Moist-Soil Plants as Ecohydrologic Indicators for Recovering the Flood Pulse in the Illinois River

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Abstract

The hydrologic regime of the Illinois River has been substantially altered by locks and dams, floodplain levees, water diversion, and development of the watershed over the past 100 years. The natural flood pulse, a fundamental rhythm to which the plants and animals of both the river and its floodplain had adapted, has been disrupted. State, federal, and non-governmental organizations are currently trying to naturalize the Illinois floodplain-river system. Little, however, is known about how to recover those elements of the flood pulse essential to the native biota. In this study we propose moist-soil plants, whose life history is dependent upon flood pulsing, as ecohydrologic indicators of the flood pulse. We explain how moist-soil plants are supported by the natural flood pulse and present a conceptual framework that links the flooding regimes of the river and the reproductive success of the plants. Successful germination and full growth of moist-soil plants can be a useful indicator for optimum naturalization of flood regimes. The framework also shows how the interdisciplinary linkages between hydrology, ecology, and spatial analysis assist in predicting, measuring, and comparing consequences of alternative naturalization scenarios. A new ecohydrologic parameter, lowest elevation for successful moist-soil plant production, is presented.

Key words: ecohydrology, ecological modeling, flood pulse, floodplain restoration, Illinois River, indicator, moist-soil plant, naturalization.

Introduction

A regular flood pulse, including a spring flood and a summer low flow, was at the heart of the Illinois floodplain-river ecosystem (Junk et al. 1989; Sparks et al. 1998, 2000) (the term "river-floodplain ecosystem" was first used by Junk et al. [1989] and adopted by the U.S. National Research Council, which defined the term thus: "... systems with a predictable long-lasting flood pulse that is exploited by fish and other aquatic organisms" [NRC 1992]. We reverse the word order in this article to emphasize the floodplain, a convention followed by The Nature Conservancy, which is undertaking floodplain naturalization projects on both the Illinois and Upper Mississippi Rivers [see The Nature Conservancy 1998]). The large, low-lying floodplain was regularly inundated, with the rise and fall of the water nourishing the floodplain and creating a wide range of habitat types and ecosystem processes that maintained the natural biological diversity of riparian species (Bayley 1991; Ward & Stanford 1995; Sparks & Spink 1998).

During the past 100 years, the hydrologic regime of the Illinois River has been altered by urban and agricultural development of the watershed: locks and dams for commercial navigation, levees that protect floodplain agriculture from flooding, and water diversion from Lake Michigan that provides and protects drinking water for Chicago (Sparks et al. 1998; Schneider 2000). Recently, public interest in the conservation and recovery of natural services has prompted major public and private investments in wetland restoration, habitat enhancement, and conversion of former agricultural drainage and levee districts back to floodplains in many rivers, including the Illinois (Galat 1998; Sparks et al. 2000). Such efforts are often termed "restoration," although restoration is defined by the National Research Council (1992) as a return to a pre-disturbance condition, which is unlikely to occur in a large, developed river basin. In this article we adopt the term "naturalization," defined by Rhoads and Herricks (1996) as the return of some components (e.g., water regime) of an ecosystem to a more natural condition, while retaining, or even enhancing, commercial uses. However, little is known about how to do naturalization properly. Moist-soil plants can be important in these efforts, not only as a valuable food source for waterfowl but also as an indicator of successful naturalization of the flood pulse.

Moist-soil plants grow on mud flats exposed when spring floods recede (Bellrose 1941; Bellrose et al. 1983) but productivity has declined in many regulated rivers because of unnaturally frequent small floods that inundate the mud flats and drown the plants during the summer growing season. One example of a moist-soil plant that is threatened due to the disruption of the flood pulse is the decurrent false aster, *Boltonia decurrens* (Torrey and Gray)

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Wood (Asteraceae), a federally listed threatened species in the United States (U.S. Fish and Wildlife Service). The number of naturally occurring populations of this species, which fluctuates annually, continues to decline, despite abundant seed production and the ability to reproduce vegetatively. When the natural spring flood and summer dry season cycle is disrupted, this species produces less biomass or even dies out (Smith et al. 1998).

In this article we review the characteristics of both the natural flood pulse and moist-soil plants. We also present an integrated conceptual framework that links the reproductive success of moist-soil plants to flood regimes of the river and describe how the framework can be used to plan, compare, and quantify alternative naturalization scenarios.

