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Riparian reforestation and channel change: How long does it take?

Maeve McBride [a,*], W. Cully Hession [b], Donna M. Rizzo [a]

[a] Civil and Environmental Engineering, University of Vermont, 213 Votey Building, Burlington, Vermont, 05405, USA
[b] Biological Systems Engineering, Virginia Tech, Blacksburg, Virginia, USA

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ABSTRACT

Repeated measurements of two small streams in northeastern Vermont document change in channel width and suggest variable rates of widening because of passive reforestation over four decades. Historic data on channel width are available for several tributaries to Sleepers River in Danville, VT, USA from the 1960s. In 2004 and 2008, we re-measured channel dimensions in two of these tributaries, in two reaches of upper Pope Brook and along seven reaches of an unnamed tributary (W12). Four reaches had reforested since 1966; two reaches remained nonforested. The other three reaches have been forested since at least the 1940s. Comparisons between 1966 and 2004 showed that reforested reaches widened significantly, and comparisons between 2004 and 2008 showed continued widening, but at a greater rate. Between 1966 and 2004, reforested reaches widened at an average rate of 4.1 cm/year, while the rate more than doubled for the last four years (8.7 cm/year). Additionally, turbulence data collected during five peak flows in the spring of 2005 showed significantly greater turbulent kinetic energy (*TKE*) in the reforested reach than in either the forested or nonforested reach. Our data add supporting information to the conceptual model of stream W12 that describes a process of incision, widening, and recovery of a stream reach transitioning from nonforested to forested riparian vegetation.

1. Introduction

Riparian vegetation exerts important influences on stream channel morphology through processes functioning at the scale of the bank (Gray and MacDonald, 1989; Thorne, 1990; Dunaway et al., 1994; Montgomery, 1997; Stott, 1997; Abernethy and Rutherfurd, 1998; Simon and Collison, 2002; Pollen et al., 2004; Rutherfurd and Grove, 2004; Wynn and Mostaghimi, 2006), the floodplain (Pasche and Rouve, 1985; Jeffries et al., 2003; Griffin and Smith, 2004; Smith, 2004; McBride et al., 2007), and the riparian corridor as a whole (Montgomery, 1997; Millar, 2000; Gurnell et al., 2001). Riparian vegetation eludes simple quantification or description because of variation in density, species diversity, maturity, and rates of growth. The influence of riparian vegetation on stream channel morphology is further complicated by variations in background conditions including, but not limited to, discharge and sediment regimes, bank material composition, climate, and anthropogenic modifications. In spite of these complicating factors, several studies have shown distinct differences in morphology resulting from two broad types of vegetation: forests and grasslands (i.e., nonforested). A collection of studies from widely different geographic locations indicates that stream reaches with riparian forests are wider than those with nonforested vegetation (Zimmerman et al., 1967; Murgatroyd and Ternan, 1983; Clifton, 1989; Sweeney, 1992; Peterson, 1993; Davies-Colley, 1997; Trimble, 1997; Scarsbrook and Halliday, 1999; Hession et al., 2000; 2003; Sweeney et al., 2004; Allmendinger et al., 2005; Roy et al., 2005; McBride et al., 2008). In contrast, other studies suggest that widths of streams through grassland are generally greater than those through forest (Charlton et al., 1978; Hey and Thorne, 1986; Gregory and Gurnell, 1988; Rosgen, 1996). On the surface, these findings appear contrary, but they may be partially explained by a scale-dependent effect of riparian vegetation with catchments of different sizes (Anderson et al., 2004).

Ideas about the geomorphic processes responsible for the observed differences in channel widths are varied and nearly all remain untested. Additionally, some processes may be influential during an adjustment period when riparian vegetation and the stream morphology are in flux (i.e., long-term transformation after a threshold change), while other processes may function to maintain a dynamic equilibrium once a particular vegetation community is established and mature (i.e., short-term fluxes around an average state; Knighton, 1998). For example, a reforesting stream may experience considerable erosion as it transitions to a wider form (Murgatroyd and Ternan, 1983; Smith, 1992), but mature riparian forests are generally found to have lower rates of bank erosion than nonforested counterparts (Pizzuto and Meckelnburg, 1989; Stott, 1997; Allmendinger et al., 2005). Previous studies have attributed the process of channel widening to two main effects: 1) the suppression of grassy and understory vegetation on the banks and within channels with a closed canopy (Murgatroyd and Ternan, 1983; Davies-Colley,

* Corresponding author. Tel.: +1 802 658 9404; fax: +1 802 656 8446.
E-mail address: mmcbride@cems.uvm.edu (M. McBride).

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1997); and 2) local scouring from large woody debris (LWD); Zimmerman et al., 1967; Murgatroyd and Ternan, 1983; Trimble, 1997; 2004); however, recent research questions the significance of these processes in long-term channel widening (McBride et al., 2008). Moreover, it is unclear how to resolve the conundrum that mature forests will continue to provide shade and continual recruitment of LWD, but also strengthen banks and slow channel migration (Stott, 1997; Parkyn et al., 2003; Allmendinger et al., 2005). Other processes may be contributing to channel widening, including the hydraulic effect of forested vegetation during overbank flows (McBride et al., 2007). A flume experiment that modeled the addition of forested vegetation to the floodplain of a small, previously nonforested stream found that turbulence was strongly amplified along a wide area between the floodplain and the main channel including the entire bank face (McBride et al., 2007).

Researchers have attempted to quantify the role that turbulence plays in stream channel erosion by incorporating measures of turbulence into estimations of boundary shear stress (Kim et al., 2000; Biron et al., 2004; Daniels and Rhoads, 2004). Because turbulence creates instantaneous forces much greater than time-averaged values, sediment transport can occur at flows where the time-averaged conditions are below the critical entrainment threshold for sediments (Nelson et al., 1993; McLean et al., 1994; Roy et al., 1999). When increased turbulence is coupled with high downstream velocities, entrainment and transport of bank sediments are likely amplified (Thompson, 2004). Reach-averaged boundary shear stress, although commonplace, does not account for the role of turbulence, and methods that incorporate turbulence parameters may be more appropriate in some applications (Hilldale and Papanicolaou, 2001; Biron et al., 2004; Daniels and Rhoads, 2004). Turbulence parameters may help to explain long-term channel-widening processes and observed differences in rates of bank erosion.

In this paper we add to a previous study that compared historic and current channel-size data from the Sleepers River Research Watershed (SRRW) in Danville, VT (McBride et al., 2005, 2008). One of the first studies to document the influence of riparian forests on channel form was completed within the SRRW by Zimmerman et al. (1967). In 2004, two of the streams described in Zimmerman et al.'s (1967) study were revisited to assess potential changes in channel dimensions and LWD characteristics in response to riparian reforestation (McBride et al., 2008). Our objectives were (i) to document more recent channel change from 2004 to 2008; (ii) to assess rates of widening of small streams in response to reforestation; and (iii) to report on in-stream measurements of turbulence and how turbulence might explain the process of stream widening. Additionally, new findings were related to the conceptual model on channel widening described in McBride et al. (2008).

2. Study area

The SRRW is located in northeastern Vermont and is one of the longest-running, cold-region research watersheds in the United States (Fig. 1). Sleepers River drains 111 km^2 of mainly forested lands (~67%); agriculture and rural residences are the other common land uses (Shanley et al., 1995). The SRRW sits within the rolling topography of the Vermont Piedmont, where elevations range from 201 to 780 m (Shanley et al., 1995). The surface geology is described as calcareous till (1 to 20 m in depth) sitting atop the Waits River Formation bedrock, a metamorphosed limestone (Shanley et al., 1995). Our studies have focused on two streams: (i) stream W12 is an unnamed tributary to Sleepers River that drains a 2.1-km^2 catchment of mixed land use; and (ii) upper Pope Brook, another tributary, is a headwater stream that drains a 1.1-km^2 forested area within State of Vermont forest lands. Forests are predominantly mixed with coniferous and deciduous trees. The most common species are Northern White Cedar (*Thuja occidentalis*), Yellow Birch (*Betula alleghaniensis*), White Spruce (*Picea glauca*), Balsam Fir (*Abies balsamea*), and Sugar Maple (*Acer saccharum*).

Local climate and discharge records for the SRRW are incomplete; however, regional long-term records reveal some important trends. Within the SRRW, mean annual temperature is 6 °C, and mean annual precipitation is 90 cm (Shanley et al., 1995). Long-term meteorological records in Burlington, Vermont provide similar statistics, with 7 °C for mean annual temperature (NWS, 2009a) and 85 cm for mean annual precipitation (NWS, 2009b). In the years preceding Zimmerman et al.'s (1967) study (1960–1965), climate conditions were cooler and dryer than these norms; on average, the mean annual temperature was 1 °C less than and mean annual precipitation was 9 cm less than normal. In the years spanning our current study (2004–2008), climate conditions were warmer and wetter than average; on average, the mean annual temperature was almost 1 °C greater than and mean annual precipitation was 19 cm more than normal. Additionally, recent discharge records from Sleepers River (United State Geological Survey gage #01135300) indicate that in August of 2008 the gage recorded the third largest peak flow since October of 1990 (USGS, 2009).

