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Understanding Stream Geomorphic State in Relation to Ecological Integrity: Evidence Using Habitat Assessments and Macroinvertebrates

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ABSTRACT / Scientists have long assumed that the physical structure and condition of stream and river channels have pervasive effects on biological communities and processes, but specific tests are few. To investigate the influence of the stream-reach geomorphic state on in-stream habitat and aquatic macroinvertebrate communities, we compared measures of habitat conditions and macroinvertebrate community composition between stable and unstable stream reaches in a paired-study design. We also explored potential associations between these ecological measures and individual geomorphic characteristics and channel adjustment processes (degradation, aggradation, overwidening, and change in planform). We found that habitat quality and heterogeneity were closely tied to stream stability, with geomorphically stable reaches supporting better habitat than unstable reaches. Geomorphic and habitat assessment scores were highly correlated ($r = 0.624$, $P < 0.006$, $n = 18$). Stable reaches did not support significantly greater macroinvertebrate densities than unstable reaches ($t = -0.415$, $P > 0.689$, $df = 8$). However, the percent of the macroinvertebrate community in the Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa was significantly correlated with the overall habitat assessment scores as well as with individual measures of geomorphic condition and habitat quality. While there is a clear need for more work in classifying and quantifying the responses of aquatic and aquatic-dependent biota to various geomorphic states and processes, this study provides solid preliminary evidence that macroinvertebrate communities are affected by the geomorphic condition of the stream reaches they inhabit and that geomorphic assessment approaches can be used as a tool for evaluating ecological integrity.

In the last several decades, a number of fluvial classification systems have been developed (Schumm 1963, 1977; Whiting and Bradley 1993; Rosgen 1994, 1996). Some of these classification systems focus on the watershed unit and are based largely on land classification and drainage network analysis (Lotspeich 1980; Lotspeich and Platts 1982; Frissell and others 1986; Montgomery and Buffington 1997), whereas others are limited to stream or river reaches and rely more on within-channel morphological characteristics of the stream (Pfankuch 1975; Poff and Ward 1990; Whiting and Bradley 1993). These classification systems have improved our understanding of stream processes and provide a useful framework for evaluating stream condition.

Although the applicability of Rosgen's (1994, 1996) classification system has been challenged (Miller and Ritter 1996; Prajapati and Lavania 1998; Harmel and Dutnell 1999; Miller and Skidmore 2001), it has become the most widely applied stream classification system in the United States (Juracek and Fitzpatrick 2003), having been adopted by hydrologists, engineers, geomorphologists, and biologists. Various state and local agencies, the US Fish and Wildlife Service, the US Environmental Protection Agency, and the US Department of Agriculture's Forest Service and Natural Resources Conservation Service have adopted its use to classify streams, categorize reaches as stable or unstable, and help restore impaired streams and rivers (NCCES 1999; Savery and others 2001; Juracek and Fitzpatrick 2003).

KEY WORDS: Geomorphic state; In-stream habitat; Macroinvertebrate communities; Stable; Unstable; Channel adjustment; EPT; Channel morphology

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Rosgen's classification has also been suggested for use in conjunction with visual riparian and stream health assessments (Ward and others 2003). In Vermont, the Department of Environmental Conservation (VTDEC) in the Agency of Natural Resources (VTANR) has proposed using fluvial morphology and channel stability assessments as a foundation for its watershed protection, management, and restoration activities (VTDEC 2001a). The VTDEC has developed a geomorphic assessment system primarily based on Rosgen's (1996) classifications and techniques, supplemented with Schumm's (Schumm 1977; Schumm and others 1984) classification of watershed zones and stream evolution models, and Montgomery and Buffington's (1997) classification system based on geomorphic bed units (e.g., cascade, step-pool, plane bed, etc.).

Because aquatic biota are intimately linked to their physical environment, both lateral (channel overwidening, change in planform) and vertical (bed degradation, bed aggradation) channel adjustments have potentially important implications for ecosystem integrity. We expect that significant channel adjustments (i.e., geomorphic impairments) change the natural habitat matrix of a lotic system. The threshold amount of impairment that must occur before changes are seen in aquatic communities remains an open question. Just as thresholds in hydrologic modification (Dynesius and Nilsson 1994) and sediment dynamics (Whiting and Bradley 1993) have been identified for watersheds, ecological effects' thresholds for stream organisms are also likely to exist (Detenbeck and others 1992; Poff and Allen 1995; Watzin and McIntosh 1999; Detenbeck and others 2000).

River channels are dynamic and naturally undergo gradual change, so a certain degree of channel instability is expected. However, because current geomorphic assessment protocols target recent channel adjustments that occur over short timescales, they are meant to capture changes that are atypical of a channel's accepted dynamic equilibrium. Although the pulsed nature and the unpredictability of channel changes make threshold identification difficult, rivers with many unstable reaches are expected to lose ecological integrity.

Very little work has been done, however, to relate changes in stream geomorphic condition to changes in aquatic habitat quality and biological condition. Aquatic macroinvertebrate communities could serve as a key link in understanding the effects of geomorphic impairment. Recognizing their direct dependence on aquatic habitat, as well as their high taxonomic and functional diversity in stream and river systems (Malmqvist 2002), scientists frequently select aquatic macroinvertebrates for use in ecological assessment protocols, using them as indicators of stream biological condition (Resh and others 1996; Barbour and others 1999; Dovciak and Perry 2002). Macroinvertebrates have been shown to respond to catchment-scale, as well as more localized gradients in stream water quality and other characteristics (Botosaneanu 1979; Roth and others 1996; Allan and others 1997; Richards and others 1997; Wiley and others 1997; Wright and Li 2002).

Although there are many macroinvertebrate metrics currently in use, most are designed to assess water quality, not physical habitat quality. Bryce and others (1999) suggested that Ephemeroptera, Plecoptera, and Trichoptera (EPT) assemblages vary in different stream geomorphic settings and have used an EPT richness metric to measure biotic response to human disturbance in stream reaches. The presence of these sensitive taxa has also been widely recognized and used as an indicator of high-quality stream reaches (Plafkin and others 1989; Lenat and Crawford 1994).

