Effect of Channel Restoration on Flood Wave Attenuation

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Abstract: Stream channel restoration can increase flow storage and energy dissipation of passing flood waves. Elements of restoration design that can enhance attenuation include remeandering, which reduces channel slope and increases channel length relative to the floodplain; restoring channel-floodplain connectivity; and revegetating banks and the floodplain. Reestablishment of floodplain hydraulic function is increasingly a goal of restoration programs, yet the approximate magnitude of possible change to attenuation due to reach-scale restoration remains poorly quantified. We examined the efficacy of channel restoration on flood attenuation using restored reaches and synthetic reaches representing median dimensions of channel restoration projects in North Carolina (e.g., ~1 km in length). We applied an industry standard dynamic flood routing model (UNET in HEC-RAS) to route floods in impaired and restored reach models. Floods routed through field-based reach models either exhibited very small increases in attenuation, largely due to assumed increases in floodplain roughness, or a decrease in attenuation. Analysis demonstrated that attenuation of peak discharge is overall most sensitive to channel and valley slope, channel and floodplain roughness, and channel and valley length in decreasing order, but is dependent on flood magnitude. Restoration most impacted floods of intermediate magnitude (between 2- and 50-year return interval), particularly those confined to the channel under the impaired morphology but able to access the floodplain under the restored morphology. Restoration may rehabilitate a channel's ability to attenuate small to intermediate floods by augmenting flood access to the floodplain, changing channel geometry, and enhancing channel and floodplain roughness over time. However, our study shows that the predominantly small scale of current channel restoration will provide minimally quantifiable enhancement to flood attenuation.

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Introduction

Channel Restoration and Flood Wave Attenuation

Stream channels are restored to meet a variety of goals including maintaining water quality, providing habitat for aquatic species, and storing and attenuating flood flows [Federal Interagency Stream Restoration Working Group (FISWRG) 1998]. Flood flows are detained within a channel throughout its length and in low, flood prone areas (Dunne and Leopold 1978). Woody debris (Shields and Gippel 1995), meanders (Fares 2000), and vegetation (Ghavasieh et al. 2006) within the channel and floodplain impact flood waves by reducing flow velocity and providing temporary storage of flood waters. A flood wave traveling through a channel with these features will have its instantaneous peak discharge (Q_{pk}) and celerity (wave speed, c), among other hydraulic parameters, reduced as it moves downstream, assuming no inputs from tributaries. Such effects will result in an attenuated downstream hydrograph, i.e., one that is longer in duration with a decreased Q_{pk}. Flood attenuation can be quantified several ways. For the purposes of this study, attenuation will be quantified by relative and absolute reductions to Q_{pk}, with units of discharge ($m^3\ s^{-1}$), and average celerity, c_{AVG}, defined as the distance traveled divided by the peak to peak travel time, with units of velocity ($m\ s^{-1}$).

Direct or indirect modifications to a channel that increase its conveyance capacity can reduce flood attenuation and cause floods to travel more quickly. Channel straightening, deepening, and widening (channelization) increase conveyance by augmenting the volume of the channel per unit length, steepening its slope, and reducing the effective roughness of the channel. Comparison of flood hydrographs between adjacent straightened and meandering streams (Doyle and Shields 1998) and between streams prior to and after channelization demonstrated increases in downstream Q_{pk}, peak stage, and c (Campbell et al. 1972; Wyzga 1996). While channelization efforts reduce flooding locally, they can increase flood hazard downstream (Shankman and Pugh 1992). Incision and enlargement caused by increased catchment runoff from land use change (e.g., Booth 1990; Doll et al. 2002) or downstream changes to slope from channelization (Wyzga 1996; Doyle and Shields 1998) can generate the same effect on floods. These represent channel modification indirectly resulting from human impacts.

From a theoretical standpoint, the capacity for a flood wave to attenuate is related to the relative magnitude of the inertia and pressure gradient components of the dynamic momentum equation compared to the magnitude of the bed slope (Sturm 2001). In order for attenuation to exist, the pressure gradient term (and possibly the inertia terms) must be of the same approximate order as the bed slope (Henderson 1966). On reaches where the bed slope is less than approximately 0.001 m/m and where the rate of change in stage is greater than approximately 0.01 $m\ hr^{-1}$, the

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inertia and pressure gradient components may not be negligible relative to the bed slope resulting in a dynamic or diffusion wave that attenuates and has a looped rating curve (Fread 1975). For steeper reaches, the kinematic approximation more closely describes the flood wave, which does not attenuate, but rather translates downstream, and has a unique relationship between stage and discharge (Henderson 1966).

One of the potential benefits of channel restoration is the reversal of the effects of channelization and incision by restoring the ability of a stream channel and floodplain to slow down and retain flood waters (e.g., Acreman et al. 2003; Campbell et al. 1972; Liu et al. 2004). This may be accomplished through various aspects of channel restoration design: (1) introduction of meanders increases sinuosity and channel flow path relative to valley length and decreases channel slope relative to valley slope; (2) vegetation (re)introduction along the banks and within the floodplain enhances roughness; and (3) creation of a smaller channel with a floodplain at a lower relative elevation allows floods of a designed frequency and magnitude to leave the channel and spread out into the floodplain where flood waters are slowed and temporarily stored. Conceptually, channel restoration has the potential to augment the ability of an incised or channelized reach to reduce Q_{pk} and disperse flood waves via enhanced energy dissipation and increased channel and floodplain storage capacity.

Previous work has quantified the effects of various channel and floodplain properties on the propagation of flood waves using flood routing models. Many of these studies found that changing channel properties produced additional attenuation, but this occurred over distances and at scales much larger than is typical in most U.S. channel restoration efforts. For example, Wolff and Burges (1994) measured attenuation over a synthetic 80-km reach, and Ghavasieh et al. (2006) and Anderson et al. (2006) modeled the effects of various synthetic vegetation arrangements along the channel and in the floodplain over 20- and 50-km reaches, respectively. However, on a national basis, the length of most stream restoration projects is on the order of 1 km (Bernhardt et al. 2007), often on first through third-order streams. It is unclear whether flood wave attenuation can be affected over such limited lengths of restoration.

While the effects of various aspects of channel and floodplain properties on flood wave attenuation have been studied, the effects of channel restoration at the scale on which it generally occurs has not been considered. This study uses measurements of floods routed through restored reaches in conjunction with a one-dimensional dynamic flood routing model to quantify the effect of reach-scale restoration on flood waves before and after channel restoration. This study pursued the following questions: (1) does the scale of common channel restoration projects allow significant enhancement to flood wave attenuation?; (2) what scale of floods (i.e., what return interval) are most amenable to restoration-enhanced attenuation?; and (3) what specific elements of channel restoration design are most critical to attenuate flood waves?

We use a one-dimensional dynamic flood routing model to route floods through reach-scale models of synthetic and field-based channels and compare attenuation metrics between impaired and restored morphologies and among hydrographs of varying return intervals (RIs). We also identify the relative importance of channel and floodplain properties altered by channel restoration on flood wave attenuation with a sensitivity analysis of channel properties on routed floods.

Analysis of Flood Routing

Unsteady Flow Model Description

The unsteady flow modeling component of Army Corps of Engineers' Hydrologic Engineering Center river analysis system [HEC-RAS version 4.0; U.S. Army Corps of Engineers (USACE) 2008], UNET, developed by (Barkau 1996) was used for dynamic flood routing in this study. HEC-RAS is widely used within the channel restoration design community; and HEC-RAS modeling, or a comparable one-dimensional model, is often required as part of channel restoration designs.

One-dimensional flood routing models are widely applied to practical and theoretical questions associated with flood wave routing (Knight 2005). However, they do not explicitly account for the two- and three-dimensional aspects of energy dissipation due to turbulence exchange at the interface of floodplain and channel flows or momentum lost in transverse flows around meander bends (Shiono 1999; Knight and Shiono 1996). Instead, it compartmentalizes channel and floodplain flow, where changes to reach sinuosity is simulated by changing the longitudinal channel length relative to the longitudinal floodplain length. Though one-dimensional models lack multidimensional sophistication and associated potential accuracy, the energy losses associated with complex and transverse flows can be approximated by the roughness coefficients used in calibrating one-dimensional models. A one-dimensional model will be able to quantify the relative change in flood wave attenuation between impaired and restored scenarios and serve for the sensitivity analysis to channel and floodplain properties. It, therefore, suffices for this study. Using HEC-RAS also promotes the applicability of this study to channel restoration practitioners because of its widespread use in the restoration industry.