3. Methods

3.1. Field methods

Data were collected in a total of nine reaches. Seven of the reaches were in W12: two nonforested sites (NF1 and NF2); one forested site (F1); and four reforested sites (R1–R4). Reforested sites were those identified as nonforested in 1966 by Zimmerman et al. (1967) but have reforested in the last 40 years. The other two forested reaches were in upper Pope Brook (F2 and F3). All reaches were 75 m long, a length equivalent to approximately 20 bankfull widths. Data collection methods for 2004 are described in McBride et al. (2008). In the fall of 2008, bankfull widths were re-measured in all reaches, mimicking the 2004 methods, where we used a flexible tape drawn taut and perpendicular to the bankfull channel. In W12 reaches, bankfull widths were measured approximately every 8 m. In upper Pope Brook, we only measured widths at permanent cross-sections. Bankfull elevations were determined considering a combination of the presence or absence of perennial vegetation, topographic breaks in the bank, and a change in sediment texture or size (Dunne and Leopold, 1978). Ice in the streams prevented us from collecting data on bed width, as was collected in 2004 to match the field methods of Zimmerman et al. (1967); McBride et al., 2008).

In the spring of 2005, we collected three-dimensional velocity data in reaches NF1, R1, and F1 during five high flows (Fig. 2). Three-dimensional velocities were measured with a Nortek Vectrino Acoustic Doppler Velocimeter (ADV; Annapolis, MD). Levels were attached to the ADV to ensure that the equipment was properly braced and maintained in a fixed position. The ADV sampled at a rate of 25 Hz for approximately 90 s, at which time stationarity was attained.

Three-dimensional velocities were measured at six locations within each reach at near-bed (approximately 1 cm from the bottom surface) and 0.6-depth elevations. Measurement locations were selected along the outer edges of two curved, unobstructed sections within each reach. The planform of stream W12 could be classified as sinuous-straight, because it does not have the morphology or organized hydraulic characteristics of a larger, meandering system with a pattern of alternating meander bends. At each section, velocities were measured at three points along a transect approximately 10 cm from the stream bank and spaced approximately 50 cm apart (Fig. 3). Although we would have preferred to sample along straight segments of the channel, we were limited by shallow

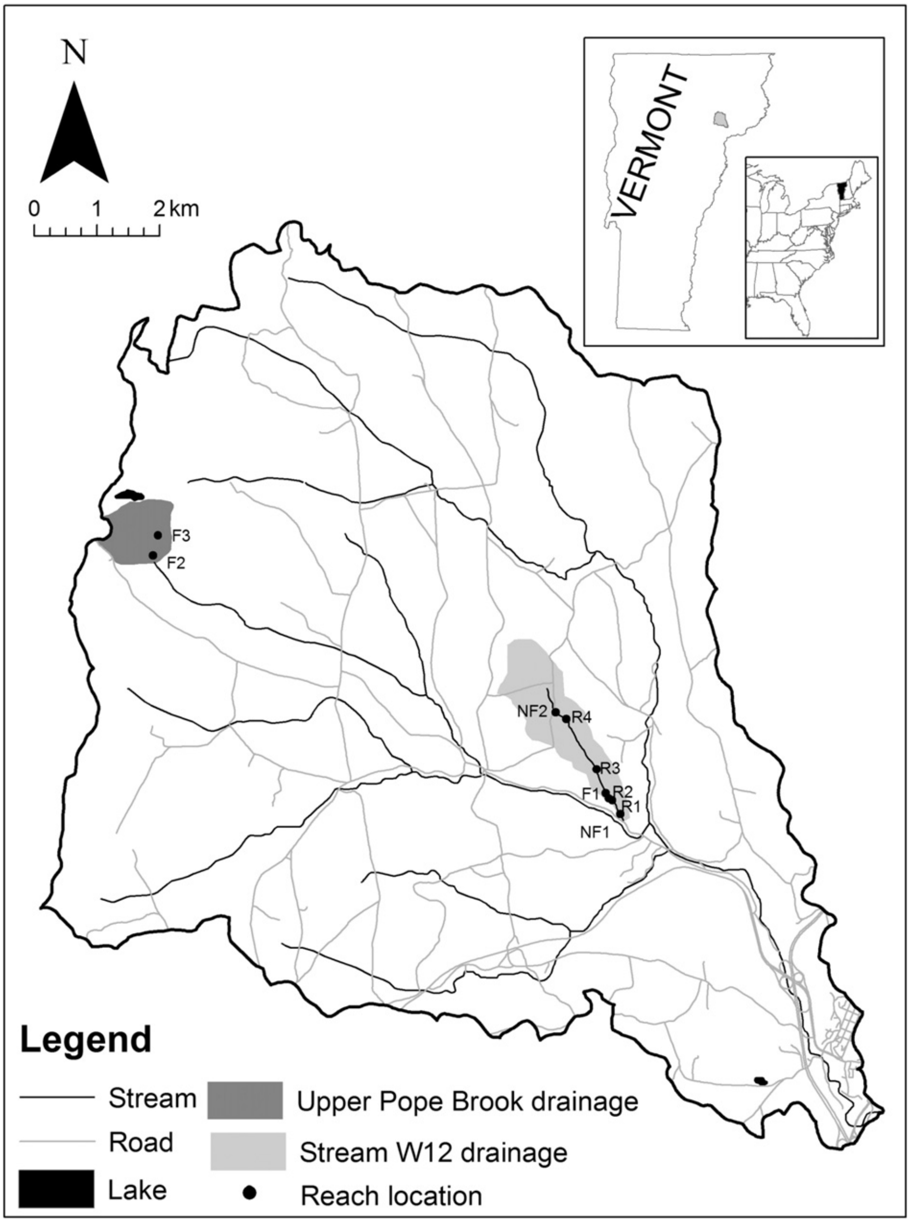

Fig. 1. Location of the SRRW showing drainages and reaches of W12 and upper Pope Brook.

water depths and a minimum depth of 12 cm required by our instrumentation.

Sampling dates were chosen during the high flow period of snow melt and following rainfalls (Table 1). We were unable to collect measurements during the highest flows of snow melt during mid-April because anchor ice remained in the forested reaches (R1 and F1). Discharges were determined using the velocity-area method, and velocities were measured using a Marsh–McBirney velocity meter (Hach Company, Loveland, CO). For each sampling date, the discharge was determined at NF1 at the beginning and end of the ADV sampling. On June 1, 2005, we collected discharge data at all three reaches.

3.2. Analytical methods for channel dimensions

Differences in mean bankfull width over four years (between 2004 and 2008) were tested using a series of two-sample *t* tests and assessed using a percent difference. A total of seven *t* tests were performed on the W12 reaches. Homogeneity of variance was tested in all cases using Levene's test (SAS, 2004). Percent differences (*PD*) between 2004 and 2008 data were determined as

$$PD = (W_{2008} - W_{2004}) / W_{2004} \times 100 \tag{1}$$

where W_{2008} is the mean bankfull width as measured in 2008, and W_{2004} is the mean bankfull width as measured in 2004. We tested whether the *PD* of reforested reaches were greater than other reaches using the nonparametric, one-tailed Mann–Whitney test (Zar, 1999). Channel dimension data from previously published, paired forested and nonforested studies (Davies-Colley, 1997; Hession, 2001) were also compiled to produce hydraulic geometry relationships between bankfull width and drainage area as described by McBride et al. (2008).

3.3. Analytical methods for ADV data

Post-processing methods were used to ensure quality ADV data and the best representation of true velocity conditions. Erroneous

