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ENVIRONMENTAL EFFECTS OF EXTREME FLOODS

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Abstract. Analyzing short- and long-term environmental effects of extreme flood events is a young science. Complicated by the obvious difficulties associated with predicting extreme events and the hazards of gathering environmental data during and in the aftermath of these often short-lived and violent events, the accumulation of good field data remains an obstacle to a better understanding of quantitative effects. This article focuses on both the known quantitative relationships and the qualitative aspects of several important natural populations, namely, macroinvertebrate communities, fish assemblages, and river corridor vegetation. Further, the roles of geomorphic change, structural flood control, and anthropogenic influence in natural environments during flooding events are discussed. Present flood management policies have severe and far-reaching impacts on natural systems. Nonstructural flood control measures, including wetland restoration, offer an environmentally sound and feasible alternative to excessive constriction of our rivers with extensive levee systems.

1. INTRODUCTION

The environmental impacts of extreme flooding are complex, interesting, and largely unused in policy making. In recent times, the focus of water management has changed from the need to dominate and control water resources to a more harmonious philosophy that seeks a balance between the structural flow control required to support and protect growing populations and environmental well-being (Myers and White, 1993; Gardiner, 1994; Gardiner, 1995; Nachtnebel, 1995; Leentvaar and Stortelder, 1995). In terms of engineering and political action, status quo policy, the need for constant flood control, and an incomplete understanding of environmental flood dynamics hinder the embracing of this philosophical change.

Recent extreme flooding in the United States, Mississippi River basin, 1993, Flint River basin, 1994, Sacramento and San Joaquin River Basins, 1997, and the Red River basin, 1997, has demonstrated the limitations of current flood protection measures and heightened interest in nonstructural flood control. As memories of flood devastation fade behind the rebuilt walls of protective levees, so goes interest in pursuing new policy embracing environmentally sound, nonstructural control measures. Extreme floods not only present an opportunity to further research natural dynamics, but to institute new policy based on previous research.

From an engineering perspective, if flood management policies address general environmental issues, natural system enhancements are likely to occur as vague, secondary benefits created through the use of different flood control practices. Environmental concerns remain an afterthought and the full potential of integrating natural systems and flood control is not achieved. On the other hand, if specific natural aspects are addressed in policy plans, focus is likely to be placed on protecting fish populations, endangered species, or riparian vegetation, all of which have a more visible worth to recreational and aesthetic demands of society. This is too narrow a viewpoint. If increased understanding of natural system flood dynamics has elucidated any single point, it is that impacts on an individual aspect of a natural system are not independent of effects experienced by other natural features. Effective flood control and environmental health are not mutually exclusive. In fact, healthy ecosystems provide natural forms of flood control precluded by the use of structural flood control measures like levees.

Opportunities to protect and enhance natural systems through policy are valuable and often fleeting. To assure that environmental concerns are properly and judiciously represented in flood management decisions, individual cases must be assessed from a basin-wide perspective. These holistic approaches ensure that critical features of natural systems, including hydrologic characteristics, key species, and strategic land areas, are identified during investigative phases of decision-making processes. After this is accomplished, the results of previous studies may be responsibly applied to new situations.

Each system is unique and generalizations regarding population responses to extreme events do not translate well between ecotypes. To provide some distinction, this paper focuses on extreme floods in two types of river systems: High-gradient rivers and large low-gradient rivers. Both types can occur in a wide variety of climates, especially the large low-gradient systems that often pass through several ecotypes along their course. The Nile River is an excellent example of this as it courses through both humid lake regions and arid desert. The principle distinction between these two types is the environmental complexity of the natural flood plains.

High-gradient systems are typically of lower stream order than the large low-gradient rivers. Comparatively, the river corridor (i.e., the stream channel and connected terrestrial areas) is smaller and more discrete in high-gradient systems. This leads to shorter periods of inundation and relatively simple natural flood plain dynamics. Flooding is usually caused by intense rain and rain on snow events. At high elevations or latitudes, hydrographs are likely to display a distinct snow pack runoff peak in late spring and early summer. Prevalent substrate tends to be coarser than that in large low-gradient rivers.

Large low-gradient rivers have comparatively complex floodplain interactions. In an unaltered natural state, the hydrologic complexity of these systems is astounding. Since these large systems have potential as transportation arteries and water sources, the hydrologic workings of most of these systems have been drastically altered in developed countries. This is true in the United States of America, where the present Mississippi River basin bears little resemblance to W. H. Keating’s 1823 description of a:

> “*low, flat and swampy prairie, very thickly covered with high grass, aquatic plants, and among others, the wild rice...The whole of this place is overflowed in the spring, and canoes pass in every direction across the prairie*.” (Wooten and Jones, 1955, as in Hey and Philippi, 1995)

Or to Meriwether Lewis’ journal entry for June 21st, 1804, which described a stretch of the lower Missouri River, roughly paraphrased by the authors, as follows:

> *The country and lands on each side of the river are various…and may be classified as follows: The low overflown points or bottom land, on which grow Cotton and Willow (trees). There is a second or high bottom of rich fertile soil, on which grow Cotton, Walnut, some Ash, Hackberry, Mulberry, Linden, and Sycamore. The third or high lands rise gradually from the second bottom. …small rivers roll back and lose themselves in the land… As for the prairies, which I am informed lie back from the river, at some places near and others a great distance.* (Bergon, (ed.), 1989)

Flooding in large low-gradient rivers is typically caused by extended periods of excess rainfall, often related to powerful tropical storms and hurricanes. Floods peak slowly and levels tend to remain above flood stage for extended periods of time, as compared to the often flashy extreme floods in high-gradient river systems. Tropical rivers share characteristics with both river classifications. In tropical and large low gradient systems, rainfall is the dominant impetus for flooding and complex floodplain interactions are typical for both types of rivers. However, tropical systems are more prone to flash flooding events and spatially diverse channel gradients. In fact, in high-gradient tropical rivers and steeply sloped drainage basins, natural responses to flooding events may be more akin to the river dynamics of the high-gradient classification. Realistically, both the high-gradient and the large low-gradient categories deserve further subdivision.

2. DYNAMICS OF NATURAL POPULATIONS IN EXTREME FLOODS

Extreme events that are destructive for humans are often a blessing for natural populations. Floods are a necessary element in the natural cycle. Periodic flooding has been shown to stimulate increased aquatic production in macroinvertebrates and result in strong reproductive year classes for fish species that use floodplain habitat for forage or spawning (Maher, 1994). Extreme events provide strong natural disturbances capable of essentially resetting aquatic and floodplain communities (Elwood and Waters, 1969; Friedman et al., 1996). Watersheds that experience frequent flooding tend to be inhabited and dominated by flood tolerant or mobile species (Poff and Ward, 1989) and early succession stages of vegetation (Yanosky, 1982; Waring and Stevens, 1987).

