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Simulated Use of 'First-Order' Ponds to Reduce Peakflow in an Eroding River System

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Introduction

One of the most widely implemented but poorly understood Best Management Practices (BMPs) for watershed protection is the construction of small reservoirs or farm ponds, which can reduce peakflow and enhance sediment and nutrient storage at the landscape scale. These important ecosystem services have been lost in many locations throughout the United States due to wetland loss (Dahl 1990, Mitsch and Gosselink 2007). In the area of Northwest Arkansas, wetland loss was probably driven largely by the widespread eradication of beaver in the landscape (Naiman 1988, Gurnell 1998). However, as wetlands were removed from the landscape, many were replaced by man-made impoundments that centralized water resources in order to open lands for other uses (Renwick et al. 2005).

Similar to wetlands, man-made impoundments decrease peakflow, increase the water residence time, and consequently store tremendous quantities of sediment and nutrients (Nurnberg 1984, Brett and Benjamin 2008). The settling velocity of abiotic and biotic particles suspended in water is determined by the size and density of the particle. Thus, the ability of a reservoir to store particles is determined by the length of time water resides in the reservoir and the various settling velocities of the particles. For models that include biological uptake, retention efficiency (R) has been shown to be a function of the flushing rate:

$$R = \sigma/(\rho+\sigma) \qquad (1)$$

where σ is a first-order rate constant for material loss (per month) and ρ is the flushing rate of the waterbody (per month). The material loss constant (σ) is a function of the type (abiotic versus biotic) and size of the particle and the flushing rate (ρ) is:

$$\rho = Q/V \qquad (2)$$

where Q is the average monthly flow into the waterbody (m^3/month) and V is the volume of the waterbody (m^3). This model represents a single formulation for estimating material storage and many others have been developed that rely upon other hydrologic predictors such as the water residence time ($\tau = V/Q$) or areal hydraulic load ($q = Q/A$ where A is surface area). These variables are all interdependent and relate to physical attributes of a system such as watershed size and relief, and waterbody capacity. As a result, in a small region with homogeneous rainfall patterns, the efficiency of material retention can be estimated by the ratio of waterbody capacity to watershed area. Thus, the storage potential of new reservoirs can be maximized by adjusting the capacity according to the size of the watershed that drains into a reservoir. These techniques can be used to develop a plan for building new reservoirs and assessing their impact on downstream water quality.

The objective of this research was to simulate the effect of building new ponds or retrofitting existing ponds on the hydrology of the West Fork White River in Northwest Arkansas. We were particularly interested in the placement of small ponds that were approximately 1 acre in surface area at the outlets of headwater streams. Further, we were interested in prioritizing the headwater streams based on their prospective contribution to peak flow in the river according to the curve number associated with each subbasin. We utilized readily available remote sensing data to simulate the potential effect of ponds on watershed hydrology and specifically peakflow conditions. While most studies have focused on the placement of single ponds on stormwater, our objective was to simulate larger scale effect of constructing a system of ponds across an entire watershed.