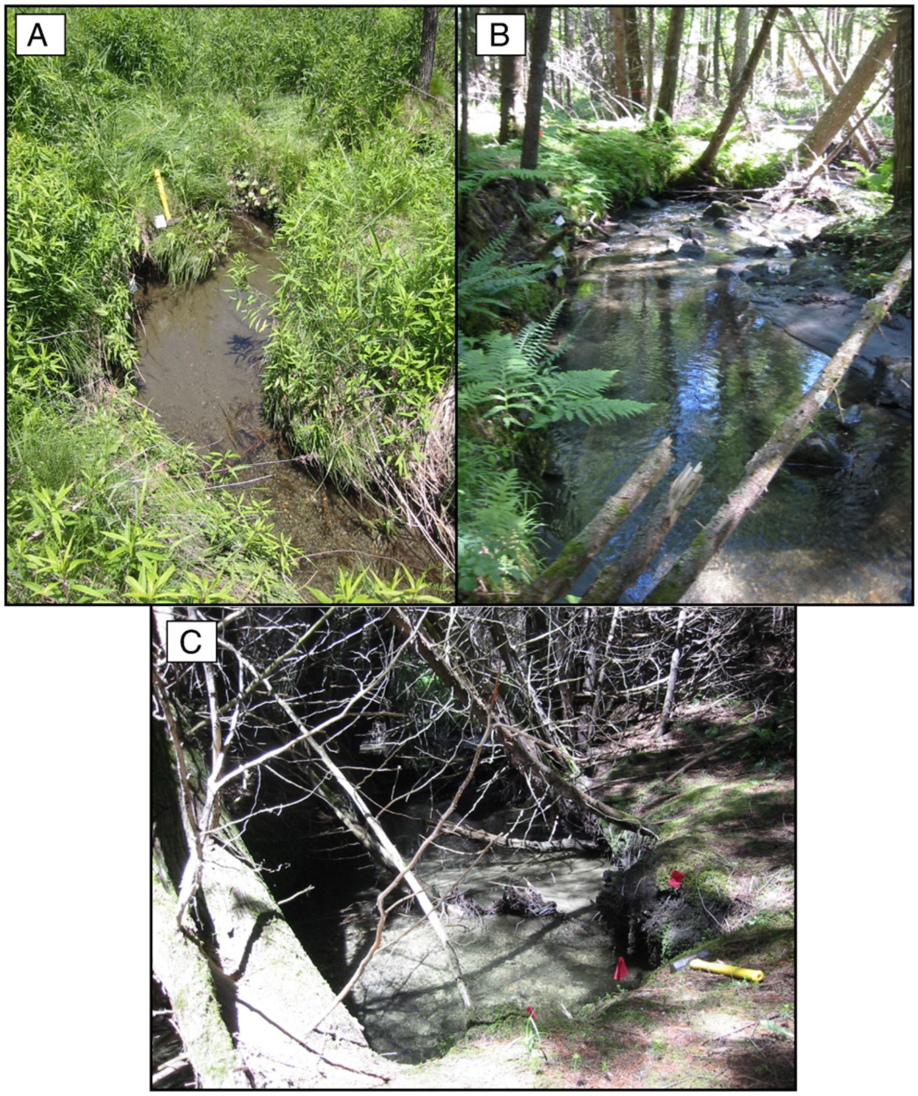

Fig. 2. Photographs of reaches NF1 (A), F1 (B), and R1 (C). Pink and white flaggings show locations of ADV sampling.

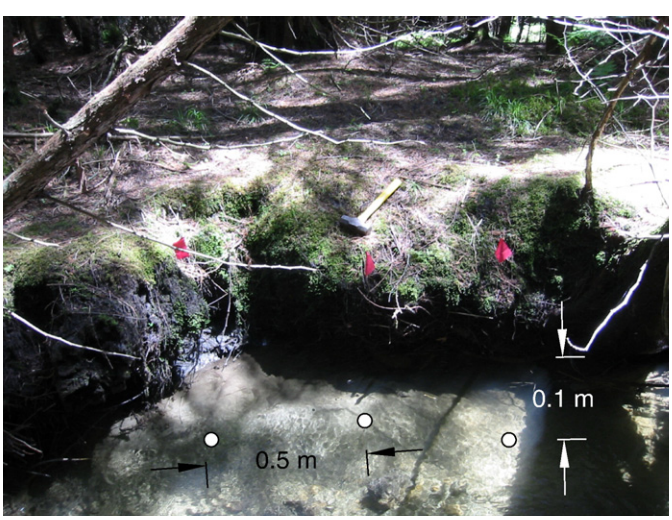

Fig. 3. Photograph of left bank of reach R1 with sampling locations shown relative to the bank surface.

data because of communication errors, low signal correlation, low signal-to-noise ratios (SNR), or effects of aliasing can bias values of mean velocity and turbulence statistics (Lane et al., 1998). Post-processing methods mirrored those of McBride et al. (2007). A total of

Table 1
ADV sampling dates, flows, and mean velocities.

Date	Time	Reach	Flow (m^3/s)	Mean velocity (m/s)	Flow estimates (m^3/s)		
					NF1	R1	F1
4/29/2005	9:00	NF1	0.082	0.59	0.079	0.066	0.055
	15:00	NF1	0.076	0.55			
5/6/2005	9:00	NF1	0.036	0.44	0.036	0.030	0.025
	15:00	NF1	0.036	0.43			
5/10/2005	11:00	NF1	0.032	0.42	0.032	0.026	0.022
	17:00	NF1	0.031	0.42			
5/11/2005	8:00	NF1	0.032	0.41	0.032	0.027	0.022
	11:00	NF1	0.032	0.42			
6/1/2005	11:00	NF1	0.032	0.40	0.030	0.025	0.021
	13:00	F1	0.021	0.13			
	14:00	R1	0.025	0.27			
	16:00	NF1	0.028	0.36			

Flow estimates for NF1 are mean values of the two measured flows each day. Flow estimates for R1 and F1 are 83% and 70%, respectively, of the NF1 flow estimates, based on the proportionality observed on June 1, 2005.

177 velocity files were recorded, and of those eighteen files were discarded because of insufficient retained data. Of the remaining files, the mean percentage of retained points was 98.9%. Post-processing of velocity data was completed using ExploreV software from NortekUSA (Annapolis, MD).

Following data post-processing, mean velocities in the streamwise (U), lateral (V), and vertical (W) directions and turbulent kinetic energy (TKE) were calculated. Because the short-term variation of velocities around the time-averaged values is an essential aspect of turbulent motion, the intensity of turbulence can be quantified as:

$$TKE = 0.5\rho(<u'^2> + <v'^2> + <w'^2>) \quad (2)$$

where ρ is the density of water (1.0 g/cm^3) and $<u'^2>$, $<v'^2>$, and $<w'^2>$ are the mean square differences between the instantaneous velocities and the time-averaged velocities in the streamwise, lateral, and vertical directions, respectively (Clifford and French, 1993).

Differences in turbulence and velocities among the three reaches were evaluated using an analysis of covariance with discharge as the covariate. Discharge values for NF1 were estimated as the average between the beginning and ending measured flows of each sampling date (Table 1). Discharge values for F1 and R1 were estimated as a proportion of the average NF1 discharge, based on the proportionality measured on June 1, 2005 (Table 1). When the analysis of covariance uncovered significant differences, Tukey's HSD multiple comparison test was used to evaluate differences in mean values (Zar, 1999). Statistical testing was completed using JMP software v.5.0.1.2 (SAS Institute, Cary, NC).

4. Results

4.1. Riparian reforestation and land use change

Substantial riparian reforestation has taken place adjacent to W12 since the Zimmerman et al. (1967) study (Fig. 4). In 1966, W12 had ~50% of its total stream length bordered by nonforested vegetation (Zimmerman et al., 1967), while during this study roughly 20% of the stream remained bordered by nonforested vegetation. These nonforested sections of W12 have been actively mowed and may have had cattle introduced periodically. Riparian forests at reaches F1, F2, and F3 were at least 60 years old, and forests surrounding F2 may be at least 85 years old (McBride et al., 2008). Between 2005 and 2008, cattle were reintroduced at reach NF1. None of the other reaches had any changes in land use or land cover of the adjacent riparian areas during the last four years.

4.2. Channel width

The reforested reaches of W12 increased in width from 1966 to 2004 (McBride et al., 2008), and continued to widen between 2004 and 2008 (Fig. 5). Among all reaches, the change in mean bankfull width ranged from −7.2 to 28.5 percent (Table 2). Only reach R1 had a significantly greater bankfull width in 2008 than that measured in 2004 ($p = 0.029$). Three of the four reforested reaches in W12 (reaches R1, R2, and R3) experienced the greatest change in mean bankfull width, as shown by the three highest PD (28.5%, 12.1%, and 11.4%, respectively). When the reforested reaches were compared against all other reaches, they had significantly greater PD ($p = 0.05$). Reach NF1 increased in width by nearly 10%, a potential response to the introduction of cattle (Belsky et al., 1999).

With width measurements available at three distinct points in time, annual rates of widening can be estimated for reforested reaches with the crude assumption of linear change. Between 1966 and 2004, the four reforested reaches widened at a rate of 4.1 cm/year. In the four years since 2004, the four reforested reaches widened at a rate of 8.7 cm/year. McBride et al. (2008) also found an increase in bed width for forested (2.1 cm/year) and nonforested reaches (1.1 cm/year) between 1966 and 2004, but within the last four years these reaches did not experience a significant change in width. The mean PD for these reaches was 0.94%, which was not significantly greater than zero ($t = 0.34$, $p = 0.375$).

Bankfull widths were plotted with hydraulic geometry relationships developed for forested and nonforested reaches of previous studies (Fig. 6). Although hydraulic geometry relationships are generally specific by region, our data corresponded well with data from Pennsylvania (Hession et al., 2003) and New Zealand (Davies-Colley, 1997). In general, widths from our study may be relatively smaller than widths from Pennsylvania and New Zealand because the

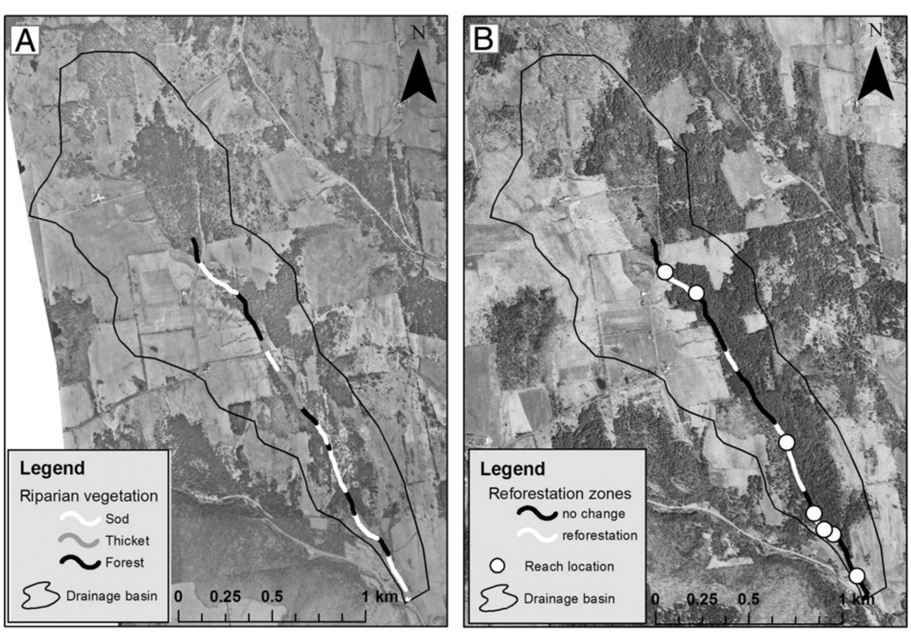

Fig. 4. Aerial photographs of the W12 in 1965 (A) with the riparian classifications of Zimmerman et al. (1967) and in 1999 (B) with reforested segments highlighted and sample reach locations identified.