Model Parameterization

We assessed the impact of channel reconfiguration on flood waves through field measurements and hydraulic modeling. Synthetic and field-based stream reaches representing impaired and restored morphologies were modeled in HEC-RAS and floods of varying magnitudes where routed through these reaches to compare attenuation. The primary response variables used in this study to quantify attenuation were changes to instantaneous peak discharge (Q_{pk}) and average celerity (c_{AVG}, distance between stations over peak to peak travel time).

The boundary conditions required for numerical unsteady flow routing in UNET include reach geometry, channel and floodplain roughness values, and upstream and downstream hydraulic boundary conditions. A constant friction slope equal to the channel bed slope was used as the downstream boundary condition and discharge hydrographs were input at the upstream boundary. The downstream boundary condition was placed several cross sections below the downstream station on each reach model to avoid influencing the flood routing at the point of hydrograph observation. The finite difference approximation weighting factor, θ, used in the numerical solution of the Saint-Venant equations in the UNET was set to 0.6 for the synthetic models and 0.7 for the field-based models. These θ values represented the minimum values that maintained model stability in each scenario while minimizing numerical dampening (Liggett and Cunge 1975). The time step in all models was kept the same at 5 min to match the time resolution of the stage data recorded in the field. As measured from the approximate beginning of rise in flow to return to base

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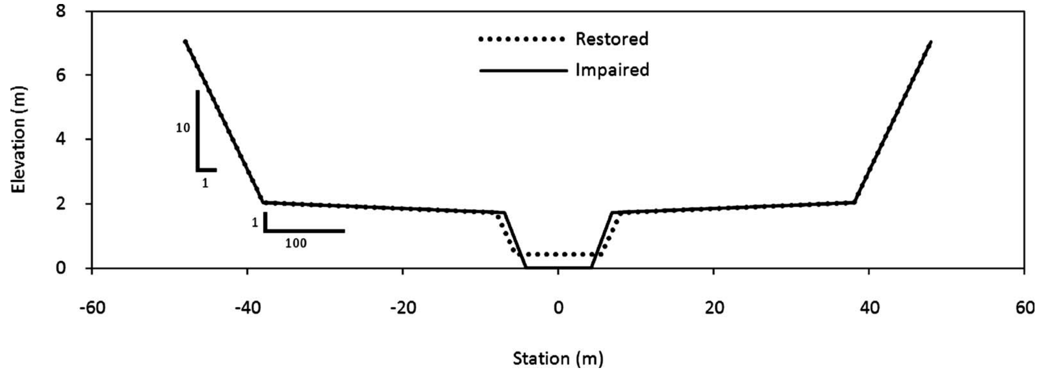

Fig. 1. Diagram of channel and floodplain geometry used in synthetic impaired and restored reach models. Channel roughness and channel flow path length were increased to represent introduction of meanders for the restored reach model.

flow, hydrographs measured in the field had durations ranging from 19 to 44 h and hydrographs used in the synthetic models had a duration of 15 h. Distance between cross sections ranged from 75 to 225 m over reaches ranging from 800 to 1,400 m in total length.

Numerical attenuation and dispersion are an issue inherent in hydraulic models that use finite difference approximations to solve equations of physical processes such as UNET (Liggett and Cunge 1975). Because of this, they may tend to overestimate physical attenuation. Three computational parameters which affect the degree of numerical attenuation were evaluated to assess their impact to routed flow output: the distance between cross sections (Δx), the computational time step (Δt), and θ, the weighting factor used in the finite difference approximation of the Saint-Venant's equations. Each parameter must be adjusted to minimize numerical damping while maintaining model stability. The sensitivity of the model to each parameter was assessed by routing synthetic hydrographs of varying RIs through the synthetic restored reach while each parameter was altered individually.

The model is most sensitive to θ, which was varied from 0.6 to 1.0, corresponding to a reduction in output Q_{pk} relative to input Q_{pk} that ranged from 3.6 to 6.1%, respectively, for the Q_{100} hydrograph and 1.9–3.1%, respectively, for the Q_2 hydrograph. The model is insensitive to cross-sectional spacing (Δx), and marginally sensitive to the time step (Δt). In each case, increasing Δx and Δt increases numerical damping due to averaging discharge values over longer spatial or temporal intervals. Numerical dampening from UNET has been shown above to significantly impact modeled attenuation. We avoid this issue by (1) maintaining the same values of θ, Δt, and Δx between each impaired and restored reach model and (2) focusing our analysis on the relative difference in attenuation metrics between impaired and restored conditions and not on absolute modeled attenuation.

Synthetic Model Generation

We first compared the differences in attenuation among synthetic flood hydrographs routed through synthetic impaired and restored reach models. We also assessed the relative importance of hydraulically significant design elements used in channel reconfiguration projects, including changes to channel sinuosity, cross-section geometry, and floodplain characteristics, by varying the values of these elements $\pm 10\%$ from a baseline condition and assessing their relative impacts on routed flood waves.

Two synthetic stream reaches were developed to quantify changes to attenuation resulting from median values of channel change associated with restoration: (1) an "impaired" reach with incised banks and (2) a "restored" reach with a greater channel length and milder channel slope (relative to the floodplain) representing meandering, including a greater width to depth ratio among other adjustments (Fig. 1). In order to understand the scale of channel restoration (i.e., length and drainage area) and the magnitude of changes to channel properties involved in restoration, we used available data from a sample of restoration projects to define our synthetic channel conditions. Data were taken from restoration projects ($n=20$) conducted through the North Carolina stream and wetland mitigation program: the Ecosystem Enhancement Program (BenDor et al. 2009). These values along with regional hydrology data (Robbins and Pope 1996) and hydraulic geometry curves (Doll et al. 2002) provided an empirical context for the synthetic impaired and restored reaches. Manning's roughness coefficients for the impaired reach were chosen to represent a straight lowland stream with some weeds and stones in the channel ($n=0.035$) and a grassy floodplain ($n=0.05$). Roughness values for the restored reach were chosen to represent a meandering stream of the same type ($n=0.045$) with a forested floodplain containing undergrowth ($n=0.15$) (Chow 1959). Table 1 outlines the parameters and their sources for these synthetic reaches.

A set of synthetic hydrographs was generated to route through the synthetic reach models. First, a 24-h synthetic unit hydrograph was generated using the TR-55 method [Natural Resources Conservation Service (NRCS) 1986] for a hypothetical urban watershed with the mean drainage area of the sample restoration projects (17 km^2) and an assumed 30% impervious surface coverage. The unit hydrograph was converted to flood hydrographs with RIs of 2, 10, 50, and 100 years (Q_2, Q_{10}, Q_{50}, and Q_{100}) using local precipitation depths for the 2- to 100-year events from National Oceanic and Atmospheric Administration (NOAA) (2006) and scaled using fitted power law equations relating Q_{pk} to drainage area and impervious cover percentage, which were developed by the USGS (Robbins and Pope 1996) for urban drainages in the North Carolina Piedmont, as described by Sholtes (2009). The channel of the synthetic restored reach was designed to accommodate the Q_{pk} of the Q_2 flood at a bankfull elevation.

The hydrographs generated for the synthetic model attenuation analysis all have the same time to peak of approximately 13 h after onset of rainfall as derived from the Soil Conservation Service (SCS) type II synthetic 24-h rainfall distribution used in the TR-55 method. These hydrographs represent a relatively short and intense precipitation event where the majority of rainfall oc-

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Table 1. Hypothetical Channel Restoration Parameters

Reach	Drainage area[a] (km^2)	Channel length[a] (m)	Valley length[a] (m)	Sinuosity	Channel slope[a] (m/m)	Manning's n channel[b]	Manning's n floodplain[b]	Bankfull width (m)	Mean depth (m)	Bankfull area (m^2)	Q at top of bank[e] $m^3\ s^{-1}$	W:D[d]	Rosgen class
Impaired	17	881	696	1.27	0.0050	0.035	0.05	13.8[c]	1.4[c]	19.3[c]	48.8	9.9	G
Restored	17	917	696	1.32	0.0048	0.045	0.15	16[d]	1.1[d]	17.6	28[c]	14.6	C

[a]Derived from sample of 20 channel restoration projects conducted in North Carolina (Sholtes 2009).

