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Riparian indicators of flow frequency in a tropical montane stream network

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S U M M A R Y

Many field indicators have been used to approximate the magnitude and frequency of flows in a variety of streams and rivers, yet due to a scarcity of long-term flow records in tropical mountain streams, little to no work has been done to establish such relationships between field features and the flow regime in these environments. Furthermore, the transition between the active channel of a river and the adjacent flood zone (i.e. bankfull) is an important geomorphologic and ecological boundary, but is rarely identifiable in steep mountain channels that lack alluvial flood plains. This study (a) quantifies relationships between field indicators and flow frequency in alluvial and steepland channels in a tropical mountain stream network and (b) identifies a reference active channel boundary in these channels, based on statistically defined combinations of riparian features, that corresponds to the same flow frequency of the bankfull stage and the effective discharge in adjacent alluvial channels. The relative elevation of transitions in riparian vegetation, soil, and substrate characteristics were first surveyed at nine stream gages in and around the Luquillo Experimental Forest in Northeastern Puerto Rico. The corresponding discharge, flow frequency, and recurrence intervals associated with these features was then determined from long-term 15-min discharge records and a partial duration series analysis. Survey data indicate that mosses and short grasses dominate at a stage often inundated by sub-effective flows. Herbaceous vegetation is associated with intermediate discharges that correspond to the threshold for sediment mobilization. Near-channel woody shrubs and trees establish at elevations along the channel margin inundated by a less frequent discharge that is coincident with the effective discharge of bed load sediment transport. Our data demonstrate that in alluvial channels in the study, both the bankfull stage (as marked by a flood plain) and the channel-forming (effective) discharge are associated with the presence of fine-grained substrate and soil, and tall, mature woody vegetation. In montane reaches that lack a flood plain, a boundary that is characterized by the incipient presence of soil, woody shrubs, and trees corresponds to the same flow frequency as the bankfull discharge of nearby alluvial channels. The reference discharge based on these riparian features in steepland sites has an average exceedance probability between 0.09% and 0.30%, and a recurrence interval between 40 and 90 days. We conclude that flows with similar frequencies influence the establishment of riparian vegetation, soil development, and substrate characteristics along channel margins in similar ways. Thus, these riparian features can be used as an indicator of hydrogeomorphic site conditions to identify active channel boundaries that occur at a constant flow frequency throughout the study stream network.

Introduction

It is common practice to identify morphological features in streams and rivers that mark the extent of flows of differing magnitude and frequency. Researchers (e.g. hydrologists, geomorphologists, ecologists, civil engineers) rely on valid functional relationships between these features and the flow regime to understand how hydrological processes influence channel boundaries. For example, the transition between the active channel of a river and the flood zone (traditionally referred to as the bankfull stage in alluvial channels) is arguably the most critical boundary in fluvial geomorphology, hydrology, and stream ecology (Leopold et al., 1964; Williams, 1978). The bankfull stage and the corresponding discharge serve as a consistent hydromorphological index that can be related to the formation, maintenance, and morphology of the channel. In many alluvial rivers it also corresponds to the effective, or dominant discharge (Wolman and Miller, 1960; Andrews, 1980). It is the standard boundary to compare cross-sectional channel geometry (Leopold and Maddock, 1953), and is also a central modeling parameter in land use planning and stream restoration (Rosgen, 1994).

Despite the utility of the bankfull concept, it is difficult (if not impossible) to consistently identify bankfull flows among physio-

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graphically different streams and rivers, particularly in mountainous environments that do not have alluvial flood plains (Navratil et al., 2006). In some mountainous channels, botanical features and morphological surfaces (other than flood plains) have been shown to correspond to the flow regime and mark channel boundaries (Osterkamp and Hupp, 1984; Hupp, 1986). The problem is that researchers always need to make assumptions about what field indicators represent in terms of flow magnitude and frequency, yet these assumptions can seldom be rigorously tested in mountainous catchments (and especially in the tropics) because of the lack of high-quality gage records. This study addresses these assumptions and quantifies relationships between field indicators and the flow regime in a tropical montane stream network by statistically relating field-based channel surveys to high-resolution hydrologic records.