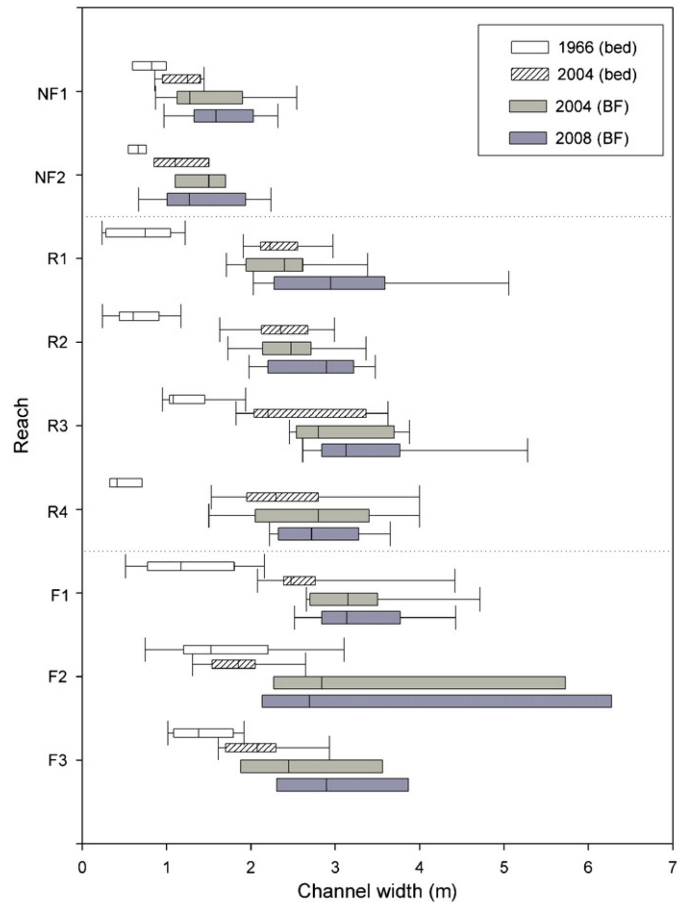

Fig. 5. Box plots of bed and bankfull width data from 1966, 2004, and 2008 showing median values (mid-line), 25th and 75th percentiles (box), and 10th and 90th percentiles (whiskers).

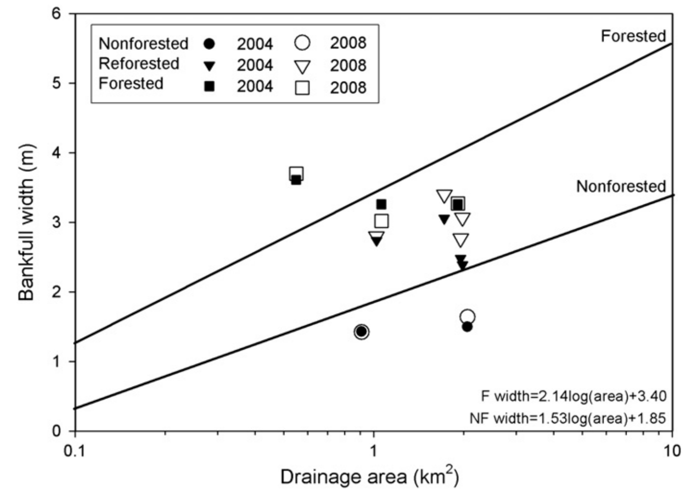

Fig. 6. Bankfull width hydraulic geometry for forested and nonforested reaches (plotted as lines) from Davies-Colley (1997) data ($n = 11$) and Hession et al. (2003) data ($n = 7$) and mean bankfull widths of nine study reaches from 2004 and 2008 (plotted as points).

northeastern Vermont climate is dryer and cooler (McBride et al., 2008). Forested reaches were substantially wider than nonforested reaches for a given drainage area, and reforested reaches plot between those two sets of points. Only reforested reaches displayed much difference between 2004 and 2008 plotting points. The three reforested reaches with the larger drainage areas exhibited the greatest increase in width between 2004 and 2008.

4.3. Velocities

Marked differences in mean velocities and point velocities were found for different riparian types and discharge events. The discharge events captured during ADV sampling ranged from 0.028 m^3/s to 0.082 m^3/s at reach NF1 (Table 1). All flows were contained within the bankfull channel. Based on the flow measurements of June 1, reaches R1 and F1 were estimated to experience a fraction of these flows (0.83 and 0.70, respectively). Mean velocities at the flow gaging cross-sections differed greatly by riparian type; mean velocity was lowest at reach F1, while the mean of NF1 was almost three times greater, and the mean of R1 was double the mean velocity of F1 (Table 1).

Conversely, the velocities recorded by ADV at distinct sampling points along outer bends in the reaches (Fig. 3) generally exhibited greater values in the downstream, *x*-direction (*U*) in reach F1 than in either NF1 or R1 (Table 3). Lateral velocities (in the *y*-direction, *V*) were most frequently directed into the adjacent bank (negative values) or were negligible. Vertical velocities (in the z-direction, *W*) were most frequently negative, or directed toward the stream bottom.

Table 2
Current and past channel width measurements.

Reach	Stream	Mean width (m)			
		1967	2004	2008	*PD*
NF1	W12	0.81 (6, 0.22)	1.50 (10, 0.54)	1.64 (10, 0.43)	9.9%
NF2	W12	0.67 (6, 0.12)	1.43 (7, 0.38)	1.42 (10, 0.52)	−0.8%
R1	W12	0.70 (9, 0.38)	**2.39** (10, 0.51)	**3.07** (10, 0.93)	28.5%
R2	W12	0.65 (10, 0.30)	2.48 (10, 0.49)	2.77 (10, 0.53)	12.1%
R3	W12	1.24 (9, 0.34)	3.06 (10, 0.57)	3.40 (10, 0.85)	11.4%
R4	W12	0.51 (8, 0.27)	2.74 (9, 0.82)	2.80 (10, 0.51)	2.1%
F1	W12	1.23 (11, 0.58)	3.26 (10, 0.67)	3.27 (10, 0.59)	0.4%
F2	Pope	1.70 (10, 0.77)	3.61 (3, 1.86)	3.70 (3, 2.25)	2.4%
F3	Pope	1.42 (10, 0.33)	3.26 (3, 0.90)	3.02 (3, 0.82)	−7.2%

Bolded mean values are significantly different with $\alpha = 0.06$. Mean widths for 1967 are bed widths, while 2004 and 2008 data are bankfull widths. Numbers in parenthesis are *n* and standard deviation. *PD* is percent difference between years 2004 and 2008.

Table 3
Turbulence and velocity parameters by sampling date and reach.

Date	Reach	n	Mean *TKE* ($x10^{-1}$ Pa)		*U* (cm/s)		*V* (cm/s)		*W* (cm/s)	
4/29/2005	NF1	10	54.2	(32.6)	8.2	(12.8)	1.4	(2.8)	2.3	(4.5)
	R1	10	61.4	(27.7)	6.6	(13.2)	2.5	(5.4)	0.5	(3.5)
	F1	11	33.8	(13.8)	20.6	(10.2)	2.5	(5.7)	2.4	(2.4)
5/6/2005	NF1	11	27.7	(20.9)	7.9	(2.4)	0.7	(2.3)	0.6	(1.2)
	R1	7	24.8	(14.4)	8.9	(3.4)	0.4	(5.0)	0.1	(1.6)
	F1	11	21.4	(11.0)	6.1	(1.9)	0.9	(4.2)	1.5	(1.8)
5/10/2005	NF1	12	32.1	(19.5)	5.7	(9.3)	0.0	(2.8)	1.0	(2.7)
	R1	8	37.6	(23.1)	3.7	(8.7)	0.1	(3.8)	0.4	(2.7)
	F1	12	18.7	(11.9)	13.8	(6.8)	1.0	(3.5)	1.1	(1.6)
5/11/2005	NF1	10	32.7	(16.5)	5.8	(9.4)	1.5	(3.7)	1.0	(2.1)
	R1	10	48.4	(37.1)	5.7	(7.2)	0.7	(4.4)	1.3	(1.9)
	F1	12	19.6	(17.3)	10.7	(7.2)	1.9	(3.9)	0.9	(1.6)
6/1/2005	NF1	12	27.8	(15.6)	4.8	(7.5)	0.4	(2.8)	0.9	(1.6)
	R1	11	45.4	(32.3)	8.8	(10.7)	1.7	(5.7)	2.1	(3.1)
	F1	12	17.2	(11.6)	11.7	(5.4)	0.5	(4.2)	0.3	(0.9)

Standard deviations in parentheses.