In terms of biological and ecological stability and integrity, some key natural populations are macroinvertebrates, fishes, and riparian vegetation. Geomorphic effects of extreme events impact all of these populations; riparian vegetation is often the most visibly affected population with respect to geomorphic changes. Table 1 details several studies that have investigated quantitative impacts on insects, fishes, and plant communities. The following sections discuss common impacts experienced by each of these biotic communities for high-gradient and large low-gradient rivers.

2.1 MACROINVERTEBRATES

Macroinvertebrates are an integral, but oft-overlooked component of lotic ecosystems. Benthic macroinvertebrates, or substrate dwellers, are roughly divided into three categories: shredders, grazers, and predators. Nektonic invertebrates are free swimming or surface dwelling insects. The greatest concentrations of these organisms are typically found at the aquatic terrestrial interface. Macroinvertebrates fulfill a key role in the primary steps of the food chain. By consuming aquatic plants and detritus (plant debris), macroinvertebrates provide a link between primary production and secondary production and a forage base for invertebrate and vertebrate predators, including birds, fishes, amphibians, reptiles, and mammals. Many of these invertebrates are the larval stage of common flying insects, thereby linking aquatic and terrestrial ecosystems.

Characteristic disturbances created by extreme events such as floods and droughts control the densities and composition of macroinvertebrates (Resh et al., 1988; Poff and Ward, 1989). In systems with modified hydrologic flow regimes, communities are often greatly altered and inherently unstable, as controlling variables are not predetermined by local natural conditions (Morgan et al., 1991). This allows exotic and poorly adapted species to become dominant taxa in systems with naturally inhospitable conditions. Though these systems may not suffer losses in biomass production, extreme flooding initiates a return to natural conditions, exposes the unstable population structure, and is likely to deplete macroinvertebrate biomass more severely than if affecting a natural population.

In high-gradient systems, extreme flooding events tend to act as cleansing mechanisms for invertebrate populations and physical habitat. Populations of macroinvertebrates are severely depressed after extreme flooding, but typically recover very quickly (Elwood and Waters, 1969; Hilsenhoff, 1996). Hilsenhoff (1996) found that the recovery is led by species who are most favored by changes in aquatic habitat created by geomorphic processes acting during extreme events. In this study, high flows flushed out much of the fine sediment and decaying material in the stream. This created a shortage of habitat and food for some species and an increase in habitat for species that prefer clean substrate. As a whole, the diversity of macroinvertebrates declined and total numbers rebounded to pre-flood levels after an initial period of population depression. However, the numbers and diversity of Ephemeroptera (mayflies) and Plecoptera (stoneflies) increased after the flood, including a 25 percent increase in the number of species represented in these genera. Both mayflies and stoneflies prefer the clean substrate habitat and increased dissolved oxygen levels created by the geomorphic system cleaning.

Populations of macroinvertebrates in large low-gradient rivers generally experience an increase in population during flooding events. The expanding water surface initiates an influx of food while increasing the amount of habitat available to these creatures (Allen, 1993). Theiling et al. (1994) found that the densities of invertebrates near the expanding shoreline more than doubled those in permanent aquatic habitats despite the significant increase in total available habitat on the Illinois River during the 1993 Mississippi River basin flood. Heightened invertebrate production cycles through the food chain and results in increased numbers of higher predators, including fish.

Large low-gradient ecosystems are not unique in providing dynamic responses to excess quantities of water. The latest El Niño event has spawned precipitation totals that greatly exceed normal rates in the southwestern United States. Desert vegetation responded to the bountiful water with record growth and has provided a substantial food base for invertebrates. A recent article by the Associated Press (1998) described hordes of locusts crippling communities along the Colorado River in northern Arizona. The biblical swarms, drawn by the lights of civilization, were so numerous that insects killed by passing cars created a traffic hazard by slicking the roads with their carcasses.

2.2 FISHES

The natural diversity of fish species complicates the impacts of extreme flooding on riverine fish assemblages. Certain fish species benefit from, and actually depend upon, seasonal or periodic extreme flooding. Seasonal flooding coordinates natural systems by providing environmental cues for spawning and migration processes (Leitman et al., 1991; John, 1963, as in Poff and Ward, 1989). Effects of extreme events on fish assemblage are separable according to fish species, life stage, and recovery period.

Fish of different species and life stages display unique sets of characteristics including abiotic tolerances, habitat preferences, feeding and spawning habits, physical appearance, and physical capabilities. Individual features allow certain species of fish, particularly those that are adapted to a wide range of conditions, to better cope with flood conditions. Also, native fish that are naturally adapted to characteristic system extremes tend to fare better than exotic species during floods (Adler, 1996).

Numerous studies have concluded that juvenile life stages are particularly susceptible to heavy losses during extreme floods in high-gradient systems (Elwood and Waters, 1969; Hoopes, 1975; Jowett and Richardson, 1989). Large numbers of young fish are even lost during average seasonal flooding in systems where the timing of high flows coincides with fragile life stages (Nehring and Miller, 1987).

The impacts on adult populations in these rivers are closely tied to the extent of geomorphic change associated with the powerful flows (see Figure 1). Elwood and Waters (1969) reported no immediate changes in an adult brook trout population despite intense channel alterations created by a series of four extreme floods, including the uprooting of large trees, destruction of small dams, elimination of all aquatic vegetation, and complete scouring of the bed. However, less than two years after the first flood, the standing crop of brook trout had been reduced by over 90 percent and showed no signs of recovery. This severe population drop was attributed to an immediate reduction in food availability, due to depressed invertebrate populations, and the destruction of suitable aquatic habitat. Jowett and Richardson (1989) noted net declines in populations of large brown trout in New Zealand Rivers after severe flooding. However, further losses of these fish were not expected as the flood scoured and deepened the pool habitat, thereby improving prime adult trout habitat through geomorphic change.

The timing and duration of the extreme event and the environmental state of the natural system determine fish population responses in large low-gradient rivers. These systems naturally have complex channel floodplain interactions. Flooding generally creates a production boom by increasing the diversity and amount of aquatic habitat available to fishes (see Figure 2) and intensifying the natural processes of the food web.

Figure 1. In high-gradient river systems, the intensity and character of geomorphic change determine the recovery period of aquatic systems. Extreme geomorphic changes, as shown in this picture of the 1976 Big Thompson River flood aftermath, have lasting impacts on riparian vegetation and fish populations. Photo from the Fort Collins Coloradoan photo library.