Many field indicators have previously been used to approximate the magnitude and frequency of flows in a variety of streams and rivers. Most of these indicators are established for alluvial channels with the intent of capturing the range and complexity of bankfull conditions, which is loosely defined as the location where stream water begins to flow out of the main channel and onto the adjacent alluvial flood plain (Leopold et al., 1964; Williams, 1978). The multitude of field indicators (see Radecki-Pawlik (2002) for a comprehensive review) fall into four general categories: (1) morphologic features, (2) geometric features, (3) bank and sediment features, and (4) riparian features (Harrelson et al., 1994). Morphologic indicators are marked by the elevation of the top of depositional surfaces that correspond to the boundary in the channel between net sediment transport and sediment deposition (Wolman and Leopold, 1957; Woodyer, 1968; Williams, 1978), or other surfaces such as a channel shelf (Osterkamp and Hedman, 1977). Geometric features are primarily based on the change in slope that occurs along the cross-section from the channel to the banks (Wolman, 1955; Riley, 1972). Bank and sediment features include changes in particle size or the extent of undercutting under dense root mats (Leopold and Skibitzke, 1967). Lastly, riparian features include stain lines marked by fine sediment and vegetation patterns such as a sharp break in the vegetation density, a change in the type of vegetation, or the lower limit of perennial vegetation (usually trees) (Williams, 1978; Osterkamp and Hupp, 1984; Hupp, 1986; Harrelson et al., 1994).

However, these relationships between field indicators and the flow regime are often confounded in mountain streams. In mountainous environments, the morphologic and geometric features typically used to mark the bankfull discharge and other flows rarely exist in steep, confined, ‘v’-shaped valleys. Some researchers have estimated high-flow conditions in mountain streams using field observations of high-flow features, including: the boundary of the active scour zone (Montgomery and Gran, 2001), flow-deposited organic debris and changes in the grain size of surface sediment (Wohl and Wilcox, 2005), changes in bank gradient and channel geometry (Wohl et al., 2004), the presence of perennial vegetation (Radecki-Pawlik, 2002), or a combination of all factors. However, the flow frequency associated with these various reference features is rarely quantified in mountain stream studies due to a lack of gage records at representative locations. Furthermore, these high-flow features may reflect the influence of the last large flood rather than the steady forcing from more frequent flows, so it is unknown whether they even indicate flows of the same frequency among different locations. Consequently, it is more appropriate to refer to these high-water marks as a ‘reference discharge’ (Wohl and Wilcox, 2005)—a term implying that the field indicators represent a flow of constant, but unknown frequency. There is no common consensus on what the ‘reference discharge’ is in mountain streams, nor how often these high-flow events occur. This problem is especially pertinent to tropical mountain streams, where a lack of high-quality long-term gage records, as well as difficult field access, means that little to no research has been done to quantify the flow frequencies associated with field indicators in such environments.

It is important to establish methods to relate field indicators and the flow regime to better understand how hydrological processes influence channel boundaries in tropical mountain streams. Typical recurrence intervals of bankfull discharge in alluvial streams are on the order of 1–3 years (Leopold et al., 1964; Harrelson et al., 1994; Knighton, 1998), and this number has been used as the basis for many stream restoration projects to construct channels with dimensions in balance with the natural flow regime (Rosgen, 1994). This recurrence interval has also been used in many downstream hydraulic geometry studies (Wohl et al., 2004; Wohl and Wilcox, 2005), where longitudinal changes in bankfull channel width, depth, and velocity are driven by the magnitude of bankfull discharge (Leopold and Maddock, 1953). Calculations of standard downstream hydraulic geometry parameters require comparing discharges that occur at the same frequency. Thus it is essential to identify a common reference marker of a geomorphically relevant discharge throughout a basin in order to make meaningful comparisons of channel cross-sectional morphology and to understand how the flow regime influences that morphology.

Bankfull discharge has also been shown to correspond to the effective, or dominant, discharge in many alluvial streams (Wolman and Miller, 1960; Andrews, 1980). The effective discharge is defined as the discharge that transports the most sediment over time (Leopold et al., 1964), and is related to the magnitude and frequency of sediment transporting floods. Low-magnitude flows are common, but transport little to no bed sediment. Conversely, high-magnitude flows exert tremendous fluvial energy, transport large amounts of sediment, and often reshape the stream channel. However, in most streams, large floods are infrequent so that their effective contribution to geomorphic work over time is typically small. Between the tranquility of baseflow and the ferocity of large floods, there exists a relatively frequent, moderate-magnitude flow that effectively transports sediment through the channel. The bankfull discharge is generally considered to be an effective flow for maintaining channel capacity in many alluvial channels (at least for some perennial streams of the eastern United States), where the morphology of the channels depend upon scour, transport and redeposition of sediment (Wolman and Miller, 1960). However, some authors (Benson and Thomas, 1966) have shown that the effective discharge does not always correspond to the bankfull discharge in a range of physiographically different streams throughout the United States, and caution against a rigid geomorphic interpretation of the effective discharge concept. This caution should be extended to tropical montane streams. It is known that streams in the tropics experience a wide range of floods and that consequently channel boundaries may be sculpted differently from those in temperate areas (Gupta, 1975; Ahmad et al., 1993). Yet it is not known what field indicators mark the effective discharge and channel-forming flows in tropical mountain streams, nor how often geomorphically effective floods occur.