[b]Manning's roughness coefficient values for channel and floodplain from Chow (1959).

[c]Derived from regional hydraulic geometry relationships for urban channels in the North Carolina Piedmont (Doll et al. 2002).

[d]Values associated with respective Rosgen (1997) stream classification.

[e]Normal depth flow at top of bank elevation.

curs in a small time frame. While hydrograph intensity, or ratio of hydrograph peak to volume, has been shown to affect attenuation (e.g., Woltemade and Potter 1994), this particular aspect of flood hydrology is outside of the scope of this study. Given the theoretical urban setting in which this synthetic restoration example occurs, peaked or flashy hydrographs most closely represent the flood hydrographs that are likely to occur (Leopold 1968).

A sensitivity analysis of flood attenuation to individual channel and floodplain properties was conducted using the synthetic restored reach model as a baseline. Modeled differences in flood attenuation metrics due to $\pm 10\%$ changes from the baseline morphology for the following channel and floodplain properties was recorded: channel sinuosity, simulated by changing the channel flow path length relative to the valley length, channel and floodplain roughness, channel slope, channel length, channel wetted perimeter, and floodplain width.

Field-Based Model Generation

We next measured flood wave attenuation in restored (i.e., reconfigured) channels at two field sites representative of other restoration projects in North Carolina (Fig. 2 and Table 2). The study reach on the Unnamed Tributary to South Fork Creek site (UT South Fork) is 808 m along this first-order stream that drains 2.3 km^2 at its inlet of actively grazed lands with minimal development and small amounts of forest cover. UT South Fork had likely been incised from a combination of impacts by cattle and accumulation of sediment from surrounding hillslopes eroded during historic farming combined with altered hydrology from land clearing. In 2004, a meandering channel with a floodplain bench was excavated at this site, increasing the study reach length

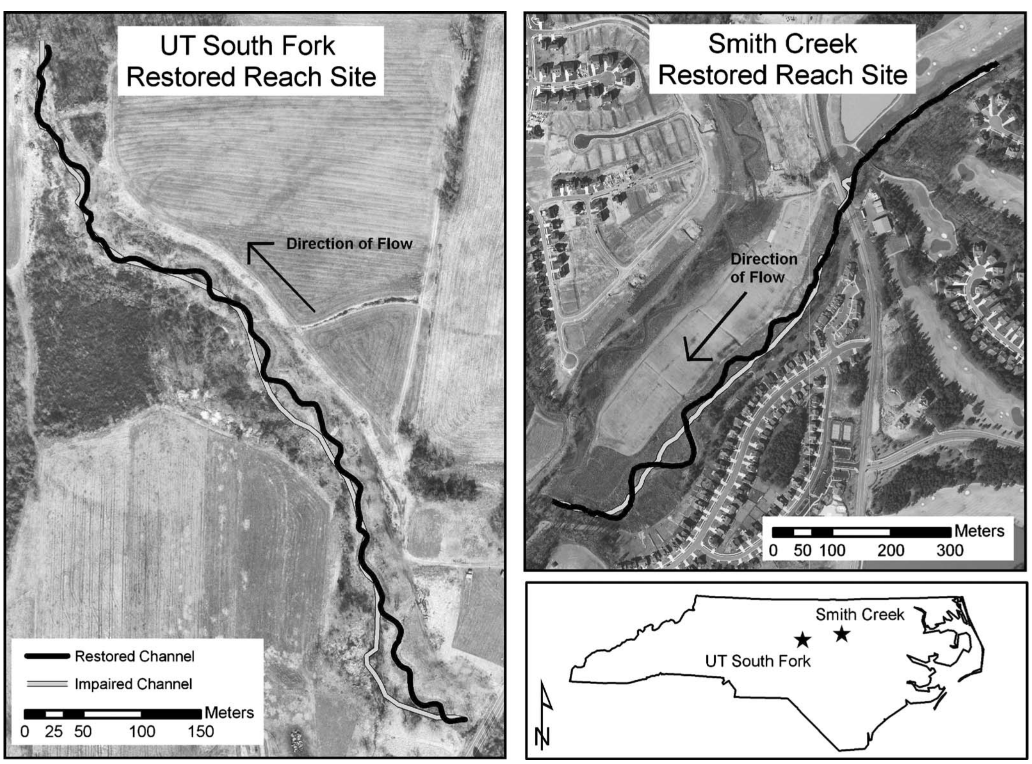

Fig. 2. Aerial photographs of restored study reaches with restored channel outline (black) and preexisting, impaired channel outline (white). Inset map of North Carolina shows site locations within the state (aerial images courtesy of Wake County, N.C.).

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Table 2. Field Reach Properties

Study reach	Drainage area (km^2)		Strahler order	Channel length (m)		Channel slope (m/m)		Sinuosity	
	Upstream	Downstream		Pre	Post	Pre	Post	Pre	Post
Smith Creek	21.9	22.6	3	1,219	1,307	0.0039	0.0036	1.0	1.1
UT South Fork	2.3	2.8	2	760	808	0.0053	0.0050	1.2	1.3

by approximately 50 m and reducing the slope from 0.0053 to 0.005 m/m relative to valley length and slope (Arcadis G&M of North Carolina, Inc. 2002).

The study reach at the Smith Creek site is along a third-order stream that drains 21.9 km^2 at its inlet of recently developed (<10 year old) low density suburban land. It is 1,307 m long, bisected by a two-lane bridge with a triple box culvert, and joins an unnamed tributary downstream that shares the valley with the lower portion of the study reach (Fig. 2, Table 2). Historically, the study reach ran alongside pasture and forest along the upstream portion and row crops and forest along the downstream portion. In the 1990s, a large flood event caused the lower portion of the reach to avulse, partially moving it into a new channel, which was subsequently dredged and straightened by the land owner (Buck Engineering 2001). This new channel was ill-defined, unstable, and aggrading. As such it was susceptible to flooding (Will Harmon, personal communication, 2009). In 2002, the right bank of the upstream portion of the study reach was regraded and a 14-m wide floodplain bench was excavated at an elevation determined to match the geomorphic bankfull flood stage at catchment build out. Downstream of the bridge a single-thread meandering channel was excavated extending this portion of the reach channel by 88 m, and reducing the channel slope from 0.0039 to 0.0036 m/m relative to valley length and slope (Buck Engineering 2003). Additionally, a recreational field was constructed during the time of the restoration project, which may have involved importing fill into the floodplain.

The designers of both channels used channel dimension and pattern parameters derived from reference reaches and regional curves. Channel dimensions were chosen to stabilize banks, convey design discharge, and maintain sediment transport capacity at bankfull discharges. Ideally, these smaller, restored channels allow floods greater than the design discharge to leave the channel and interact with the floodplain where flood waters encounter trees and brush and are slowed and temporarily stored. These general channel designs goals used by restoration practitioners contain elements that should enhance flood wave attenuation if the preexisting impaired channel geometry is incised. As is described in the example of the downstream portion of restored Smith Creek study reach, this is not always the case.

At each site, preconstruction (i.e., impaired conditions) surveys were available, and existing (i.e., restored) channel conditions were surveyed. Based on these surveys, HEC-RAS models of the reaches in their restored and impaired configuration were developed and calibrated to evaluate the changes to attenuation of routed floods between the two morphologies. The study reaches were chosen to contain minimal sources of lateral flow inputs other than overland flow so that incoming and outgoing hydrographs could be assumed to contain approximately the same volume of water. The entire length of each reach between the upstream and downstream stations had been restored.

Hydraulic Field Measurements and Field Model Calibration

Study reaches were instrumented with pressure transducer data loggers (Onset HOBO Water Level Logger, Bourne, Massachusetts) that recorded water stage at 5-min intervals. Three recorded hydrographs with a range of magnitudes from bankfull to overbank events were recorded at each site and used for flood routing (Fig. 3). A unit hydrograph was developed for UT South Fork and scaled for floods with RIs (magnitudes) greater than those measured in the field using standard methods (10, 25, 50, and 100 years) (Sholtes 2009). These scaled hydrographs were routed through UT South Fork reach models of impaired and restored morphologies to measure how the difference in attenuation between the two channel morphologies changed with increasing flood magnitude.

