev AY, Burlakova LE. Dreissena in the Great Lakes: what have we learned in  
26 30 years of invasion. *Hydrobiologia.* 2025 Mar 1;852(5):1103–30.  
27 <https://doi.org/10.1007/s10750-022-04990-x>
- 28 248. Li J, Ianaiev V, Huff A, Zalusky J, Ozersky T, Katsev S. Benthic invaders control the  
29 phosphorus cycle in the world’s largest freshwater ecosystem. *Proc Natl Acad Sci.*  
30 2021 Feb 9;118(6):e2008223118. <https://doi.org/10.1073/pnas.2008223118>
- 31 249. Bartholomew JL, Reno PW. Whirling Disease: Reviews and Current Topics. In:  
32 Department of Microbiology and Center for Fish Disease Research Oregon State  
33 University, Corvallis, Oregon 97331-3804, USA, Bartholomew JL, Christopher Wilson J,  
34 Utah Division of Wildlife Resources, Fisheries Experiment Station 1465 West 200  
35 North, Logan, Utah 84321-6262, USA, editors. *Whirling Disease: Reviews and Current*

- 1 Topics [Internet]. American Fisheries Society; 2002 [2025 Dec 15].  
2 <https://doi.org/10.47886/9781888569377.ch1>
- 3 250. Kim R, Faisal M. Emergence and resurgence of the viral hemorrhagic septicemia virus  
4 (*Novirhabdovirus*, *Rhabdoviridae*, *Mononegavirales*). *J Adv Res*. 2011 Jan 1;2(1):9–23.  
5 <https://doi.org/10.1016/j.jare.2010.05.007>
- 6 251. Sarker S, Kallert DM, Hedrick RP, El-Matbouli M. Whirling disease revisited:  
7 pathogenesis, parasite biology and disease intervention. *Dis Aquat Organ*. 2015 May  
8 21;114(2):155–75. <https://doi.org/10.3354/dao02856>
- 9 252. Cuthbert RN, Pattison Z, Taylor NG, Verbrugge L, Diagne C, Ahmed DA, et al. Global  
10 economic costs of aquatic invasive alien species. *Sci Total Environ*. 2021  
11 Jun;775:145238. <https://doi.org/10.1016/j.scitotenv.2021.145238>
- 12 253. Fantle-Lepczyk JE, Haubrock PJ, Kramer AM, Cuthbert RN, Turbelin AJ, Crystal-Ornelas  
13 R, et al. Economic costs of biological invasions in the United States. *Sci Total Environ*.  
14 2022 Feb;806:151318. <https://doi.org/10.1016/j.scitotenv.2021.151318>
- 15 254. Turbelin AJ, Cuthbert RN, Essl F, Haubrock PJ, Ricciardi A, Courchamp F. Biological  
16 invasions are as costly as natural hazards. *Perspect Ecol Conserv*. 2023  
17 Apr;21(2):143–50. <https://doi.org/10.1016/j.pecon.2023.03.002>
- 18 255. Vaughn CC. *Functional Ecology of Freshwater Mussels*. Baltimore, MD: Johns Hopkins  
19 University Press; 2026.
- 20 256. Vaughn CC. Ecosystem services provided by freshwater mussels. *Hydrobiologia*. 2018  
21 Mar;810(1):15–27. <https://doi.org/10.1007/s10750-017-3139-x>
- 22 257. Gessner MO, Swan CM, Dang CK, McKie BG, Bardgett RD, Wall DH, et al. Diversity  
23 meets decomposition. *Trends Ecol Evol*. 2010 Jun;25(6):372–80.  
24 <https://doi.org/10.1016/j.tree.2010.01.010>
- 25 258. Strecker AL, Arnott SE. Invasive Predator, *Bythotrephes*, has Varied Effects on  
26 Ecosystem Function in Freshwater Lakes. *Ecosystems*. 2008 Apr 1;11(3):490–503.  
27 <https://doi.org/10.1007/s10021-008-9137-0>
- 28 259. Walsh JR, Carpenter SR, Vander Zanden MJ. Invasive species triggers a massive loss of  
29 ecosystem services through a trophic cascade. *Proc Natl Acad Sci*.  
30 2016;113(15):4081–5.
- 31 260. Connelly NA, O'Neill CR, Knuth BA, Brown TL. Economic Impacts of Zebra Mussels on  
32 Drinking Water Treatment and Electric Power Generation Facilities. *Environ Manage*.  
33 2007 Jul;40(1):105–12. <https://doi.org/10.1007/s00267-006-0296-5>

- 1 261. Nakano D, Strayer DL. Biofouling animals in fresh water: biology, impacts, and  
2 ecosystem engineering. *Front Ecol Environ*. 2014 Apr;12(3):167–75.  
3 <https://doi.org/10.1890/130071>
- 4 262. Whiles MR, Hall RO, Dodds WK, Verburg P, Huryn AD, Pringle CM, et al. Disease-Driven  
5 Amphibian Declines Alter Ecosystem Processes in a Tropical Stream. *Ecosystems*.  
6 2013 Jan;16(1):146–57. <https://doi.org/10.1007/s10021-012-9602-7>
- 7 263. Belasen AM, Peek RA, Adams AJ, Russell ID, De León ME, Adams MJ, et al. Chytrid  
8 infections exhibit historical spread and contemporary seasonality in a declining  
9 stream-breeding frog. *R Soc Open Sci*. 2024 Jan;11(1):231270.  
10 <https://doi.org/10.1098/rsos.231270>
- 11 264. Wipfli MS, Richardson JS, Naiman RJ. Ecological Linkages Between Headwaters and  
12 Downstream Ecosystems: Transport of Organic Matter, Invertebrates, and Wood Down  
13 Headwater Channels<sup>1</sup>. *JAWRA J Am Water Resour Assoc*. 2007 Feb;43(1):72–85.  
14 <https://doi.org/10.1111/j.1752-1688.2007.00007.x>
- 15 265. Schindler DE, Carpenter SR, Cottingham KL, He X, Hodgson JR, Kitchell JF, et al. Food  
16 Web Structure and Littoral Zone Coupling to Pelagic Trophic Cascades. In: Polis GA,  
17 Winemiller KO, editors. *Food Webs: Integration of Patterns & Dynamics* [Internet].  
18 Boston, MA: Springer US; 1996 [2026 Jan 12]. p. 96–105. [https://doi.org/10.1007/978-1-4615-7007-3\\_9](https://doi.org/10.1007/978-1-4615-7007-3_9)
- 20 266. Moore JW, Schindler DE, Carter JL, Fox J, Griffiths J, Holtgrieve GW. BIOTIC CONTROL  
21 OF STREAM FLUXES: SPAWNING SALMON DRIVE NUTRIENT AND MATTER EXPORT.  
22 *Ecology*. 2007 May;88(5):1278–91. <https://doi.org/10.1890/06-0782>
- 23 267. Merz JE, Moyle PB. Salmon, Wildlife, And Wine: Marine-Derived Nutrients In Human-  
24 Dominated Ecosystems Of Central California. *Ecol Appl*. 2006 Jun;16(3):999–1009.  
25 [https://doi.org/10.1890/1051-0761\(2006\)016%255B0999:SWAWMN%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(2006)016%255B0999:SWAWMN%255D2.0.CO;2)
- 26 268. Wipfli MS, Hudson J, Caouette J. Influence of salmon carcasses on stream  
27 productivity: response of biofilm and benthic macroinvertebrates in southeastern  
28 Alaska, U.S.A. *Can J Fish Aquat Sci*. 1998 Jun 1;55(6):1503–11.  
29 <https://doi.org/10.1139/f98-031>
- 30 269. Cederholm CJ, Kunze MD, Murota T, Sibatani A. Pacific Salmon Carcasses: Essential  
31 Contributions of Nutrients and Energy for Aquatic and Terrestrial Ecosystems.  
32 *Fisheries*. 1999 Oct 1;24(10):6–15. [https://doi.org/10.1577/1548-8446\(1999\)024%253C0006:PSC%253E2.0.CO;2](https://doi.org/10.1577/1548-8446(1999)024%253C0006:PSC%253E2.0.CO;2)
- 34 270. USGCRP. Fifth National Climate Assessment [Internet]. Crimmins AR, Avery CW,  
35 Easterling DR, Kunkel KE, Maycock TK, editors. Fifth National Climate Assessment.