Materials and Methods

Study Location and Data Sources

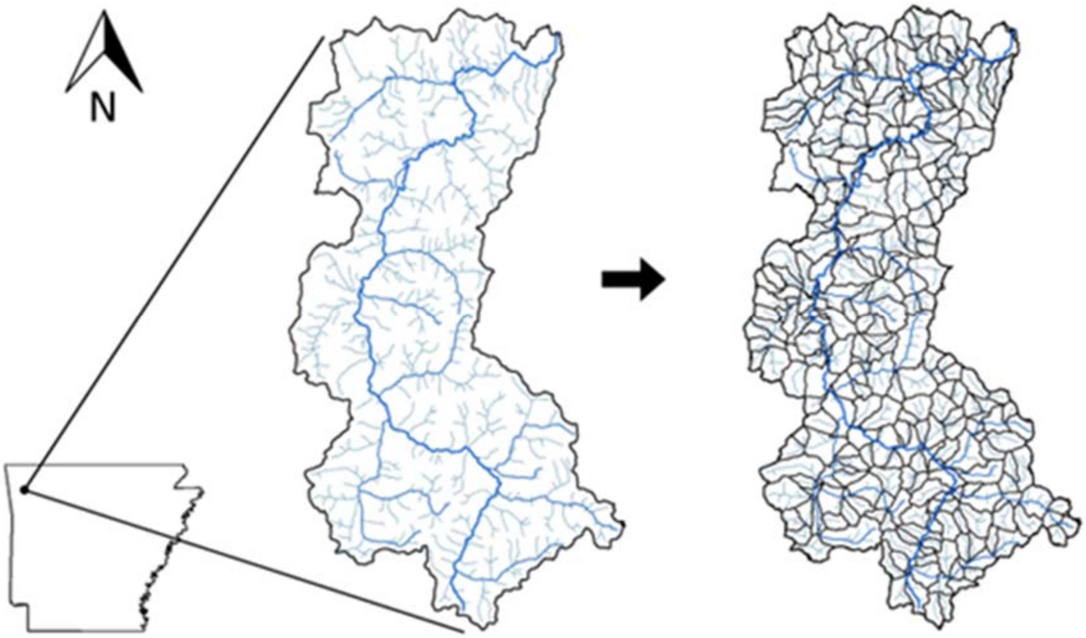
The West Fork of the White River drains 322 km^2 of land in Northwest Arkansas. The river flows primarily north and drains into the White River immediately east of Fayetteville, Arkansas. The West Fork White River drainage boundary was downloaded along with river flow lines from the National Hydrography Database (USGS 2013a; Figure 1). A LIDAR digital elevation model for Washington County Arkansas was downloaded from the Arkansas GIS Office (gis.arkansas.gov). These datasets were used in combination with the ArcHydroTools application in ArcGIS 10.2 to develop layer of sub-basins in the watershed which were approximately 1 – 5 km^2. As a result, 278 sub-basins were identified in the West Fork White River watershed (Figure 1). In addition to these spatial data, land cover data for the watershed were downloaded from the 2006 National Landcover Database (USGS 2013b) and soil data were downloaded from the SSURGO Database (NRCS 2015).

Sub-basin Characterization, Prioritization, and Pond Design

Because our interest was simulating the effect of ponds that were relatively high in the landscape, we chose to work with 143 sub-basins in the West Fork White River that represented the headwater streams of the watershed. Sub-basins were characterized based on their soil type and landcover. The most spatially frequent hydrologic soil group (A-D) from the SSURGO database was identified for each sub-basin and assigned to represent the whole sub-basin. Similarly, the dominant landcover category was estimated for each sub-basin and assigned to represent the whole sub-basin. The information on dominant hydrologic soil group and dominant landcover were combined to derive a runoff curve number for average antecedent moisture conditions (AMC II; Mays 2011). The 143 sub-basins were ranked according to their curve number and placed into four hierarchical groups: 1. All headwater sub-basins, 2. Headwater sub-basins with moderate hydrologic risk, 3. Headwater sub-basins with elevated hydrologic risk, and 4. Headwater sub-basins with severe hydrologic risk. Hydrologic risk was estimated from the unique curve number value assigned to each sub-basin (Table 1).

The optimal flood volume of a receiving pond (m^3) at the outlet of each of the sub-basins was derived by multiplying the sub-basin area (km^2) by 10,000, which approximates the reservoir capacity to watershed area that maximizes retention efficiency (Verstraeten and Poesen 2000). The surface area of the ponds was computed by assuming that all ponds had an aver-

Figure 1. West Fork White River Watershed located in Northwest Arkansas. The watershed was divided into 278 unique sub-basins of similar size in order to simulate the effect of pond construction on watershed hydrology.



age flood pool thickness of 2.5 m. We assumed that the ponds could be constructed or retrofitted so that the complete flood pool would drain automatically over a period of seven days. Based on this assumption and the size of the flood pool for ponds in each sub-basin, a pond-specific drainage rate (Q_{drain}) was computed and expressed as discharge (m^3/s).

Hydrologic Simulations

Snyder's synthetic unit hydrographs (Mays 2011) were created for each headwater sub-basin to evaluate the effect of ponds on simulated peakflow in the West Fork White River. Briefly, channel length (L), centroid to outflow length (L_c), and watershed area were derived from sub-basin layers generated as previously described. The watershed-specific parameters C_1 and C_t were assumed to be 1 and 2, respectively, across all sub-basins. Time to peak flow (t_p) was computed as:

$$t_p = C_1 C_t (L * L_c)^{0.3} \qquad (3)$$

and peak duration was computed as:

$$t_r = t_p / 5.5 \qquad (4)$$

so that the time to peak for a desired duration (t_{pR}) was:

$$t_{pR} = t_p + 0.25\,(t_R - t_r) \qquad (5)$$

where t_R was 0.5. Using the time to peakflow for a given duration, peakflow per unit rain (Q_{pR}) was computed as:

$$Q_{pR} = \frac{C_2 C_p A}{t_{pR}} \qquad (6)$$

Table 1. Curve numbers assigned to each sub-basin based on the combination of landcover categories and hydrologic soil groups.

