# Estimating Potential Reduction Flood Benefits of Restored Wetlands

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## Introduction

Throughout the summer of 1993 a recurring question was the impact of wetland drainage on the severity of the flooding in the Upper Mississippi River watershed. In the aftermath of the flooding, a dominant policy question has been the potential role of wetland restoration in reducing future flood damages. *Sharing the Challenge* makes several specific recommendations on this Issue, focusing mainly on federal recognition of the flood-mitigation benefits of wetland restoration. Shabman (1994) discusses the analytical framework required to estimate the economic value of specific restoration alternatives. At framework presupposes the requisite technical ability to assess the flood-mitigating impacts of wetland restoration. Does the current state of the art justify this assumption?

In evaluating any flood-mitigation project, whether or not it involves wetland restoration, it is necessary to estimate its impact on downstream flood damages. In particular, we must be able to estimate how the project changes the probability distribution of flood levels at all downstream locations which are subject to flood damage. The overall methodology used to perform this estimation must incorporate principles of hydrology, hydraulics and statistics. In the United States, flood-mitigation projects have virtually all been evaluated using so-called design events. Although this approach has been used to evaluate many successful projects, it has several limitations which make it generally unsuitable for evaluating the flood benefits of wetland restoration projects. For example, for reasons explained in this paper, wetland evaluation should be based on continuous hydrologic simulation, which accounts for both storm and interstorm processes, rather than on a handful of design events. Fortunately, there do exist hydrological, hydraulic, and statistical models which can be incorporated into an effective methodology for evaluating the flood benefits of wetland restoration projects. Use of such a methodology will yield more accurate evaluations and will make it possible to design restoration projects so as to optimize flood benefits, subject to economic and ecological constraints. In this paper I discuss the limitations of the use of design events and outline an alternative methodology for evaluating flood-mitigation benefits of specific restoration projects. But first I begin with a discussion of the flood-mitigation benefits of wetlands.

## Role of Wetlands In Reducing Downstream Flood Levels

The drainage or restoration of a wetland can affect downstream flood levels in several ways. Storage of water in a wetland attenuates and delays downstream flood peaks. In the case of wetlands which have no downstream surface connections, drainage increases the total area contributing to downstream locations. Another mechanism has to do with the water balance of a wetland. In general, restoration of a wetland will increase local evapotranspiration losses. In dry regions it is possible for this increased loss to affect downstream flood levels, particularly for floods affecting large areas and occurring over relatively long time scales. Of these ways in which wetlands affect downstream flood levels, the storage mechanism is most important in the context of wetland restoration.

### Wetland Storage

By definition, wetlands store water. When this storage is short-term, which is often the case, flood peaks are delayed and attenuated. In the case of long-term storage, flood volumes are also reduced. In most cases, when wetlands are drained, their storage capacity is not actually lost. (The filling of wetlands is a notable exception.) Instead, what does change is the way that flood waters interact with that storage capacity. In particular, wetland drainage changes the storage-outflow relationship of the wetland and the access of stormwater to the wetland.

### Storage-Outflow Relationship

The role of the storage-outflow relationship is most relevant in the case of upland wetlands. In general, draining an upland wetland greatly steepens the lower portion of storage-outflow relationship. This means that, for a given amount of water in storage, the discharge of water is much greater from a drained wetland than from the original or restored wetland. For example, in a prairie pothole wetland, drainage is accomplished by installing a drain at the lowest point in the pothole and tile drains in the soil. Both the drained and undrained wetland have the capacity to store water; but because the undrained wetland drains so much more slowly, it stores more water in a given storm event.

The slowly-draining nature of a wetland also means that all of its potential storage may not be available at the time of a particular flood. This is especially important for large regional floods, which require weeks or months to develop. In order to properly evaluate the flood benefits of a particular wetland restoration project it is necessary to model the long-term variation of water stored in the wetland. This requires continuous hydrologic modeling, which simulates wetland storage between as well as during major storm events. Such modeling could be complicated by locally important factors. In highly seasonal climates, snow accumulation and melt may be critical. In regions with high water tables, wetland restoration may change the fundamental interactions between surface and ground water.