Table 4
Analysis of covariance results for turbulence and velocity parameters.

Parameter	Riparian	Discharge	Whole model	Tukey HSD
	p-value	*p*-value	*p*-value	Groupings
TKE ($\times 10^{-1}$ Pa)	<0.0001	<0.0001	<0.0001	R>NF≈F
U (cm/s)	<0.0001	0.035	<0.0001	F>NF≈R
V (cm/s)	0.024	0.643	na	R>F
W (cm/s)	0.723	0.111	na	na

Analysis of covariance results showed that downstream velocities were significantly different by riparian type and significantly influenced by the covariate, discharge (Table 4). A subsequent test of means confirmed that the forested reach F1 had significantly greater downstream velocities than the nonforested (NF1) and reforested (R1) reaches. As described above, average velocities were lowest in the F1 reach, but point velocities were greatest. For lateral velocities, discharge was not a significant predictor, but riparian type corresponded to significant differences. Reaches F1 and R1 were separated by the Tukey's HSD multiple comparison test, indicating that lateral velocities were more often directed away from the bank (positive values) in R1, while the opposite was true in reach F1.

4.4. Turbulence

Turbulence, as measured by *TKE*, was significantly influenced by riparian type and discharge. The least squares (LS) mean *TKE* for the reforested reach R1 (44.8×10^{-1} Pa) was roughly double the LS mean *TKE* of the forested reach F1 (25.0×10^{-1} Pa) and approximately 40% greater than the LS mean *TKE* of the nonforested reach NF1 (31.4×10^{-1} Pa). Turbulence increased with increasing discharge for all riparian types (i.e., no interaction effect between the riparian factor and the discharge factor). Within the reach segment, *TKE* values recorded near the stream bottom were not significantly different than those values recorded at 0.6-depth.

5. Discussion

5.1. Channel width and rates of widening

The long history of deforestation, reforestation, and variable agricultural uses in Vermont, and undoubtedly in other locations as well, sets a complex context for geomorphic inquiries (Fig. 7). Within the context of more than one, overlapping, long-term changes, the response of a stream or river to a single anthropogenic or natural change may be difficult to determine, such as the riparian reforestation impacts. Channel width is one of the most responsive and adjustable geomorphic parameters (Knighton, 1998). Although the channel widths in our study area may still be "recovering" from the historic deforestation centuries ago and may continue to evolve in response to climate change or watershed-scale changes, the decadal change in riparian vegetation has created a strong and discernable imprint on the channel morphology. Our measurements over a shorter period of 4 years confirm that reaches reforested in the last 30 to 40 years continue to undergo the most significant widening. Even though the climatic conditions were generally warmer and wetter in the last 4 years, any changes in the discharge regime of stream W12 would have been universal across all of the study reaches.

With our results and other related research, we created an historic timeline of channel width for stream W12. We presumed that W12 would have had its largest width prior to the impacts of colonization (e.g. land clearing, channel modifications). The historic channel may have been a wide, complex and anastamosing system (Walter and Merritts, 2008). When the W12 catchment was converted to agricultural land, we expect that the stream would have rapidly in-filled with the increased sediment load and the effects of grassy riparian vegetation (Leopold, 1973; Davies-Colley, 1997). Sometime post-narrowing, the sediment load likely decreased because forests recolonized portions of the catchment (Bierman et al., 1997; Albers, 2000), and streams perhaps slowly widened in response. This slow widening was observed in forested and nonforested reaches between

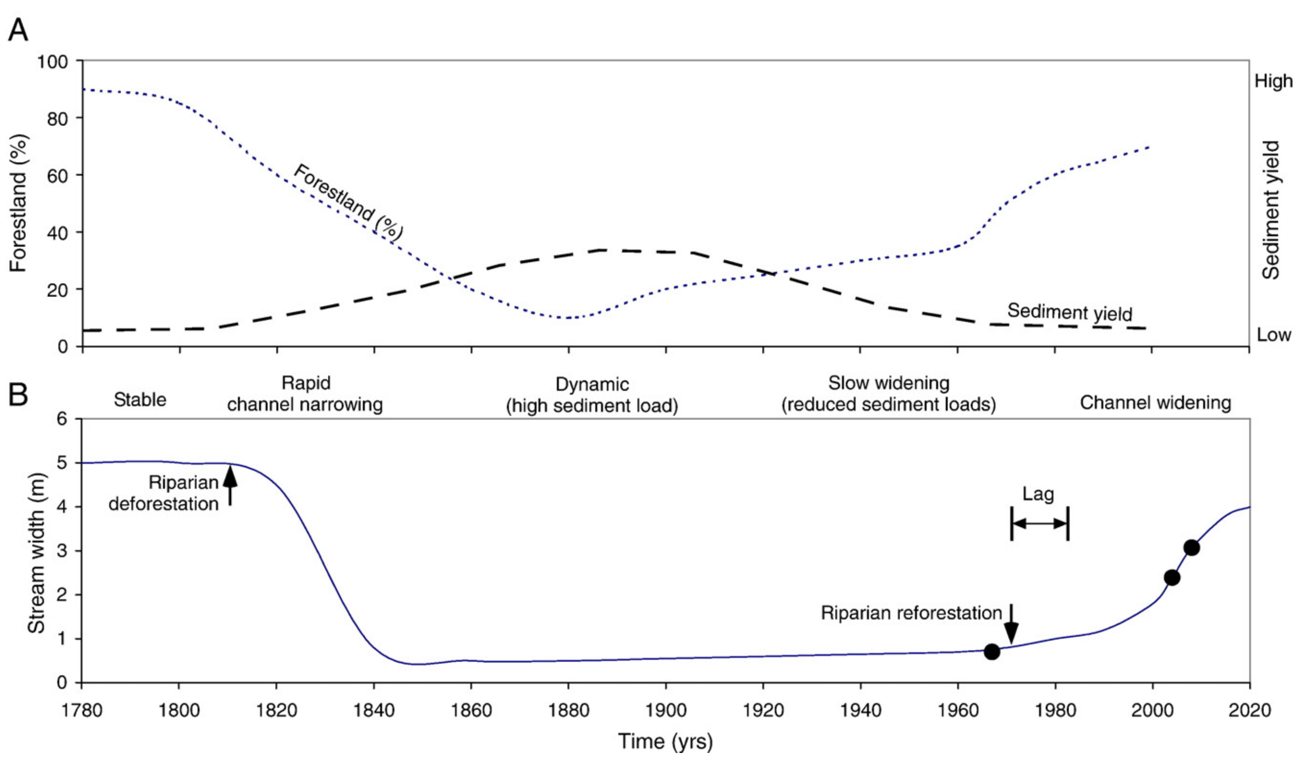

Fig. 7. Suspected historic channel response to riparian and catchment-scale deforestation and reforestation. Presumed catchment-scale trends in forested area and sediment yield (A) are based on several resources (Leopold, 1973; Bierman et al., 1997; Albers, 2000). Mean stream width versus time (B) is plotted with known data points (●) along a plausible historic trend.

1966 and 2004. As riparian forests re-grow at W12, we found a fairly rapid widening following, perhaps, a lag period.

At present, reforested reaches may not be as wide as forested reaches and are actively widening. The hydraulic geometry relationships show that for a given drainage area forested reaches are wider than nonforested reaches, confirming previous findings (Zimmerman et al., 1967; Murgatroyd and Ternan, 1983; Sweeney, 1992; Peterson, 1993; Davies-Colley, 1997; Trimble, 1997; Scarsbrook and Halliday, 1999; Hession et al., 2003; Sweeney et al., 2004; Allmendinger et al., 2005), while reforested reaches are wider than nonforested reaches and narrower than forested reaches (Fig. 6). Reach R1 had the greatest increase in mean width (67 cm) over the four-year period. Relative to the other reforested reaches, reach R1 was the most undersized given its drainage area and had the greatest amount of LWD in 2004 (McBride et al., 2008).

Width adjustments can take place at various rates over various lengths of time (ASCE, 1998; Knighton, 1998). We discovered two different rates of width enlargement during the time period since historic data were collected at our study streams. Because reforestation began at stream W12 sometime between 1966 and 1974 (based on observations of aerial photographs), the average, long-term widening rate for reforested reaches may fall between 4.1 cm/year and 5.1 cm/year. This average rate assumes a linear change in width; however, we would expect the rate to vary with forest maturity and year-to-year hydrologic conditions (Fig. 7). Recently, between 2004 and 2008, the reforested reaches widened at an average rate of 8.7 cm/year. The recent, faster widening rate may have been partially driven by the warm and wet climatic conditions of 2004 to 2008. Few other studies have attempted to estimate widening rates following reforestation, but Murgatroyd and Ternan (1983) approximated a rate of 2.5 cm/year for a stream within a 50-year-old spruce plantation. Observations of streams in pine plantations suggested that widening could occur as soon as 18 years following reforestation (Davies-Colley, 1997), and several agree that the process may take decades (Davies-Colley, 1997; Trimble, 2004; McBride et al., 2008). Some studies have considered differences in erosion or migration rates between paired forested and nonforested streams (Table 5), and generally have found greater rates of erosion associated with nonforested reaches (Pizzuto and Meckelnburg, 1989; Stott, 1997; Allmendinger et al., 2005). Although measures of bank erosion or migration rates should not be directly compared with our rates of stream widening, the similarity among these rates is noteworthy. The rates of erosion of Murgatroyd and Ternan (1983), based on erosion pin data, may be uncharacteristically low given their 19-month monitoring period (Table 5).