Flood Pulse Paradigm and Its Ecological Implications

A central idea describing floodplain-river dynamics is the flood pulse concept, which treats rivers and their floodplains as integrated components of a single dynamic system (Junk et al. 1989; Tockner et al. 2000). The major driving force is the pulsing of river discharge that determines the degree of connectivity and the exchange of matter and organisms across floodplain-river gradients (Middleton 1999; Tockner et al. 2000). The regular annual rise and fall of water levels is a fundamental rhythm to which the plants and animals of both the river and its floodplain have adapted. Understanding the flood pulse paradigm provides essential guidance for the naturalization of such systems that have been altered by regulation of water levels or flows (Middleton 1999).

Before regulation, moist-soil plants grew on extensive mud flats that were exposed when seasonal floods receded. The seasonal inundation of the floodplain, combined with the responses of plant communities, provided a unique suite of habitats to which native fishes and birds adapted (Middleton 1999; Koel & Sparks 2002). The spring flood sent the river beyond its banks, thus providing access to spawning and nursery habitats for many fishes in the shallow water covering the floodplain. The spring flood was followed by a predictable period of low water through the summer. The recession of the flood forced the fish to retreat into the remaining channels and shrinking lakes. This concentration of young fish provided a seasonal flush of food for predators, including larger fish, herons, and egrets (Sparks et al. 1998).

As the river receded, low-lying floodplain soils drained. The drying of the soils in the summer provided an environment where moist-soil plants germinated and grew to maturity before rising water in the fall again flooded the area. Moist-soil plants produce seeds and tubers, an important food source for waterfowl during their fall and spring migrations (Bellrose 1941; Bellrose et al. 1983). During the following spring, the dead stems of these moist-soil plants also provided valuable substrate for invertebrates and underwater cover for fish when they again left the deeper waters and entered the flooded shallows to spawn (Sparks et al. 1998). The dead organic matter also probably entered the detritus food web.

A Regulated River and Its Naturalization: The Case of the Illinois River

The Illinois River

The Illinois River, with a drainage area of 75,156 sq km, is one of the major tributaries of the Mississippi River (Fig. 1). The river valley is part of the Mississippi Flyway, a migratory corridor for 40% of North America's shorebirds and waterfowl (Fredrickson & Reid 1987). Before development, the floodplain-river system provided a richly productive area for the migrating waterfowl (Sparks et al. 2000). At present, the natural flood pulse pattern essential to that system is impaired (Sparks et al. 1998; Koel & Sparks 2002). River water levels have become erratic since regulation (Fig. 2). The period before 1900, which predates the modern navigation dams and the diversion of water from Lake Michigan, may be considered representative of the relatively undisturbed condition of the river. The river in this period had a protracted spring flood followed by low, fairly stable water levels in midsummer. The river now has unnaturally high water levels in the summer, often with several minor floods in midsummer that drown moist-soil plants (Fig. 2).

Efforts in Naturalization of the Flood Regimes in the Illinois River

State, federal, and non-governmental agencies are currently investing significant resources to naturalize the Illinois floodplain-river ecosystem (Sparks et al. 2000; Clancy 2001). Two distinctly different approaches to hydrologic manipulation have been discussed for this naturalization (Sparks et al. 1998). One is to keep the existing levees and manage the water levels on project sites

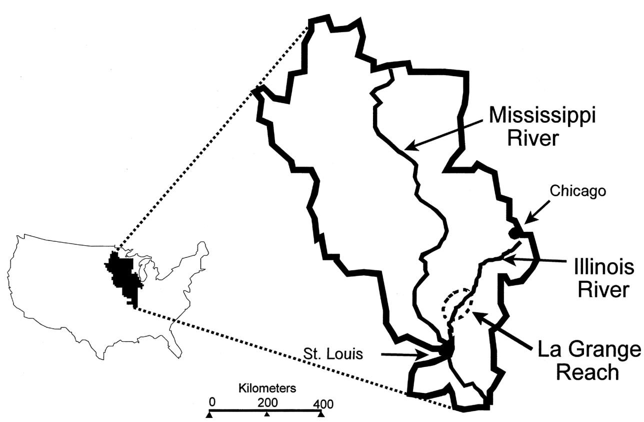

Figure 1. The Upper Mississippi River System, including the Illinois River and the La Grange Reach.