In the absence of traditional depositional and morphologic bankfull indicators in tropical mountain streams, we hypothesize that the occurrence of riparian vegetation can be used as a marker of flow frequency in tropical montane streams. Riparian vegetation has been shown to be a robust indicator of flow frequency in humid environments where vegetation is abundant (Hupp and Osterkamp, 1985). There is often a consistent zonation in the type and structure of riparian vegetation along a gradient from the active channel to the banks (Osterkamp and Hupp, 1984). It has been shown that such patterns in riparian vegetation are strongly influenced and maintained by the natural flow regime of a river (Poff et al., 1997). The active channel is a physically harsh environment for terrestrial vegetation because of frequent flooding and scouring (Naiman et al., 1998; Swanson et al., 1998). Woody plants may be mechanically broken by the force of floodwaters, uprooted by erosion of the substrate in which they are rooted, or unable to establish in their seedling stage (Sigafoos, 1964; Bendix and Hupp, 2000). Since periodic flooding is an important physical determinant of the establishment and growth of many riparian plants, there is often a functional relationship between flood hydrology and riparian plant community patterns (Hupp and Osterkamp, 1996; Bendix, 1999; Chopin et al., 2002). In aseasonal humid tropical environments where vegetation is abundant and rapidly colonizes disturbed surfaces, streamside vegetation should closely reflect the flood disturbance regime. Therefore, vegetation characteristics and corresponding surficial features (substrate type, degree of soil development, organic matter) are presumably reliable indicators of hydrogeomorphic conditions (Hupp and Osterkamp, 1985). Furthermore, it is likely that some combination of these riparian vegetation characteristics and surficial features can approximate bankfull on the basis of flow frequency.

This study investigates these relationships between the flow regime and riparian field indicators in streams of the Luquillo Mountains in Northeastern Puerto Rico. The field site described here is one of the few places (if not the only place) in the world where spatially-dense high-resolution long-term flow records exist to quantify detailed correlations between field indicators and flow characteristics in a tropical montane environment. We have three primary objectives. First, we quantify the flow frequency associated with transitions in riparian vegetation, soil, and substrate characteristics from the channel to the hillslopes at a series of long-term stream gages. Second, we statistically determine combinations of these features that represent boundaries that are inundated at a similar frequency throughout the stream network. Third, we compare the associated flow frequencies of these boundaries in steepland reaches to the frequency of bankfull and effective discharge in adjacent alluvial channels. Ultimately, this analysis is used to demarcate active channel boundaries and establish a reference stage for the channel-forming/maintaining discharge in tropical montane streams based on visually identifiable field indicators.

Study area

Northeastern Puerto Rico

This study was conducted in the streams draining the Luquillo Mountains in Northeastern Puerto Rico. The Luquillo Mountains rise steeply from sea level to over 1000 m in elevation over a distance of 15–20 km. The climate is maritime subtropical and is influenced by convective storms, easterly waves, cold fronts, tropical storms and hurricanes (Scatena, 1995). Mean annual temperatures at mid-elevations are 26 °C, and range from an average of 22 °C in the winter to 30 °C in the summer (Ramirez and Melendez-Colom, 2003). Mean annual rainfall increases with elevation from approximately 1500 mm/year at the coast to 4500 mm/year at the highest elevations (García-Martinó et al., 1996). Rainfall events at mid-elevations are generally small (median daily rainfall 3 mm/day) and numerous (267 rain days per year) (Schellekens et al., 1999). Rainfall is generally evenly distributed throughout the year, with no well-defined rainy season, and high-intensity rainfall events and floods can occur in any given month. Hurricanes are common between August through October and typically bring high daily rainfall in excess of 200 mm/day (Heartsill-Scalley et al., 2007). The maximum recorded daily rainfall and runoff in the region are in excess of 600 mm/day (Scatena and Larsen, 1991).

The landscape of the Luquillo Mountains is tectonically active and prone to massive landsliding (Larsen and Torres-Sanchez, 1998). The streams, similar to other montane streams in the Greater Antilles, are steep and have channels lined with coarse boulder-sized sediment, as well as numerous bedrock cascades. Their morphology has been called ‘flood dominated’ and, like many mountain streams, traditional depositional forms built by sand, pebbles, cobbles, and boulders are found sporadically or only within the lowest gradient reaches (Gupta, 1975, 1988; Ahmad et al., 1993). It has also been cautioned that the standard descriptions of alluvial channel form and behavior are not necessarily adequate for these rivers (Ahmad et al., 1993).