To illustrate the need for continuous hydrologic modeling, I have conducted a simple Monte Carlo simulation, the results of which are shown in Figure 1. The simulation is of a single prairie pothole, with a maximum depth of 2 meters and draining a region with ten times its surface area. The simulated surface hydrology is roughly analogous to that of the the prairie-pothole region of Iowa, with the exception that winter is not simulated. Inflows to the pothole include direct rainfall and surface runoff from the contributing area. In addition to evaporation, outflow is modeled as discharge from a linear reservoir. Simulation runs were made with different discharge constants, ranging from 4 hours to 180 days. A time constant of N days implies that a full pothole will drain to 37% of its full depth in N days, assuming no other inputs or outputs. With a time constant of months, the pothole mimics the behavior of a natural pothole, which drains by seepage to the groundwater (as well as evaporation). With a time constant of about a week, the pothole mimics the behavior of a drained pothole. A time constant of a day or less is characteristic of a typical urban detention basin.

Figure 1 gives the results of the pothole simulations, for time constants of 4 hours, 1 day, 7 days, 30 days, 90 days, and 180 days. For each simulation I have plotted the probability distribution of the annual maximum daily flow from the pothole (the maximum average daily flow in each year). Each distribution is based on 10,000 years of simulated hydrology. An averaging period of 1 day was chosen to demonstrate the impact of the pothole on a downstream location with a time of concentration of about one day. Figure 1 shows that the potholes with time constants of 4 hours and 1 day offer the least flood protection. (This confirms the conventional wisdom that flood-mitigation benefits of urban detention basins do not extend far downstream.) The potholes with the very long time constants, corresponding to the natural case, offer good protection for small to moderate floods, but are much less effective for larger floods. This is because these potholes hold water during the year and hence are likely to be partially filled prior to a major sotrm. The most effective time constants are 7 and 30 days. In particular, the 7-day case, which roughly corresponds to the agriculturally drained pothole, is most effective for the largest floods. It should be noted, however, that because of the simplifying assumptions, the results do not demonstrate that drainage of the prairie potholes in Iowa have decreased the peaks of large floods. What they do indicate is the necessity for using continuous hydrologic simulation to evaluate the flood-mitigation benefits of a wetland restoration project.

Storage Timing

In many cases wetland storage is small relative to the volume of floodwater in large floods. This is clearly the case for most riparian wetlands. For such storage to be maximally effective in a large flood, it must be available at the right time, just before the flood peak. This means that it is possible for wetland drainage to actually reduce the peaks of large downstream floods.

Consider, for example, a riparian wetland which is drained and isolated from the river by a levee. For a flood which just overtops the levee (or causes its failure), the storage behind the levee would be made available at just the right time. In this case downstream flood peaks would be lower without the wetland. (Of course, the failure of the levee may result in local damage.) Note, however, that if the levee is retained the former wetland could be restored without adversely affecting downstream flood levels. Such an approach would, of course, require some means of providing water to the wetland. Evaluation of this kind of wetland restoration project would require use of dynamic flood routing models which explicitly account for storage.

Timing of Downstream Peaks

Storage of water in a wetland delays the time of the peak of the downstream hydrograph. In cases where the volume of wetland storage is small compared to flood volumes, this timing change may be the most significant impact. Note that delaying a flood peak does not necessarily mean reducing it. Evaluation of the impact of peak delay in specific cases requires careful attention to the spatial and temporal characteristics of precipitation, stormflow generation, and stormflow conveyance.

Summary of Modeling Requirements

Wetland storage affects downstream flood peaks in complex ways which are event- and site-specific. Accurate assessment of the flood-mitigation benefits of a specific wetland restoration project requires: use of continuous hydrologic simulation, which accounts for the continuous variation of water stored in the wetland, soil, and groundwater; careful attention to the spatial and temporal characteristics of precipitation, stormflow generation, and stormflow conveyance; dynamic routing of flood hydrographs to account for storage effects on the magnitude and timing of flood peaks. Can these requirements be met by commonly-used design methods?

## Use of Design Events In Engineering Practice

In the United States, most flood-related analysis is based on simulation of a small number of design events. When stream-gage data are available, these events are based on statistical analysis of flood peaks and volumes. When streamflow data are not available, which is most often the case, the design events are based on design storms, which are constructed in the following way. First, statistical analysis is performed on historical rainfall data to produce estimates of the probability distribution of rainfall intensities for various durations. These relationships are then used to specify the intensities of design storms, which are in turn used as input to a hydrologic simulation model. It is assumed that the flood peak resulting from a given design storm has the same exceedance probability as the storm used to simulate it. Finally, a steady-state hydraulic model is used to estimate the stage associated with each peak discharge.