- 1 Washington, DC: U.S. Global Change Research Program; 2023 [2024 Apr 29].  
2 <https://doi.org/10.7930/NCA5.2023>
- 3 271. Williams AP, Livneh B, McKinnon KA, Hansen WD, Mankin JS, Cook BI, et al. Growing  
4 impact of wildfire on western US water supply. *Proc Natl Acad Sci*. 2022 Mar  
5 8;119(10):e2114069119. <https://doi.org/10.1073/pnas.2114069119>
- 6 272. Fyfe JC, Derksen C, Mudryk L, Flato GM, Santer BD, Swart NC, et al. Large near-term  
7 projected snowpack loss over the western United States. *Nat Commun*. 2017 Apr  
8 18;8:14996. <https://doi.org/10.1038/ncomms14996>
- 9 273. Rixen C, Høye TT, Macek P, Aerts R, Alatalo JM, Anderson JT, et al. Winters are  
10 changing: snow effects on Arctic and alpine tundra ecosystems. *Arct Sci*. 2022  
11 Sep;8(3):572–608. <https://doi.org/10.1139/as-2020-0058>
- 12 274. Barbero R, Fowler HJ, Lenderink G, Blenkinsop S. Is the intensification of precipitation  
13 extremes with global warming better detected at hourly than daily resolutions?  
14 *Geophys Res Lett*. 2017 Jan 28;44(2):974–83. <https://doi.org/10.1002/2016GL071917>
- 15 275. Ashley ST, Ashley WS. Flood Fatalities in the United States. *J Appl Meteorol Climatol*.  
16 2008 Mar 1;47(3):805–18. <https://doi.org/10.1175/2007JAMC1611.1>
- 17 276. Brody SD, Highfield WE, Kang JE. *Rising Waters: The Causes and Consequences of*  
18 *Flooding in the United States*. Cambridge, UK: Cambridge University Press; 2011.
- 19 277. Brody SD, Zahran S, Maghelal P, Grover H, Highfield WE. The Rising Costs of Floods:  
20 Examining the Impact of Planning and Development Decisions on Property Damage in  
21 Florida. *J Am Plann Assoc*. 2007 Sep 30;73(3):330–45.  
22 <https://doi.org/10.1080/01944360708977981>
- 23 278. Gies E. *Water always wins: thriving in an age of drought and deluge*. Paperback edition.  
24 Chicago: University of Chicago Press; 2023. 327 p.
- 25 279. VEDA Dashboard [Internet]. 2025 [2026 Jan 13]. Guadalupe River Flood Tragedy.  
26 <https://www.earthdata.nasa.gov/stories/tx-flood>
- 27 280. Stewart IT, Cayan DR, Dettinger MD. Changes toward Earlier Streamflow Timing across  
28 Western North America. *J Clim*. 2005 Apr 15;18(8):1136–55.  
29 <https://doi.org/10.1175/JCLI3321.1>
- 30 281. Alberiko Gil-Alana L. Time Trends and Persistence in the Snowpack Percentages by  
31 Watershed in Colorado. In: Saifullah M, editor. *Weather Forecasting* [Internet].  
32 IntechOpen; 2021 [2025 Nov 23]. <https://doi.org/10.5772/intechopen.95911>

- 1 282. Xiao M, Udall B, Lettenmaier DP. On the Causes of Declining Colorado River  
2 Streamflows. *Water Resour Res.* 2018 Sep;54(9):6739–56.  
3 <https://doi.org/10.1029/2018WR023153>
- 4 283. Kaushal SS, Likens G, Jaworski, N, Pace M, 8: tures in the UStatesFEE. Rising stream  
5 and river temperatures in the United States. *Front Ecol Environ.* 2010;8:461–6.
- 6 284. Kaandorp VP, Doornenbal PJ, Kooi H, Peter Broers H, De Louw PGB. Temperature  
7 buffering by groundwater in ecologically valuable lowland streams under current and  
8 future climate conditions. *J Hydrol X.* 2019 Apr;3:100031.  
9 <https://doi.org/10.1016/j.hydroa.2019.100031>
- 10 285. Marchionni V, Daly E, Manoli G, Tapper NJ, Walker JP, Fatichi S. Groundwater Buffers  
11 Drought Effects and Climate Variability in Urban Reserves. *Water Resour Res.*  
12 2020;56(5):e2019WR026192. <https://doi.org/10.1029/2019WR026192>
- 13 286. Yarnell SM, Petts GE, Schmidt JC, Whipple AA, Beller EE, Dahm CN, et al. Functional  
14 Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities. *BioScience.*  
15 2015 Oct 1;65(10):963–72. <https://doi.org/10.1093/biosci/biv102>
- 16 287. Bellmore JR, Fellman JB, Hood E, Dunkle MR, Edwards RT. A melting cryosphere  
17 constrains fish growth by synchronizing the seasonal phenology of river food webs.  
18 *Glob Change Biol.* 2022;28(16):4807–18. <https://doi.org/10.1111/gcb.16273>
- 19 288. Mote PW, Li S, Lettenmaier DP, Xiao M, Engel R. Dramatic declines in snowpack in the  
20 western US. *Npj Clim Atmospheric Sci.* 2018 Mar 2;1(1):2.  
21 <https://doi.org/10.1038/s41612-018-0012-1>
- 22 289. Rogers JB, Stein ED, Beck MW, Ambrose RF. The impact of climate change induced  
23 alterations of streamflow and stream temperature on the distribution of riparian  
24 species. Jones JA, editor. *PLOS ONE.* 2020 Nov 24;15(11):e0242682.  
25 <https://doi.org/10.1371/journal.pone.0242682>
- 26 290. Siirila-Woodburn ER, Rhoades AM, Hatchett BJ, Huning LS, Szinai J, Tague C, et al. A  
27 low-to-no snow future and its impacts on water resources in the western United  
28 States. *Nat Rev Earth Environ.* 2021 Oct 26;2(11):800–19.  
29 <https://doi.org/10.1038/s43017-021-00219-y>
- 30 291. Bennett KE, Schwenk J, Bachand C, Gasarch E, Stachelek J, Bolton WR, et al. Recent  
31 streamflow trends across permafrost basins of North America. *Front Water.* 2023 Jun  
32 29;5:1099660. <https://doi.org/10.3389/frwa.2023.1099660>
- 33 292. Curran JH, Rick B, Littell JS, Sass LC. Streamflow Response to Glacier Mass Loss  
34 Varies With Basin Precipitation Across Alaska. *Water Resour Res.* 2025  
35 Apr;61(4):e2024WR037859. <https://doi.org/10.1029/2024WR037859>