The flow regime is extremely flashy due to intense tropical rains, steep slopes, and rapid runoff generation (Schellekens et al., 2004). High-magnitude, but short-lived, floods occur repeatedly throughout the year. Peak discharges can be approximately 1000 times greater than baseflow in Luquillo and other Caribbean streams (Gupta, 1995). The average unit discharge of baseflow is 0.02 $m^3/s/km^2$, whereas the highest peak unit discharge measured by regional USGS stream gages is 19.7 $m^3/s/km^2$. High-flow hydrographs are short and stormflow runoff is quickly flushed through the system such that the streams return to baseflow within hours, even after the largest events. These large floods are primarily driven by atmospheric disturbances that occur throughout the year rather than by seasonal events (such as snowmelt) that are common in temperate basins. Consequently, flood discharges that are close to the annual peak are often experienced independently several times in a year (Scatena et al., 2004).

These frequent and intense floods generate a powerful flow regime that is capable of overcoming channel boundary resistance and mobilizing coarse sediment. Although the rivers are incisional boulder- and bedrock-lined channels, the channel geometry is locally adjusted to the sediment characteristics flow regime. In this sense, these montane stream channels have morphological dynamics similar to those of some alluvial rivers (Pike et al., in press). Therefore, the concepts of bankfull and effective discharge can be justifiable applied to these streams.

The morphology of Luquillo stream channels, as well as the composition of the channel bed, are directly related to the underlying lithology (Ahmad et al., 1993). There are three dominant lithologies in the study region: volcaniclastics, granodiorite, and coastal plain alluvium (Seiders, 1971). The streams draining volcaniclastics are steep and typically have a bed composed of large boulders (up to several meters in diameter), interspersed with finer cobbles and gravels, as well as sporadic bedrock outcrops. Although the volcaniclastic rocks weather to deep clayey saprolite, the channels are relatively devoid of sands, silts and clays because these sediments are quickly transported out of the mountains as suspended load in floods. These channels are generally situated at the bottom of steeply-walled bedrock valleys and lack flood plains along the channel margins.

In contrast to areas underlain by the volcaniclastic rocks, streams draining granodiorite are almost entirely composed of sand and large case-hardened boulders that can be several meters in diameter. This granodiorite bedrock has one of the highest documented weathering rates in the world (White et al., 1998). The sandy beds of these channels are constantly mobile, even at low flows, and are readily reworked during high flows. These reaches do have some bars and depositional surfaces within the channels, but they still generally lack a continuous or well-defined flood plain. Like the streams draining the volcaniclastic bedrock, they are lined with large immobile boulders, even though the fluvial transport capacity is considered to exceed the sediment supply (i.e. a ‘supply limited’ environment), (Larsen, 1997). Many of the larger boulders in both volcaniclastic and granodioritic channels were apparently delivered to the channels by landslides and are not readily transported by fluvial processes. Furthermore, some of the largest boulders have not moved in the years of modern observation, and have been estimated to only be mobile in a 500-year flood or larger.

Streams flowing across the coastal plain alluvium typically have a comparatively gentle gradient compared to channels on bedrock, and have beds composed of cobbles and gravels. These lowland streams have several overflow and bench surfaces that are typical of many alluvial channels, including a morphological bankfull surface (Gupta, 1975). The lowest alluvial surface is typically an in-channel partially vegetated inset deposit or longitudinal bar composed of cobbles (Clark, 1997). A slightly higher inset flood plain surface marks the bankfull stage, and is generally between 1 m and 1.5 m above the baseflow water level, and approximately 1.5–3 m above the channel thalweg. A discontinuous terrace at an elevation between 1.75 and 3 m above the flood plain occurs throughout the coastal plain, and is most evident on the cutbank side of the channel. There is also a distinctive higher terrace approximately 9 m above the river that occurs sporadically along the length of the channel. These terraces are thought to be remnant alluvial surfaces from Puerto Rico's pre-agricultural period before 1830 A.D. (Clark and Wilcock, 2000).

Regional stream gages

Nine long-term stream gaging stations in and around the Luquillo Mountains that are owned and operated by the United States Geological Survey (USGS) were selected as sites for this study (Fig. 1). Selection criteria included: (1) currently operating gages, with (2) greater than 10 years of record, and (3) instantaneous (i.e. 15-min) discharge records. The gages are located in five adjacent watersheds: Río Blanco, Río Espiritu Santo, Río Fajardo, Río Mameyes, and Río Sabana (Fig. 1). The sites range from small 1st order headwater streams to larger 3rd and 4th order streams, with drainage basin areas ranging from 0.3 km^2 to 39 km^2. Basic site information is available in Table 1. The reaches near the stream gages are pictured in Fig. 2.