In general, the use of design events cannot provide accurate assessments of the flood-mitigation benefits of wetland restoration. Design event methods are based on hydrologic modeling of discrete events, rather than on continuous hydrologic modeling. They do not account for the pre-storm water stored in the wetland system, including ponded water, snowpack, soil moisture, and groundwater. They do not accurately account for the wide variations that can occur in individual flood events in the spatial and temporal characteristics of precipitation, stormflow generation, and stormflow conveyance. And while they could make use of dynamic flood-routing models, they cannot do so as effectively as can continuous simulation.

## Continuous Simulation-- An Alternative to Design Events

Continuous simulation is an alternative approach which overcomes many of the drawbacks of design event methods. In this approach one or more long historical rainfall records are used as input to a continuous-time hydrologic simulation model to produce long streamflow records at all locations of interest. Each of these streamflow records can then be analyzed as if it were an historical streamflow record obtained at a gaging station, providing an estimate of the probability distribution of peak flood discharges. The simulation can be conducted with and without various restoration designs, and the estimated probability distributions can be used in conjunction with stage-damage relationships to estimate the flood-mitigation benefits of the restoration designs.

Continuous simulation enables the modeler to explicitly account for many of the important factors which are ignored in an approach using design events. Continuous-time hydrologic simulation models were specifically developed to model the temporal variation of soil moisture, both during and between storm events. Modeling in continuous time allows for explicit representation of surface-water storages. Continuous simulation can account for spatial and temporal variability in rainfall, depending on the resolution of the available rainfall data in space and time. Continuous-time hydrologic models can be linked to fully dynamic flood-routing models. This makes it possible to capture the complex interactions which often occur at tributary confluences where hydrograph timing is critical to the resulting peak. Finally, the use of historical rainfall results in a large diversity of hydrologic responses, and hence provides a good test of alternative strategies for flood mitigation.

### Availability of Hydrologic and Hydraulic Models

There are a number of hydrologic and hydraulic models, both public-domain and proprietary, which can be used for continuous simulation. HSPF is a widely-used continuous hydrologic simulation model maintained by the U.S. Environmental Protection Agency. The Modular Modeling System, recently developed by the U.S. Geological Survey, is a continuous hydrologic modeling system which gives the user a number of modeling options. DWOPER and UNET are dynamic flood-routing models developed and maintained respectively by the U.S. Weather Service and U.S. Army Corps of Engineers. FEQ is a proprietary dynamic flood-routing model which has been coupled by the developer to HSPF. The Danish Hydrologic Institute (DHI) has developed a proprietary model which couples a continuous hydrologic model to a dynamic flood routing model. DHI models, as well as HSPF, have some capacity to model water quality.

### Statistical Limitations

As traditionally applied, continuous simulation has one serious drawback: for large discharges there can be significant errors in the resulting probability estimates. In the United States, digitized hourly rainfall records rarely begin before 1948. With such short simulation periods, conventional methods of flood-frequency analysis may produce highly inaccurate estimates of the upper tail of the probability distribution of peak flood discharges. Furthermore, probability distributions for design alternatives incorporating complex flood mitigation strategies often violate the distributional assumptions of conventional methods. The resulting uncertainties in the upper tail can seriously hamper the evaluation of alternative designs. In some cases the uncertainties are so large that the results violate common sense, undermining the credibility of the entire decision-making process. Note that this latter problem is much less likely with design storm methods, since the use of the same storms throughout the analysis forces consistency across simulations.

Bradley and Potter (1992) address this problem with a new approach for estimating the probability distribution of floods generated by continuous simulation models. The method, which they call the "peak-to-volume" approach, was explicitly developed for use in evaluating various benefits of flood-mitigation projects. Continuous streamflows are simulated using available historical data. At each location of interest the probability distribution of flood volumes is estimated for all storm events which produce a peak discharge above a specified threshold. Then a statistical model is developed for the relationship between peak discharge and flood volume. The critical innovation in this step is the use of information from extreme storms which have occurred in the meteorologically homogeneous region containing the watershed of interest. These storms are used to simulate large floods. They help define the upper tail of the relationship between flood peaks and volumes and provide a wide diversity of events to test various strategies for flood mitigation. Finally, the probability distribution of peak discharge is estimated by numerically integrating the distribution of flood volume with the conditional distribution of peak discharge on volume. Bradley *et al*. (1994) illustrate application of this approach in conjunction with the use of HSPF and FEQ.