Stage-discharge relationships were developed by measuring discharge at various stages, including at least one overbank event, at upstream and downstream stations on both study reaches. Discharge was measured by summing the areas and average velocities of at least 10 channel subsections measured with a Marsh McBirney one-dimensional electromagnetic velocimeter (Model 2000; Loveland, Colorado) at 60% of the water depth from the top of the water surface according to standard methodology (Harrelson et al. 1994). Water surface slope (S_o) was also measured during each stage-discharge measurement and used in lieu of friction slope (S_f) in channel roughness calculations at each discharge using the one-dimensional Manning's equation

$$n = V^{-1}\left(\frac{A}{P}\right)^{2/3} S_0^{1/2} \quad (1)$$

where V represents average cross sectional velocity; A=flow area; P=wetted perimeter; and S_0=water surface slope. Using this method, average channel Manning's n values for Smith Creek were estimated to be 0.046 and 0.035 at the up- and downstream stations, respectively; and for UT South Fork they were 0.061 and 0.065 at the up- and downstream stations, respectively.

Restored reach HEC-RAS models were initially calibrated by minimizing the difference between observed and modeled stage-discharge relationships via adjusting n from its measured value under steady flow conditions. Additional adjustments to n were made to best match the timing of routed hydrograph peaks to those recorded at downstream stations of the study reaches. The final calibrated n for each channel was 0.035 for the Smith Creek restored reach model and 0.072 for the UT South Fork restored reach model. Manning's n was varied laterally at each modeled cross section to represent floodplain coverage types and densities according to aerial photographs from time periods before and after channel restoration. An n value of 0.05 was used to represent grassy conditions, 0.03 for row crops, and 0.18 to represent mature forest with dense undergrowth (Chow 1959; see Sholtes 2009 for complete model calibration details).

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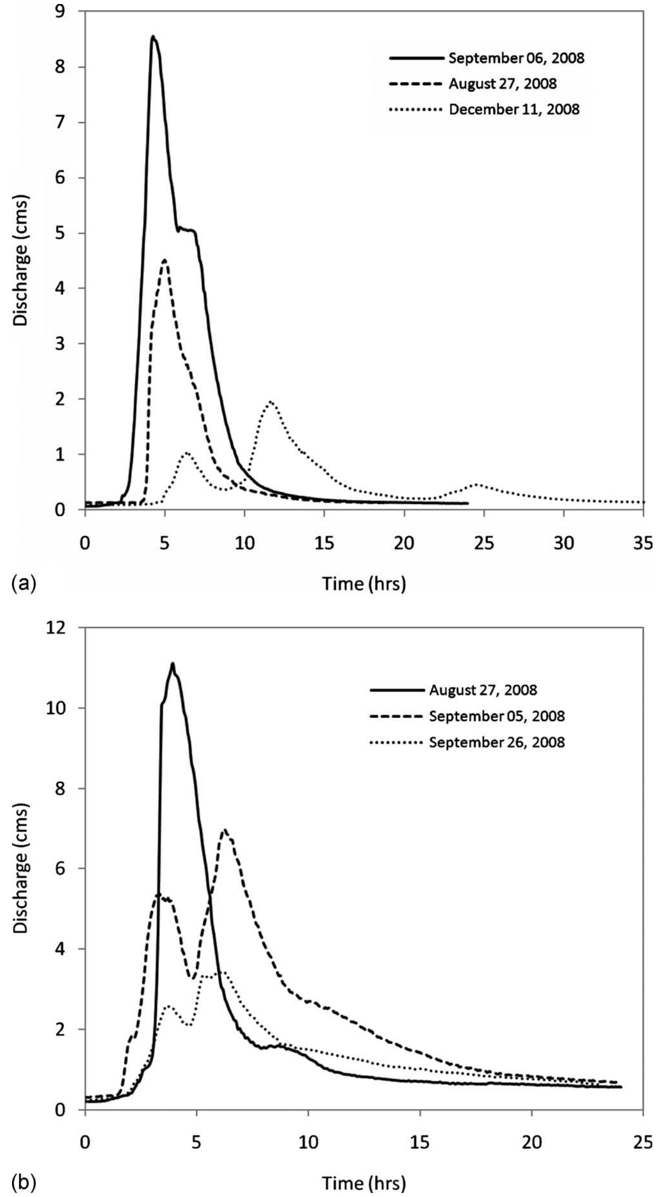

Fig. 3. Selected hydrographs as measured in the upstream cross section at (a) UT South Fork; (b) Smith Creek, then converted to discharge hydrographs on reach models in UNET

The routed hydrographs in each analysis were evaluated for their theoretical ability to attenuate based on a metric reported in Ponce (1989) to determine the applicability of the kinematic wave model for flood routing

$$\frac{T_r V_0 S_0}{y_0} > 85 \quad (2)$$

where V_0 and y_0 represent average flow velocity and depth, respectively; S_0 represents bed slope; and T_r represents time of rise of the inflow hydrograph. Values greater than 85 indicate that the flood wave is kinematic in behavior and theoretically will not attenuate. Input values for this metric were obtained for the largest hydrographs used in the synthetic and field-based analyses and channel properties in the restored scenarios (Table 3).

Recorded stage hydrographs were converted to discharge hydrographs in UNET and routed through reach models of impaired and restored morphologies. Attenuation metrics were measured

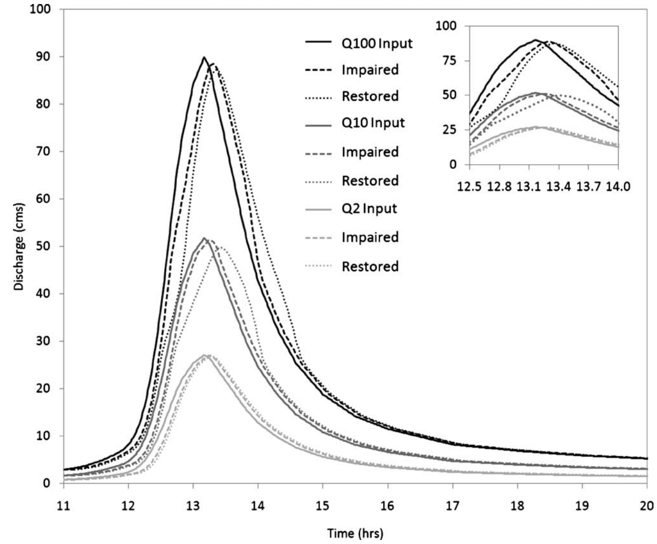

Fig. 4. Comparison of input (solid lines) and output (routed) hydrographs in the impaired (dotted lines) and restored (dashed lines) synthetic reach scenarios for 24 h synthetic hydrographs with RIs of 100, 10, and 2 years. Inset shows differences in magnitude and timing of peak among hydrographs.

and compared for the various hydrographs routed in the reach models between the impaired and restored morphologies. Given the available time frame for this research, there was no opportunity to measure flood wave passage at field sites prior to the restoration of each reach. Therefore, no direct comparison of flood wave attenuation in the field is made in this study. The following presentation and analysis of the results focus solely on the comparison of modeled flood routing results.

Results

Impact of Channel Restoration on Flood Wave Attenuation

Synthetic Reach

Comparison of floods routed in the synthetic reach representative of a restored channel morphology demonstrated a relatively small increase in attenuation at all flood frequencies over those routed through the synthetic impaired channel morphology model (Fig. 4). For example, the instantaneous peak flow, Q_{pk}, of the Q_{100} decreased by 0.62 $m^3\ s^{-1}$ (0.7%) more in the restored synthetic reach over the impaired synthetic reach [Figs. 5(a and b)]. A larger response was found in the c_{AVG} attenuation metric. Greater changes were observed with c_{AVG}, which was slower by 1.3 $km\ h^{-1}$ (22.2%) for the Q_{100} routed in the restored reach [Fig. 5(c)]. The magnitude of the difference in attenuation to Q_{pk} recorded for the restored reach over the impaired reach is on the same order of magnitude as the reduction to Q_{pk} brought on by numerical attenuation associated with increasing the value of the finite difference weighting factor, θ, as discussed above.