The gaged reaches were divided into three physiographic categories: lowland (0–50 m), mid-elevation (50–150 m), and steepland (>150 m). The lowland reaches are low-gradient, slightly

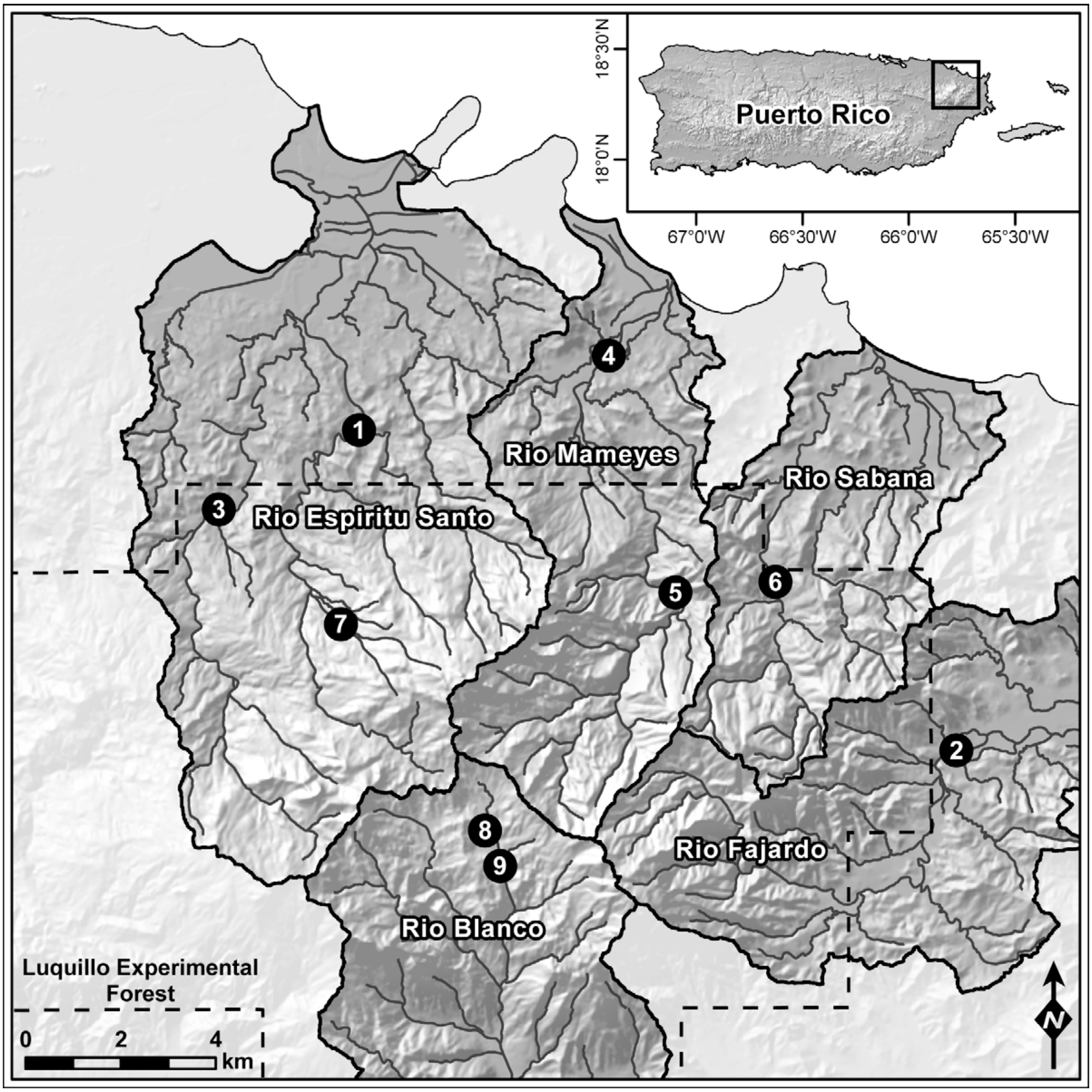


Fig. 1. Location map of the selected study gages in and around the Luquillo Experimental Forest in Northeastern Puerto Rico.

Table 1
Physiographic site information for the selected study gages.

	USGS gage #	Gage name	Channel type	Geology	Bed substrate	Elevation (m)	Drainage area (km^2)	Reach slope (m/m)	Median grain size, d_{50} (m)
1	50063800	Rio Espiritu Santo nr Rio Grande	Lowland	Alluvium	Cobble, gravel, bedrock	12	22.4	0.011	0.127
2	50071000	Rio Fajardo nr Fajardo	Lowland	Alluvium	Cobble, gravel	42	38.8	0.008	0.090
3	50064200	Rio Grande nr El Verde	Lowland	Alluvium	Cobble, gravel, bedrock	50	19.0	0.012	0.177
4	50065700	Rio Mameyes at Mameyes	Lowland	Alluvium	Gravel, sand, silt	5	34.9	0.002	0.038
5	50065500	Rio Mameyes nr Sabana	Mid-elevation	Volcaniclastic	Boulder, cobble, bedrock	84	17.9	0.015	0.159
6	50067000	Rio Sabana at Sabana	Mid-elevation	Volcaniclastic	Cobble, gravel	79	10.3	0.013	0.068
7	50063440	Quebrada Sonadora nr El Verde	Steepland	Volcaniclastic	Boulder	375	2.6	0.233	0.483
8	50074950	Quebrada Guaba nr Naguabo	Steepland	Granodiorite	Sand, boulder	640	0.3	0.102	0.019
9	50075000	Rio Icacos nr Naguabo	Steepland	Granodiorite	Sand, boulder	616	3.3	0.020	0.019