The influx of terrestrial nutrients and food sources at the advancing shoreline supports rapidly growing populations of zooplankton and macroinvertebrates. Higher predators feast on these creatures, spreading the increased production throughout the food chain (Junk et al., 1989; Allen, 1993). Many species of fish actually depend on floodplain areas for spawning habitat, flood protection, and forage. Maher (1994) determined that floodplains supported a high number and diversity of fishes and that several species had extremely successful spawning years in the Illinois River during the 1993 Mississippi River basin flood. Leitman et al. (1991) found that 75 percent of the main channel species utilized floodplain habitat and 17 percent of the total fish diversity consisted of species dependent primarily or entirely on floodplain and backwater habitat in the Ochlockonee River, Florida, USA. The increase in production is so evident that Bayley (1991) coined the term “flood pulse advantage” to describe the increase in fish yield per unit mean water area during natural flood pulses. More often than not, flooding has a positive effect on fisheries in large low-gradient rivers. This is a major contrast with documented short and long-term fish population declines in high-gradient systems after extreme events. Another example of contrasting dynamics involves benthic species, fishes that reside primarily in the substrate of the riverbed. In high-gradient systems, these fish suffer extremely high mortality as the bed shifts (Erman et al., 1988, as in Pearsons et al., 1992). In large low-gradient rivers, benthic fish may actually be more likely to survive floods due to a higher tolerance for suspended sediment (Whitfield and Paterson, 1995).

Figure 2. In large low-gradient river systems, extreme floods typically submerge vast areas of land. This creates new fish habitat and an abundance of food for invertebrates. Production throughout the aquatic food web tends to increase. Vegetation is damaged, often mortally, during long periods of inundation. Photo shows the Mississippi River reclaiming part of its natural floodplain during the flood of 1993. Photo by Scott Dine, St. Louis Post-Dispatch.

In both types of systems, direct impacts on fish are inseparable from habitat changes and fluctuations in other parts of the food chain. In high-gradient systems, recovery periods and long-term effects of flooding on fish populations are closely tied to geomorphic changes in aquatic habitat. In cases where key habitat is lost and must be repaired by future geomorphic processes, population levels may be depressed for decades. Flooding benefits in large low-gradient rivers depend on the natural, proportional relationship between flow and the amount of suitable fish habitat. All relations are jeopardized if the natural state of the river is altered to separate the natural floodplain from the river channel.

2.3 VEGETATION AND GEOMORPHIC EFFECTS

Vegetation plays several diverse roles during extreme events. Vegetation usually mollifies damage by dissipating energy of the flow, and by stabilizing banks and steep slopes against the erosive forces of overland flow (Shroba et al., 1979). In the most extreme events, like the Big Thompson River flood of 1976, vegetation cannot withstand the power of the floodwaters and is broken or uprooted. Ironically, the same vegetation instrumental in weakening the flood then becomes destructive debris capable of inflicting more damage to inundated structures than the floodwater itself (Soule, 1979).

Geomorphologic effects of extreme events are closely tied to vegetation dynamics in a number of ways. Through geomorphic change, extreme events reset the successional state of plant communities. In high-gradient systems, many shade intolerant tree species rely on geomorphic processes to open canopy space and clear moist areas of land to serve as seedling establishment sites (Friedman et al., 1996; Scott et al., 1997). Scott et al. (1997) found that 72 percent of cottonwood tree establishment occurred within two years after a flooding event that exceeded a 9.3-year return period (refer to table 1). Friedman et al. (1996) cited post-flood channel narrowing as the dominant influence on vegetation patterns in an eastern Colorado stream.

In large low-gradient systems, plant survival is largely a function of the species of inundated plant life, the duration and amplitude of flooding, and the size of affected individuals (Yin et al., 1994). Trees that are native to bottomland areas are typically adapted to periodic flooding and fare quite well during extreme events. Exotic ornamental varieties, established for aesthetic benefits, suffer severe mortality (Allen, 1993). However, during extended periods of flooding, even native trees that appear to survive nicely (Dieffenbach, 1993) sustain damage severe enough to prove lethal in future growing seasons (Yin et al., 1994).

Harvesting and clearing of floodplain forests reduces the energy dissipation capacity of the vegetation (Jacobsen and Oberg, 1993) and increases the erosivity of the riverbanks and floodplain lands. The drainage of wetland and floodplain areas compounds the problem by speeding the conveyance of floodwaters to the main channel and increasing flood stages. Recognition of the protective value of vegetation during floods is shown by the construction of tree screens, protective measures designed to stabilize stream banks and buffer the impacts of flooding (McGuire, 1989), and the public call for wetlands restoration.

Wetland areas play positive roles in biotic and abiotic responses to flooding. Flooding in wetlands generally spurs an increase in biological production throughout the food chain (Bayley 1991). Abiotically, wetlands improve water quality by intercepting sediment and using nutrient rich overland runoff in vegetative growth (Gilliam, 1994; Hey et al., 1994; Haertel et al., 1995). These areas also act as floodwater retention devices, slowing flows and lowering flood peaks (Demissie and Khan, 1993, as in Faber, 1993).

Wetlands and forested floodplains are important components in ecological processes. Throughout history these areas have been targeted for transition to agricultural and urban lands (Hey and Philippi, 1995). The potential protective and biological values of these areas are now recognized, but large-scale wetland restoration remains rare. Given the chance, land returned to the river is capable of restoring itself to environmental health with great speed (Edwards, 1997).

3. EFFECTS OF FLOOD CONTROL STRUCTURES

Human nature pushes mankind to confront and attack natural challenges. There is a greater, but often unwarranted, confidence associated with constructing an impressive, visible defense. As man constructs flood control levees and develops settlements in the natural flood plain, a dangerous and often unwinnable game of hydrologic roulette begins.

Structural flood controls, as is typical of engineering projects, maintain a specified degree of protection. Once operational conditions exceed this limit, the constructed protection is not designed to withstand the onslaught of floodwaters. It is a probabilistic reality that the level of protection will eventually be exceeded. At this point, cities that have developed dangerously close to rivers under the limited security of structural flood control are jeopardized and extreme economic losses are experienced. Immediately after the event, the affected towns and cities are forced to rethink the flood control that just proved to be insufficient. Local, state, and federal governments are confronted with a difficult choice to either relocate communities to lower risk areas or reestablish the false sense of security by strengthening the flood control. As flood protection is required as soon as possible, the usual solution is to repair existing structures and resume the game. This dilemma is just one aspect of the struggle to find a balance between development and nature, the people's right versus the river's legacy.

Organized structural efforts to control floods began in the United States in the early 1800's. In 1861, the United States adopted a flood control policy dominated by levee use for flood protection (Myers and White, 1993). Prior to this date, settlers were actively using levees to protect individual dwellings and agricultural land. The "levee only" period ended with the Flood Control Act of 1928, which called for additional and diversified structural control measures. In this case, the impetus for change was a powerful, destructive flood in the lower Mississippi basin, which displaced over 700,000 people and claimed more than 200 lives (Myers and White, 1993; Hey and Philippi, 1995).

Unfortunately, the relationship between disaster and progressive policy continues today. Recent extreme flooding events in the United States, particularly the 1993 flood in the Mississippi and Missouri River basins, have raised questions regarding the dependence of affected communities on structural flood control measures. Extensive levee and reservoir systems performed extremely well during the flood, but still proved to be inadequate. Though 1,082 levees broke (Jacobsen and Oberg, 1993), only one federally constructed and maintained levee, designed for a 100-year return period, failed (U.S. Army Corps of Engineers, 1994). Flows and stages that exceeded design specifications destroyed all others, especially state and locally maintained levees with lower frequency classifications.