Although the terms ''stability'' and ''instability'' have engendered debate (Montgomery 1994; Juracek and Fitzpatrick 2003), they are central to Rosgen's (1996) concept of ''natural'' channels and to Rosgen's (1998) reference approach to stream restoration that uses stable reaches as blueprints for rehabilitating unstable reaches. Stable stream and river reaches move their water and sediment load in balance, typically exhibiting very little lateral bank movement from year to year (Lane 1955). Although there is minor natural erosion, there are no large in-stream deposits of sand or gravel. Unstable reaches can change their course by meters each year and often avulse and cut new channels altogether. Characteristics of unstable reaches include bed degradation (incision) or aggradation, channel widening, and planform adjustment processes (VTDEC 2001a). Whereas these terms carry significant meaning for the physical state of the stream channel, their ecological significance remains unexplored.

If stream geomorphic stability and instability are to be used as a basis for watershed planning and management, then it is vitally important to know how these geomorphic conditions relate to aquatic habitat quality and ecological integrity. The goal of this research, therefore, was to investigate the potential links among stream channel geomorphology, aquatic habitat characteristics and quality, and the macroinvertebrate community. Pairing stable and unstable stream reaches, we looked for associations between stream geomorphic assessment scores and characteristics, between habitat assessment scores and characteristics, and among functional, taxonomic, and productivity measures of the aquatic macroinvertebrate community. By evaluating these associations, we gathered preliminary data about the appropriateness of using geomorphic assessment approaches as a tool in making decisions about restoration, management, and conservation of stream ecosystems.

Methods

Study Reaches

We selected 18 study reaches in the Lewis Creek and White River watersheds in Vermont, USA. Lewis Creek flows east from the Green Mountains to Lake Champlain. It is 64 km long and has a watershed of about 218 km^2. Approximately 60% of the watershed (including most of the headwaters) is forested, about 25% is in agriculture, and the remainder is wetland or in urban and suburban development (Capen and others 2000). The majority of the surficial geology is lake-bottom clays, with alluvium in the riparian corridor (VTDEC 2001b). The White River is part of the larger Connecticut River watershed and is approximately 1838 km^2 in size, flowing south along a main stem of 87 km. Land cover in the watershed consists of 84% forest, 7% agriculture, 5% development, and 4% wetland (VTDEC 2002).

Following a paired-study design, we selected six paired reaches along the main stem of Lewis Creek (Pairs 1–6) and three paired reaches in the upper quarter of the Whiter River main stem (Pairs 7–9). All locations selected were classified using Rosgen (1994) as type C (e.g., riffle-pool streams with floodplain) or E-C (e.g., slightly entrenched, low width:depth ratio, riffle-pool bedform features with floodplain), with a slope <1%, and confined within U-shaped valleys. Each pair included a stable and a nearby unstable reach based on field indicators of geomorphic stability and instability as outlined by VTDEC's (2001a) Phase 2 rapid stream geomorphic assessment (RGA) protocols. The paired reaches were selected to have similar watershed size, land-use, flow, and sediment conditions.

Each study reach contained at least three riffles and varied from 63 to 327 m (Table 1), or 3.9 to 13.5 times the bankfull width, respectively. Primary indicators of significant channel adjustment included high entrenchment ratios; abandoned bank terraces; severe bank erosion or failure; high degrees of embeddedness; unvegetated bars; widened channels; flood chutes and channel avulsions; grossly undercut banks; thalwegs out of alignment with planform; and steep, transverse, or partial riffles.

Geomorphic and Habitat Assessments

All field assessments and sampling were conducted during low-flow conditions in July and August. The six reach pairs in Lewis Creek were sampled in 2001 and the three reach pairs in the White River were sampled in 2002.

We followed VTDEC's (2001a) Phase 2 protocols for all field assessments using both qualitative and quantitative evaluations to characterize the geomorphic state and in-stream habitat conditions of each reach. Assessments were conducted across the length of each reach, over a 2–3-day period, thus capturing a ''snapshot'' profile of each reach (Rosgen 1996). All geomorphic and habitat assessments were conducted by the same observer to ensure consistency across reaches.

Geomorphic assessments followed the guidelines established by the Vermont Rapid Geomorphic Assessment (RGA) and Assessment Field Notes (VTDEC 2001a). At each reach, we assessed the condition of each of the four primary geomorphic adjustment processes (degree of channel degradation, degree of channel aggradation, overwidened channel, and change in planform) through evaluation of field indicators. A score from 0 (poor condition, representative of channel instability with severe lateral and/or vertical mobility) to 20 (optimal condition, representative of channel stability with negligible lateral or vertical mobility) was assigned for each of the four primary geomorphic adjustment processes. The four adjustment processes were weighted equally, each contributing a maximum of 20 value points to a total potential RGA score of 80. The adjustment process with the lowest score was selected as dominant, although any process receiving a score of 10 or lower was noted as codominant. Stable reaches were those receiving a suboptimal to optimal geomorphic assessment value of 52–80; and unstable reaches were those characterized by poor to marginal geomorphic condition, reflected in assessment values of 0–51.

After surveying the stream reach and its riparian corridor for signs of abandoned floodplains, degradation, or widening, we also placed each reach in one of Schumm's stages of channel evolution (*I* = Stable, *II* = Incision, *III* = Widening, *IV* = Stabilizing, *V* = Stable; Schumm 1977). Sensitivity to disturbance was determined using Rosgen's stream-type sensitivity descriptors (Rosgen 1996). Previous and current adjustments for each reach were qualitatively compared against expected stream type given the valley setting and parent material.