Differences between the long-term and short-term rates observed at stream W12 may be attributable to a lag effect between cause and effect (Fig. 7). A lag effect can be pronounced for cases of narrowing, a transition that requires the import and trapping of large amounts of sediment (Knighton, 1998). The processes presumed responsible for channel widening (i.e., scour around LWD, shading of understory vegetation, increased resistance during overbank flows) will also develop over time as the forest vegetation matures. Recruitment of LWD to the stream will be delayed until the forest matures and is disturbed in some manner (e.g., bank erosion, wind throw). Shading of understory vegetation and changes to the herbaceous plant community will increase slowly as the tree canopy develops. The hydraulics of overbank flows will be more immediately impacted by young woody stems, but the nature of the resistance and turbulence will likely change over time as the forest succeeds and matures.

Table 5
Comparison of bank erosion rates between paired forested and nonforested sites.

Location	Catchment area (km^2)	Riparian type	Erosion rate (cm/yr)	Reference
Central Scotland, UK	6.9–7.7	Forest	4.7	Stott (1997)
		Moorland	5.9	
Pennsylvania, US	0.4–12.3	Forest	7	Allmendinger et al. (2005)
		Nonforest	34	
Southwest England, UK	4.8	Reforest	0.52	Murgatroyd and Ternan (1983)
		Nonforest	0.07	
Pennsylvania, US	743	Trees	4	Pizzuto and Meckelnburg (1989)
		No trees	26	

5.2. Turbulence and velocity

Differences in *TKE* and velocity characteristics among the riparian types may help explain the widening process at reforested reaches and describe some persistent differences between forested and nonforested reaches. The original intent of the in-stream turbulence measures was to test the hydraulic conditions during overbank flows, as was studied in flume experiments (Pasche and Rouve, 1985; McBride et al., 2007). We were not able to collect ADV data during overbank flow conditions in the snow melt period because of ice remaining in the forested reaches; however, observations of within bank flows showed marked differences in velocities and turbulence. Although we were not able to test for turbulence differences while flows interacted with the riparian vegetation, our measurements provided other insights.

First, flow conditions observed during the spring of 2005 confirmed that a greater proportion of the bankfull channel was filled in reach NF1 than in reaches R1 or F1 for a given flow, similar to peak stage records of (McBride, 2007). We, in addition to others (Murgatroyd and Ternan, 1983; Davies-Colley, 1997), suspect that nonforested reaches have a greater frequency of overbank flows than either reforested or forested reaches (Fig. 8). Second, average cross-sectional velocities were lower in F1 and R1 than in NF1, presumably because the cross-sectional area of those reaches is larger. Although our finding is based on only one flow, this difference has been found elsewhere where they also found higher roughness values in forested stream channels (Quinn et al., 1997; Sweeney et al., 2004). Interestingly, mean velocities downstream along the outer edge of curved segments of our reaches were significantly greater in forested reaches. Presumably, greater variation occurs in velocities downstream within forested cross-sections because of the larger cross-sectional area with variable water depths and roughness elements.

Finally, turbulence differences between the riparian types were not as extreme as those differences found in physical models but were significant nonetheless (McBride et al., 2007). Our finding that the *TKE* of R1 was significantly greater than NF1 or F1 suggests that the reforested reaches of stream W12 may have a greater potential for erosion during peak flows. The greater turbulence in reforested reaches when contained within the banks and when the floodplain is inundated (McBride et al., 2007) may partially explain the high rates of channel widening documented in the last four years and since reforestation began. Because our turbulence measures were only replicated at six locations within each reach, we were unable to identify the driver of these turbulent characteristics. We surmise that higher turbulence in reforested reaches is a function of an undersized channel (relative to forested counterparts) with in-stream roughness similar to forested reaches. A study of turbulent flow at the reach-scale found that velocities and turbulence intensities were primarily responding to the gross morphology of the channel, not individual roughness elements (Legleiter et al., 2007). Relatedly, Buffin-Belanger et al. (2006) found that variations in *TKE* at different sampling heights in a water column were relatively small. Likewise, we found no significant differences between *TKE* measured near the bottom of the channel and at 0.6-depth. *TKE* was greater at NF1 than F1, which we attribute to the narrower width of the channel, greater filling of the bankfull channel, and, hence, greater interaction of flows with the channel boundary.

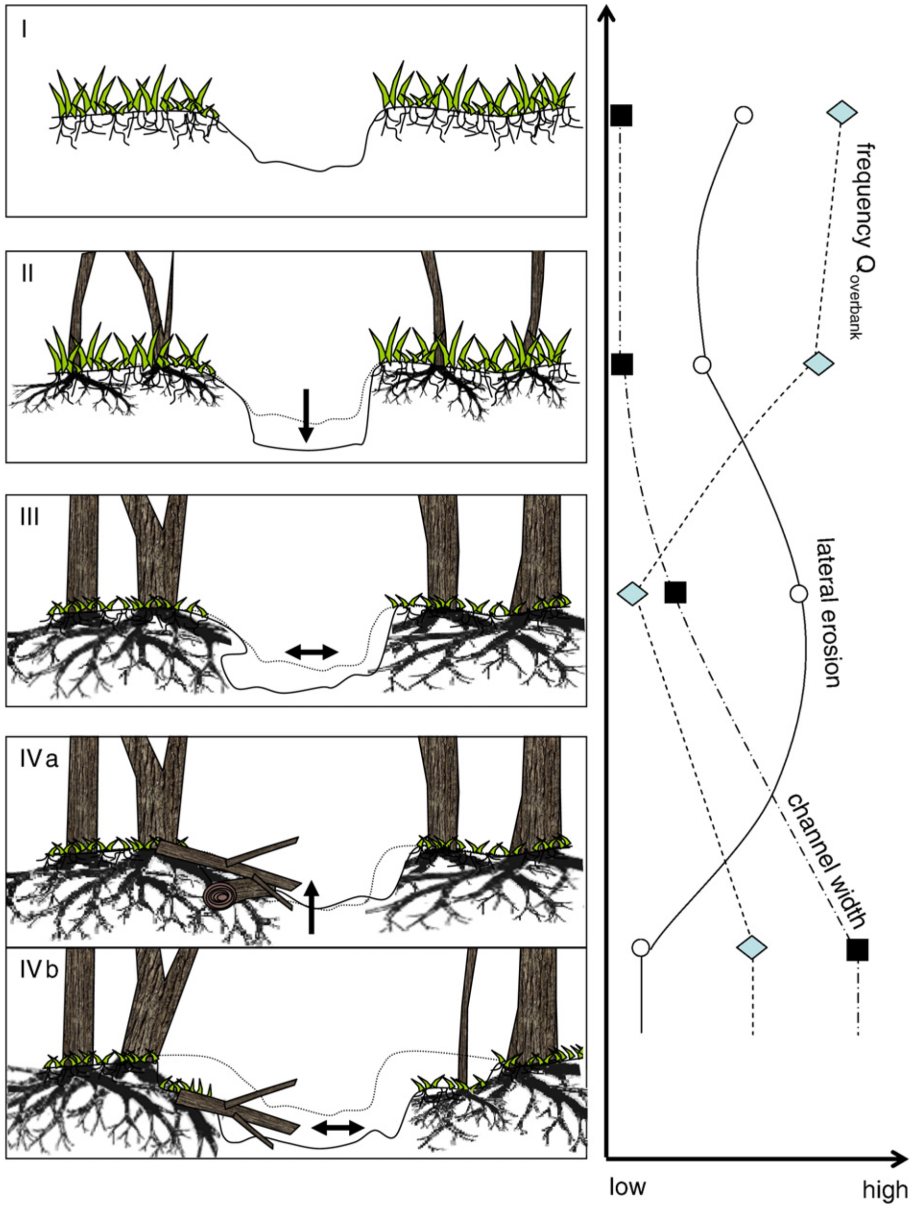

Fig. 8. Sketch of conceptual model of stream W12 with original channel profile repeated throughout. Stage I — equilibrium nonforested; stage II — reforestation begins and channel incises; stage III — incision slows, channel widens, forest matures; stage IV — channel reaches forested equilibrium by either (a) aggradation or (b) creating an inset floodplain. Relative levels of stream width, rates of lateral erosion, and rates of deposition are graphed adjacently.

5.3. Conceptual model for channel widening of stream W12

With our new findings, we expand on the conceptual model for widening conceived by McBride et al. (2008); Fig. 8). The conceptual model explains a multiphase channel adjustment in response to reforestation at stream W12 where the channel first incises and then widens in response to changes in the local hydraulics and bank-resisting forces (McBride et al., 2008). Our conceptual model is similar to other models that have been proposed for channel evolution following other disturbances such as channelization and urbanization (Schumm et al., 1984; Booth, 1990; Hupp and Simon, 1991); however, our model emphasizes the role of riparian vegetation more than previous models. Based on width, velocity, and turbulence measurements, we overlaid the model with plausible changes in three key parameters: channel width; lateral erosion (widening capacity), and the frequency of overbank flows ($Q_{overbank}$; trapping capacity). The following is a step-by-step description of the conceptual model of stream W12 in relation to these parameters.