The greatest difference in attenuation between the impaired and restored synthetic models was found for the Q_{10} flood, which inundated the entire floodplain at its peak on the restored reach and only just left the channel on the impaired reach. Attenuation to Q_{pk} was augmented by 0.63 $m^3\ s^{-1}$ (1.2%) and c_{AVG} was reduced an additional 3.5 $km\ h^{-1}$ (50.0%) by the restored reach

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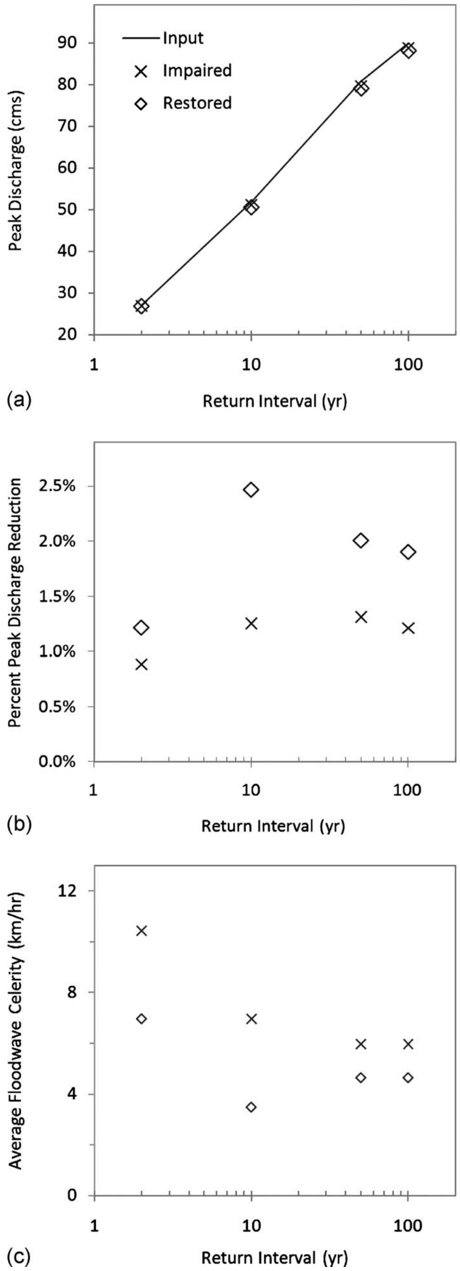

Fig. 5. Comparison between input and output hydrographs routed through impaired and restored synthetic reaches at each flood return interval. (a) Absolute changes to instantaneous peak discharge, Q_{pk}; (b) percent reduction in Q_{pk}; and (c) average celerity, c_{AVG} (distance over peak to peak travel time).

morphology. Here, the exposure to wetted perimeter and roughness elements on the floodplain is at its maximum relative to flow area (Fig. 6). Given the steep slope of the valley wall in this model, exposure to frictional forces from the floodplain surface increased only marginally from the Q_{10} to the Q_{50}, and even less so from the Q_{50} to the Q_{100}, hence the small difference in attenuation between the Q_{50} and Q_{100} floods.

Field Based Reaches

We first compared the change in attenuation among three measured floods routed in models of impaired and restored reaches at each site. Floods routed on impaired and restored reach models of UT South Fork demonstrated slight differences. For example, no significant change to Q_{pk} attenuation was observed between the largest routed flood (September 6, 2008), and an approximately 1% (0.04 $m^3 s^{-1}$) and 0.5% (0.01 $m^3 s^{-1}$) reduction to Q_{pk} was observed with the medium overbank flood (August 27, 2008) and bankfull flood (December 11, 2008) over a distance of 808 m, respectively [Fig. 7(a)]. Celerity was impacted more between the impaired and restored scenarios at UT South Fork, with decreases in celerity from the impaired to the restored reach ranging from 50 to nearly 100% for the three floods [Fig. 7(b)].

The differences in attenuation metrics between the impaired and restored morphologies increased for routed floods with greater RIs than those measured on the UT South Fork reaches (Q_{10}, Q_{25}, Q_{50}, and Q_{100}). For example, the Q_{pk} of the Q_{100} decreased by 1.7% (0.3 $m^3 s^{-1}$) more in the restored reach over the impaired reach [Fig. 8(a)]. This difference, however, remains relatively small and is largely a result of assumed increases to channel and floodplain roughness. By reducing estimated floodplain and channel roughness coefficients on the restored reach model to match those estimated for the impaired reach model, the difference in Q_{pk} between Q_{100} hydrographs routed in the impaired and restored morphologies shrinks to less than 1% (0.1 $m^3 s^{-1}$).

Floods routed through impaired and restored reach models of Smith Creek did not demonstrate even small increases in attenuation under restored morphologies. Rather, attenuation was greater under the impaired channel morphologies. Reduction in Q_{pk} from upstream hydrographs ranged from 0.12 (3.5%) to 2.55 $m^3 s^{-1}$ (23.0%) under the restored morphology and 0.55 (16.1%) to 5.05 $m^3 s^{-1}$ (45.5%) under the impaired morphology [Fig. 7(c)]. Average celerity increased with decreasing flood magnitude in routed floods, and increased by approximately 30 to 60% for all storms from the impaired to the restored morphologies.

Sensitivity of Flood Wave Attenuation to Channel Properties

We examined sensitivity of flood attenuation to channel and floodplain properties by routing floods of various magnitudes through the synthetic restored reaches, altering values of these properties (i.e., slope, length, and roughness) by $\pm 10\%$ and comparing. We summed the differences in relative reduction to Q_{pk} for floods routed through the $\pm 10\%$ conditions ($Q_{pk+10\%}/Q_{pk0} - Q_{pk-10\%}/Q_{pk0}$) in all scenarios to identify properties which impart the strongest influence on attenuation [Fig. 9(a)]. Differences in relative reduction between the $\pm 10\%$ scenarios where generally very small ranging from 0.05% (0.04 $m^3 s^{-1}$) for the Q_{50} in the sinuosity scenario to 0.48% (0.25 $m^3 s^{-1}$) for the Q_{10} in the slope scenario. Dynamic wave routing was sensitive to several elements of the channel and floodplain that are either altered by channel restoration projects or are site dependent, and this sensitivity was dependent on the magnitude of the routed flood. Comparing the sum of the differences to relative Q_{pk} attenuation for each stream property over all flood magnitudes demonstrated that channel and valley slope, channel and floodplain roughness, channel and floodplain longitudinal length, wetted perimeter, floodplain width, and sinuosity all contributed to relative Q_{pk} reduction in decreasing order.

The majority of the routed floods were insensitive to $\pm 10\%$ changes in channel and floodplain properties at the reach scale when comparing the difference in c_{AVG} between each scenario at each flood frequency. Average celerity was measured by dividing the longitudinal distance traveled by the flood wave by the difference in time between peaks at up- and downstream stations. Ab-