	Hydrologic Soil Group			
Land Use Category	A	B	C	D
Developed - Open Spaces	72	82	87	89
Developed - Low Impact	76	85	89	91
Developed - Medium Impact	83	89	92	93
Pasture	68	79	86	89
Deciduous Forest	32	58	72	79

where C_2 was 640 and A was the sub-basin area. In order to construct the unit hydrograph, the width of the hydrograph at $0.5Q_{pR}$ and $0.75Q_{pR}$ was also needed. Hydrograph width at $0.5Q_{pR}$ was calculated as:

$$W_{50} = \frac{C_{50}}{(Q_{pR}/A)^{1.08}} \qquad (7)$$

where C_{50} was 770. Hydrograph width at $0.75Q_{pR}$ was calculated as:

$$W_{75} = \frac{C_{75}}{(Q_{pR}/A)^{1.08}} \qquad (8)$$

where C_{75} was 770. In order to simulate that the unit hydrograph represented 1 inch of direct runoff, the base (T_b) was calculated as:

$$T_b = 2{,}581\,\frac{A}{Q_{pR}} - 1.5W_{50} - W_{75} \quad (9)$$

The slopes of the rising and falling limbs and the intercept value of the falling limb of the hydrographs were computed for a simulated 1 inch runoff event. The events were propagated for all sub-basins to a 12 hour potential hydrograph that yielded the flow volumes for each sub-basin based on 1 inch of runoff so that the synthetic unit hydrographs output flow volumes expressed as $m^3\ s^{-1}\ in^{-1}$.

The rainfall runoff relationship for each sub-basin was simulated using the NRCS empirical relationship:

$$S = \frac{1000}{CN} - 10 \qquad (10)$$

where S is the maximum potential retention of surface runoff from a sub-basin and CN is the curve number associated with each unique sub-basin. S was used to estimate the approximate amount of runoff yielded from the individual basins assuming 1 inch of rain on a moderately wet watershed. The runoff amount (inches) was then multiplied by the unit hydrograph solved on 30 minute intervals over a 12 hour duration to drive flow volumes of a simulated runoff event. Similar simulations were computed to estimate the effect of ponds when antecedent rainfall conditions were excessively dry and excessively wet.

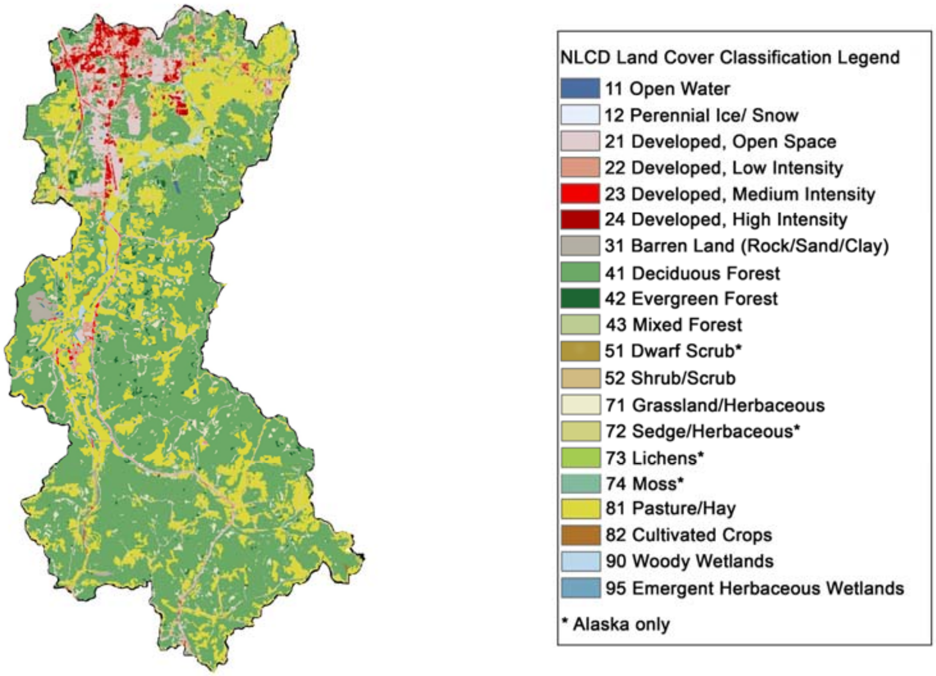
An algorithm was derived to simulate the retention, flow through, and outflow of water from ponds based on the pond flood volume, the accumulated volume during a runoff event, and the drainage rate for each pond (Q_{drain}). When pond volume exceed the flood pool volume, outflow rate was set equal to the inflow rate. Otherwise, inflow volumes resulted in water accumulation to the maximum flood pool for each pond. Because the simulations were intended to demonstrate the effect of headwater sub-basins, the flows were not routed and we assumed that a 1 inch rainfall event was homogeneous across the entire watershed. As a result, flow outflow volumes from the ponds were summed to indicate the effect of pond retention on simulated river peakflow. Peakflow (Q_{max}) was simulated for each sub-basin based on the presence or absence of a pond at the outlet. The percent reduction in peakflow caused by a pond installation was calculated as the difference between peakflow with and without a pond and divided by the simulated peakflow when no pond was present.