Habitat quality assessments were conducted according to the guidelines of the Vermont Rapid Habitat Assessment (RHA) protocols (VTDEC 2001a), which are derived from the USEPA's Rapid Bioassessment Protocols (RBP) (Plafkin and others 1989; Barbour and others 1999). Specifically, we evaluated the 10 categories of the RHA: epifaunal substrate and

Table 1. Principal geomorphic measurements and characteristics of the study sites

Pair	Watershed size[a] (km^2)	Valley confinement[b]	Site length (m)	Bankfull width (m)	Entrenchment ratio	Width/depth ratio	Sinuosity[c]	Channel slope (%)	Dominant bed material	Stream type
Pair 1 (M6S& M6U)	75.80	NU/NU	99/ 159	70.7/ 67.5	1.7/7.4	27/23	Low-moderate/moderate	0.56/0.56	Gravel/gravel	B4/C4
Pair 2 (M10S& M10U)	69.10	NU/NU	106/70	61.3/52.5	1.6/2.3	23/20	Low/moderate	0.43/0.43	Cobble/gravel	B3/C4
Pair 3 (M15S& M15U)	37.80	BAT/BAT	63/117	52.7/74.7	5.7/6.7	23/66	Moderate/moderate	0.17/0.17	Gravel/gravel	C4/C4
Pair 4 (M17S& M17U)	22.70	BU/NU	126/144	31.2/37.0	6.4/2.6	15/16	Moderate/high	0.31/0.31	Gravel/gravel	C4/E4
Pair 5 (M20S& M20U)	16.40	BAT/BU	108/101	37.9/39.4	13.2/6.6	19/21	Moderate/low	0.58/0.58	Gravel/gravel	C4/C4
Pair 6 (M21S& M21U)	10.80	NU/SC	72/104	27.0/33.9	1.6/6.5	17/22	Low/moderate	0.42/0.42	Gravel/gravel	B4/C4
Pair 7 (M22S& M22U)	69.10	BU/NU	327/211	85.7/79.5	1.2/3.1	50/53	Low/low-moderate	0.26/0.14	Gravel/cobble	C4/C3
Pair 8 (M24S& M24U)	27.80	BU/BU	122/242	43.0/69.0	11.6/7.2	35/37	Low/moderate	0.41/0.38	Gravel/gravel	C4/C4
Pair 9 (M25S& M25U)	22.0/22.0	BU/BU	75/110	57.5/54.5	8.7/9.2	27/33	Low-moderate/low	0.67/0.91	Gravel/gravel	C4/C4

Note: Slash separates stable/unstable parameter values or characteristics.

[a] Approximate watershed size from downstream reach of each pair.

[b] NU = narrow, U-shaped; BU = broad, U-shaped; BAT = broad with abandoned terraces.

[c] low < 1.2, moderate = 1.2–1.5, high > 1.5.

available in-stream cover, degree of embeddedness, representation of a heterogeneous mixture of velocity and depth regimes, amount of sediment deposition, status of channel flow, degree of channel alteration, frequency of riffles, bank stability, vegetative protection, and the width of the riparian vegetative zone. Each of these parameters was assessed using the indicators of the RHA (VTDEC 2001a) and assigned a value from 0 to 20. These values were aggregated according to the RHA to arrive at an overall habitat evaluation ranging from 0 to 200. Higher assessment scores indicate better aquatic habitat conditions.

We followed these semiquantitative measures with a series of quantitative measurements that helped us refine our geomorphic and habitat assessment scores. Geomorphic measurements included bankfull width, maximum depth, flood-prone width (corresponding to a flow with a recurrence interval of 1.5 to 2 years; Rosgen 1994) and meander pattern. From these measurements we calculated width/depth and entrenchment ratios. We measured bed sediment particle size with a gravelometer in one representative riffle within each site using Wolman (1954) pebble-count procedures. Using a measuring tape and stadia rod at a midreach riffle, we measured cross sections and reach lengths, major bed features, length between riffles, and longitudinal profiles. Additionally, we counted pieces of large woody debris that were at least 0.1 m in diameter and 1.0 m long within the bankfull channel (Montgomery and others 1995).

Macroinvertebrates

We collected macroinvertebrates from the beginning of July to mid-August each year, when temperate stream diversity tends to be the greatest and when low-flow conditions tend to minimize the effects of variation in stream flow and life-cycle stages of the organisms (Barbour and others 1999). We collected three samples at each reach, concentrating our efforts in the riffle farthest downstream of each reach, as we expected this riffle to capture the cumulative effects of potential geomorphic influences on the macroinvertebrate community within each reach. Samples were collected at three positions across the lateral riffle length: mid-left, mid, mid-right. For each sample, organisms were collected using a Surber sampler with a 500-μm-mesh net by disturbing the riffle substrate and scraping larger rocks for a 60-s interval. Samples were preserved in 70% ethanol until enumeration in the laboratory. In the laboratory, aliquots were removed and examined under the microscope until the entire sample had been picked and identified.

We selected EPT abundance, percent EPT taxa, percent chironomid taxa, and total community abundance (i.e., density) as our primary macroinvertebrate metrics. To this end, all insects were identified as belonging to the family Chironomidae, one of the EPT orders, or ''other.''

To explore the possibility that a finer taxonomic resolution might be required to capture differences in community composition between stable and unstable reaches, we identified all stream macroinvertebrates except for the chironomids and oligochaetes to the level of genus for the 12 Lewis Creek reaches (Pairs 1–6). Each insect was also categorized according to its functional feeding group (FFG) using Merritt and Cummins (1996) as a guide. For those genera whose species potentially span more than one FFG, we divided the total number in the genus evenly among the FFGs represented in the genus in order to obtain an estimate of the percentage represented by the FFG.

Statistical Analysis

All statistical analyses were performed using JMP® 5.0 Statistical Discovery Software (SAS Institute, Cary, NC). Logarithmic ($\ln[x + 1]$), square (x^2), or arcsine-square root (for percents) transformations were used to normalize data and eliminate heteroscedasticity prior to analysis (Zar 1996). Based on our paired-reach study design, our primary tool for analyzing differences seen in habitat condition and macroinvertebrate community measures between stable and unstable reaches was the Student's paired *t*-test. Additional relationships among macroinvertebrate metrics, habitat assessment variables, and primary geomorphic adjustment processes were analyzed using Pearson's correlation matrices. When appropriate, we used simple regression analysis to quantify significant relationships. Spearman's Rho correlations were used for nonparametric data and to look for potential nonlinear relationships. All data were tested at the $\alpha = 0.05$ level.