- 1 293. Hidalgo HG, Das T, Dettinger MD, Cayan DR, Pierce DW, Barnett TP, et al. Detection  
2 and Attribution of Streamflow Timing Changes to Climate Change in the Western  
3 United States. *J Clim.* 2009 Jul 1;22(13):3838–55.  
4 <https://doi.org/10.1175/2009JCLI2470.1>
- 5 294. Coffey R, Paul MJ, Stamp J, Hamilton A, Johnson T. A Review of Water Quality  
6 Responses to Air Temperature and Precipitation Changes 2: Nutrients, Algal Blooms,  
7 Sediment, Pathogens. *JAWRA J Am Water Resour Assoc.* 2019 Aug;55(4):844–68.  
8 <https://doi.org/10.1111/1752-1688.12711>
- 9 295. Cheng X, Huang Y, Li R, Pu X, Huang W, Yuan X. Impacts of water temperature on  
10 phosphorus release of sediments under flowing overlying water. *J Contam Hydrol.*  
11 2020 Nov;235:103717. <https://doi.org/10.1016/j.jconhyd.2020.103717>
- 12 296. Carpenter SR, Ludwig D, Brock WA. MANAGEMENT OF EUTROPHICATION FOR LAKES  
13 SUBJECT TO POTENTIALLY IRREVERSIBLE CHANGE. *Ecol Appl.* 1999;9(3):751–71.
- 14 297. Diefenbaugh NS, Scherer M, Trapp RJ. Robust increases in severe thunderstorm  
15 environments in response to greenhouse forcing. *Proc Natl Acad Sci.* 2013 Oct  
16 8;110(41):16361–6. <https://doi.org/10.1073/pnas.1307758110>
- 17 298. Sinha E, Michalak AM, Balaji V. Eutrophication will increase during the 21st century as  
18 a result of precipitation changes. *Science.* 2017 Jul 28;357(6349):405–8.  
19 <https://doi.org/10.1126/science.aan2409>
- 20 299. Yang Y, Tilman D, Jin Z, Smith P, Barrett CB, Zhu YG, et al. Climate change exacerbates  
21 the environmental impacts of agriculture. *Science.* 2024 Sep 6;385(6713):eadn3747.  
22 <https://doi.org/10.1126/science.adn3747>
- 23 300. Kelly PT, Renwick WH, Knoll L, Vanni MJ. Stream Nitrogen and Phosphorus Loads Are  
24 Differentially Affected by Storm Events and the Difference May Be Exacerbated by  
25 Conservation Tillage. *Environ Sci Technol.* 2019 May 21;53(10):5613–21.  
26 <https://doi.org/10.1021/acs.est.8b05152>
- 27 301. Carpenter SR, Booth EG, Kucharik CJ. Extreme precipitation and phosphorus loads  
28 from two agricultural watersheds. *Limnol Oceanogr.* 2018 May;63(3):1221–33.  
29 <https://doi.org/10.1002/lno.10767>
- 30 302. Dokulil MT, Teubner K. Cyanobacterial dominance in lakes. *Hydrobiologia.* 2000 Nov  
31 1;438(1):1–12. <https://doi.org/10.1023/A:1004155810302>
- 32 303. Paerl HW, Huisman J. Blooms Like It Hot. *Science.* 2008 Apr 4;320(5872):57–8.  
33 <https://doi.org/10.1126/science.1155398>

- 1 304. Paerl HW, Huisman J. Climate change: a catalyst for global expansion of harmful  
2 cyanobacterial blooms. *Environ Microbiol Rep*. 2009 Feb;1(1):27–37.  
3 <https://doi.org/10.1111/j.1758-2229.2008.00004.x>
- 4 305. Paerl HW. Controlling harmful cyanobacterial blooms in a climatically more extreme  
5 world: management options and research needs. *J Plankton Res*. 2017 Aug;1–9.  
6 <https://doi.org/10.1093/plankt/fbx042>
- 7 306. Lürling M, Mello MM e, van Oosterhout F, de Senerpont Domis L, Marinho MM.  
8 Response of Natural Cyanobacteria and Algae Assemblages to a Nutrient Pulse and  
9 Elevated Temperature. *Front Microbiol* [Internet]. 2018 Aug 13 [2025 Nov 23];9.  
10 <https://doi.org/10.3389/fmicb.2018.01851>
- 11 307. Steffen MM, Davis TW, McKay RML, Bullerjahn GS, Krausfeldt LE, Stough JMA, et al.  
12 Ecophysiological Examination of the Lake Erie *Microcystis* Bloom in 2014: Linkages  
13 between Biology and the Water Supply Shutdown of Toledo, OH. *Environ Sci Technol*.  
14 2017 Jun 20;51(12):6745–55. <https://doi.org/10.1021/acs.est.7b00856>
- 15 308. Sorte CJB, Ibáñez I, Blumenthal DM, Molinari NA, Miller LP, Grosholz ED, et al. Poised  
16 to prosper? A cross-system comparison of climate change effects on native and non-  
17 native species performance. *Suding K, editor. Ecol Lett*. 2013 Feb;16(2):261–70.  
18 <https://doi.org/10.1111/ele.12017>
- 19 309. Bates AE, McKelvie CM, Sorte CJB, Morley SA, Jones NAR, Mondon JA, et al.  
20 Geographical range, heat tolerance and invasion success in aquatic species. *Proc R*  
21 *Soc B Biol Sci*. 2013 Dec 7;280(1772):20131958.  
22 <https://doi.org/10.1098/rspb.2013.1958>
- 23 310. Moyle PB, Light T. Fish Invasions in California: Do Abiotic Factors Determine Success?  
24 *Ecology*. 1996 Sep;77(6):1666–70. <https://doi.org/10.2307/2265770>
- 25 311. Woodruff SM, Grasso RL, Halstead BJ, Todd BD. Effects of invasive American bullfrogs  
26 and their removal on Northwestern pond turtles. *Biol Conserv*. 2025 May;305:111090.  
27 <https://doi.org/10.1016/j.biocon.2025.111090>
- 28 312. Hayes MP, Jennings MR. Decline of Ranid Frog Species in Western North America: Are  
29 Bullfrogs (*Rana catesbeiana*) Responsible? *J Herpetol*. 1986 Dec;20(4):490.  
30 <https://doi.org/10.2307/1564246>
- 31 313. Reese CD, Harvey BC. Temperature-Dependent Interactions between Juvenile  
32 Steelhead and Sacramento Pikeminnow in Laboratory Streams. *Trans Am Fish Soc*.  
33 2002 Jul 1;131(4):599–606. [https://doi.org/10.1577/1548-  
34 8659\(2002\)131%253C0599:TDIBJS%253E2.0.CO;2](https://doi.org/10.1577/1548-8659(2002)131%253C0599:TDIBJS%253E2.0.CO;2)
- 35 314. Georgakakos PB, Dralle DN, Power ME. Spring temperature predicts upstream  
36 migration timing of invasive Sacramento pikeminnow within its introduced range.