Environmental effects of flow control structures are overshadowed by the need for protection. Structural flood controls, especially levee systems and flood control reservoirs, deprive river systems of natural disturbance and stimulation. Environmental effects of utmost importance include separation of main channel and natural floodplain, dessication and destruction of wetland areas, alteration of the hydrologic regime, depression of geomorphic influence of floods, and masking of natural cues.

The separation of channel and floodplain is directly related to the alteration of the hydrologic regime and the loss of wetland areas that naturally border river systems. Certain aquatic species depend primarily or exclusively on floodplain habitat (Leitman et al., 1991). Others rely on flooded areas as spawning and foraging grounds (Copp and Penaz, 1988). Wetlands are dynamic centers of biologic activity. Seasonally inundated wetlands are exceptionally productive land areas (Neckles et al., 1990; Theiling et al., 1994). Separation of channel and floodplain is an unnatural state that destroys key aquatic habitat and depresses the productive potential of aquatic systems.

Levees often bound the river at its banks. Without the natural room to expand, stream power, stage, and water velocity increase artificially until the levees succumb and floodwaters violently reclaim their natural territories (see Figure 3) (Belt, 1973). Agricultural crops and concrete have replaced wetlands and forested floodplains that were originally capable of storing massive amounts of floodwater and decreasing flood peaks (Allen, 1993; Faber, 1993). This reduces the time it takes for precipitation to concentrate in the river channels. All of these factors alter hydrologic processes and lead to more powerful and rapid flood peaking. Belt (1973) points out that man caused the devastating flood of 1973 by overly constricting the

Mississippi River. His hydrologic analysis of the event revealed that a 30-year flow created a record stage, surpassing the previous record with only 64 percent of that event's flow.

Flood control reservoirs alleviate potentially damaging flows by providing storage space for excess runoff. An obvious environmental effect of reservoirs is the change of long river reaches from lotic (moving water) to lentic (still water) ecosystems. This may seem like an acceptable tradeoff, but in flood control reservoirs water levels often fluctuate significantly in preparation to accept and route floodwaters. This disrupts the spawning habitat of several lentic species and creates areas of desolation in the fluctuation zone.

By altering the hydrologic nature of extreme events, reservoirs mask natural cues and depress downstream channel alterations. Fish populations depend upon heavy river flows to provide cues to initiate migration and spawning activities (John, 1963, as in Poff and Ward, 1989; Leitman et al., 1991). Downstream biotic communities change as certain species are favored by the unnatural flow and temperature regimes (Morgan et al., 1991; Webb and Walling, 1997). By intercepting the sediment load carried by upstream floodwaters, reservoirs deprive downstream stretches of bed material required to construct and maintain backwater areas and sand and gravel bars, which are essential spawning and rearing habitat for fishes (Adler, 1996). All told, reservoirs offer a fraction of the storage of natural wetlands and floodplains without providing any of the natural benefits.

Figure 3. "Without levees, even a great flood…meant only a gradual and gentle rising and spreading of water. But if a levee towering as high as a four-story building gave way, the river could explode upon the land with the power and suddenness of a dam bursting (Barry, 1997)." Photo shows one of the 1,082 levee breaks during the Mississippi River flood of 1993. Photo by Jim Rackwitz, St. Louis Post-Dispatch.

Structural flood control is a deterrent to the health of natural systems, but remains a valuable tool in flood management. Flood control reservoirs stored a total of 18,700,000 acre-feet of floodwater during the 1993 Mississippi River basin flood. Seventy percent of this volume was stored in the month of July. This reduced the average daily peak flow by 211,000 cfs at St. Louis for the entire month (Perry, 1993). In the Kansas River, during the same 1993 flooding event, reservoirs were directly responsible for 30 to 70 percent reductions in flood discharges (Perry, 1993) in river stretches where flows still exceeded 100-year flood levels (Southard, 1993).

The U.S. Army Corps of Engineers (1994) estimates that structural flood control has reduced flood damages by 170 billion dollars between 1983 and 1993. The total historic expenditure by the United States on flood control is only 25 to 30 billion dollars. This indicates that the flood control system pays for itself every 18 months (U.S. Army Corps of Engineers, 1994). However, the extensive use of levees and reservoirs increases the frequency of extreme flooding. This creates an interesting dilemma for policy makers.

Hey and Philippi (1995) outlined a basic plan involving the purchase of 13.3 million acres of agricultural lands, which were historical in the floodplain, for the construction of large wetlands areas capable of providing adequate flood control for the 100-year event. While the social challenges of such a plan are likely to be insurmountable, the plan does introduce an environmentally sound alternative to traditional flood control measures. The challenge facing policy makers centers on finding a balance between structural and non-structural controls.

4. ANTHROPOGENIC CONTRIBUTIONS TO ENVIRONMENTAL EFFECTS

In the New World, man's influence on the natural dynamics of flooding began in earnest shortly after the pilgrim's landing at Plymouth Rock. Settlers immediately began to alter the landscape of their surroundings. Forests and native vegetation were cleared to make way for agricultural fields. Trappers were one of the single most influential groups of pioneers. Beaver populations, which had constructed and maintained millions of dams, were harvested en masse for their pelts (Hey and Philippi, 1995). Empty dams were cleared to facilitate navigation and lower surrounding water levels, thereby removing a powerful hydraulic control and huge reservoir system. To compound the problem, land that was naturally inundated was cleared for farming, further elevating conveyance rates. Structural flood control was used to protect newly claimed lands and as a response to the artificially strengthened floods.

Today, anthropogenic influences are recognized to extend beyond the realm of flood control structures. In many instances, man creates hazards that rival the most dangerous and bizarre of natural flood conditions. Often man's influences on natural systems are long-term and go unrecognized until conditions gradually deteriorate to critical levels. Examples of this include the transport of chemicals in floodwaters, creation or aggravation of extreme events, and dangers associated with social works that are not related to aquatic systems.

Water quality is of key importance to man and nature. Flooding tends to reduce water quality by introducing large amounts of eroded materials. By transforming low lying areas to farm lands, man has removed much of the floodplain vegetation and wetland areas that act as natural stilling ponds, sediment intercepts, hydraulic sponges, and erosion protection. Compounding the problem, large quantities of chemicals are flushed into the surface water by overland flows. Chemical loading and poor water quality can have long and short-term consequences. Point sources for chemical introductions include inundated municipal and industrial sites, including wastewater treatment plants, chemical processing and manufacturing centers, and disposal or holding areas (Goolsby et al., 1993). The largest non-point pollution source is runoff from agricultural land.

In the catastrophic Mississippi River basin flood of 1993, extremely large amounts of nitrate and herbicides were transported (Goolsby et al., 1993). The Mississippi River basin contains 65 percent of the cropland in the United States. An estimated 100,000 metric tons of pesticides and 6,300,000 metric tons of nitrogen fertilizer are used annually in the basin. In comparing 1992 and 1993 loads at the mouth of the Mississippi, Goolsby et al. (1993) found a 112 percent increase in the 1993 total load of nitrate. Similarly, the load of atrazine, a common herbicide used in corn production, increased by 235 percent.