Results

Three primary landcover patterns occurred in the West Fork White River Watershed. Deciduous forest comprised 57% of the watershed area, developed pastures comprised 25% and various intensity urban comprised 13% (Figure 2). Based on the hydrologic soil groups and landuse with the sub-basins, potential curve numbers assigned to the basins could have ranged from 32 – 95. However, soil hydrologic groups even in highly forested sub-basins rarely represented well-drained conditions that would result in a high hydrologic ranking. Thus, curve numbers assigned across the sub-basins ranged only from 60 – 95. The vast majority of these sub-basins had a curve number of approximately 75 (Figure 3).

Of the 143 headwater sub-basins, 115 were classified as moderate hydrologic risk because their assigned curve numbers were between 70 – 74; 41 sub-basins were classified as having elevated hydrologic risk because their curve numbers were between 75 – 79; 22 sub-basins were classified as having severe hydrologic risk because their curve numbers exceeded 80 (Table 2). The 28 ponds that were considered as

Figure 2. Landcover/landuse patterns in the West Fork White River Watershed.



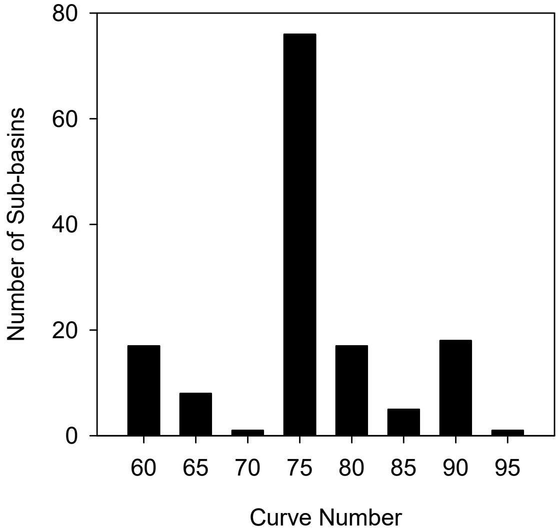


Figure 3. Histogram showing the number of sub-basins assigned various curve numbers based on the dominant land-cover and dominant soil hydrologic condition in each sub-basin, respectively.

low hydrologic risk were almost exclusively in forested sub-basins (Figure 4). Conversely, many of the moderate and elevated hydrologic risk sub-basins had a relatively high proportion of pasture lands, and sub-basins classified as having severe hydrologic risk were either exclusively urban or had a high proportion of both pasture and urban land cover (Figure 4). The average pond volume across all sub-basins was approximately 12,500 m^3, and did not vary with varying hydrologic risk across sub-basins (Table 2).

The shapes of simulated unit hydrographs were obviously different when ponds were included or excluded from the simulations (Figure 5). When all 143 sub-basins were simulated to have a pond, flow conditions in the first two hours of the hydrograph were substantially reduced (Figure 5a). Further, peakflow was reduced by 65% in this scenario and by as much as 87% when antecedent moisture conditions were assumed to be dry (Table 3). A similar result was apparent when only the sub-basins at moderate hydrologic risk were included in the analysis (Figure 5b, Table 3). The efficiency of ponds decreased substantially when they were simulated in only the sub-basins with elevated or severe hydrologic risk (Figure 5c and 5d). However, installing ponds in the elevated and severe hydrologic risk sub-basins still resulted in a 13 – 25% reduction in peakflow based on average moisture conditions (Table 3). In fact, the proportion of peakflow reduction caused by pond installation appeared to increase proportionally to the number of ponds installed in the headwater sub-basins (Figure 6).