- 1 Environ Biol Fishes. 2023 Nov;106(11):2069–82. [https://doi.org/10.1007/s10641-023-](https://doi.org/10.1007/s10641-023-01486-y)  
2 [01486-y](https://doi.org/10.1007/s10641-023-01486-y)
- 3 315. Cohen JM, Sauer EL, Santiago O, Spencer S, Rohr JR. Divergent impacts of warming  
4 weather on wildlife disease risk across climates. *Science*. 2020 Nov  
5 20;370(6519):eabb1702. <https://doi.org/10.1126/science.abb1702>
- 6 316. Tomamichel MM, Lowe KI, Arnold KMH, Frischer MarcE, Irwin BJ, Osenberg CW, et al.  
7 Warmer Is Deadlier: A Meta-Analysis Reveals Increasing Temperatures Accentuate  
8 Disease Effects on Fisheries Hosts. *Ecol Lett*. 2025 Jul;28(7):e70156.  
9 <https://doi.org/10.1111/ele.70156>
- 10 317. Marcogliese DJ. Implications of climate change for parasitism of animals in the  
11 aquatic environment. *Can J Zool*. 2001 Aug 1;79(8):1331–52.  
12 <https://doi.org/10.1139/z01-067>
- 13 318. Kupferberg SJ, Catenazzi A, Lunde K, Lind AJ, Palen WJ. Parasitic Copepod (*Lernaea*  
14 *cyprinacea*) Outbreaks in Foothill Yellow-legged Frogs (*Rana boylei*) Linked to  
15 Unusually Warm Summers and Amphibian Malformations in Northern California.  
16 *Copeia*. 2009 Sep 3;2009(3):529–37. <https://doi.org/10.1643/CH-08-011>
- 17 319. Schaaf CJ, Kelson SJ, Nusslé SC, Carlson SM. Black spot infection in juvenile  
18 steelhead trout increases with stream temperature in northern California. *Environ Biol*  
19 *Fishes*. 2017 Jun;100(6):733–44. <https://doi.org/10.1007/s10641-017-0599-9>
- 20 320. Power ME, Parker MS, Dietrich WE. SEASONAL REASSEMBLY OF A RIVER FOOD WEB:  
21 FLOODS, DROUGHTS, AND IMPACTS OF FISH. *Ecol Monogr*. 2008 May;78(2):263–82.  
22 <https://doi.org/10.1890/06-0902.1>
- 23 321. Meffe GK. Effects of Abiotic Disturbance on Coexistence of Predator-Prey Fish  
24 Species. *Ecology*. 1984 Oct;65(5):1525–34. <https://doi.org/10.2307/1939132>
- 25 322. Lytle DA, Bogan MT, Finn DS. Evolution of aquatic insect behaviours across a gradient  
26 of disturbance predictability. *Proc R Soc B Biol Sci*. 2008 Feb 22;275(1633):453–62.  
27 <https://doi.org/10.1098/rspb.2007.1157>
- 28 323. Hendry AP, Castric V, Kinnison MT, Quinn TP. The evolution of philopatry and dispersal:  
29 homing vs. straying in salmonids. In: Hendry AP, Stearns SC, editors. *Evolution*  
30 *illuminated: salmon and their relatives*. Oxford New York: Oxford University Press;  
31 2004. p. 53–91.
- 32 324. Beechie T, Buhle E, Ruckelshaus M, Fullerton A, Holsinger L. Hydrologic regime and  
33 the conservation of salmon life history diversity. *Biol Conserv*. 2006 Jul;130(4):560–72.  
34 <https://doi.org/10.1016/j.biocon.2006.01.019>