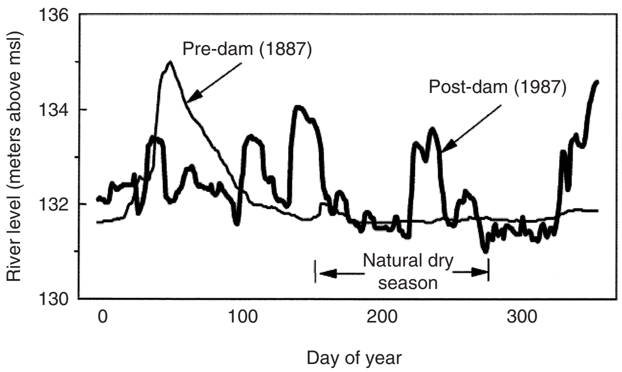

Figure 2. As the navigation dams have been in place on the Illinois River, the natural water regime of a spring flood followed by a summer low flow has been replaced by unnaturally rapid fluctuations year-round. The 1887 water levels are representative of the pre-dam pattern and the 1987 levels are representative of the post-dam pattern, although there are year-to-year variations in both periods. Hydrographs were provided by the Illinois State Water Survey. msl, mean sea level.

independently from the river. This approach allows water levels to be manipulated to produce wetland vegetation, including moist-soil plants. However, this option has two important shortcomings.

Moist-soil plants are pioneer species that occupy seasonally exposed mud flats. Under natural conditions, these areas are kept free of less flood-tolerant species by occasional spring floods that last long enough to keep competing woody species at bay. In areas that are not flooded deep enough and long enough in the spring (in at least some years), woody plant species will replace moist-soil plants (Toner & Keddy 1997). An even more fundamental shortcoming of the isolation strategy is that it does not provide the connection between the river and its floodplain that is essential to many important fish species and to many important ecological processes (e.g., nutrient cycling and retention).

A second, more systemic, approach to naturalization of the water regime is to reconnect the floodplain to the river by breaching the levee or (more likely) installing a gate. Such an approach would recover more of the natural interaction of the floodplain-river system and allow fish access, but there are very few experiences with this type of naturalization to guide current efforts. Also, the same excessive water level fluctuations that currently occur in the river would occur to some degree in the reconnected areas, although any opening in the levee that allowed a relatively small amount of water to enter or leave at a time, in comparison to the total hydraulic storage capacity of the levee district, would tend to dampen water level fluctuations within the district. If enough floodplain levee districts were reconnected to the river, the combined flood storage and conveyance capacity might even be sufficient to absorb and smooth out the small, unnatural summer floods in the river itself. With the gate option the floodplains could be reconnected when water levels in the river were high in the spring, kept open to drain the floodplains as the river receded but closed to exclude unnatural floods during the summer growing season. An occasional great flood, as occurred in the Upper Mississippi river in 1993, would require that the gates be opened to equalize water levels on both sides of the levees to prevent catastrophic breaching of the levees. Such infrequent, emergency use would be unlikely to damage moist-soil vegetation beyond loss of one summer's production but might help reduce damaging flood levels.

The above discussion of alternatives is not merely academic, because The Nature Conservancy (TNC), a nongovernmental conservation organization (NGO), proposes to reconnect the Illinois River to a recently acquired approximately 3,000-ha agricultural levee district along the La Grange Reach of the Illinois River (Fig. 1). Called "Emiquon," the area to be naturalized was once a backwater lake connected to the Illinois River during high water. It was drained and leveed in the 1920s and was farmed for 80 years (The Nature Conservancy 2001). Naturalization planning is currently in progress, including building both hydrologic and ecological models to predict the impact of various naturalization and management scenarios on water flow, sedimentation, and vegetation (especially moist-soil plants). Experience and wisdom gained through this project should benefit naturalization efforts elsewhere along the Illinois River as well as on other large-floodplain Rivers. We next describe how a moist-soil plant model can be used to evaluate naturalization alternatives.

Moist-Soil Plants: An Ecohydrologic Indicator

Millets, the Most Representative Group of Moist-Soil Plants

At least six species of moist-soil plants provide abundant food for wildlife in the Illinois floodplain-river system (Table 1). One of the most representative groups of moist-soil plant found in Illinois and Missouri are *Echinochloa* sp. (millets), which are summer annual plants that grow up to 1.5 m height with red or purple stem bases and panicles. A single plant can produce up to 20,000 seeds (Keeley & Thullen 1989). They prefer wet (but not inundated) soils and warm temperatures to germinate. Only one of the three millets listed in Table 1 is native; the others were introduced and subsequently thrived in the Illinois River.