In addition to short-term impacts on water quality, Michael Dowgiallo of the National Oceanic and Atmospheric Administration (as cited in Goolsby et al., 1993) noted that the chemical loads were boosting primary production, which resulted in elevated levels of marine phytoplankton in the Gulf of Mexico. By consuming phytoplanktonic algae and providing a forage base for higher predators, zooplankton are an influential part of aquatic food chains. Increasing nutrient levels is likely to affect forage fish populations, which often feed on zooplankton, and eventually increase the size and number of sport fish, but may cause problematic responses like algal blooms.

In isolated and disastrous situations, mankind creates or amplifies extreme events. The 1972 flood in Buffalo Creek, West Virginia, is a particularly tragic example. On February 26th, 1972, a dam failure released a torrent of water and mine waste on downstream communities. In 1960, the dam was initially constructed to a height of less than 20-feet high. To expand storage capacity, mine tailings were periodically layered and compacted atop the original structure. By 1972, the haphazard dam had reached a maximum height of 60-feet (Erikson, 1976).

The steady rains that fell continuously for three days prior to failure were apparently the final straw for the dangerous structure (Nugent, 1973). Just as the dam was beginning to overtop, the piled waste became saturated, liquefied, and collapsed completely within seconds of the initial failure. Over two million tons of waste materials, which had been described by a miner just prior to failure as having gone soft, were completely swept away in the released waters to form a black wave of fluid. It took just one minute to reach and destroy the community of Saunders. Hours later, the valley lay silent in shock, covered by a layer of sludge. Over 125 were killed as the wave coursed through several small streamside communities (Erikson, 1976). After the flood, a weather report stated that the rains would have created flows that can be expected once every ten years, but magnified by the dam failure, flows at Saunders were forty times higher than a 50-year flood (Nugent, 1973).

In bizarre situations, anthropogenic developments introduce flood hazards that are completely foreign to water systems. One noteworthy occurrence was the potential danger associated with the inundation of a park of propane tanks during the 1993 Mississippi River basin floods. On July 30th, floodwaters reached and swamped a large propane filling station adjacent to the Des Peres River, Illinois. Fifty-one 30,000-gallon tanks that were supported by concrete saddles began to float. The imminent danger of tanks breaking away from the park, colliding with emergent downstream obstacles and exploding posed a fire hazard strong enough to force 12,000 residents to abandon their homes for 12 days (U.S. Army Corps of Engineers, 1994).

The threat of fire during flooding events is a primary concern of local law enforcement officials. As every capable hand is employed directly in the flood fight, fire fighting efforts are often much less efficient than normal. In the Red River flood of 1997, waters from the 500-year event (Jacobs, 1997) ruptured gas lines igniting a severe fire that raged through several downtown blocks claiming homes and 11 downtown office buildings (see Figure 4) (MacDonald, 1997; James, 1998). Stymied by floodwaters that concealed fire hydrants and downed six firefighters with hypothermia, efforts to combat the fire were helpless until a U.S. Air Force helicopter dumped 2,000 gallons of floodwater on the fire (Schothorst, as in Collins, 1997). By the end of this flood, 83 percent of all the 23,000 local private residences sustained flood damages (Collins, 1997) and an estimated 100,000 head of livestock drowned and floated downstream into Canada (MacDonald, 1997).

Figure 4. Downtown Grand Forks, North Dakota, after floodwaters from a once in 500-year flood ruptured a gas line, igniting a fire that claimed eleven office buildings. Photo by Eric Hylden, Grand Forks Herald.

Such devastating and complete damage creates serious environmental health concerns for humans. Flooding reduces society to primitive conditions. Electricity, plumbing, drinking water supply, health care, and communications are often jeopardized. Collins (1997) cites the following health problems associated with post flood recovery: exposure to toxic chemicals in the floodwater; inhalation of mold spores that grow on flood damaged indoor sheetrock; consumption of contaminated food and water; spread of infectious disease; and the spread of respiratory illnesses. Illnesses tend to thrive as general health is weakened by the stresses associated with trauma, the close living conditions in flood shelters, and the long hours spent trying to repair damaged property.

In spite of these negative effects of flooding, man is becoming more aware of the environmental benefits of flooding and the widespread negative impacts created during his short stay in the world. Allen (1993) states that it comes as no surprise that the states that sustained the most damage during the 1993 Mississippi River basin flood are the same ones who eliminated almost 90 percent of their wetlands, turned over all the land to agriculture, and channelized and leveed the rivers. A 1993 report by the Illinois State Water Survey (as cited in Faber, 1993) clearly confirmed the importance of wetland areas by concluding that every one percent increase in wetland area within a watershed decreases the peak flood runoff of that watershed by 3.7 percent.

As the interactions of the anthropogenic influences and natural systems come into focus, the question of how to incorporate new science into flood management is raised. Often, an incomplete understanding of natural dynamics stalls progress. An exciting concept is experimental or human induced floods, designed to stimulate specific natural system responses, which are monitored before, during, and after the planned flooding. These premeditated floods offer scientists the opportunity to observe riparian systems under quasi-natural conditions and establish data sets critical to the better understanding of flood-ecosystem relationships, while attempting to improve the environmental health of the riverine corridor. In March, 1996, a controlled flooding experiment was performed on the Colorado River by releasing 45,000 cubic feet per second of stored water for one week from the Glen Canyon Dam (Adler, 1996). While the scientific success of this event is debatable, from a logistical and management perspective the flood is an amazing achievement and a valuable precedent. The flood symbolizes man’s recognition that flooding is essential to natural systems and has potential as an environmental management tool.

5. CONCLUSIONS AND RECOMMENDED RESEARCH

Extreme flooding events are reset mechanisms for nature, civilization, and political policy. Driven by an instinct to master his surroundings and prevent the periodic regressions created by floods, man has warped natural systems by greatly altering hydrologic regimes. Some forms of structural flood control are now known to increase the frequency of extreme high water. Nonstructural flood control presents an opportunity to reduce the frequency and magnitude of extreme events and improve aquatic environments.

Hey and Philippi (1995) estimate that 13.3 million acres of wetlands would provide the Mississippi River basin with non-structural flood control capable of handling the once in 100-year event. Missouri was one of nine states that sustained significant damages in the Great Flood of 1993 (Meyers and White, 1993). In Missouri alone, 227,585-acres of cropped floodplain lands were covered by over nine inches of sand and are unlikely to ever return to agricultural production (U.S. Congress, 1994). Assuming that only five of the other eight states sustained similar agricultural losses to those in Missouri, ten percent of the area required by Hey and Philippi’s plan is now dormant under a blanket of sand. At the very least, a large-scale study area of the now nonarable land should be used as an experimental site for floodplain restoration and wetland construction.