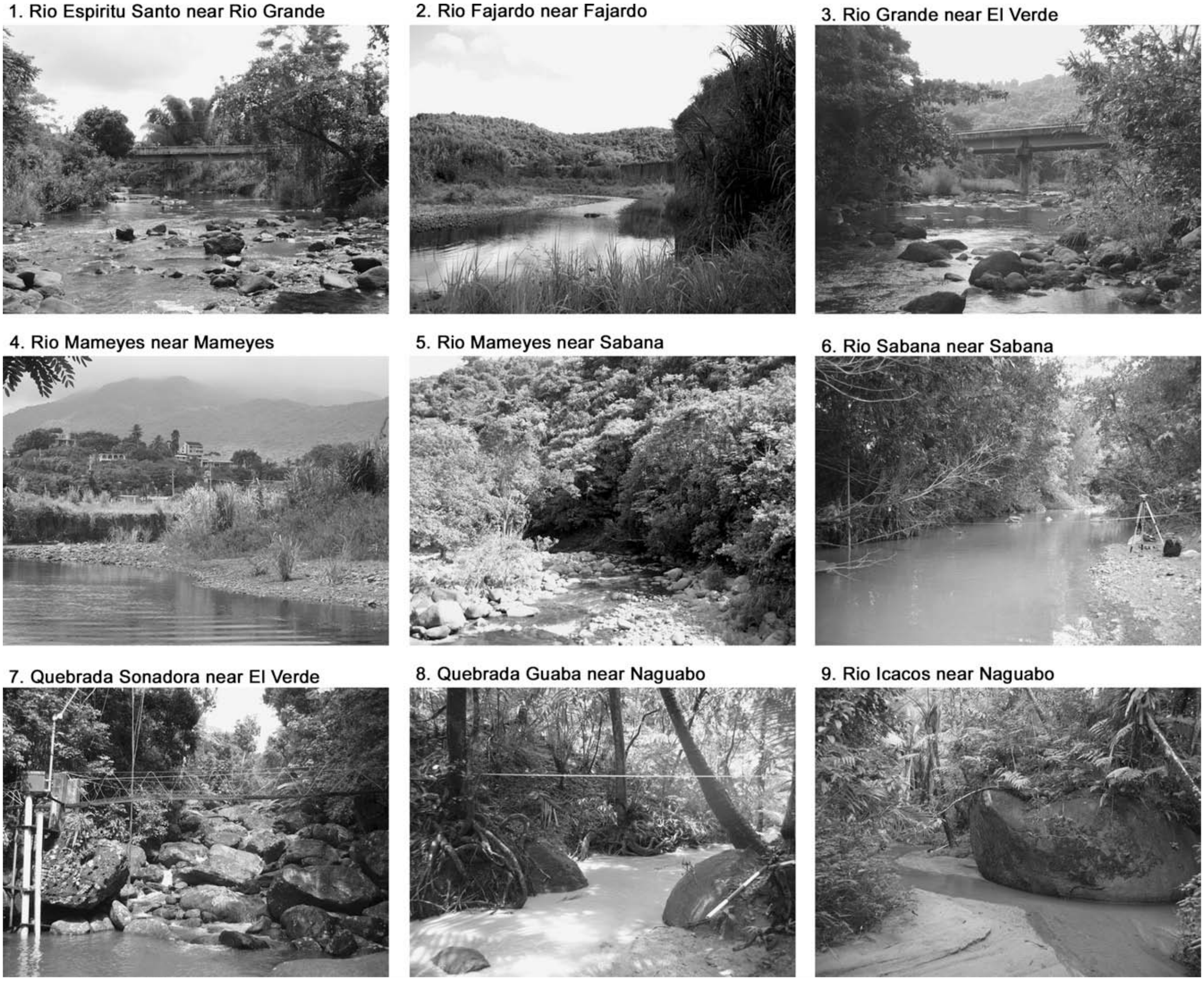

1. Rio Espiritu Santo near Rio Grande
2. Rio Fajardo near Fajardo
3. Rio Grande near El Verde
4. Rio Mameyes near Mameyes
5. Rio Mameyes near Sabana
6. Rio Sabana near Sabana
7. Quebrada Sonadora near El Verde
8. Quebrada Guaba near Naguabo
9. Rio Icacos near Naguabo