The first stage of the model (stage I; Fig. 8) represents the nonforested condition as observed in reaches NF1 and NF2. The channel size is relatively small and provides for frequent floodplain inundation. Bank erosion and lateral migration are hypothesized to be relatively high (Pizzuto and Meckelnburg, 1989; Stott, 1997; Allmendinger et al., 2005), but are coupled with a high rate of deposition because of trapping of sediment by the grassy vegetation and rapid regrowth of grassy vegetation on exposed deposits (Davies-Colley, 1997; Trimble, 1997; Sweeney et al., 2004). The transition process begins when trees colonize the nonforested floodplain and bank edge (stage II; Fig. 8).

In the second stage, the trees are too young to shade out grassy vegetation or to yet provide LWD to the stream; therefore, minimal change is expected in bank resistance, in-stream roughness, or bank erosion. Increased roughness on the floodplain may cause near-bank turbulence during overbank flows (McBride et al., 2007) and drive channel incision (McBride et al., 2008). Flume studies have shown a two-fold increase in *TKE* at the interface of the floodplain and main channel during overbank flows when woody stems are introduced to the floodplain surface (McBride et al., 2007). Increased turbulence may initiate incision as the stream compensates for the increase of in-stream energy; however, the amount of vertical and lateral adjustments to the increased turbulence will be site-specific and will depend upon many factors such as bed substrate and armoring, bank cohesion, rooting depth, and upstream sediment supply. If incision is dominant, we would expect the frequency of overbank floods to decline. As the roots of woody vegetation begin to grow more deeply than the nonforested vegetation, lateral erosion may decline for a period as banks are reinforced with woody and herbaceous roots.

The third stage of the model represents the current conditions at the reforested reaches (R1–R4). In stage III (Fig. 8), the channel is deeper and wider than stage I or II. Assuming the hydrologic regime is constant throughout the stages of the model, the floodplain inundation frequency will have decreased as the channel has incised and widened. In-stream turbulence during the peak flows contained within the channel is expected to be high and drive lateral expansion. The forest vegetation has likely matured at this stage to provide more shade to limit the growth of grassy vegetation, potentially weakening streambanks, as speculated in previous studies (Davies-Colley, 1997; Trimble, 1997). Streambanks may be additionally weakened by the weight of young trees along the edge of the stream channel (Thorne, 1990; Simon and Collison, 2002).

In the final stage, the channel reaches a new "forested" equilibrium with a wide, complex channel. Reaches F1, F2, and F3 may not have yet attained this final stage of the model. We suspect that the channel will recover from the incision to create an active floodplain either by aggrading back to the original bed level (stage IVa; Fig. 8) or by creating a new inset floodplain surface (stage IVb; Fig. 8), or a combination thereof. Ultimately, the new "forested" channel reaches a state where the channel has adequate capacity for the discharge and sediment regimes, given the added roughness of both in-stream LWD and the forested floodplain. The rate of bank erosion and the frequency of overbank floods are hypothesized to be lower than the channel in stage I producing a more "stable" channel; however, scour and deposition around LWD and logjams may create local "unstable" zones (i.e., stage IV is not a "static" stream system, rather one that is in "dynamic" equilibrium).

6. Conclusions

Reforested reaches were shown to have widened by a comparison of measurements collected in 1966, 2004, and 2008. When narrow, nonforested reaches of small streams are replanted or re-colonized with forest vegetation, they begin a long process of reestablishing a wider, more complex form. Our measurements show a non-linear widening process that begins slowly and accelerates once riparian forests have matured. The rate of widening found within the last four years was perhaps double the rate of widening that occurred between the time forests re-grow and our first set of data collection in 2004. Measurements of in-stream velocity and turbulence, collected during peak flows, demonstrated that the reforested reaches may be experiencing the greatest turbulence and consequently are the most dynamic or "unstable" of the three reach types on stream W12. Although our sample size is small and our geographic extent is limited, when coupled with previous research and the conceptual model, generalized conclusions about the dynamics of riparian vegetation and channel size in small streams are more possible. We hope our speculations presented in the conceptual model of stream W12 will prompt future investigations into the effects of widening on sediment delivery, sediment transport, inundation frequency, and stream habitat. Because riparian reforestation is a ubiquitous stream restoration technique, once lost stream habitat may be resurrected and re-exposed with this channel-widening response in small streams (Sweeney et al., 2004); however, unanticipated increases may occur in sediment loads accompanying the width change (Trimble, 2004). With an awareness of this channel-widening response and its timescale, stream restoration efforts could be amended to accommodate or mitigate for possible undesirable short-term outcomes. For example, stream restoration activities that involve riparian reforestation and in-stream modifications might be designed to accommodate width changes ("flexible" instead of fixed, armored channel margins) or might include strategies to trap sediment within the restored reach (e.g. with large woody debris). In other cases, when riparian reforestation is the exclusive treatment for a restored reach, an adaptive management plan might be needed to respond to anticipated morphologic change (e.g, deepening, widening) in the decades following the riparian planting.

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References

Abernethy, B., Rutherfurd, I.D., 1998. Where along a river's length will vegetation most effectively stabilise stream banks? Geomorphology 23 (1), 55–75.
Albers, J., 2000. Hands on the Land: A History of the Vermont Landscape. MIT Press, Cambridge, MA.
Allmendinger, N.E., Pizzuto, J.E., Potter, N., Johnson, T.E., Hession, W.C., 2005. Riparian vegetation and width adjustment in laterally migrating rivers of eastern Pennsylvania, U.S.A. Geological Society of America Bulletin 117 (1/2), 229–243.
Anderson, R.J., Bledsoe, B.P., Hession, W.C., 2004. Stream and river channel width response to riparian vegetation, bank material texture, and other factors. Journal of the American Water Resources Association 40 (5), 1159–1172.
ASCE, 1998. Bank mechanics and modeling of river width adjustment, I: Processes and mechanisms. Task Committee on Hydraulics. Journal of Hydraulic Engineering 124 (9), 888–902.
Belsky, A.J., Matzke, A., Uselman, S., 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54 (1), 419–431.
Bierman, P., Lini, A., Zehfuss, P., Church, A., Davis, P.T., Southon, J., Baldwin, L., 1997. Postglacial ponds and alluvial fans: recorders of Holocene landscape history. GSA Today 7 (10), 1–8.
Biron, P.M., Robson, C., Lapointe, M.F., Gaskin, S.J., 2004. Comparing different methods of bed shear stress estimates in simple and complex flow fields. Earth Surface Processes and Landforms 29 (11), 1403–1415.
Booth, D.B., 1990. Stream-channel incision following drainage-basin urbanization. Water Resources Bulletin 26 (3), 407–417.
Buffin-Belanger, T., Rice, S., Reid, I., Lancaster, J., 2006. Spatial heterogeneity of near-bed hydraulics above a patch of river gravel. Water Resources Research 42 (4), 12.
Charlton, F.G., Brown, P.M., Benson, R.W., 1978. The Hydraulic Geometry of Some Gravel Rivers in Britain: Wallingford, England. Rep. INT-180. Hydraulics Research Station, Wallingford, England.
Clifford, N.J., French, J.R., 1993. Monitoring and modelling turbulent flows: historical and contemporary perspectives. In: Clifford, N.J., French, J.R., Hardisty, J. (Eds.), Turbulence: Perspectives on Flow and Sediment Transport. John Wiley & Sons, Chichester, pp. 1–34.
Clifton, C.F., 1989. Effects of vegetation and land use on channel morphology. In: Gresswell, R.E., Barton, B.A., Kershner, J.L. (Eds.), Practical Approaches to Riparian Resource Management. U.S. Bureau of Land Management. U.S. Government Printing Office, Billings, MT, pp. 121–129.
Daniels, M.D., Rhoads, B.L., 2004. Spatial pattern of turbulence kinetic energy and shear stress in a meander bend with large woody debris. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, D.C, pp. 87–98.
Davies-Colley, R.J., 1997. Stream channels are narrower in pasture than in forest. New Zealand Journal of Marine and Freshwater Research 31 (5), 599–608.
Dunaway, D., Swanson, S.R., Wendel, J., Clary, W., 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. Geomorphology 9 (1), 47–56.