Japanese millet (*E. frumantacea* [L.] Beauv.) is planted extensively in floodplain areas along the Illinois River that are managed for waterfowl (personal communication with Ross Adams, October 2002, Chautauqua National Wildlife Refuge Manager, Havana, Illinois), because it is a choice duck food eaten by 17 species of waterfowl (Fredrickson & Taylor 1982; Combs & Fredrickson 1996). Millions of dollars are spent annually in the Upper Mississippi System to grow Japanese millet on the floodplain compartments where water levels can be controlled behind levees with gates or pumps (Reid et al. 1989; personal communication with Ross Adams, October 2002, Chautauqua NWR, Havana, Illinois).

Table 1. Moist-soil plants historically observed in the Illinois floodplain-river system that are highly valued as food for waterfowl.*

Common Name	*Scientific Name*	
Water hemp	*Acnida tuberculata* (Moq.) Sauer	Native†
Nutgrass	*Cyperus strigosus* L.	Native
Wildmillet (Duckmillet)	*Echinochloa crus-galli* (L.) Beauv.	Naturalized
Japanese millet	*E. frumentacea* (L.) Beauv.	Naturalized
Walter's millet	*E. walteri* (Pursh) Heller	Native
Rice cutgrass	*Leersia oryzoides* (L) Sw.	Native

*Bellrose (1941); Bellrose et al. (1979); and Bellrose et al. (1983).
†Determination of native range based on Godfrey and Wooten (1981). "Naturalized" means the plant was native to another continent but was introduced to North America and has become adapted and widespread in moist soil habitats.

Boltonia decurrens: A Threatened Moist-Soil Plant Species

Boltonia decurrens is a moist-soil plant species that is endemic to the Illinois River (Torrey & Gray 1840). It is currently listed as endangered in Missouri and threatened in Illinois (Smith et al. 1998). This rare plant depends on the river's natural ebb and flow (The Nature Conservancy 2001).

Proliferation of the plant requires regular spring flooding which eliminates flood-intolerant species and creates open moist areas for seed germination (Smith 1991). Field observations indicate that in areas without regular spring floods this species is eliminated by competition within 3–5 years (U.S. Fish and Wildlife Service 1990). Populations are revitalized or new ones are established when a disturbance clears a site and seedlings are generated from the soil seed bank or from seeds that have been deposited by receding flood waters (U.S. Fish and Wildlife Service 1990). Smith et al. (1998) suggest that *B. decurrens* and other threatened floodplain endemics may have value as indicator species by which the integrity of the whole floodplain-river system can be measured.

Ecophysiology of Moist-Soil Plants

Moist-soil plants are a valuable hydrologic indicator because of close ties between their life history requirements and the rhythm of the flood pulse (Bellrose et al. 1983; Sparks et al. 1998; Middleton 1999). The plants require that mud flats be exposed during the period from 10 July to 1 October (Bellrose et al. 1983). If moist-soil plants can grow for at least 70 days without being overtopped by water, they will mature and produce seeds, which are then available to waterfowl (Bellrose et al. 1983). The timing of the flood is critical for a successful seed crop.

Inundation during germination or early seedling development is detrimental to the establishment of moist-soil plants. Once germinated, they cannot tolerate flooding until the plants are at least 15 cm tall (Fredrickson & Taylor 1982). Even after the growing season, food may not be available for waterfowl, if autumn floods raise the water level too fast during the migration period (Fredrickson & Taylor 1982). Different birds forage at different water