Results

Geomorphic and Habitat Assessments

The RGA scores are presented in Table 2. Salient results were similar between the Lewis Creek and White River reaches, suggesting that interannual variations in environmental factors such as rainfall, temperature, and flow had negligible effects on the assessment endpoints.

There were significant differences between the RGA scores of the stable reaches and their paired unstable counterparts ($t = -10.817$, $P < 0.0001$, $df = 8$) (Fig-

Table 2. Geomorphic and habitat conditions at paired sites in the Lewis Creek (Pairs 1–6) and White River (Pairs 7–9) watersheds

Pair	RGA score[a]	RHA score[b]	Dominant adjustment process	Stage of channel evolution	Sensitivity to disturbance
Pair 1 (M6S & M6U)	66/38	153/140	Aggrading/changing planform	Stable/stabilizing	Moderate/high
Pair 2 (M10S & M10U)	67/36	175/125	Stable/changing planform	Stable/widening	Moderate/high
Pair 3 (M15S & M15U)	55/39	169/156	Stable/changing planform	Stabilizing/stabilizing	High/high
Pair 4 (M17S & M17U)	62/39	160/99	Aggrading/aggrading	Stable/widening	High/high
Pair 5 (M20S & M20U)	66/44	147/115	Slightly aggrading/overwidening	Stable/widening	High/high
Pair 6 (M21S & M21U)	68/33	153/139	Stable/overwidening	Stable/widening	Moderate/high
Pair 7 (M22S & M22U)	61/42	153/141	Aggrading/overwidening	Stablilizing/widening	Moderate/high
Pair 8 (M24S & M24U)	66/47	145/119	Slightly aggrading/changing planform	Stabilizing/widening	Moderate/high
Pair 9 (M25S & M25U)	64/46	161/115	Slightly aggrading/overwidening	Stabilizing/widening	Moderate/high

Note: Slash separates stable/unstable parameter values or characteristics.

[a] Qualitative score equivalents: 0–27, poor condition; 28–51, marginal condition; 52–67, suboptimal condition; 68–80, optimal condition.

[b] Qualitative score equivalents: 0–68, poor condition; 69–128, marginal condition; 70–168, suboptimal condition; 169–200, optimal condition.

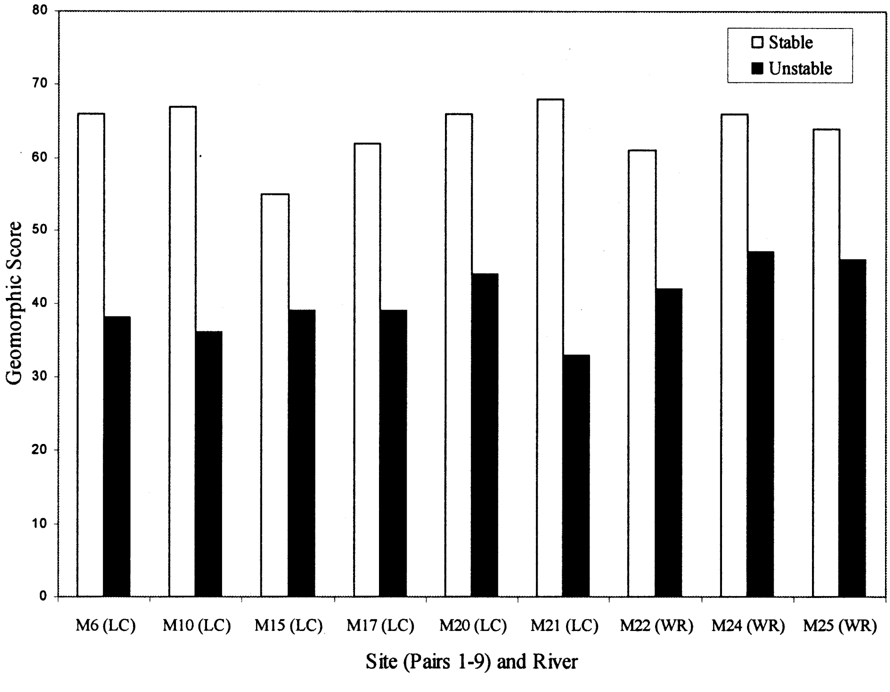

Figure 1. Rapid geomorphic assessment (RGA) scores of paired sites. Score equivalents: 0–27, poor condition; 28–51, marginal condition; 52–67, suboptimal condition; 68–80, optimal condition. LC = Lewis Creek, WR = White River.

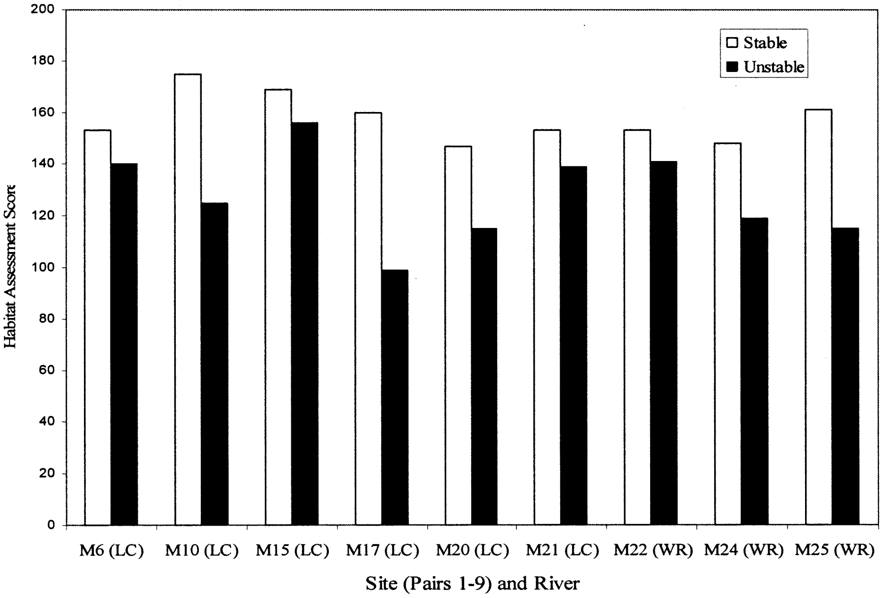

Figure 2. Rapid habitat assessment (RHA) scores of paired sites. Score equivalents: 0–68, poor condition; 69–128, marginal condition; 70–168, suboptimal condition; 169–200, optimal condition. LC = Lewis Creek, WR = White River.