- 1 325. Waples RS, Pess GR, Beechie T. Evolutionary history of Pacific salmon in dynamic  
2 environments. *Evol Appl.* 2008 May;1(2):189–206. [https://doi.org/10.1111/j.1752-](https://doi.org/10.1111/j.1752-4571.2008.00023.x)  
3 [4571.2008.00023.x](https://doi.org/10.1111/j.1752-4571.2008.00023.x)
- 4 326. Gray LJ, Fisher SG. Postflood recolonization pathways of macroinvertebrates in a  
5 lowland Sonoran Desert stream. *Am Midl Nat.* 1981;106:249–57.
- 6 327. Quinn TP, Hodgson S, Flynn L, Hilborn R, Rogers DE. Directional selection by fisheries  
7 and the timing of sockeye salmon (*Oncorhynchus nerka*) migrations. *Ecol Appl Publ*  
8 *Ecol Soc Am.* 2013 Feb;17(3):731–9.
- 9 328. Montgomery DR. Coevolution of the Pacific salmon and Pacific Rim topography.  
10 *Geology.* 2000;28(12):1107–10. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(2000)28%253C1107:cotpsa%253E2.0.co;2)  
11 [7613\(2000\)28%253C1107:cotpsa%253E2.0.co;2](https://doi.org/10.1130/0091-7613(2000)28%253C1107:cotpsa%253E2.0.co;2)
- 12 329. Jiang C, Storey KB, Yang H, Sun L. Aestivation in Nature: Physiological Strategies and  
13 Evolutionary Adaptations in Hypometabolic States. *Int J Mol Sci.* 2023 Sep  
14 14;24(18):14093. <https://doi.org/10.3390/ijms241814093>
- 15 330. Jackson DC, Ultsch GR. Physiology of hibernation under the ice by turtles and frogs. *J*  
16 *Exp Zool Part Ecol Genet Physiol.* 2010 Jul 1;313(6):311–27.  
17 <https://doi.org/10.1002/jez.603>
- 18 331. Hairston NG, Van Brunt RA, Kearns CM, Engstrom DR. Age and Survivorship of  
19 Diapausing Eggs in a Sediment Egg Bank. *Ecology.* 1995 Sep;76(6):1706–11.  
20 <https://doi.org/10.2307/1940704>
- 21 332. Sand-Jensen K. Ecophysiology of gelatinous Nostoc colonies: unprecedented slow  
22 growth and survival in resource-poor and harsh environments. *Ann Bot.* 2014  
23 Jul;114(1):17–33. <https://doi.org/10.1093/aob/mcu085>
- 24 333. Kupferberg SJ, Palen WJ, Lind AJ, Bobzien S, Catenazzi A, Drennan J, et al. Effects of  
25 Flow Regimes Altered by Dams on Survival, Population Declines, and Range-Wide  
26 Losses of California River-Breeding Frogs. *Conserv Biol.* 2012;26(3):513–24.  
27 <https://doi.org/10.1111/j.1523-1739.2012.01837.x>
- 28 334. Dodds WK, Oakes RM. Headwater Influences on Downstream Water Quality. *Environ*  
29 *Manage.* 2008 Mar;41(3):367–77. <https://doi.org/10.1007/s00267-007-9033-y>
- 30 335. McClure MM, Carlson SM, Beechie TJ, Pess GR, Jorgensen JC, Sogard SM, et al.  
31 Evolutionary consequences of habitat loss for Pacific anadromous salmonids. *Evol*  
32 *Appl.* 2008;1(2):300–18.
- 33 336. Stanford JA, Hauer FR, Ward JV. Serial discontinuity in a large river system. *Verh Intern*  
34 *Ver Tehor Angewa Limnol.* 1988;23:1114–8.

- 1 337. Warrick JA, Bountry JA, East AE, Magirl CS, Randle TJ, Gelfenbaum G, et al. Large-scale  
2 dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget  
3 and synthesis. *Geomorphology*. 2015 Oct;246:729–50.  
4 <https://doi.org/10.1016/j.geomorph.2015.01.010>
- 5 338. Pess G, Morley S, Roni P. Chapter 10 Evaluating Fish Response to Culvert  
6 Replacement and Other Methods for Reconnecting Isolated Aquatic Habitats. 2005;
- 7 339. Carpenter SR, Ludwig D, Brock WA. MANAGEMENT OF EUTROPHICATION FOR LAKES  
8 SUBJECT TO POTENTIALLY IRREVERSIBLE CHANGE. *Ecol Appl*. 1999 Aug;9(3):751–71.  
9 [https://doi.org/10.1890/1051-0761\(1999\)009%255B0751:MOEFLS%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(1999)009%255B0751:MOEFLS%255D2.0.CO;2)
- 10 340. DeMelo R, France R, McQueen DJ. Biomanipulation: Hit or Myth? *Limnol Oceanogr*.  
11 1992;37(1):192–207.
- 12 341. Carpenter SR, Kitchell JF. Consumer Control of Lake Productivity. *BioScience*. 1988  
13 Dec;38(11):764–9. <https://doi.org/10.2307/1310785>
- 14 342. Dyer SD, White-Hull C, Carr GJ, Smith EP, Wang X. Bottom-up and top-down  
15 approaches to assess multiple stressors over large geographic areas. *Environ Toxicol*  
16 *Chem*. 2000 Apr 1;19(4):1066–75. <https://doi.org/10.1002/etc.5620190437>
- 17 343. Edmondson WT. Sixty Years of Lake Washington: a Curriculum Vitae. *Lake Reserv*  
18 *Manag*. 1994 Dec;10(2):75–84. <https://doi.org/10.1080/07438149409354178>
- 19 344. Nidzgorski DA, DeGasperi CL. Cities can grow without harming lakes: Lake  
20 Washington has become less eutrophic despite rapid population growth. *Ecosphere*.  
21 2025 Nov;16(11):e70456. <https://doi.org/10.1002/ecs2.70456>
- 22 345. Van Meter KJ, Van Cappellen P, Basu NB. Legacy nitrogen may prevent achievement of  
23 water quality goals in the Gulf of Mexico. *Science*. 2018 Apr 27;360(6387):427–30.  
24 <https://doi.org/10.1126/science.aar4462>
- 25 346. Basu NB, Van Meter KJ, Byrnes DK, Van Cappellen P, Brouwer R, Jacobsen BH, et al.  
26 Managing nitrogen legacies to accelerate water quality improvement. *Nat Geosci*.  
27 2022 Feb;15(2):97–105. <https://doi.org/10.1038/s41561-021-00889-9>
- 28 347. Anderson HS, Johengen TH, Godwin CM, Purcell H, Alsip PJ, Ruberg SA, et al.  
29 Continuous *In Situ* Nutrient Analyzers Pinpoint the Onset and Rate of Internal P  
30 Loading under Anoxia in Lake Erie’s Central Basin. *ACS EST Water*. 2021 Apr  
31 9;1(4):774–81. <https://doi.org/10.1021/acsestwater.0c00138>
- 32 348. McCrackin ML, Jones HP, Jones PC, Moreno-Mateos D. Recovery of lakes and coastal  
33 marine ecosystems from eutrophication: A global meta-analysis. *Limnol Oceanogr*.  
34 2017 Mar;62(2):507–18. <https://doi.org/10.1002/lno.10441>