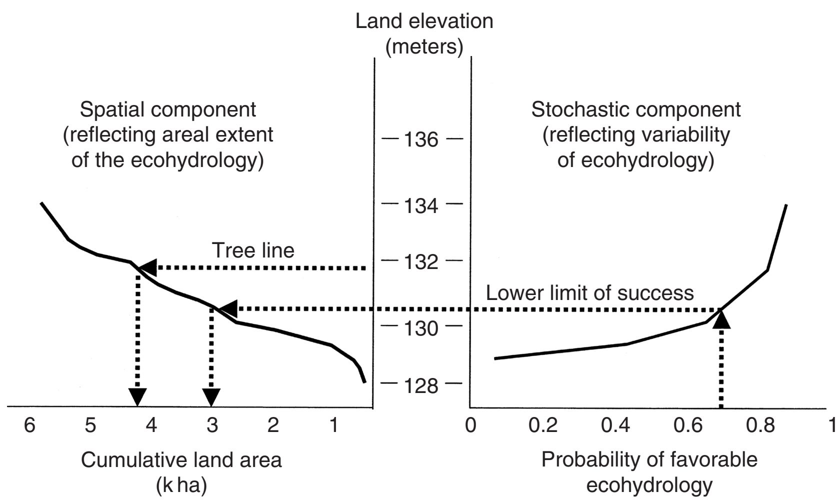

Figure 3. A conceptual framework linking the variability of river hydrology to the areal extent of successful moist-soil plant production. Probability of favorable ecohydrology on the *x*-axis on the right side of the graph means the probability of a hydrologic regime of the river favorable to the germination, survival, and growth of moist-soil plants. The left side of the graph is a cumulative land area representing a relevant segment of floodplain. The lowest elevation is at the river's edge during low flow conditions. As one moves up in elevation, plant growth increases with less frequent flooding and more of the floodplain is included. Tree line indicates the upper boundary of land elevation for moist-soil plants.

depths (Fredrickson & Reid 1986; Moorehouse 2000); hence, as autumn floods rise, fewer waterfowl species are able to access the seeds on the bottom.

Linking Moist-Soil Plant Potential to the Hydrology of the Illinois River

We have developed a conceptual framework linking the variability of river hydrology to the areal extent of successful moist-soil plant production (Fig. 3). There are two major components of the flood pulse that determine its impact on the floodplain-river ecosystem: the annual stage hydrograph of the river and the areal extent of the floodplain exposed to that hydrograph. The shared dimension of land elevation on the vertical axis links the two components (Fig. 3).

The left side of the graph is a cumulative area curve representing a relevant segment of floodplain. A point on the curve represents the area of land at or below a given elevation (Fig. 3). The lowest elevation is at the river's edge during low flow conditions. As one moves up in elevation, more of the floodplain is included and plant growth increases with less frequent flooding. Projecting the elevation bands for moist-soil plants onto the cumulative area curve of the floodplain provides our estimates for the areal extent of the plants.

The right side of the graph (Fig. 3) is a cumulative probability density function (pdf) of a selected parameter of river behavior. It reflects the rise and fall of the river captured probabilistically through the responses of moist-soil plants. This embodies the specific influence that the river has on the year-to-year likelihood of success of moist-soil plants. The procedure for estimating this cumulative pdf is "return frequency analysis," which is often used in engineering hydrology to estimate risk of floods and droughts (Hoggan 1997). The resulting function provides the likelihood or probability of having a successful "ecohydrology"—hydrology favorable for moist-soil plants—at a given land elevation. The elevation associated with a given probability then becomes a threshold, the lowest elevation having that probability of experiencing successful "ecohydrology." As land elevation increases above the lowest threshold, the hydrology still remains favorable to moist-soil plants, but at some point, the moist-soil plants will be out-competed by woody species (Fredrickson & Reid 1987). In other words the upper boundary of moist-soil plants is defined by the lower boundary of woody plants and is observed as a relatively permanent tree line (Fowells 1965). Trees generally are less flood tolerant than moist-soil plants, but moist-soil plants cannot germinate and grow in the shade of trees. Catastrophic floods or droughts may cause the tree line to shift, but it persists for long periods due to the perennial nature of woody vegetation (Toner & Keddy 1997). The tree line elevation in our study is obtained empirically from aerial photos, map analysis, and field measurements.

Linking the two panels together allows us to estimate the area of successful moist-soil plant production that will be achieved at a given likelihood of ecohydrology, at a specific land elevation. We can project both the upper and lower boundaries of moist-soil plant hydrology onto the cumulative area curve in the left panel of Figure 3 to quantify the areal extent. The area is obtained by subtracting the cumulative area below the lower elevation boundary from the cumulative area below the upper boundary. Both upper and lower limits of moist-soil plants are a function of the variability of river hydrology. In the hypothetical example in Figure 3, the area of moist-soil plants will occur in about 7 out of 10 years (70% probability) and will occupy the zone from the tree line, shown as a contour at 132 m of elevation which circumscribes about 4.2K ha, down to the lowest elevation of moist-soil plant success, shown as a contour at 130.5 m circumscribing approximately 3K ha. The difference between these circumscribed areas is 1.2K ha, the area occupied by moist-soil plants.

Realization of the Conceptual Linkages: An Interdisciplinary Modeling Project

To implement the conceptual framework presented above we are currently developing interdisciplinary models involving hydrologic and ecological models and GIS analysis.