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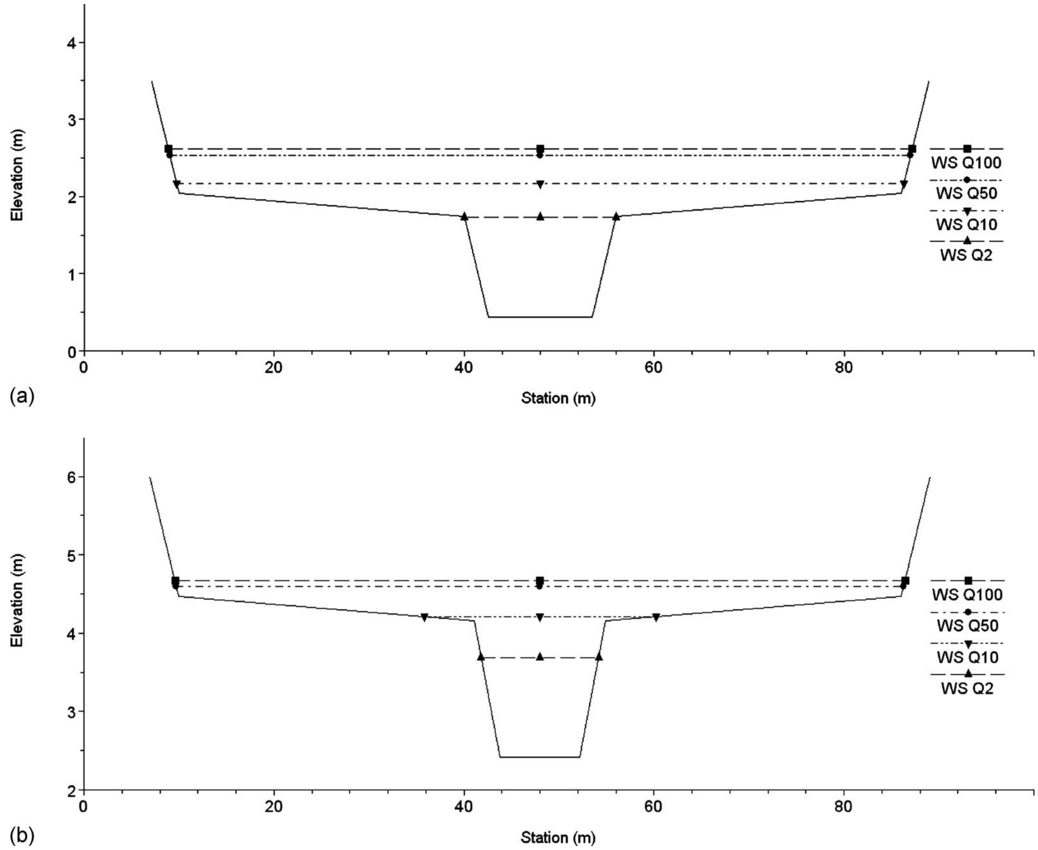

Fig. 6. Maximum water surface heights at the downstream station cross section for 100-, 50-, 10-, and 2-year floods routed through hypothetical (a) restored; (b) impaired reaches. Only the 50- and 100-year floods leave the channel banks in the impaired reach. The 10-year flood leaves the channel and just covers the entire floodplain in the restored reach.

solute differences in c_{AVG} between the $\pm 10\%$ conditions ranged from 0.0 to 0.42 $km\ h^{-1}$ in the majority of cases [Fig. 9(b)]. An exception to this was the Q_2 flood in the roughness, length, and wetted perimeter scenarios, which resulted in a difference ranging from 0.99 to 2.32 $km\ h^{-1}$. For the overbank floods, no difference in c_{AVG} was observed between the various $\pm 10\%$ changes to channel and floodplain properties for the Q_{50} and Q_{100} floods with the exception of channel length.

Theoretical Potential for Attenuation

Analysis of flood wave and channel properties was conducted in order to determine the theoretical potential for attenuation in the largest flood waves routed in each restored scenario. This analysis resulted in values for the kinematic wave model applicability criterion of 21, 15, and 30 for the restored synthetic, Smith Creek, and UT to South Fork reaches, respectively (Table 3). Additionally, according to Fread (1975), the steep bed slope (>0.001 m/m) of these reaches would lend to more kinematic flood waves, but the fast rise in stage observed in the hydrographs (>0.3 $m\ h^{-1}$) would lend to more dynamic waves. Therefore, because the criterion values reported above for all three reaches and hydrographs are under 85, the threshold over which Ponce (1989) indicates the kinematic model applies, the flood waves were not likely to be entirely kinematic in nature and theoretically have the potential for attenuation.

Discussion and Applications

Discussion of Results

Floods routed in impaired and restored reaches exhibited either very small augmentation in attenuation or a decrease in attenuation. In the case on the UT South Fork, the augmented attenuation in the restored reach was primarily a result of assumed increases to floodplain roughness from the impaired to the restored conditions. As stated in the results, the augmentation in attenuation metrics between the models of the impaired and restored morphologies nearly disappeared when assumed increases in channel and floodplain roughness in the restored reach model were made equal to the roughness values in the impaired reach model. Other studies have quantified the impact of increasing floodplain roughness on flood wave attenuation, finding it to be a significant factor over long distances (20–50 km, Anderson et al. 2006; Ghavasieh et al. 2006). However, channel restoration generally reduces floodplain roughness initially through removal of large woody vegetation for channel regrading. It may take the floodplain of a restored reach up to a decade to return to its preexisting roughness. This creates a situation in which a dominant driver of attenuation for overbank floods, floodplain roughness, is initially diminished by restoration and only through time reaches the conditions which create the hydraulic functions sought from restoration.

Smith Creek, a formerly braided and aggrading channel was

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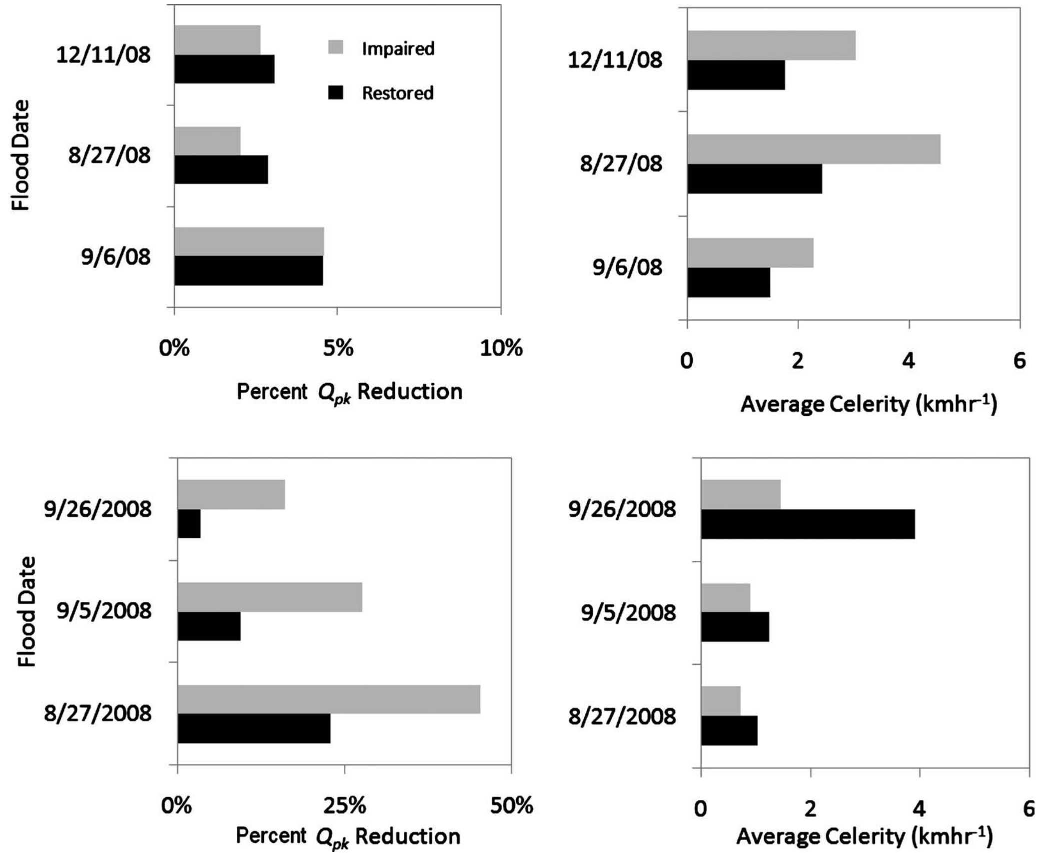

Fig. 7. Comparison of changes to Q_{pk} and c_{AVG} in floods routed through (a) impaired; (b) restored reach models of UT South Fork; (c) impaired; and (d) restored reach models of Smith Creek. Flood magnitude increases moving down the y-axis.

reconfigured into a single-thread meandering channel, and its valley likely filled for the creation of a park. This contributed to the decrease in attenuation documented in routed floods in the restored reach [Figs. 7(c and d)]. Prior to restoration, the lower portion of the impaired channel was unstable, in a depositional phase, and susceptible to flooding. Aerial photographs of the reach and discussions with the project manager (Will Harmon, personal communication, 2009) confirm the existence of a slightly braided channel with ill-defined banks. A survey of several cross sections of this portion of the reach conducted by the consultant prior to restoration showed a small channel flanked by alluvial levees (Buck Engineering 2001). The floodplain, which lay beyond the levees, was nearly level to the channel thalweg. Flood events were able to access the floodplain much more readily than under the current, restored, and single-thread morphology.