Table 3. Significant correlations (tested at the $\alpha = 0.05$ level) between primary geomorphic processes and habitat assessment parameters at sites in the Lewis Creek and White River watersheds

Geomorphic adjustment process[a]	Habitat assessment parameter[a]	r
Degree of degradation	Embeddedness	−0.634
	Sediment deposition	0.553
	Channel flow status	0.502
	Bank stability	0.720
	Vegetative protection	0.739
	Riparian vegetative zone width	0.484
Degree of aggradation	Sediment deposition	0.651
Channel overwidening	Embeddedness	−0.494
	Channel flow status	0.763
	Bank stability	0.815
	Vegetative protection	0.573
Change in planform	Embeddedness	−0.556
	Vegetative protection	0.531

[a] Each adjustment process and habitat assessment parameter was scored on a scale of 1–20, with 20 = optimal condition.

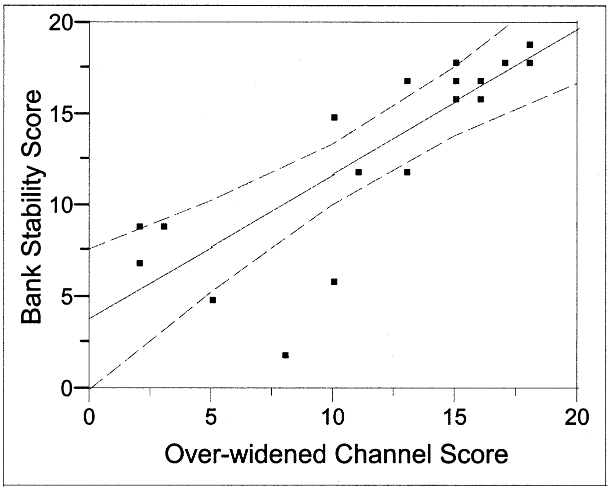

Figure 3. Linear regression of overwidened channel scores and bank stability scores ($R^2 = 0.664$, $P < 0.0001$). Low values are evidence of severe overwidening, whereas higher values indicate negligible overwidening. Low bank stability (extensive exposed streambank and areas of erosion) equates to low bank stability values. High values indicate stable banks. Dashed lines represent confidence curves at $\alpha = 0.05$.

ure 1). Stable reaches consistently exhibited a strong tendency toward a dynamic equilibrium and fell within the "suboptimal" to "optimal" range (Table 2). Conversely, unstable reaches, classified as "marginal" to "poor," represented actively or recently adjusting reaches. The mean stable reach score was 64, whereas the mean unstable reach score was 40.

The RHA scores shared a similar pattern, with mean habitat scores of 158 at the stable reaches and 128 at the unstable reaches (Figure 2). Reaches classified as geomorphically stable supported significantly higher habitat scores than did the unstable reaches

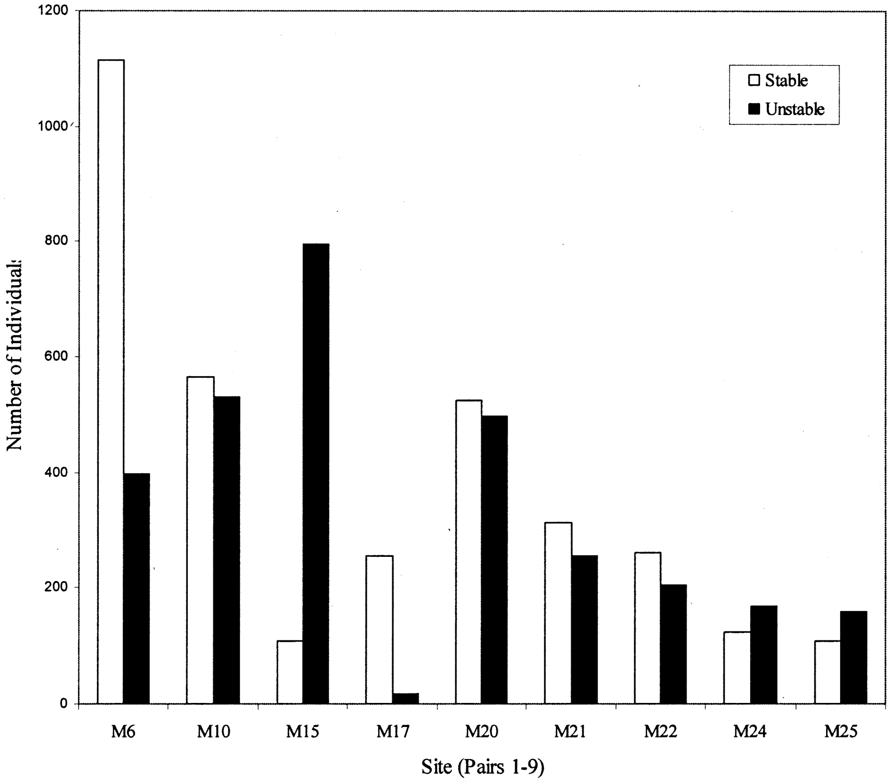

Figure 4. Total number of macroinvertebrates at paired sites.