Fig. 2. Selected study gages. Note the abundance of vegetation along the channel margins, the bankfull forms of the alluvial sites (#1–4), and the absence of bankfull forms in mid-elevation and steepland sites (#5–9).

meandering channels that flow across an alluvial coastal plain. These reaches are unconfined by valley walls, and are typically accompanied by an adjacent flood plain, high-flow channels, and/or terrace deposits. The mid-elevation reaches are moderate gradient channels that are located upstream of where the mountains grade to the coastal plain, but downstream of the major cascades and waterfalls. They are generally confined by steep hillslopes, and have coarse boulder- and bedrock-lined channels. The steep-

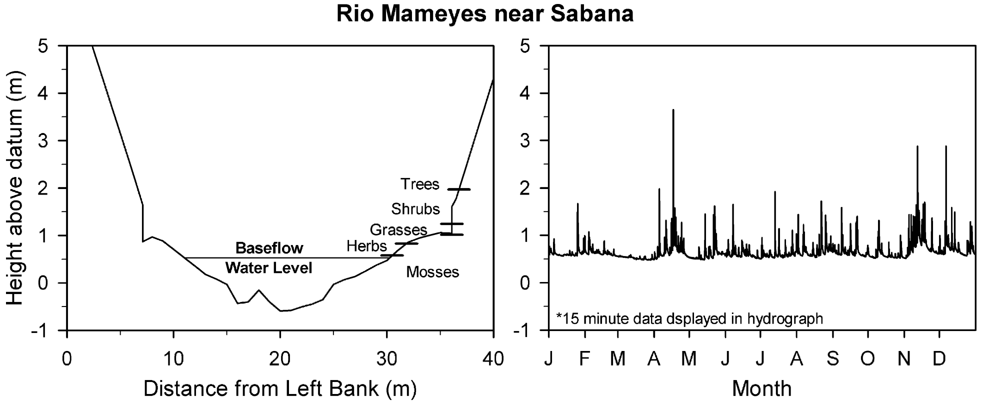


Fig. 3. Cross-section at Río Mameyes near Sabana, a mid-elevation site. There is a vertical zonation of vegetation types, from mosses to herbs to grasses to shrubs to trees. The vegetation reflects the flow regime, and hydrograph on the right is used to visually compare the inundation periods of each vegetation type. Note the several intra-annual floods reaching each surface. Hydrograph discharge data is 15-min resolution for the year 2003.

land reaches are high gradient channels located in the bottom of deeply incised 'v-notch' shaped valleys. Cascades, waterfalls, and long step-pool sequences composed of large boulders are common in these steepland streams.

Riparian vegetation

The vegetation of the Luquillo Mountains is typical of a humid tropical rainforest, with greater tree species diversity, vegetation density, and productivity than most temperate forests. There are approximately native 240 tree species in the Luquillo Experimental Forest, and four major forest types (Lugo and Scatena, 1995). Although tree species diversity is higher than in montane temperate forests, the diversity of understory herbs, ferns, grasses, and shrubs is typically less (Arnold, 1996).

Vegetation in the Luquillo Mountains is dense and productive due to the tropical climate and year-round growing season, and covers virtually any surface that is not frequently disturbed. As such, the active stream channels are one of the only surfaces consistently devoid of vegetation. A vegetation transect along a fluvial disturbance gradient from the middle of the channel into the adjacent forest follows a consistent pattern. Cushion mosses colonize in-channel boulders, whereas herbs, ferns, and grasses grow along channel margins, and woody shrubs and trees establish on higher, less frequently flooded surfaces (Fig. 3). Vegetation stature similarly increases with the relative elevation above the channel. Short-stature vegetation grows along the channel and tall closed-canopy woody vegetation and tall grasses grow on the banks and hillslopes.

Although there are consistent vegetation patterns at a given reach, not all the types of vegetation are present everywhere, because the abundance of certain species can also be influenced by differences in microclimate, light availability, and land-use legacies (Heartsill-Scalley and Aide, 2003; Brown et al., 2006). In the study areas surrounded by forests, the riparian understory vegetation is mainly composed of shrubs, herbs, and ferns (Scatena, 1990; Heartsill-Scalley, 2005). Riparian zones surrounded by pastures and mixed land uses are commonly dominated by grasses, vines, and bare soil. Mosses and lichens that require shade are more common in steepland streams having ample canopy cover. Conversely, wider lowland channels have a greater amount of incident light and consequently have a greater abundance of grasses. Furthermore, unlike many arid and semi-arid riparian forests, there is no distinct riparian forest community in the headwater streams of the Luquillo Mountains (Heartsill-Scalley, 2005). Riparian forests along many alluvial streams in arid and semi-arid regions often have a unique composition and greater productivity than the surrounding vegetation due to increased availability of water. Yet in the continually humid climate of the Luquillo Mountains, both riparian and non-riparian forests have ample moisture availability and are consequently similar in composition, but can be different in structure and biomass (Scatena and Lugo, 1995).