Recommended research areas pertaining to this manuscript are:

- Continued study of managed floods as tools for reestablishing natural dynamics. The Glen Canyon dam flood expanded the scope of controlled floods to include the initiation of geomorphic processes important in maintaining aquatic habitat for native species. This was an invaluable contribution. In large low-gradient systems, the biotic production boost from flooding in wetlands and floodplains should be quantified for a range of return frequencies. This would refine controlled flooding as a tool for biologists and environmental managers.

- Identify system weaknesses and operational shortcomings based on historic floods and develop conceptual improvements, including the integration of non-structural alternatives, in anticipation of major floods instead of in response to them. This may be accomplished by approaching problems holistically. By considering the entire system, operational plans should integrate existing and proposed structural and non-structural flood control measures to compose comprehensive flood management strategies. If severe flooding remains the major impetus for policy change, a plan in hand will allow full utilization of the post-flood window of opportunity created by heightened social awareness and disabled structural controls.

- Continued study of the quantitative environmental aspects of severe flooding. A new branch of study should include ecological and biological modeling. Currently, there are computer models available for modeling aquatic habitat (Bovee, (ed.), 1996) and fish populations in temperate river systems (Cheslak and Jacobson, 1990; Bartholow et al., 1993). As these models rely on hydraulic calibration data that are best gathered at low flows, use of these evaluative natural system models is suspect at the high flow levels critical to population dynamics. Even though geomorphic changes during extreme events upset characteristics of the physical stream habitat, the validity of model responses to extreme flows should be tested.

The game of hydrologic roulette can be weighted in our favor by incorporating nonstructural flood control measures into flood management. This includes the restoration of wetland areas and reconnection of key floodplain areas. By applying new science to old lessons we can break the cycle of policy change in response to destruction.

6. REFERENCES

Adler, T. (1996). “Healing waters: Flooding rivers to repent for the damage done by dams”, Science News, 150(12), 188-189.

Allen, W.H. (1993). “The great flood of 1993: Animals and plants of the floodplain thrive, while river researchers have a field day”, BioScience, 43(11):732-737.

Associated Press (1998). “Swarms of hopping madness plague Southwest”, in M. Anton (ed.), Rocky Mountain News, Denver, Colorado, p. 42A.

Barry, J.M. (1997). “Rising tide: The great flood of 1927 and how it changed America”, Simon & Schuster, New York.

Bartholow, J.M.. Laake, J.L., Stalnaker, C.B. and Williamson, S.C. (1993). “A salmonid population model with emphasis on habitat limitations”, Rivers, 4(4):265-279.

Bayley, P.B. (1991). “The flood pulse advantage and the restoration of river-floodplain systems”, Regulated Rivers: Research and Management, 6:75-86.

Bergon, F., (ed.). (1989). “The journals of Lewis and Clark”, Penguin Books USA Inc., New York.

Belt, C.B. Jr. (1975). “The 1973 flood and man’s constriction of the Mississippi River”, Science, 189, 681-684.

Bovee, K.D. (ed.). (1996). “The compleat IFIM: A coursebook for IF 250”, U.S. Geological Survey, Washington, D.C.

Cheslak, E.F. and Jacobson, A.S. (1990). “Integrating the Instream Flow Incremental Methodology with a population response model”, Rivers, 1(4), 264-288.

Collins, J. (1997). “Environmental health effects of the Red River flood of 1997”, Environmental Health, 60(2), 17-21.

Copp, G.H. and Penaz, M. (1988). “Ecology of flood spawning and nursery zones in the flood plain, using a new sampling approach”, Hydrobiologia, 169(2), 209-224.

Dieffenbach, B. (1993). “Raging Rivers: Did Mother Nature cause the devastating floods of 1993, or did man?”, Missouri Conservationist, 54(9), 4-9.

Edwards, R. (1997). “Return of the pelican”, New Scientist, 153(2075), 32-35.

Elwood, J.W. and Waters, T.F. (1969). “Effects of floods on food consumption and production rates of a stream brook trout population”, Transactions of the American Fisheries Society, 98(2), 253-262.

Erikson, K.T. (1976). “Everything in its path: Destruction of Community in the Buffalo Creek Flood”, Simon and Schuster, New York.

Faber, S. (1993). “Overview: The Mississippi flood”, Environment, 35(10), 2-3.

Friedman, J.M., Osterkamp, W.R. and Lewis, W.M. Jr. (1996). “Channel narrowing and vegetation development following a great plains flood”, Ecology, 77(7), 2167-2181.

Gardiner, J. (1994). “Environmental impact of floods”, in G. Rossi, N. Harmancioglu, and V. Yevjevich, (eds.), Coping with Floods, Kluwer Academic Publishers, Dordrecht, Boston and London, pps. 529-548.

Gardiner, J. (1995). “Developing flood defence as a sustainable hazard alleviation measure”, in J. Gardiner, O. Starosolszky, and V. Yevjevich (eds.), Defence from floods and floodplain management, Kluwer Academic Publishers, Dordrecht, Boston and London, pp. 13-40.

Gilliam, J.W. (1994). “Riparian wetlands and water quality”, Journal of Environmental Quality, 23(5), 896-900.

Goolsby, D.A., Battaglin, W.A., and Thurman, E.M. (1993). “Occurrence and transport of agricultural chemicals in the Mississippi River basin July through August 1993”, U.S. Geological Survey circular 1120-C, U.S. Government Printing Office, Washington D.C.

Haertel, L., Duffy, W.G., and Kokesh, D.E. (1995). “Influence of vegetated wetlands on the water quality of two glacial prairie lakes”, Journal of the Minnesota Academy of Science, 60(1), 1-10.

Hey, D.L., Kenimer, A.L., and Barrett, K.R. (1994). “Water quality improvement by four experimental wetlands”, Ecological Engineering, 3, 381-397.

Hey, D.L., and Philippi, N.S. (1995). “Flood reduction through wetlands restoration: The Upper Mississippi River basin as a case history”, Restoration Ecology, 3(1), 4-17.

Hilsenhoff, W. L. (1996). “Effects of a catastrophic flood on the insect fauna of Otter Creek, Sauk County, Wisconsin”, Transactions of the Wisconsin Academy of Science, 84, 103-110.

Hoopes, R. L. (1975). “Flooding as the result of Hurricane Agnes, and its effects on a native brook trout population in an infertile headwater stream in central Pennsylvania”, Transactions of the American Fisheries Society, 104(1), 96-99.

Jacobs, M. (1997). “Come hell and high water”, North Dakota Horizons, 27(3), 8-9.

Jacobsen, R.B. and Oberg, K.A. (1993). “Geomorphic changes in the Mississippi River floodplain at Miller City, IL as a result of the flood of 1993”, U.S. Geological Survey circular 1120-J, U.S. Government Printing Office, Washington D.C.

James, M. H. (1998). “The Grand Forks flood”, QST, 82, 28-30.

Jowett, I.G. and Richardson, C. (1989). “Effects of a severe flood on instream habitat and trout populations in seven New Zealand rivers”, New Zealand Journal of Marine and Freshwater Research, 23, 11-17.