- 1 349. Fleming PM, Merritts DJ, Walter RC. Legacy sediment erosion hot spots: A cost-  
2 effective approach for targeting water quality improvements. *J Soil Water Conserv.*  
3 2019 Jul;74(4):1. <https://doi.org/10.2489/jswc.74.4.67A>
- 4 350. Keisman J, Blomquist J, Bohlke JK, Davis-Martin J, Dennison W, Friedrichs C, et al.  
5 Integrating Recent Findings to Explain Water-Quality Change: Support for the Mid-  
6 Point Assessment and Beyond [Internet]. Edgewater, MD: STAC; 2018 [2026 Jan 25] p.  
7 27. (STAC). Report No.: 18–005. [https://www.chesapeake.org/stac/document-](https://www.chesapeake.org/stac/document-library/integrating-recent-findings-to-explain-water-quality-change-support-for-the-mid-point-assessment-and-beyond/)  
8 [library/integrating-recent-findings-to-explain-water-quality-change-support-for-the-](https://www.chesapeake.org/stac/document-library/integrating-recent-findings-to-explain-water-quality-change-support-for-the-mid-point-assessment-and-beyond/)  
9 [mid-point-assessment-and-beyond/](https://www.chesapeake.org/stac/document-library/integrating-recent-findings-to-explain-water-quality-change-support-for-the-mid-point-assessment-and-beyond/)
- 10 351. Walter RC, Merritts DJ. Natural Streams and the Legacy of Water-Powered Mills.  
11 *Science.* 2008 Jan 18;319(5861):299–304. <https://doi.org/10.1126/science.1151716>
- 12 352. Forshay KJ, Weitzman JN, Wilhelm JF, Hartranft J, Merritts DJ, Rahnis MA, et al.  
13 Unearthing a stream-wetland floodplain system: increased denitrification and nitrate  
14 retention at a legacy sediment removal restoration site, Big Spring Run, PA, USA.  
15 *Biogeochemistry.* 2022 Nov 1;161(2):171–91. [https://doi.org/10.1007/s10533-022-](https://doi.org/10.1007/s10533-022-00975-z)  
16 [00975-z](https://doi.org/10.1007/s10533-022-00975-z)
- 17 353. Merritts D, Walter R, Rahnis M, Hartranft J, Cox S, Gellis A, et al. Anthropocene  
18 streams and base-level controls from historic dams in the unglaciated mid-Atlantic  
19 region, USA. *Philos Transact A Math Phys Eng Sci.* 2011 Mar 13;369(1938):976–1009.  
20 <https://doi.org/10.1098/rsta.2010.0335>
- 21 354. Weitzman JN, Forshay KJ, Kaye JP, Mayer PM, Koval JC, Walter RC. Potential nitrogen  
22 and carbon processing in a landscape rich in milldam legacy sediments.  
23 *Biogeochemistry.* 2014 Aug;120(1–3):337–57. [https://doi.org/10.1007/s10533-014-](https://doi.org/10.1007/s10533-014-0003-1)  
24 [0003-1](https://doi.org/10.1007/s10533-014-0003-1)
- 25 355. Reisner M, Bates SF. Overtapped oasis: reform or revolution for western water.  
26 Washington, D.C: Island Press; 1990. 200 p.
- 27 356. Reisner M. Cadillac desert: the American West and its disappearing water. Rev. and  
28 updated. New York, N.Y., U.S.A: Penguin Books; 1993. 582 p.
- 29 357. Leopold LB, Maddox TJr. The flood control controversy: Big dams, little dams, and land  
30 management. 1954 [2026 Jan 13]; <https://pubs.usgs.gov/publication/70185465>
- 31 358. Hansen AT, Dolph CL, Foufoula-Georgiou E, Finlay JC. Contribution of wetlands to  
32 nitrate removal at the watershed scale. *Nat Geosci.* 2018 Feb;11(2):127–32.  
33 <https://doi.org/10.1038/s41561-017-0056-6>
- 34 359. Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. Floodplain rearing of  
35 juvenile chinook salmon: evidence of enhanced growth and survival. *Can J Fish Aquat*  
36 *Sci.* 2001 Feb 1;58(2):325–33. <https://doi.org/10.1139/f00-245>

- 1 360. Jeffres CA, Holmes EJ, Sommer TR, Katz JVE. Detrital food web contributes to aquatic  
2 ecosystem productivity and rapid salmon growth in a managed floodplain. Hovel RA,  
3 editor. PLOS ONE. 2020 Sep 18;15(9):e0216019.  
4 <https://doi.org/10.1371/journal.pone.0216019>
- 5 361. INDR Division of Fish and Wildlife. Did you Know? ...Healthy Wetlands Devour  
6 Mosquitoes. [Internet]. Indiana Department of Natural Resources; 2021 [2025 Nov 21].  
7 <https://www.in.gov/dnr/fish-and-wildlife/files/hlywet.pdf>
- 8 362. Russell MC, Herzog CM, Gajewski Z, Ramsay C, El Moustaid F, Evans MV, et al. Both  
9 consumptive and non-consumptive effects of predators impact mosquito populations  
10 and have implications for disease transmission. eLife. 2022 Jan 19;11:e71503.  
11 <https://doi.org/10.7554/eLife.71503>
- 12 363. Dworrak TV, Sauer FG, Kiel E. Wetland Conservation and Its Effects on Mosquito  
13 Populations. Wetlands. 2022 Oct;42(7):96. [https://doi.org/10.1007/s13157-022-](https://doi.org/10.1007/s13157-022-01613-y)  
14 [01613-y](https://doi.org/10.1007/s13157-022-01613-y)
- 15 364. Swenson RO, Whitener K, Eaton M. Restoring floods on floodplains: riparian and  
16 floodplain restoration at the Cosumnes River Preserve. In: Faber PM, editor. California  
17 riparian systems: processes and floodplain management, ecology, and restoration.  
18 Sacramento, CA, Mill Valley, CA: Riparian Habitat Joint Venture ; Pickleweed Press;  
19 2003. p. 224–9.
- 20 365. Sparks RE, Douglas Blodgett K, Casper AF, Hagy HM, Lemke MJ, Velho LFM, et al. Why  
21 experiment with success? Opportunities and risks in applying assessment and  
22 adaptive management to the Emiquon floodplain restoration project. Hydrobiologia.  
23 2017 Dec;804(1):177–200. <https://doi.org/10.1007/s10750-016-2785-8>
- 24 366. Sommer TR, Harrell WC, Nobriga ML, Brown R, Moyle PB, Kimmerer WJ, et al.  
25 California's Yolo Bypass: Evidence that flood control can be compatible with fisheries,  
26 wetlands, wildlife, and agriculture. Fisheries. 2001;26:6–16.
- 27 367. Normand A. Dam Removal: The Federal Role. Washington D.C.: Congressional  
28 Research Service; 2024. (Congressional Research Service Reports). Report No.:  
29 R46946.
- 30 368. Pess GR, McHenry ML, Denton K, Anderson JH, Liermann MC, Peters RJ, et al. Initial  
31 responses of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead  
32 (*Oncorhynchus mykiss*) to removal of two dams on the Elwha River, Washington State,  
33 U.S.A. Front Ecol Evol [Internet]. 2024 Jul 17 [2025 Dec 1];12.  
34 <https://doi.org/10.3389/fevo.2024.1241028>
- 35 369. Fraik AK, McMillan JR, Liermann M, Bennett T, McHenry ML, McKinney GJ, et al. The  
36 Impacts of Dam Construction and Removal on the Genetics of Recovering Steelhead