Table 2. Sub-basin and pond characteristics for each of the four modeling scenarios.

Priority	# Sub-basins	Curve Numbers	Avg. Pond Flood Volume (m^3 ± SD)	Total Pond Flood Volume (m^3)
All Headwater Sub-basins	143	All	12,257 ± 7,257	1.75 x 10^6
Moderate Risk Sub-basins	115	70-74	12,741 ± 7,588	1.47 x 10^6
Elevated Risk Sub-basins	41	75-79	12,679 ± 7,549	5.20 x 10^5
Severe Risk Sub-basins	22	≥ 80	12,740 ± 8,346	2.80 x 10^5

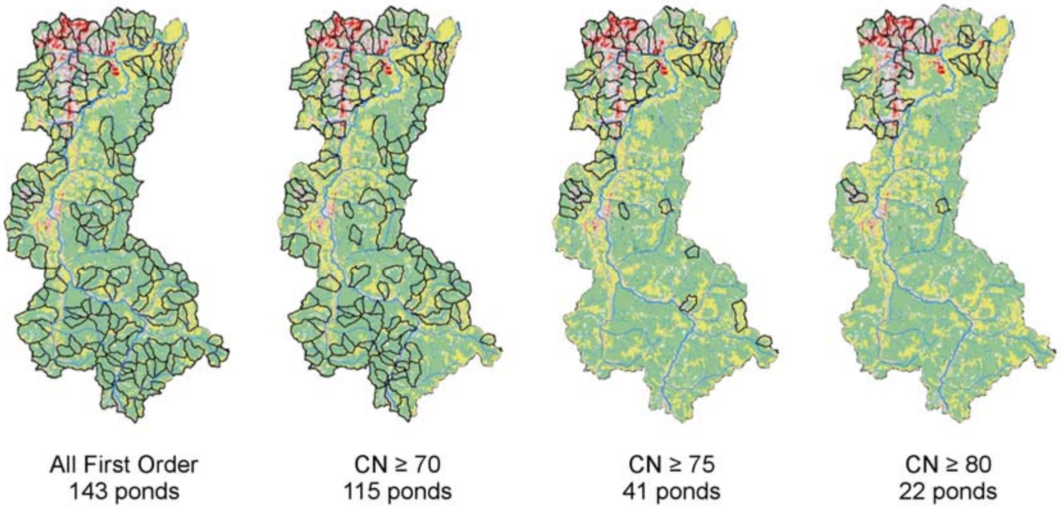


Figure 4. Sub-basins used in four distinct simulations that included all headwater sub-basins, moderate hydrologic risk sub-basins (CN ≥ 70), elevated hydrologic risk sub-basins (CN ≥ 75), and severe hydrologic risk sub-basins (CN ≥ 80).

Discussion

Peakflow reductions from pond construction

The objective of this work was to simulate the effect of constructing or retrofitting ponds in the West Fork White River watershed in order to increase the water residence time and decrease the peakflow experienced by the river. Indeed, our analysis suggested that the construction of only 22 ponds in the severe risk sub-basins could decrease peakflow by almost 15% (Table 3). These results show that relatively small waterbodies placed strategically within a watershed can have a major effect on watershed hydrology. The 22 ponds simulated in the severe risk sub-basins were approximately 1 acre in surface area and had an average flood pool depth of 2.5 m. However, they have the potential to measurably decrease peakflow in a watershed that is greater that is greater than 75,000 acres in surface area.

Our analysis also suggested that the percent reduction in peakflow in the watershed increased proportionally to the number of ponds constructed, to a maximum of approximately 65% reduction in peakflow (Figure 6). In fact, the percent peakflow reduction appeared proportional to the number of ponds added up to approximately 120 ponds in the watershed (% reduction = 0.52 * #ponds; $r^2 = 0.99$). This indicates that river peakflow decreases by 0.52% for every new pond added at the outlet of a headwater sub-basin, up to the 120 most at risk sub-basins. The decrease in peakflow slows rapidly with the construction of more than 120 ponds in the watershed. If these results were used to inform a watershed management scenario, the priority should be on constructing ponds at the outlet of sub-basins that were classified as a severe hydrologic risk (i.e. CN ≥ 80). These severe hydrologic risk sub-basins were highly developed and included much of the high-intensity urban environment in the northwest region of the watershed (Figure 4).