Junk, W.J., Bayley, P.B., and Sparks, R.E. (1989). “The flood pulse concept in river-floodplain systems”, in D. P. Dodge (ed.), Proceedings of the International Large Rivers Symposium, Canadian Special Publication of Fisheries and Aquatic Sciences (106), pp. 110-127.

Leitman, H.M., Darst, M.R., and Nordhaus, J.J. (1991). “Floodplain of the Ochlockonee River, Florida, during flood and drought conditions”, U.S. Geological Survey, Water-Resources Investigations (90-4202), Tallahassee, Florida.

Leentvaar, J. and Stortelder, P.B.M. (1995). “The methods and mechanisms of establishing consensus on water management policy in the Netherlands”, in J. Gardiner, O. Starosolszky, and V. Yevjevich (eds.), Defence from floods and floodplain management, Kluwer Academic Publishers, Dordrecht, Boston and London, pp. 555-564.

MacDonald, J. (1997). “The flood of the century: Manitobans flee the surging waters of the angry Red River”, MacLean’s, 110(18), 30-33.

Maher, R.J. (1994). “Observations of fish community structure and reproductive success in flooded terrestrial areas during an extreme flood on the lower Illinois River”, in J. W. Barko and M. M. Wise (eds.), Long Term Resource Monitoring Program 1993 Flood Observations (LTRMP 94-S011), National Biological Service, Environmental Management Technical Center, Onalaska, Wisconsin, pp. 95-115.

McGuire, W.D. (1989). “Healing Thompson Bend”, Missouri Conservationist, 50(8), 24-27.

Morgan, R.P. II, Jacobsen, R.E., Weisberg, S.B., McDowell, L.A., and Wilson H.T. (1991). “Effects of flow alteration on benthic macroinvertebrate communities below the Brighton Hydroelectric Dam”, Journal of Freshwater Ecology, 6(4), 419-429.

Myers, M.F., and White G.F. (1993). “The Challenge of the Mississippi Flood”, Environment, 35(10), 6-9 and 25-35.

Nachtnebel, H.P. (1995). “Environmentally and socially sound utilization of floodplains; some Austrian experiences”, in J. Gardiner, O. Starosolszky, and V. Yevjevich (eds.), Defence from floods and floodplain management, Kluwer Academic Publishers, Dordrecht, Boston and London, pp. 539-554.

Neckles, H.A., Murkin, H.R., and Cooper, J.A. (1990). “Influences of seasonal flooding on macroinvertebrate abundance in wetland habitats”, Freshwater Biology, 23, 311-322.

Nehring, R.B. and Miller D.D. (1987). “The influence of spring discharge levels on brown and rainbow trout recruitment and survival, Black Canyon of the Gunnison River, Colorado, as determined by IFIM, PHABSIM models”, Proceedings Annual Conference, Western Association of Fish and Wildlife Agencies, Salt Lake City, Utah, pp. 388-397.

Nugent, T. (1973). “Death at Buffalo Creek: The 1972 West Virginia flood disaster”, W.W. Norton and Company Inc., New York.

Pearsons, T.N., Li H.W., and Lamberti, G.A. (1992). “Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages”, Transactions of the American Fisheries Society, 121, 427-436.

Perry, C.A. (1993). “Effects of reservoirs on flood discharges in the Kansas and Missouri River basins, 1993”, U.S. Geological Survey circular 1120-E, U.S. Government Printing Office, Washington D.C.

Poff, N.L. and Ward, J.V. (1989). “Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns”, Canadian Journal of Fisheries and Aquatic Science, 46, 1805-1818.

Poff, N.L. and Ward, J.V. (1990). “Physical habitat template of lotic systems: Recovery in the context of historical pattern of spatiotemporal heterogeneity”, Environmental Management, 14(5), 629-645.

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R. Sheldon, A.L., Wallace, J.B., and Wissmar R.C. (1988). “The role of disturbance in stream ecology”, Journal of the North American Benthological Society, 7(4), 433-455.

Scott, M.L., Auble, G.T., and Friedman, J.M.. (1997). “Flood dependency of cottonwood establishment along the Missouri River, Montana, USA”, Ecological Applications, 7(2), 677-690.

Seigel, R.A., Sheil, C.A., and Doody J.S. (1998) “Changes in a population of an endangered rattlesnake *Sistrurus catenatus* following a severe flood”, Biological Conservation, 83(2), 127-131.

Shroba, R.R., Schmidt, P.W., Crosby, E.J., and Hansen, W.R. (1979). “Geologic and geomorphic effects in the Big Thompson Canyon area, Larimer county: Part B in the Storm and flood of July 31-August 1, 1976, in the Big Thompson River and Cache La Poudre River Basins, Larimer and Weld counties, Colorado”. U.S. Geological Survey (G.S. Professional Paper 1115), Washington, D.C.

Soule, J.M. (1979). “Damage caused by geologic processes during flood-produced storms; Storm and flood of July 31-August 1, 1976, in the Big Thompson River and Cache La Poudre River Basins, Larimer and Weld counties, Colorado”. U.S. Geological Survey (G.S. Professional Paper 1115), Washington, D.C.

Southard, R.E. (1993). “Flood volumes in the upper Mississippi River basin, April 1 through September 30, 1993”, U.S. Geological Survey Circular 1120-H, U.S. Government Printing Office, Washington D.C.

Sparks, R.E., Bayley, P.B., Kohler, S.L., and Osborne L.L. (1990) “Disturbance and recovery of large floodplain rivers”, Environmental Management, 14(5), 699-709.

Theiling, C.H., Tucker, J.K., and Gannon, P.A. (1994). “Nektonic invertebrate distribution and abundance during prolonged summer flooding on the lower Illinois River”, in J.W. Barko and M.M. Wise (eds.), Long Term Resource Monitoring Program 1993 Flood Observations (LTRMP 94-S011), National Biological Service, Environmental Management Technical Center, Onalaska, Wisconsin, pp. 63-81.

U.S. Congress, House, Committee on Agriculture, Subcommittee on General Farm Commodities. (1994). “Condition of agricultural land damaged by the Midwest flood”, U.S. Government Printing Office (103-30), Washington, D.C.

U.S. Army Corps of Engineers. (1994). “The great flood of 1993 post-flood report: Upper Mississippi River and lower Missouri River basins”, U.S. Army Corps of Engineers.

Waring, G.L. and Stevens, L.E. (1987). “The effects of recent flooding on riparian plant establishment in Grand Canyon”, National Park Service, Glen Canyon Environmental Studies (GCES/21/87), Flagstaff, Arizona.

Webb, B.W. and Walling, D.E. (1997). “Complex summer water temperature behavior below a UK regulated river”, Regulated Rivers: Research and Management 13(5):463-477.

Whitfield, A.K. and Paterson. Q.W. (1995). “Flood-associated mass mortalities of fishes in the Sundays Estuary”, Water SA, 21(4), 385-389.