- 1 (Oncorhynchus mykiss) Populations across the Elwha River Watershed. Genes. 2021  
2 Jan;12(1):89. <https://doi.org/10.3390/genes12010089>
- 3 370. Brenkman SJ, Peters RJ, Tabor RA, Geffre JJ, Sutton KT. Rapid Recolonization and Life  
4 History Responses of Bull Trout Following Dam Removal in Washington's Elwha River.  
5 North Am J Fish Manag. 2019 Jun 1;39(3):560–73. <https://doi.org/10.1002/nafm.10291>
- 6 371. Liermann M, Pess G, McHenry M, McMillan J, Elofson M, Bennett T, et al. Relocation  
7 and Recolonization of Coho Salmon in Two Tributaries to the Elwha River: Implications  
8 for Management and Monitoring. Trans Am Fish Soc. 2017 Sep 1;146(5):955–66.  
9 <https://doi.org/10.1080/00028487.2017.1317664>
- 10 372. A River Reborn: One Year After Klamath River Dam Removal - Hydropower Reform  
11 Coalition [Internet]. 2025 [2026 Jan 13]. <https://hydroreform.org/2025/10/a-river-reborn-one-year-after-klamath-river-dam-removal/>
- 13 373. Whittum KA, Zydlewski JD, Coghlan SM, Hayes DB, Watson J, Kiraly I. Fish  
14 Assemblages in the Penobscot River: A Decade after Dam Removal. Mar Coast Fish.  
15 2023 Feb 1;15(1):e210227. <https://doi.org/10.1002/mcf2.10227>
- 16 374. Fisheries N. NOAA. 2025 [2026 Jan 11]. Barriers to Fish Migration | NOAA Fisheries.  
17 <https://www.fisheries.noaa.gov/insight/barriers-fish-migration>
- 18 375. An Open Penobscot | U.S. Fish & Wildlife Service [Internet]. 2023 [2026 Jan 11].  
19 <https://www.fws.gov/story/2023-05/open-penobscot>
- 20 376. Johnston C, Zydlewski GB, Smith S, Zydlewski J, Kinnison MT. River Reach Restored by  
21 Dam Removal Offers Suitable Spawning Habitat for Endangered Shortnose Sturgeon.  
22 Trans Am Fish Soc. 2019 Jan;148(1):163–75. <https://doi.org/10.1002/tafs.10126>
- 23 377. Richter BD, Mathews R, Harrison DL, Wigington R. ECOLOGICALLY SUSTAINABLE  
24 WATER MANAGEMENT: MANAGING RIVER FLOWS FOR ECOLOGICAL INTEGRITY. Ecol  
25 Appl. 2003 Feb;13(1):206–24. [https://doi.org/10.1890/1051-0761\(2003\)013%255B0206:ESWMMR%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(2003)013%255B0206:ESWMMR%255D2.0.CO;2)
- 27 378. Lytle DA, Merritt DM. Hydrologic Regimes and Riparian Forests: A Structured  
28 Population Model for Cottonwood. Ecology. 2004;85(9):2493–503.  
29 <https://doi.org/10.1890/04-0282>
- 30 379. Klotz JR, Swanson S. Managed instream flows for woody vegetation recruitment, a  
31 case study. In: Warwick JJ, American Water Resources Association, Universities  
32 Council on Water Resources, editors. Water resources education, training, and  
33 practice--opportunities for the next century: proceedings AWRA/UCOWR symposium:  
34 June 29-July 3, 1997, Keystone, Colorado. Herndon, VA: American Water Resources  
35 Association; 1997. p. 483–9. (American Water Resources Association technical  
36 publication series).

- 1 380. Clark GM, Goolsby DA. Occurrence and load of selected herbicides and metabolites  
2 in the lower Mississippi River. *Sci Total Environ.* 2000 Apr;248(2–3):101–13.  
3 [https://doi.org/10.1016/S0048-9697\(99\)00534-3](https://doi.org/10.1016/S0048-9697(99)00534-3)
- 4 381. Goolsby DA, Pereira WE. Contaminants in the Mississippi River [Internet]. Reston, VA:  
5 U.S. Geological Survey; 1995 [2026 Jan 25]. Report No.: C1133.  
6 <https://pubs.usgs.gov/circ/circ1133/pesticides.html>
- 7 382. Kolpin D. Importance of the Mississippi River Basin for investigating agricultural–  
8 chemical contamination of the hydrologic cycle. *Sci Total Environ.* 2000 Apr;248(2–  
9 3):71–2. [https://doi.org/10.1016/S0048-9697\(99\)00530-6](https://doi.org/10.1016/S0048-9697(99)00530-6)
- 10 383. Hansen GJA. Novel thermal habitat in lakes. *Nat Clim Change.* 2021 Jun;11(6):470–1.  
11 <https://doi.org/10.1038/s41558-021-01067-w>
- 12 384. Cheng FY, Van Meter KJ, Byrnes DK, Basu NB. Maximizing US nitrate removal through  
13 wetland protection and restoration. *Nature.* 2020 Dec;588(7839):625–30.  
14 <https://doi.org/10.1038/s41586-020-03042-5>
- 15 385. Delaney RL, Craig MR. Upper Midwest Environmental Sciences Center. 1997.  
16 Longitudinal Changes in Mississippi River Floodplain Structure.  
17 [https://www.umesc.usgs.gov/reports\\_publications/psrs/psr\\_1997\\_02.html](https://www.umesc.usgs.gov/reports_publications/psrs/psr_1997_02.html)
- 18 386. Schneider DW. Enclosing the Floodplain: Resource Conflict on the Illinois River, 1880–  
19 1920. *Environ Hist.* 1996 Apr 1;1(2):70–96. <https://doi.org/10.2307/3985113>
- 20 387. Marks JC, Parnell R, Carter C, Dinger EC, Haden GA. Interactions between  
21 geomorphology and ecosystem processes in travertine streams: Implications for  
22 decommissioning a dam on Fossil Creek, Arizona. *Geomorphology.* 2006 Jul  
23 30;77(3):299–307. <https://doi.org/10.1016/j.geomorph.2006.01.008>
- 24 388. Lodge DM, Williams S, MacIsaac HJ, Hayes KR, Leung B, Reichard S, et al.  
25 BIOLOGICAL INVASIONS: RECOMMENDATIONS FOR U.S. POLICY AND  
26 MANAGEMENT. *Ecol Appl.* 2006 Dec;16(6):2035–54. [https://doi.org/10.1890/1051-  
27 0761\(2006\)016%255B2035:BIRFUP%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(2006)016%255B2035:BIRFUP%255D2.0.CO;2)
- 28 389. Glassic HC, Chagaris DD, Guy CS, Tronstad LM, Lujan DR, Briggs MA, et al.  
29 Yellowstone Cutthroat Trout Recovery in Yellowstone Lake: Complex Interactions  
30 Among Invasive Species Suppression, Disease, and Climate Change. *Fisheries.* 2024  
31 Feb 1;49(2):55–70. <https://doi.org/10.1002/fsh.10998>
- 32 390. Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, et al.  
33 Synthesizing U.S. River Restoration Efforts. *Science.* 2005 Apr 29;308(5722):636–7.  
34 <https://doi.org/10.1126/science.1109769>