Table 3. Simulated peakflow from modeled sub-basins with and without simulated pond conditions and the percent reduction in peakflow caused by placing a pond at the outflow of the simulated sub-basins for various antecedent hydrologic conditions.

Curve Number Category	Q_{max} (m^3/s)		Q_{max} Reduction (%)
Antecedent Rainfall Conditions	Without Ponds	With Ponds	
All headwater sub-basins			
Dry	20.2	2.7	86.8
Intermediate	146.8	51.7	64.8
Wet	485.6	442.4	8.9
Moderate risk sub-basins			
Dry	20.2	15.1	25.3
Intermediate	146.8	55.0	62.5
Wet	485.6	461.2	5.0
Elevated risk sub-basins			
Dry	20.2	16.8	16.6
Intermediate	146.8	110.3	24.9
Wet	485.6	481.0	0.9
High risk sub-basins			
Dry	20.2	16.6	17.6
Intermediate	146.8	127.4	13.2
Wet	485.6	480.7	1.0

Model limitations, assumptions, and recommendations for future work

It is important to stress that the analysis presented herein was a simulation exercise that would benefit greatly from an empirical analysis or model validation. There were numerous assumptions made regarding watershed hydrology, geomorphology, and the potential for constructing ponds of similar size and flood volumes at disparate locations throughout the watershed. One major limitation to the approach used was that the variability in curve numbers across the watershed was not ideal. For example, sub-basin curve numbers ranged from as low as 60 to as high as 95, but the vast majority of sub-basins had a curve number of approximately 75. The consequence of the homogeneity in curve numbers is that there was a substantial disconnect in evaluating peakflow reductions when ponds were gradually and systematically added to the analysis. Rather, in going from the elevated to moderate risk hydrologic sub-basins in the analysis, the number of sub-basins with ponds increased from 41 to 115. This was the result of such a large number of sub-basins having similar curve numbers in the range of 75.