Comparison of floods routed in models of impaired and re-

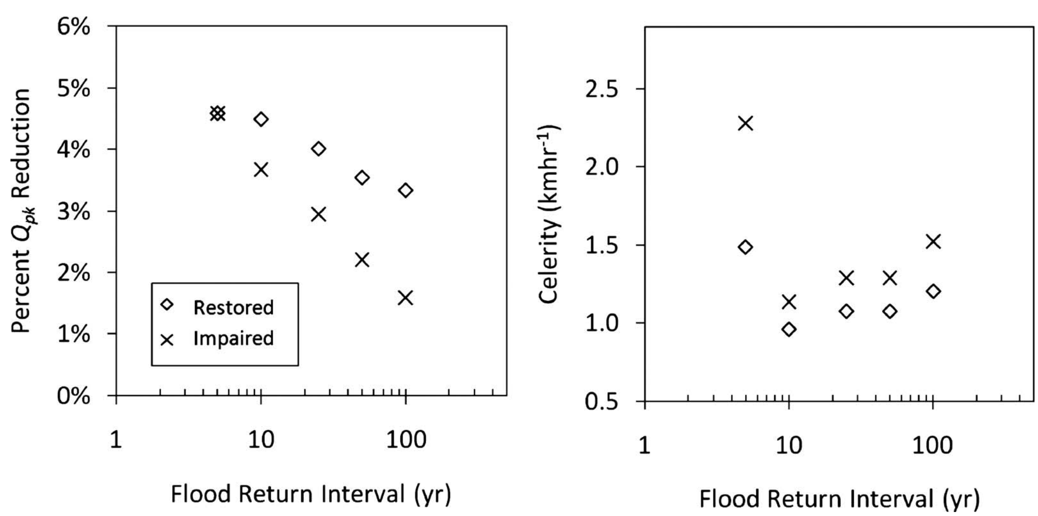

Fig. 8. (a) Comparisons of relative reduction to Q_{pk}; (b) comparison of c_{AVG} for floods of various RIs routed through synthetic impaired and restored reach models

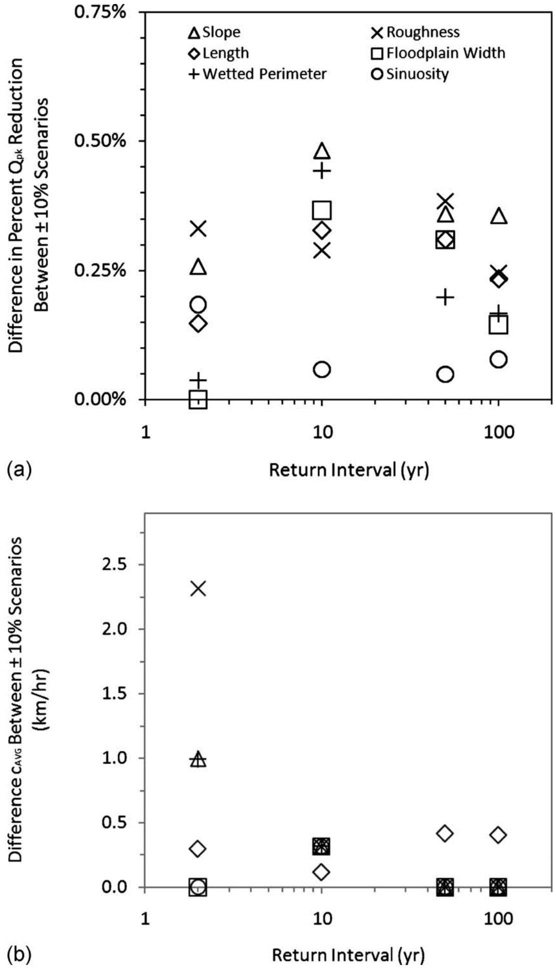

Fig. 9. (a) Comparison of differences in percent reduction to Q_{pk}; (b) difference in c_{AVG} on synthetic reach models between +10 and −10% scenarios of differing channel and floodplain conditions across all studied flood frequencies

stored reach models of Smith Creek [Fig. 7(c and d)] and the above evidence indicates that the restoration of Smith Creek reduced its ability to attenuate floods. While excavation of a bench into the right bank at bankfull elevation on the upper portion of the reach allowed flood waters more contact with a floodplain, the restoration of the lower portion coupled with apparent valley fill for a park construction undermined any enhancements to attenuation that this provided. It should be noted that flood attenuation was not an explicit goal of this particular restoration project. The restoration created a stable, single-thread channel with a vegetated floodplain, markedly improving channel conditions over the impaired channel by metrics of geomorphic stability, riparian habitat, and aesthetics. However, the stability, aesthetics, and utility of the channel and surrounding land were restored at the cost of flood attenuation. The morphology of the downstream portion of the impaired Smith Creek reach did not fit the incised preexisting channel condition assumed to exist in the natural channel design paradigm (Rosgen 1997). This example illustrates the fact that the diverse goals of channel restoration can sometimes conflict.

Comparing the extent of channel change brought on by restoration at the field sites to the median changes to channel morphology found in this study (Tables 1 and 2) provides some explanation for the marginal enhancements to attenuation documented herein. With remeandering, the channel length of the field reaches increased at most by 7.5% (Smith Creek) and channel slope decreased at most by 5.6% (UT South Fork) with respect to valley slope (Table 2). These values fall below the median values of change used in the synthetic restored reach model (14.6% increase to length and 12.7% decrease to slope, Table 1). A small, but clearer enhancement to attenuation was documented in the synthetic scenarios.

Table 3. Kinematic Wave Model Applicability Analysis

Parameter	Restored syntheticQ100	Smith Creek (August 26, 2008)	UT South Fork (September 9, 2008)
T_r (h)	2.2	3.1	3.6
S_o (m/m)	0.0048	0.0036	0.0050
V_o (m h^{-1})	4,320	2,040	2,700
y_o average (m)	2.2	1.6	1.6
Stage rise rate (m h^{-1})	1.0	0.6	0.5
$(T_r^* V_o^* S_o)/y_o$=	21	15	30

The sensitivity analysis indicated that Q_{pk} attenuation is most sensitive to channel and floodplain longitudinal slope, roughness, and longitudinal length. This corresponds well to the degree of sensitivity of flood attenuation to channel properties found by Wolff and Burges (1994). In their study, stream slope, floodplain width, and roughness, respectively, provided the greatest impact to flood waves.

The channel and floodplain properties assessed in the sensitivity analysis are not all mutually exclusive. Changes to the values of these properties are also not accomplished with equal work and resources. For example, a channel's length cannot be extended without changing its slope relative to the valley slope. Aggregate channel roughness also generally increases with meandering (Chow 1959). Increasing floodplain roughness via planting woody vegetation likely represents the most cost-effective enhancement to attenuation. However, the benefit of this takes years to establish, and channel morphology must also allow flood waters to leave the channel and interact with the floodplain. Additionally, some properties studied are not likely to be changed as a result of channel restoration, such as channel and valley longitudinal slope. Quantifying the significance of these properties can aid in restoration-site selection.