- 1 391. Wilson RS, Hardisty DJ, Epanchin-Niell RS, Runge MC, Cottingham KL, Urban DL, et al.  
2 A typology of time-scale mismatches and behavioral interventions to diagnose and  
3 solve conservation problems. *Conserv Biol.* 2016 Feb;30(1):42–9.  
4 <https://doi.org/10.1111/cobi.12632>
- 5 392. Stets E. U.S. Geological Survey Integrated Water Availability Assessment—2010–20  
6 [Internet]. USGS; 2025 [2025 Nov 15]. Report No.: U.S. Geological Survey Professional  
7 Paper 1894, [variously paged], <https://doi.org/10.3133/pp1894>.  
8 <https://pubs.usgs.gov/publication/pp1894>
- 9 393. Nahlik AM, Paulsen SG, Dumelle M, Holdsworth S, Lehmann S, Tolve NS, et al.  
10 National Aquatic Resource Surveys (NARS): the foundation for long-term aquatic  
11 monitoring data across the United States. *Environ Monit Assess.* 2025 Nov  
12 3;197(12):1291. <https://doi.org/10.1007/s10661-025-14629-8>
- 13 394. Likens GE, Butler TJ, Claybrooke R, Vermeylen F, Larson R. Long-term monitoring of  
14 precipitation chemistry in the U.S.: Insights into changes and condition. *Atmos  
15 Environ.* 2021 Jan 15;245:118031. <https://doi.org/10.1016/j.atmosenv.2020.118031>
- 16 395. Baldigo BP, George SD, Lawrence GB. Fish-assemblage and water-quality recovery  
17 with declining acidic deposition in Adirondack mountain streams, New York, USA.  
18 *Freshw Sci.* 2025 Dec 1;44(4):443–62. <https://doi.org/10.1086/738871>
- 19 396. Allaire M, Wu H, Lall U. National trends in drinking water quality violations. *Proc Natl  
20 Acad Sci.* 2018 Feb 27;115(9):2078–83. <https://doi.org/10.1073/pnas.1719805115>
- 21 397. Smith RA, Alexander RB, Wolman MG. Water-Quality Trends in the Nation’s Rivers.  
22 *Science.* 1987 Mar 27;235(4796):1607–15.  
23 <https://doi.org/10.1126/science.235.4796.1607>
- 24 398. Adler JH. Fables of the Cuyahoga: Reconstructing a History of Environmental  
25 Protection. *SSRN Electron J [Internet]*. 2002 [2026 Jan 11];  
26 <https://doi.org/10.2139/ssrn.333140>
- 27 399. Lehmann CMB, Bowersox VC, Larson SM. Spatial and temporal trends of precipitation  
28 chemistry in the United States, 1985–2002. *Environ Pollut.* 2005 Jun;135(3):347–61.  
29 <https://doi.org/10.1016/j.envpol.2004.11.016>
- 30 400. Jarvie HP, Johnson LT, Sharpley AN, Smith DR, Baker DB, Bruulsema TW, et al.  
31 Increased Soluble Phosphorus Loads to Lake Erie: Unintended Consequences of  
32 Conservation Practices? *J Environ Qual.* 2017 Jan;46(1):123–32.  
33 <https://doi.org/10.2134/jeq2016.07.0248>
- 34 401. Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, et al. Standards  
35 for ecologically successful river restoration. *J Appl Ecol.* 2005 Apr;42(2):208–17.  
36 <https://doi.org/10.1111/j.1365-2664.2005.01004.x>

- 1 402. Bartholomew JL, Alexander JD, Alvarez J, Atkinson SD, Belchik M, Bjork SJ, et al.  
2 Deconstructing dams and disease: predictions for salmon disease risk following  
3 Klamath River dam removals. *Front Ecol Evol.* 2023 Oct 27;11:1245967.  
4 <https://doi.org/10.3389/fevo.2023.1245967>
- 5 403. Diver S, Oberholzer Dent JR, Sarna-Wojcicki D, Reed R, Dill-De Sa C. Recasting  
6 Klamath Dam Removal as Eco-Cultural Revitalization and Restorative Justice through  
7 Karuk Tribal Leadership. *Water.* 2024 Aug 14;16(16):2295.  
8 <https://doi.org/10.3390/w16162295>
- 9 404. Benefits flow quickly as historic dam removal restores Klamath River [Internet]. [2026  
10 Jan 12]. [https://www.asce.org/publications-and-news/civil-engineering-  
11 source/article/2025/02/13/benefits-flow-as-historic-dam-removal-restores-klamath-  
12 river](https://www.asce.org/publications-and-news/civil-engineering-source/article/2025/02/13/benefits-flow-as-historic-dam-removal-restores-klamath-river)
- 13 405. McCully P. *Silenced rivers: the ecology and politics of large dams.* Enlarged&updated  
14 ed. London ; New York: Zed Books; 2001. 359 p.
- 15 406. Boelens R, Vos J. Legal pluralism, hydraulic property creation and sustainability: the  
16 materialized nature of water rights in user-managed systems. *Curr Opin Environ  
17 Sustain.* 2014 Dec 1;11:55–62. <https://doi.org/10.1016/j.cosust.2014.10.001>
- 18 407. Apoliona-Brown P. Hāloa: The long breath of Hawaiian sovereignty, water rights, and  
19 Indigenous law. *J Agric Food Syst Community Dev.* 2025;29–58.  
20 <https://doi.org/10.5304/jafscd.2024.141.021>
- 21 408. Liddie JM, Schaidler LA, Sunderland EM. Sociodemographic Factors Are Associated  
22 with the Abundance of PFAS Sources and Detection in U.S. Community Water  
23 Systems. *Environ Sci Technol.* 2023 May 30;57(21):7902–12.  
24 <https://doi.org/10.1021/acs.est.2c07255>
- 25 409. Cozzetto K, Chief K, Dittmer K, Brubaker M, Gough R, Souza K, et al. Climate change  
26 impacts on the water resources of American Indians and Alaska Natives in the U.S. In  
27 Springer; 2013. DOI: [org/10.1007/978-3-319-05266-3\\_6](https://doi.org/10.1007/978-3-319-05266-3_6)
- 28 410. Bowden WB, Gooseff MN, Balsler A, Green A, Peterson BJ, Bradford J. Sediment and  
29 nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska:  
30 Potential impacts on headwater stream ecosystems. *J Geophys Res Biogeosciences*  
31 [Internet]. 2008 [2026 Jan 12];113(G2). <https://doi.org/10.1029/2007JG000470>
- 32 411. Power ME. Synthetic threads through the web of life. *Proc Natl Acad Sci.* 2021  
33 Jun;118(22):e2004833118. <https://doi.org/10.1073/pnas.2004833118>
- 34