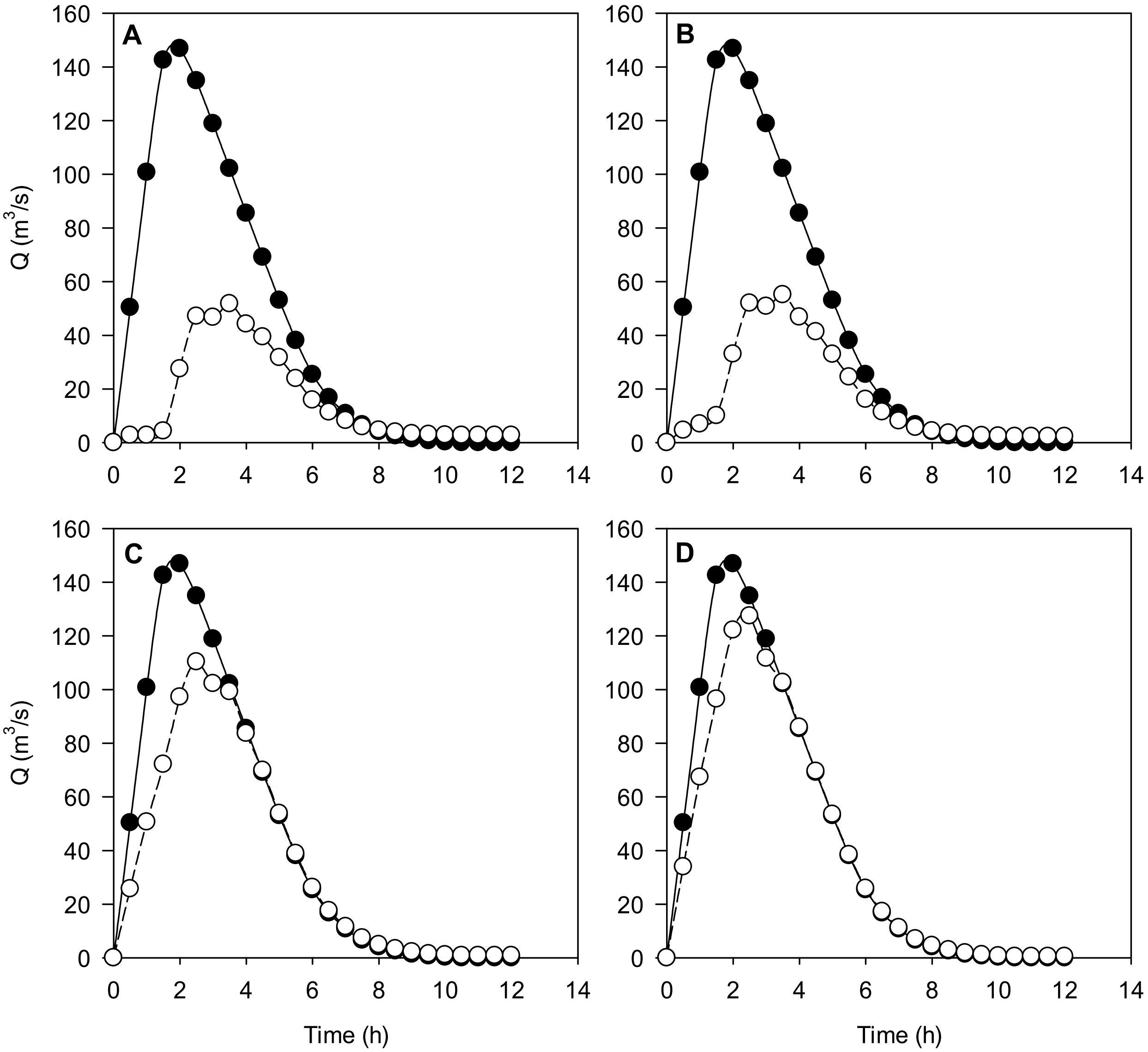


Figure 5. Simulated peakflow without (black circles and line) and with (white circles and line) ponds across A) all headwater sub-basins, B) moderate hydrologic risk sub-basins (CN ≥ 70), C) elevated hydrologic risk sub-basins (CN ≥ 75), or D) severe hydrologic risk sub-basins (CN ≥ 80).

Another major assumption in the study included selecting curve numbers based on the average sub-basin conditions. Another approach would have been to use spatially-explicit information on landuse and soil hydrologic condition to weight the identification of the curve number, but this would have required the development of an automation procedure that was beyond the scope of the study. The study presented here was also limited to the 143 sub-basins that qualified as headwaters. This was based on the idea that the target size for new ponds in the basin should be approximately 1 acre with an average depth of 2.5 m, and assumed a constant proportion between flood capacity and optimal watershed size.

This study represents a first-cut analysis of the

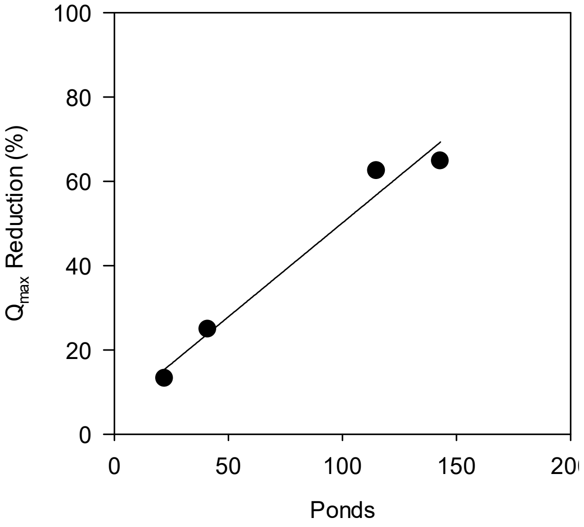


Figure 6. Relationship between the number of ponds added based on their prioritization through sub-basins or varying hydrologic risk and the percent reduction in peakflow associated with adding ponds.

potential for ponds to reduce peakflow and presumably enhance sediment and nutrient retention at the landscape scale. The estimates provided here represent a scientifically defensible estimate of how ponds can reduce peakflow in the West Fork White River Watershed. However, these estimates could be greatly enhanced with the development of a fully calibrated watershed model. Such a model could address some of the assumptions made in the simulations provided in this study, and could also build upon the constraining factors used here such as pond size and location. However, even a fully-calibrated watershed model would only represent a simulation of expected events. What remains needed in watershed science is a large-scale empirical analysis of the effect of pond construction on watershed hydrology. Given the background information available, the West Fork White River Watershed is an ideal candidate for that type of research if a sufficient funding source could be identified.

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