**Conclusions**

The commonly-used methodology for designing and evaluating flood-mitigation projects is not adequate to evaluate wetland restoration projects. The latter requires the use of hydrologic and hydraulic models which account for long-term variations in water storage and which correctly represent the spatial and temporal characteristics of precipitation, stormflow generation, and stormflow conveyance. Fortunately, the necessary models are available, as well as a statistical framework for their use. Application of these methods will lead to more accurate evaluations of wetland restorations called for in *Sharing the Challenge*, and will even enable a degree of design to maximize flood benefits.

**References**

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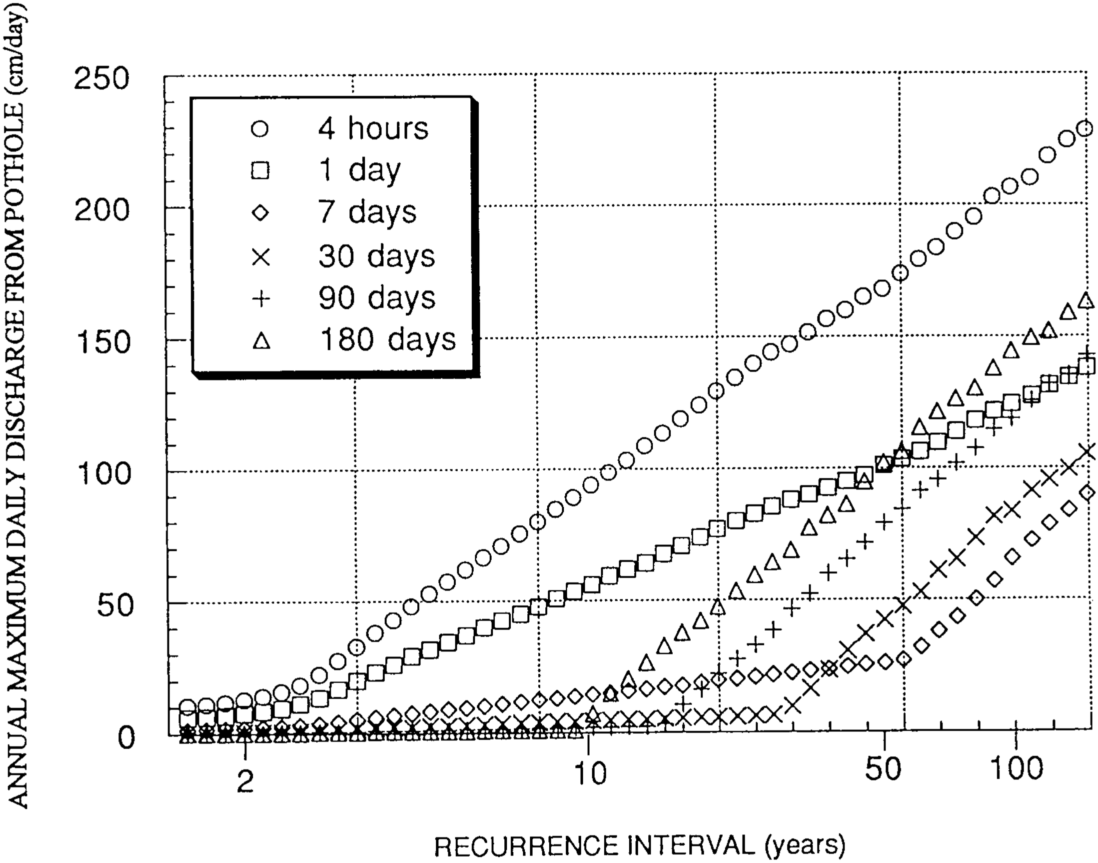

Figure 1. Flood frequency distribution of annual maximum daily discharge from pothole for time constants of 4 hours, 1 day, 7 days, 30 days, 90 days, and 180 days.