($t = 10.871$, $P < 0.001$, $df = 8$). Four of nine stable sites were categorized as "stabilizing" (Schumm 1977). Twelve of the 18 sites were judged sensitive to disturbance (Table 2; Rosgen 1996).

Among all reaches, there was a strong correlation ($r = 0.624$, $P < 0.006$, $n = 18$) between the overall geomorphic score and the overall habitat score, suggesting that reaches of higher geomorphic condition score also supported higher quality habitat. There were also a number of significant relationships between the RGA and RHA measured parameters (Table 3), which underscored the linkages between geomorphic state and habitat quality and, in part, supported the accuracy of the RGA.

The degree of degradation was significantly correlated with 6 of the 10 habitat variables (Table 3). The strongest relationships appeared between bank stability and channel overwidening. This relationship was highly significant in a linear regression (Figure 3).

Vegetative protection, a measure of the quality and extent of vegetation protecting the streambank and near-stream portion of the riparian zone, positively correlated with three of the four geomorphic adjustment processes (degradation, overwidening, and change in planform) and showed a similar trend with the fourth, channel aggradation ($r = 0.454$, $n = 18$). Of these associations, degrading channels exhibited the strongest association ($r = 0.739$, $n = 18$) with vegetative protection. Our evaluation of the width of the riparian vegetative zone did not correlate with any of the geomorphic adjustment processes, indicating that the quality and composition of riparian vegetation might be more linked to channel disturbance than its extent.

Macroinvertebrates

A variety of relationships among geomorphic condition, habitat quality, and macroinvertebrate community characteristics were revealed. Although there was no significant difference in macroinvertebrate abundance ($t = -0.415$, $P > 0.689$, $df = 8$), we did observe that stable reaches supported a greater total number of macroinvertebrates than did unstable reaches at six of the nine paired reaches (Figure 4). The insect communities at stable reaches also tended to be dominated by higher percentages of the EPT orders, but this difference was also not significant ($t = 1.535$, $P > 0.163$, $df = 8$). However, when we removed the values of those paired reaches whose unstable reaches were categorized as stabilizing (Stage *IV*) according to Schumm's channel evolution model, the difference was highly significant (stable mean = 47%, unstable mean = 34%; $t = 3.11$, $P < 0.021$, $df = 7$).

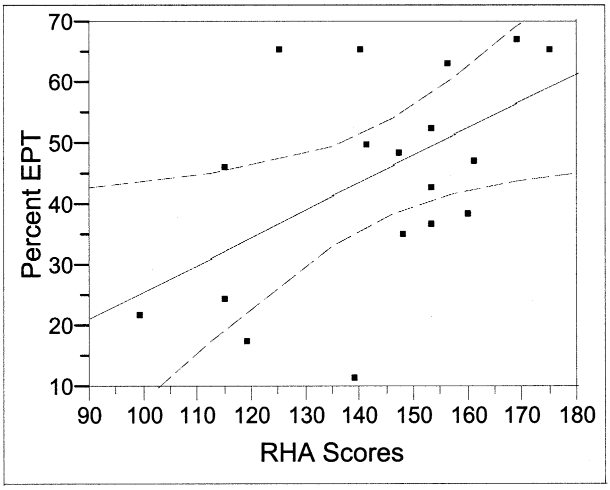

Figure 5. Linear regression of habitat assessment scores and percent EPT taxa ($R^2 = 0.277$, $P < 0.025$). Increasing RHA scores reflect better habitat. Percent EPT reflects the percentage of the EPT taxa of the overall macroinvertebrate community. Dashed lines represent confidence curves at $\alpha = 0.05$.

Using linear regression to explore potential relationships between the overall RHA score and macroinvertebrate measures, we found that RHA scores explained about 28% of the variance seen in EPT taxa ($P < 0.025$, $n = 18$) (Figure 5). There was also a trend toward a decrease in percent chironomids with increased RHA scores ($R^2 = 0.187$, $P < 0.073$, $n = 18$).

We found a number of significant correlations between the primary geomorphic adjustment processes and habitat parameters. Reaches that received higher scores for change in planform (i.e., less planform change occurring) were associated with higher percentages of chironomids in the macroinvertebrate community ($r = 0.584$, $P < 0.011$, $n = 18$). Velocity/depth regime, riparian vegetative zone width, and channel flow status were all significantly associated with percent chironomids, percent EPT, and the number of EPT individuals (Table 4).

The finer taxonomic resolution used for the Lewis Creek reaches produced little additional information. Stable reaches did support greater numbers of Baetidae than their unstable counterparts ($t = 2.589$, $P < 0.049$, $df = 5$). FFG analysis showed that collector-gatherers represented a larger percentage of the macroinvertebrate community composition at stable ($\bar{x} = 40$ %) reaches than at unstable ($\bar{x} = 33$ %) reaches ($t = 3.262$, $P < 0.022$, $df = 5$).

In exploring the relationships between the measured macroinvertebrate parameters and habitat characteristics (Table 4), we found the strongest correlation between the epifaunal substrate/available cover and the percent predators in the macroinvertebrate community ($r = 0.824$, $P = 0.001$, $n = 12$). Increased riparian zone widths correlated with an increase in total number of genera as well as an increase in number of Trichoptera families.

Table 4. Significant associations (tested at the $\alpha = 0.05$ level) between habitat assessment parameters and macroinvertebrate community characteristics

Habitat parameter	Macroinvertebrate association	r
Velocity/depth regime	% Chironomidae	−0.617
Riparian vegetative zone width	% EPT	0.591
	% Chironomidae	−0.518
	# EPT	0.488
Channel flow status	% EPT	0.488
Velocity/depth regime[a]	% Filterers	0.66
Epifaunal substrate/available cover[a]	% Predators	0.824
Riparian vegetative zone width[a]	# Taxa	0.579
	# Trichoptera families	0.665

[a] Tested using Lewis Creek Sites (Pairs 1–6) only.