Of the range of floods analyzed, those of intermediate magnitude (2 years < RI < 50 years) were impacted the most by restoration, particularly those confined to the channel under the impaired morphology but able to access the floodplain under the restored morphology. This is demonstrated by the relatively larger decrease to Q_{pk} and c_{AVG} for the Q_{10} flood between the impaired and restored reaches in the synthetic study [Fig. 5(a–c)]. This paralleled the findings of Turner-Gillespie et al. (2003) and Knight and Shiono (1996) who documented that flood wave celerity increases as water levels approaching the bankfull elevation. Beyond bankfull stage, celerity slows down to a minimum at a certain level where the mixing of momentum between floodplain and channel flow reaches a maximum, after which celerity increases as the flood waters fill the floodplain. UNET does not explicitly account for these two- and three-dimensional aspects of flood flow. The sharp increase in the ratio of wetted perimeter to flow area that occurs at the transition between in channel and floodplain flow can explain the peak in attenuation at the Q_{10} flood in this one-dimensional model. If the synthetic valley was not confined, attenuation would continue to increase with flood

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Table 4. Summary of Flood Attenuation Studies

Study	Date	Channel and floodplain characteristics studied	Findings
Campbell et al.	1972	Channel slope and length	Peak discharge increased 90 to 190%, flood wave travel time reduced 60 to 70%, and duration of flooding decreased 30 to 40 h after channelization along a 93-km stretch of the Boyer River, Iowa.
Wolff and Burgess	1994	Channel slope, channel and floodplain roughness, channel morphology, and floodplain valley width	Peak discharge and average flood wave celerity were attenuated by changes to slope, floodplain width, floodplain roughness, and channel morphology (in order of decreasing impact) as measured on a hypothetical 80-km reach. Floods of greater magnitude experienced the greatest attenuation.
Woltemade and Potter	1994	Channel morphology, slope, channel and floodplain roughness, and floodplain valley width	Quantified attenuation along a network of streams in the 690 km^2 watershed on the Grant River, Wis. Floods of intermediate recurrence intervals (5 to 50 years) were most impacted by changes to channel morphology (up to 29% reduction in Q_{pk}). Changes to floodplain valley width impacted floods with greater RIs. Changes to channel slope, and channel and floodplain roughness reduced Q_{pk} by a maximum of 22 and 21%, respectively.
Acreman et al.	2003	Floodplain valley width and channel morphology	Peak discharge decreased by a maximum of 16% and increased by a maximum of 153% compared to baseline conditions and scenarios of channel and floodplain restoration and levee construction, respectively.
Turner-Gillespie et al.	2003	Floodplain width	Changes to floodplain roughness representing an enhancement in vegetation density resulted in a 3% reduction in a model of a 10-km section of Briar Creek, Charlotte, N.C.
Liu et al.	2004	Channel roughness, length, slope, and placement within catchment	Measured effects of increasing channel roughness and sinuosity of all first and second order streams in a 408 km^2 watershed of the River Steinsel, Luxembourg. Peak discharge was decreased by an average of 14% over all floods modeled compared to baseline.
Anderson et al.	2006	Channel and floodplain roughness	Peak discharge and mean celerity were decreased by a maximum of 12 and 70%, respectively, from scenarios of no floodplain vegetation to tall floodplain vegetation along a hypothetical 50-km reach.
Ghavasieh et al.	2006	Floodplain roughness	Peak discharge and mean flood wave celerity were decreased by a maximum of 3.8 and 9.3%, respectively, along a hypothetical 20-km reach in which vegetated strips were introduced.
Sholtes	2009	Channel slope, length, sinuosity, roughness, and floodplain width	Small enhancements and even reductions to flood attenuation were observed on models of field-based reaches. An additional 2.5% decrease to Q_{pk} and at 10% decrease to c_{AVG} were the maximum enhancements to attenuation observed in a hypothetical ~1 km restored reach. Floods of intermediate magnitude (2 years $\leq$ RI $\leq$ 50 years) were most impacted. Channel and valley slope, channel and floodplain roughness, and channel and valley length in decreasing order most enhanced attenuation.

magnitude. This is because the rate of increase in exposure to wetted perimeter and floodplain roughness would continue to increase (or not decrease as rapidly) with increases to discharge.

The discussion up to this point has considered the impacts to attenuation as a result of changes to channel and floodplain properties brought on by channel restoration. While it is important to understand these impacts, the hydrologic and hydraulic aspects of flood waves may also affect attenuation. For example, Woltemade and Potter (1994) found that higher intensity floods (higher flood peak to volume ratio) were attenuated more in terms of Q_{pk} relative to lower intensity, high volume floods. They attribute this result to floodplain storage. Floods with smaller volumes and high peaks may not completely fill the floodplain and are therefore more susceptible to attenuation over higher volume floods. The present study utilizes hydrographs with uniform times to peak as generated by the SCS type II rainfall distribution curve [Natural Resources Conservation Service (NRCS) 1986] and does not explicitly consider the possible changes to attenuation resulting from differences in hydrograph intensity. It is therefore important to not only consider the return interval (Q_{pk}) of the floods targeted for augmented attenuation by a restoration project, but also the regional climatology and expected hydrograph intensity.

Hydraulic characteristics of the flood wave and the channel theoretically have the ability to impact the extent to which attenuation is possible as well. Flood waves generally exhibit characteristics of both kinematic (main body) and diffusion or dynamic waves depending on the relative magnitude of the pressure gradient (diffusion wave) and inertia terms (dynamic wave) (Sturm 2001). But under certain conditions, such as a steep channel ($S_o > 0.001$ m/m) flood waves behave mostly as kinematic waves,

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which theoretically only translate and do not attenuate. According to various metrics used to determine the applicability of the kinematic model to the hydraulic conditions present in this study, the flood waves are not entirely kinematic in nature. Given that restoration often occurs on lower order reaches, which are predominantly located in steeper topography, it is possible that flood waves that are kinematic in nature predominate in these restored reaches, which may be limited in their potential to attenuate. However, given the rapid time of rise to flood crest representative in urbanized and agricultural areas, flood waves in these settings may theoretically have the ability to attenuate in spite of steep reach slopes, though to a more limited extent than would be possible in milder sloped streams. This may also help explain the limited attenuation in routed floods observed within the study reaches.

Applicability to Restoration Design

We now turn to assessing the potential for and appropriateness of channel restoration to attenuate floods. This study quantified the ability of channel restoration to reduce floods via changes solely within the channel and floodplain. The results demonstrate that some, albeit limited, attenuation can be achieved in idealized examples of channel restoration. Given the small extent of most restoration projects in the United States (~1 km, Bernhardt et al. 2007), and the small size of channels generally restored (first to third order in North Carolina, BenDor et al. 2009), our results indicate that restoration-derived enhancement to flood attenuation is difficult to definitively measure and even harder to demonstrate. Much longer reaches than analyzed here, perhaps as much as 5–10 km (Table 4), are needed to produce the attenuation necessary to justify channel restoration as a realistic tool for watershed hydrology management.

With these constraints in mind, our results do offer some guidance on how restoration design can be used to increase potential attenuation. A change in bankfull discharge threshold represented one of the more important changes to channel and floodplain properties that channel restoration can accomplish; this impacted floods of intermediate magnitude (2 years $\leq$ RI $\leq$ 50 years). Excavation of a smaller or shallower and wider channel with an adjoining floodplain at a relatively lower elevation than the preexisting incised morphology can produce these effects. In urban settings where space lateral to the channel is often limited, a compound channel design represents a viable alternative to the excavation of a new, meandering channel. Compound channels involve the construction of a small channel that conveys an annual or biannual flood and a larger channel or floodplain bench that accommodates floods of greater magnitude. Compound channels are also effective at concentrating low flows for habitat provision. Thus, there appear to be multiple hydrologic benefits to using compound, inset channel designs in restoration.

In this study we considered the potential role of channel restoration as a tool for attenuating floods or, in essence a structural storm water best management practice. Many strategies for flood control are currently used to reduce the potential of damaging floods, from regional scale flood control reservoirs to lot-scale storm water control devices. Walsh et al. (2005) and Ladson et al. (2006) argued that any restoration done on channels will not be successful at recovering ecological functions if the problems associated with hydrologic impact (impervious cover) within the watershed are not first addressed (e.g., Emerson et al. 2005). Our study showed that channel restoration itself, as currently practiced, is insufficient to provide such hydrologic changes, but it may be useful when applied at substantially larger scales to provide both hydrologic and ecological benefits.

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Notation

A = cross sectional area of flow (m^2);
c_{AVG} = average celerity ($km\ h^{-1}$);
n = Manning's coefficient of surface roughness;
P = wetted perimeter (m);
Q = discharge ($m^3\ s^{-1}$);
Q_{pk} = instantaneous peak discharge ($m^3\ s^{-1}$);
Q_2–Q_{100} = floods with 2 to 100-year return intervals;
RI = return interval (year);
S_f = friction slope (m/m);
S_o = bed slope (m/m);
T_r = time of hydrograph rise to crest (h);
V_0 = average velocity of flood wave flow ($m\ s^{-1}$);
y_0 = maximum depth of flow for a given flood (m); and
θ = weighting factor in implicit numerical solution for Saint-Venant equations.

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