Yanosky, T.M. (1982). “The effects of flooding on woody vegetation along parts of the Potomac River flood plain”. U.S. Geological Survey (G.S. Professional Paper 1201), Washington, D.C.

Yin, Y., Nelson, J.C., Swenson, G.V., Langrehr, H.A., and Blackburn, T.A. (1994). “Tree mortality in the upper Mississippi River and floodplain following an extreme flood in 1993”, in J.W. Barko and M.M. Wise (eds.), Long Term Resource Monitoring Program 1993 Flood Observations (LTRMP 94-S011), National Biological Service, Environmental Management Technical Center, Onalaska, Wisconsin, pp. 39-60.

Table 1. Quantitative studies linking population dynamics with flood events. Where appropriate, the common names of specific populations under investigation are listed under population types. Under river type, HG and LLG represent high-gradient rivers and large low-gradient rivers, respectively. Temporal classifications are based on the temporal scope of the study and the life cycle dynamics of each study's population type. Long-term studies include at least one complete life cycle of the study organism. Short-term studies focus on acute impacts of flooding.

Event	**River Type**	**Frequency (Return Period, years)**	**Population Type**	**Number, Biomass, Density, and/or Diversity**	**Temporal**	**Source**
1965-1966 Valley Creek, MN	HG	Not available (Series of four floods)	Invertebrates: Gammerus (sps.) Baetis (sps.)	Severe decline after floods, recovered fully by 07/1966.	Long and Short-term	Elwood and Waters (1969)
1993 Otter Creek, Baxter's Hollow, WI	HG	Not available	Aquatic insects: Benthic and nektonic invertebrates	Diversity decreased, total number remained nearly unchanged, high water quality species favored.	Long and Short-term	Hilsenhoff (1996)
1965-1966 Valley Creek, MN	HG	Not available (Series of four floods)	Fishes: Brook trout (Juveniles and Adults)	Juveniles: loss of 1965 and 1966 year classes. Adults: no change	Short-term	Elwood and Waters (1969)
1965-1966 Valley Creek, MN	HG	Not available (Series of four floods)	Fishes: Brook trout (Adults)	84% drop in biomass by 1967.	Long-term	Elwood and Waters (1969)
1972 Burns Run, PA	HG	>300	Fishes: Brook trout	23% loss in total numbers.	Short-term	Hoopes (1975)
1986 Orari River, New Zealand	HG	19	Fishes: Brown trout	92% loss in total numbers.	Short-term	Jowett and Richardson (1989)
1986 Opihi River, New Zealand	HG	433	Fishes: Brown trout	77% loss in total numbers.	Short-term	Jowett and Richardson (1989)
1986 Otematata River, New Zealand	HG	22	Fishes: Brown and rainbow trout	Brown trout: 94% loss in total numbers. Rainbow trout: 100% loss in total numbers.	Short-term	Jowett and Richardson (1989)

1986 Hakataramea River, New Zealand	HG	>500	Fishes: Brown and rainbow trout	Brown trout: 93% loss in total numbers. Rainbow trout: 79% loss in total numbers.	Short-term	Jowett and Richardson (1989)
1986 Maerewhenua River, New Zealand	HG	21	Fishes: Brown and rainbow trout	Brown trout: 100% loss in total numbers. Rainbow trout: 100% loss in total numbers.	Short-term	Jowett and Richardson (1989)
1986 Kakanui River, New Zealand	HG	28	Fishes: Brown trout	300% gain in total numbers.	Short-term	Jowett and Richardson (1989)
1986 Shag River, New Zealand	HG	19	Fishes: Brown trout	36% loss in total numbers.	Short-term	Jowett and Richardson (1989)
1988-1989 Rock Creek, OR	HG	Three floods: 08/13/88 Flash flood; 04/26/89 and 05/10/89 Spring floods	Fishes: Rainbow trout, speckled dace, bridgelip suckers	Densities in 06/89 were 2 to 67% of 07/88 levels, but rebounded by 08/89. Diversity decreased, but rebounded.	Long and Short-term	Pearsons et al. (1992)
1965 Plum Creek, near Louviers, CO	HG	Flash flood, over 10^7% of the median daily discharge	Vegetation: Vascular plants (includes woody plants)	50% loss of trees, washout of all stream bank colonies, indirect promotion of Cottonwoods.	Long and Short-term	Friedman et al. (1996)
1983 Colorado River, Grand Canyon	HG	Not available	Vegetation: Woody plants	50% loss of riparian or riverside plants, significant recolonization within 3 yrs.	Short-term	Waring and Stevens (1987)
1881-1992 Missouri River, Central MT	HG	>9.3	Vegetation: Cottonwood tree establishment	72% of trees that are successfully established are associated with flooding >1:9.3.	Long-term	Scott et al. (1997)
1973 Mississippi River	LLG	30 (flow) 200 (stage) (Belt, 1975)	Benthic macro-invertebrates	No change.	Long and Short-term	Sparks et al. (1990)

1987-1989 Ochlockonee River, near Tallahassee, FL	LLG	Seasonal Flooding (2 to 4)	Fish assemblage	75% of mainstem fish utilize floodplain when available, floodplain habitat is primary or exclusive habitat for 17% of fish species.	Short-term	Leitman et al. (1991)
1993 Illinois River, near Grafton, IL	LLG	Near record (Theiling et al., 1994); 14 for an upstream site (Southard, 1993)	Nektonic macro-Invertebrates	On the rising stage, diversity dropped and numbers increased significantly; on the falling stage, diversity increased and numbers decreased.	Short-term	Theiling et al. (1994)
1993 Illinois River, near Grafton, IL	LLG	Near record (Theiling et al., 1994); 14 for an upstream site (Southard, 1993)	Fish assemblage	Strong reproductive year classes of floodplain spawning fish, biomass of floodplain increased with mainstem flow, high diversity, high productivity.	Short-term	Maher (1994)
1972 Potomac River, near Washington DC	LLG	>10	Vegetation: Woody plants	Vegetative establishment occurs after major events, survival is a function of species and shelter from flow velocity.	Short-term	Yanosky (1982)
1973 Mississippi River	LLG	30 (flow) 200 (stage) (Belt, 1975)	Vegetation: General	No change.	Long and Short-term	Sparks et al. (1990)
1993 Mississippi River, WI to just above St. Louis	LLG	>100 (Southard, 1993)	Vegetation: Trees	1.1-37.2% tree mortality, 1.8-80.1% sapling mortality, trees mortality was not fully revealed until the next growing season.	Long and Short-term	Yin et al. (1994)
1993 Missouri River, Northwestern MO	LLG	>100	Terrestrial fauna: massasauga rattlesnake	Virtually eradicated small snakes (<40 cm) .	Short-term	Seigel et al. (1998)
1993 Mississippi River, between Cairo, IL and MO-AR border	LLG	>100 (Southard, 1993)	Birds: Least tern (endangered species)	78% loss of active nesting sites, more than 80% loss in young of the year chicks.	Short-term	Renken as in Allen (1993)