Discussion

The geomorphic matrix of streams and rivers is potentially a key element in structuring and supporting habitat heterogeneity (Lane 1995; Amoros and Bornette 2002); therefore, it is important to understand the interplay between channel morphology and habitat quality and between habitat quality and the associated biotic responses.

Stability Versus Instability

Our results strongly suggest that geomorphically stable stream reaches provide better physical habitat than their unstable, adjusting counterparts. Total habitat score (RHA) was positively correlated with total geomorphic score (RGA), and stable reaches consistently exhibited relatively high levels of in-stream habitat structural diversity and quality.

The parameters used in the RHA were also correlated with the primary geomorphic adjustment processes. For example, channel degradation commonly results in a localized scouring of the stream bottom. Because larger clasts are removed during this process, the degree of embeddedness decreases (Table 3).

Likewise, a reachwide response to channel widening is a decrease in mean water depth and coverage, leaving a significant amount of exposed channel. Reaches with the lowest overwidening scores (thus showing the most adjustment) also had the lowest channel flow status scores in the habitat assessment (Table 3).

We found no conclusive evidence that stable reaches were associated with greater abundances of macroinvertebrates. However, all three stream reach pairs with higher densities of macroinvertebrates at the unstable reach (M15, M23, and M24) had stable reaches that were classified as suboptimal. Therefore, we had fewer differences in geomorphic condition between reaches at these pairs than at the other paired locations.

A first analysis of the macroinvertebrate data showed no difference between the abundance or percent of the EPT taxa at stable and unstable reaches. However, when the unstable reaches in the ''stabilizing'' stage of channel evolution (Schumm 1977; Schumm and others 1984) were excluded, then the stable reaches showed higher percentages of the EPT taxa than did unstable reaches. These results are consistent with the general notion that insects in the EPT taxa tend to be more sensitive to stream impairments than other aquatic invertebrate taxonomic groups (Patrick 1949; Hynem 1960; Loch and others 1996; Angradi 1999; Fitzpatrick and others 2001; Timm and others 2001).

It is reasonable to expect streams that have recently become unstable to show different patterns than streams that are ''stabilizing,'' or at that stage of channel evolution directly preceding stable conditions. Our results support the idea that stabilizing stream reaches, although still classified as unstable, might, indeed, have characteristics that more closely approach stable reaches.

The generic analysis of the Lewis Creek stream reaches also showed a higher percentage of collector-gatherers at stable reaches than unstable ones. Collector-gatherers likely need a stable substrate in order to maintain feeding structures and positions (Merritt and Cummins 1996).

Geomorphic Adjustment Processes

The RGA combines individual evaluations of the four primary adjustment processes. As the quantities of water and sediments change over time, streams can adjust in two directions: vertically and horizontally (Ward 1989; Langendoen and others 1999; Amoros and Bornette 2002). Vertical adjustment manifests as aggrading or degrading conditions, whereas horizontal adjustment plays out through channel widening (bank erosion) and changes in planform (lateral migration). These adjustment processes can occur either independently or in conjunction with one another, but the assignment of a stability or instability rating to a reach is the result of the overall RGA score rather than a reflection of individual adjustment processes.

We recognize, however, that certain in-stream conditions are more detrimental to aquatic biota than are others. Therefore, these principal adjustment processes might not have equivalent ecological consequences. To explore this possibility, we examined potential associations between these four processes and both our habitat assessment parameters and macroinvertebrate measures.

The degree of degradation associated with the greatest number of habitat parameters: sediment deposition, channel flow status, bank stability, vegetative protection, riparian vegetative zone width, and embeddedness (Table 3). Channel overwidening also correlated with a number of habitat assessment parameters, including channel flow status, bank stability, vegetative protection, and embeddedness. Notably, the observed relationships were not the same across the four geomorphic adjustment processes, indicating that each process does, indeed, associate with different types of habitat impairment.

Two habitat parameters, however, correlated with more than one adjustment process. Embeddedness and vegetative protection each correlated with three of the principal geomorphic adjustment processes. Embeddedness is a measure of the degree to which gravel, cobble, and boulder particles are surrounded by fine sediment. We observed that reaches with low levels of embeddedness (e.g., high score for degree of embeddedness) were undergoing channel adjustment in the form of degradation, overwidening, or change in planform. Although increased levels of embeddedness reduce available habitat for both fish and macroinvertebrates, limiting the available epifaunal substrate and potential cover (Cooper 1993; Barbour and others 1999), these particular adjustment processes might increase habitat availability in some cases. However, we suspect that this result might be confounded by the nature of some of these adjustments. For example, channel degradation likely associated with low levels of embeddedness because of the scouring action inherent in channel bed incision, where gravel and cobble particles are removed, leaving no clasts to become embedded. Recent planform change might initially support low levels of embeddedness as new channels are formed through avulsions and floods, submerging gravel, cobble, and boulders. However, as these new chutes become permanent extensions of the channel's flow pattern, embeddedness is expected to increase as sediment is transported and deposited.

Vegetative protection is a measure based primarily on the percentage of native trees, shrubs, and nonwoody macrophytes, as well as lack of disruption through grazing or other activities. This measure was significantly or marginally correlated with all adjustment process scores. Vegetative protection, or buffering, has been shown to influence channel morphology (Hession and others 2003a, 2003b) as well as in-stream habitat (Sweeney 1992). With adequate vegetative buffers, habitat is improved through increased shading and input of terrestrial litter and large woody debris (Mundie and others 1973; Dolloff 1986; Maser and Sedell 1994; Gurnell and Sweet 1998; Gurnell and others 2002).

The riparian vegetative zone width was also positively associated with degree of channel degradation. Severely degrading channels tended to be found in reaches with narrow bands of riparian vegetation that were highly disturbed by human activities such as agriculture, roadbeds, and lawns. Because the riparian corridor connects terrestrial and aquatic systems, this habitat can be very diverse (Naiman and others 1993); when the width of the corridor is reduced, that habitat diversity also declines, with potentially negative effects on wildlife. For example, Croonquist and Brooks (1993) have shown that in Pennsylvania, sensitive bird species will not persist unless the riparian corridor has a width of at least 25 m on each bank. Wider riparian zones provide better vegetation cover and structure (Popotnick and Guiliano 2000). The RHA methodology classifies a 25-m riparian zone as suboptimal (VTDEC 2001a).