Cumulative Area

Creating a cumulative area curve for a particular segment of the floodplain is straightforward GIS work, assuming the necessary data are available at sufficient resolution. The vertical range of the potential zone for moist-soil plants is only about 2–3 m. The contour interval of commonly available U.S. Geological Survey (USGS) 7.5-min quadrangle topographic maps is approximately at the same range (U.S. Geological Survey 2003). Our modeling requires elevation data with higher resolution, because responses of moist-soil plants and land area available for the plants to grow are highly dependent on small variations in both water and land surface elevation. Studies on floodplain topography using recently available elevation data with the resolution in the range of 0.3–1.0 m are currently being conducted for the La Grange Reach of the Illinois River by the Geographic Modeling Systems Laboratories at the University of Illinois.

Probability of Ecohydrology

This component has two major subcomponents: a hydrology model and a plant growth simulation model.

Water level fluctuations taken directly from historical gauging station data can be analyzed for probability of occurrence of favorable hydrology, but this approach does not permit simulation of naturalization strategies in which river behavior is altered (for example, scenarios involving alterations in dam operation). To be able to play "what if" games, hydrologic/hydraulic simulation is required. Currently, we have calibrated a non–steady state, one-dimensional hydraulic model, UNET (U.S. Army Corps of Engineers 1995), for the La Grange Reach of the river. The model is being used to generate scenario-based annual hydrographs of the river based on alternative naturalization strategies. The resulting simulated hydrographs are used as input to a moist-soil plant growth model developed by Ahn et al. (2004), which quantifies moist-soil plant "success" in terms of germination and growth. The plant growth simulation model responds to daily water depth, flood timing, and flood duration and has been qualitatively verified using historical records of water levels and moist-soil plant coverage for three areas along the Illinois River (Ahn et al. 2004). Using the same hydrographs, recursive running of the plant model at progressively lower elevations determines a desired ecohydrologic parameter: the lowest elevation of successful moist-soil plant production. Repeating the recursive modeling for several years of historical hydrographs provides a distribution of "lowest successful elevations." Return frequency analysis is then used to analyze the resulting multiyear record to assign a probability of moist-soil plant production to each historically observed lowest land elevation. This is the cumulative pdf shown in the right panel of Figure 3. The steps described above define a new ecohydrologic parameter, the lowest elevation of successful moist-soil plant production for each year of the hydrologic record. The approach then uses that parameter in an established framework of engineering hydrology to quantify and compare the "probable success" of alternative naturalization plans.

Conclusion

Moist-soil plants, as a critical reflection of the flood pulse paradigm, can be used to connect the manipulation of flood regimes with the naturalization of the Illinois floodplain-river system. The conceptual framework and approaches taken in this study provide a useful tool to predict, measure, and compare consequences of alternative naturalization scenarios for floodplain-river systems, but only for the summer growing season, normally the low, stable part of the annual flood pulse in the Illinois and Upper Mississippi rivers. What happens during the rest of the year does not affect the moist-soil plants, at least based on current information. Koel and Sparks (2002) describe an approach that includes the spring flood season for characterizing beneficial and detrimental effects of the water regime on fish. Their analysis used the historical catch of 1-year-old fish coupled with Richter et al.'s (1996) Index of Hydraulic Alteration to determine whether changes in fish catch (which is a relative index of population abundance) correspond to certain aspects of the water regime (duration of the flood, rate-of-rise, rate-of-fall, etc.). Where long-term, quantitative datasets on both water regime and biota are not available, then explanatory models such as our moist-soil plant model must substitute for empirical U.S. approaches such as those described by Koel and Sparks (2002).

Modeling components involved in our approach are well grounded in their respective literature and reflect the current state of knowledge. However, restoring an ecologically meaningful level of the flood pulse still presents difficult challenges. Not all of the factors involved in moist-soil plant success are fully understood, and factors such as nutrient levels and sedimentation rates, which are not explicitly included in our modeling, may prove critical.

Wider application of this approach will require addressing site-specific issues. Topographic information for an area of floodplain of interest needs to be of higher resolution than is typically available from USGS 7.5-min quadrangle maps. Also, details such as whether the naturalized floodplain is to serve as flood storage or flood conveyance are important and need to be specified, as scenarios are developed in preparation for modeling.

This analytical framework is viewed as part of a cyclic process of adaptive management, including modeling (as part of planning), implementing, monitoring, learning, and modeling again. Collecting more experimental and field-oriented information on the response of moist-soil plants, as naturalization efforts proceed, will be important. Our interdisciplinary project involving the development of linkages between hydraulic and ecological models and GIS analysis is ongoing.

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