Dunne, T., Leopold, L.B., 1978. Water in Environmental Planning. W.H. Freeman, San Francisco.
Gray, D.H., MacDonald, A., 1989. The role of vegetation in river bank erosion. In: Ports, M.A. (Ed.), National Conference on Hydraulic Engineering. American Society of Civil Engineers, New York.
Gregory, K.J., Gurnell, A.M., 1988. Vegetation and river channel form and process. In: Viles, H.A. (Ed.), Biogeomorphology. Blackwell, Oxford, UK, pp. 11–42.
Griffin, E.R., Smith, J.D., 2004. Floodplain stabilization by woody riparian vegetation during an extreme flood. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, D.C, pp. 221–236.
Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollman, J., Ward, J.V., Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms 26 (1), 31–62.
Hession, W.C., 2001. Riparian forest and urban hydrology influences on stream channel morphology: Implications for restoration. In: Phelps, D., Sehlke, G. (Eds.), World Water and Environmental Resources Congress. American Society of Civil Engineers, Reston, VA.
Hession, W.C., Johnson, T.E., Charles, D.F., Hart, D.D., Horwitz, R.J., Kreeger, D.A., Pizzuto, J.E., Velinsky, D.J., Newbold, J.D., Cianfrani, C., Clason, T., Compton, A.M., Coulter, N., Fuselier, L., Marshall, B.D., Reed, J., 2000. Ecological benefits of riparian reforestation in urban watersheds: study design and preliminary results. Environmental Monitoring and Assessment 63 (1), 211–222.
Hession, W.C., Pizzuto, J.E., Johnson, T.E., Horwitz, R.J., 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology 31 (2), 147–150.
Hey, R.D., Thorne, C.R., 1986. Stable channels with mobile gravel beds. Journal of Hydraulic Engineering 112 (8), 671–689.
Hilldale, R., Papanicolaou, A., 2001. Characteristics of flow and erosion in a natural stream with loess-type banks. Proceedings of the Seventh Federal Interagency Sedimentation Conference. U.S. Subcommittee on Sedimentation, Reno, NV.
Hupp, C.R., Simon, A., 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. Geomorphology 4 (2), 111–124.
Jeffries, R., Darby, S.E., Sear, D.A., 2003. The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. Geomorphology 51 (1–3), 61–80.
Kim, S.C., Friedrichs, C.T., Maa, J.P.Y., Wright, L.D., 2000. Estimating bottom stress in tidal boundary layer from acoustic Doppler velocimeter data. Journal of Hydraulic Engineering-ASCE 126 (6), 399–406.
Knighton, A.D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London.
Lane, S.N., Biron, P.M., Bradbrook, K.F., Butler, J.B., Chandler, J.H., Crowell, M.D., McLelland, S.J., Richards, K.S., Roy, A.G., 1998. Three-dimensional measurement of river channel flow processes using acoustic Doppler velocimetry. Earth Surface Processes and Landforms 23 (13), 1247–1267.
Legleiter, C.J., Phelps, T.L., Wohl, E.E., 2007. Geostatistical analysis of the effects of stage and roughness on reach-scale spatial patterns of velocity and turbulence intensity. Elsevier Science Bv.
Leopold, L.B., 1973. River channel change with time: An example. Geological Society of America Bulletin 84 (6), 1845–1860.
McBride, M., 2007. Riparian reforestation and channel change: key driving mechanisms in small streams. Ph.D. dissertation, University of Vermont, Burlington, 185 pp.
McBride, M., Hession, W.C., Rizzo, D.M., 2008. Riparian reforestation and channel change: a case study of two small tributaries to Sleepers River, northeastern Vermont, USA. Geomorphology 102, 445–459.
McBride, M., Hession, W.C., Rizzo, D.M., Thompson, D.M., 2007. The influence of riparian vegetation on near-bank turbulence: a flume experiment. Earth Surface Processes and Landforms 32, 2019–2037.
McBride, M., Hession, W.C., Thompson, D.M., 2005. Riparian vegetation influence on channel widths of small streams: revisiting Sleepers River. In: Moglen, G.E. (Ed.), Managing Watersheds for Human and Natural Impacts. American Society of Civil Engineers, Williamsburg, VA.
McLean, S.R., Nelson, J.M., Wolfe, S.R., 1994. Turbulence structure over 2-dimensional bed forms — implications for sediment transport. Journal of Geophysical Research-Oceans 99 (C6), 12729–12747.
Millar, R.G., 2000. Influence of bank vegetation on alluvial channel patterns. Water Resources Research 36 (4), 1109–1118.
Montgomery, D.R., 1997. What's best on the banks? Nature 388 (6640), 328–329.
Murgatroyd, A.L., Ternan, J.L., 1983. The impact of afforestation on stream bank erosion and channel form. Earth Surface Processes and Landforms 8 (4), 357–369.
National Weather Service (NWS), 2009a. Burlington International Airport (KBTV) Monthly Totals/Averages Average Temperature (degrees F) Years: 1884–2008. NWS, National Oceanic and Atmospheric Administration, South Burlington, VT. http://www.erh.noaa.gov/btv/climo/BTV/monthly_totals/avgtemp.shtml.
National Weather Service (NWS), 2009b. Burlington International Airport (KBTV) Monthly Totals/Averages Precipitation (inches) Years: 1884–2008. NWS, National Oceanic and Atmospheric Administration, South Burlington, VT. http://www.erh.noaa.gov/btv/climo/BTV/monthly_totals/precip.shtml.
Nelson, J.M., McLean, S.R., Wolfe, S.R., 1993. Mean flow and turbulence fields over 2-dimensional bed forms. Water Resources Research 29 (12), 3935–3953.
Parkyn, S.M., Davies-Colley, R.J., Halliday, N.J., Costley, K.J., Croker, G.F., 2003. Planted riparian buffer zones in New Zealand: do they live up to expectations? Restoration Ecology 11 (4), 436–447.
Pasche, E., Rouve, G., 1985. Overbank flow with vegetatively roughened flood plains. Journal of Hydraulic Engineering-ASCE 111 (9), 1262–1278.
Peterson, A.M., 1993. Effects of electric transmission rights-of-way on trout in forested headwater streams in New York. North American Journal of Fisheries Management 13 (3), 581–585.
Pizzuto, J.E., Meckelnburg, T.S., 1989. Evaluation of a linear bank erosion equation. Water Resources Research 25 (5), 1005–1013.
Pollen, N., Simon, A., Collison, A., 2004. Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, DC, pp. 125–140.
Quinn, J.M., Cooper, A.B., Davies-Colley, R.J., Rutherford, J.C., Williamson, R.B., 1997. Land use effects on habitat, water quality, periphyton, and benthic invertebrates in Waikato, New Zealand, hill-country streams. New Zealand Journal of Marine and Freshwater Research 31 (5), 579–597.
Rosgen, D., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO.
Roy, A.G., Biron, P.M., Buffin-Belanger, T., Levasseur, M., 1999. Combined visual and quantitative techniques in the study of natural turbulent flows. Water Resources Research 35 (3), 871–877.
Roy, A.H., Faust, C.L., Freeman, M.C., Meyer, J.L., 2005. Reach-scale effects of riparian forest cover on urban stream ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 62 (10), 2312–2329.
Rutherfurd, I.D., Grove, J.R., 2004. The influence of trees on stream bank erosion: evidence from root-plate abutments. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, DC, pp. 141–152.
SAS, 2004. SAS Online Doc 9.1.3. SAS Institute, Cary, NC.
Scarsbrook, M.R., Halliday, J., 1999. Transition from pasture to native forest land-use along stream continua: effects on stream ecosystems and implications for restoration. New Zealand Journal of Marine and Freshwater Research 33 (2), 293–310.
Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. Incised Channels: Morphology, Dynamics, and Control. Water Resources Publications, Littleton, CO.
Shanley, J.B., Sundquist, E.T., Kendall, C., 1995. Water, Energy, and Biogeochemical Budget Research at Sleepers River Research Watershed, Vermont. U.S. Geological Survey, Bow, NH.
Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27 (5), 527–546.
Smith, C.M., 1992. Riparian afforestation effects on water yields and water quality in pasture catchments. Journal of Environmental Quality 21 (2), 237–245.
Smith, J.D., 2004. The role of riparian shrubs in preventing floodplain unraveling along the Clark Fork of the Columbia River in the Deer Lodge Valley, Montana. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, D.C, pp. 71–85.
Stott, T., 1997. A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, central Scotland. Earth Surface Processes and Landforms 22 (4), 383–399.
Sweeney, B.W., 1992. Streamside forests and the physical, chemical, and trophic characteristics of piedmont streams in eastern North America. Water Science and Technology 26 (12), 2653–2673.
Sweeney, B.W., Bott, T.L., Jackson, J.K., Kaplan, L.A., Newbold, J.D., Stanley, L.J., Hession, W.C., Horwitz, R.J., 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceeding of the National Academy of Sciences, vol. 101(39), pp. 14132–14137.
Thompson, D.M., 2004. The influence of pool length on local turbulence production and energy slope: a flume experiment. Earth Surface Processes and Landforms 29 (11), 1341–1358.
Thorne, C.R., 1990. Effects of vegetation on riverbank erosion and stability. In: Thornes, J.B. (Ed.), Vegetation and Erosion: Processes and Environments. John Wiley, New York, pp. 125–144.
Trimble, S.W., 1997. Stream channel erosion and change resulting from riparian forests. Geology 25 (5), 467–469.
Trimble, S.W., 2004. Effects of riparian vegetation on stream channel stability and sediment budgets. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington, D.C, pp. 153–170.
United State Geological Survey (USGS), 2009. Peak Streamflow for Vermont. National Water Information System, USGS, Pembroke, NH. http://nwis.waterdata.usgs.gov/vt/nwis/peak/?site_no=01135300&agency_cd=USGS.
Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319 (5861), 299–304.
Wynn, T., Mostaghimi, S., 2006. The effects of vegetation and soil type on streambank erosion, southwestern Virginia, USA. Journal of the American Water Resources Association 42 (1), 69–82.
Zar, J.H., 1999. Biostatistical Analysis. Prentice Hall, Upper Saddle River, NJ.
Zimmerman, R.C., Goodlett, J.C., Comer, G.H., 1967. The influence of vegetation on channel form of small streams. Symposium on River Morphology. International Association of Scientific Hydrology, Bern, Switzerland, pp. 255–275.