Bank stability is often a primary concern for stream restoration projects and management efforts. Bank stability was positively correlated with the scores for both degree of degradation and overwidening, and the relationship with overwidening was particularly strong (Table 3). Although intuitive, these results have important ecological implications. Increased input of sediment from compromised stream banks can cause a disequilibrium between sediment size and amount, and stream slope and discharge (Lane 1955). Bank erosion can also add significant amounts of sediment to the stream channel (Langendoen and others 1999). Increased sedimentation in streams reduces the amount of rubble habitat, which is preferentially occupied by macroinvertebrates. Soil from collapsing banks may also add phosphorus and other pollutants to the stream system, causing localized effects on water quality as well as cumulative effects downstream (e.g., eutrophication in lakes; Nelson and Booth 2002).

Macroinvertebrates and Geomorphic Condition

Several geomorphic and habitat parameters were significantly associated with the macroinvertebrate community (Table 4). In particular, riparian vegetative zone width and channel flow status were associated with several macroinvertebrate measures. Across all of our reaches, RHA values exhibited a positive linear relationship with percent EPT taxa (Figure 5). Although the nature of the scatterplot and the low coefficient of determination (0.277) show a weak relationship, it is an important initial step in understanding the nature of macroinvertebrate associations with geomorphic condition.

Stream reaches with undisturbed zones of riparian vegetation tended to have lower percentages of chironomids and higher percentages of EPT taxa. Increased percentages of chironomids are commonly found in degraded stream systems (Barbour and others 1999).

Channel flow status is a measure of the amount of exposed substrate (and the resulting decrease in accessible habitat) in the stream channel. This measure associated positively with percent EPT taxa. Although any aquatic taxon is expected to be sensitive to low water levels, EPT taxa might be particularly susceptible to low-flow conditions.

Interestingly, we found no additional associations when we explored relationships between specific genera and geomorphic or habitat assessment measures (Table 4), but links between riparian corridor width and flow were reinforced. The strongest association was between predatory insects, and epifaunal substrate and available cover. The velocity/depth regime, which assesses the presence and distribution of slow-deep, fast-deep, slow-shallow, and fast-shallow flows, positively associated with percent filterers.

The correlations between the total number of genera and the number of Trichoptera families and riparian vegetative zone width suggest that the presence and extent of a vegetative buffer zone might be more important to in-stream ecological integrity than the quality of the zone itself. Reaches with limited or no buffer zone would be expected, then, to decrease integrity possibly because of decreased shading, reduced inputs of vegetative material, and increased erosion resulting from lack of cohesive root mats.

Although macroinvertebrate measures are commonly used in stream assessments, and they clearly show a response to geomorphic condition, they might not be the best overall biological response measure to capture effects of geomorphic condition. Macroinvertebrates are small in size, generally show high abundance, density, and diversity, and have limited mobility. Because of these traits, macroinvertebrates are probably associated more strongly with microhabitats, such as sample riffles or small pools, rather than macrohabitats, such as relatively large stream reaches (*sensu* Angradi 1999).

Functional feeding groups might respond more to changes in energy sources rather than to physical alterations in the stream (Wright and Li 2002). Geomorphic condition is primarily a physical factor and, therefore, we would not expect the highly variable distributions of FFGs to correlate with these characteristics. However, widespread geomorphic impairment could affect the relationship between stream size and energy sources. This is an area that needs further study.

Conclusions

Biological integrity refers to the habitat's ability to support and maintain a balanced, integrated community of organisms that is capable of adaptation (Karr 1991). Geomorphic condition and processes potentially play a large role in governing the level of biotic integrity in a stream reach. Our study strongly suggests that geomorphic condition and aquatic habitat are closely linked and supports the use of geomorphic assessments in assessing the ecological integrity of rivers and streams. Although there is a clear need for more work in classifying and quantifying the responses of aquatic and aquatic-dependent biota to various geomorphic states and processes, this study provides solid preliminary evidence that macroinvertebrate communities are, indeed, affected by the geomorphic condition of the stream reach they inhabit.

However, the most appropriate macroinvertebrate metric to use in accurately capturing differences in macroinvertebrate communities resulting from channel geomorphic condition is still an open question. In this study, the percent EPT taxa yielded the most promising results, and total abundance warranted additional investigation. Moreover, analyses of genus-level identification and functional feeding groups in relation to geomorphic condition resulted in minimal additional information. This, in addition to the widespread use of the EPT index by state and federal natural resource agencies in water quality assessments, suggests the EPT index is a useful measure within geomorphic assessment approaches.

Conditions such as flow regime, quantity and size of sediment, and the topographic setting are known to set geomorphic thresholds that define changes in processes and form, separating riverine landscapes and habitats from one another (Church 2002). However, the threshold level of stream impairment that must occur before changes are seen in biological integrity is unknown. Our results show significant ecological differences between reaches classified as stable and unstable. However, until thresholds of impairment can be accurately determined, stream channels should be evaluated in terms of dynamic stability and adjustment rather than being strictly categorized as stable and unstable.

If geomorphic assessments continue to be used to guide both physical and biological restoration and stream management decision-making, there is a need to determine which geomorphic impairments lead to the greatest loss of biological integrity. To move in this direction, it is important to consider geomorphic condition as a continuous gradient rather than categorically as stable or unstable. To better understand true ecosystemwide relationships between geomorphology and biological communities, it will be important to consider a range of aquatic organisms, potentially including algae, fish, and water-obligate birds, as well as macroinvertebrates. Finally, modeling approaches that link geomorphology to habitat and biological condition could be a critical step for identifying and examining important causal relationships in future studies.

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