There is no distinct Luquillo riparian forest community, but some tree species are more abundant along the streams. Valley floors are typically dominated by palms, herbs, and by light-gap colonizing species, whereas the dominant hardwoods are confined to more stable ridges (Scatena, 1990). Native species commonly found alongside the steepland streams include: *Guarea glabra* (alligatorwood), *Pterocarpus officinalis* (dragonsblood tree), *Inga vera* (river koko), and *Prestoea montana* (sierra palm). Non-native tree species are common along lowland to mid-elevation streams and are generally associated with reforesting former agricultural land (O'Connor et al., 2000; Brown et al., 2006). Common non-natives found alongside the streams are: *Syzygium jambos* (rose apple), *Spathodea campanulata* (african tulip tree), *Mangifera indica* (mango), and *Bambusa* spp. (bamboo).

Following a disturbance (flood, treefall gap, hurricane), grasses and herbs can begin colonizing within days and are typically well established within weeks to months (Scatena et al., 1996). Likewise, early successional trees can become established within a year. Given this rapid establishment of vegetation, it is assumed in this study, and supported by our observations over the years, that there is a general balance between the frequency and magnitude of floods and the vegetation and soil features adjacent to the stream channel. Small floods frequently cover in-channel and side-channel boulders that are habitat for cushion mosses and lichen. Intermediate-magnitude floods inundate channel bars and low-lying benches, mobilize coarse sediment, and disturb the substrate occupied by herbs and grasses. Larger floods can have sufficient power to flatten in-channel vegetation, particularly grasses and shrubs, but rarely uproot trees. It is only the rarest and largest floods, like those observed during Hurricane Hugo (Scatena and Larsen, 1990), that uproot mature riparian trees, scour the banks, and completely rework the channel morphology. These observations indicate that vegetation structure is a highly sensitive indicator of flow frequency and that differences in vegetation near the active channel can be used to define flow regimes and flow frequencies.

Methods

Our general method involved surveying the relative elevation of vegetation transitions and changes in riparian features at a series

Table 2
Riparian features that were recorded at each survey point. Vegetation, substrate, and soil characteristics were divided into numerical categories for multivariate statistical analysis.

Riparian features					
Vegetation type	0 – mosses (continuous cover on boulder or bedrock)	1 – herbs, ferns (saplings included)	2 – grasses (both short and tall)	3 – shrubs (woody stem,<2.5 cm dbh)	4 – trees (woody stem, > 2.5 cm dbh)
Vegetation height	0 – short (<30 cm)	1 – short/medium (30–60 cm)	2 – medium (60–90 cm)	3 – medium/tall (90–120 cm)	4 – tall (>120 cm, includes some grasses)
Substrate	0 – soil, clay (0–1/256 mm)	1 – sand, silt (1/256–2 mm)	2 – gravel (2–64 mm)	3 – cobble, boulder (> 64 mm)	4 – bedrock
Soil	0 – none (bare rock and/or no soil)	1 – discontinuous (some soil and/or some bare rock)	2 – continuous (stable, developed accumulation of soil)		
Leaf litter	0 – none (no litter)	1 – discontinuous (litter present in small patches)	2 – continuous (continuous litter present)		
Canopy cover	0 – none (full light, no canopy cover)	1 – partial shade (under canopy, but receives direct incident light)	2 – full shade (under closed canopy)	3 – canopy tree (a canopy dominant tree)	

of long-term stream gages, and relating the elevation of each of these transition points to the corresponding discharge and flow frequency. Multivariate regression techniques were then used to statistically partition these transition points into categorical groups based on the vegetation, soil, and substrate characteristics that maximized the difference in average flow frequency between groups. These groups represent ‘transition zones’ that are identifiable on the basis of riparian features and that also demarcate boundaries of flows occurring at different frequencies. Lastly, it was determined which of these transition zones was statistically analogous to the bankfull stage and computed effective discharge of adjacent alluvial channels, based on a comparison of flow frequency.

Field surveys

We surveyed between 8 and 10 transects spanning from the channel into the adjacent forest in the immediate vicinity of each USGS gage. Along each transect we surveyed the relative elevation of each vegetation transition (moss, herb, grass, shrub, and tree). This allowed us to capture the boundary of incipient vegetation growth and the minimum flow frequency associated with the establishment of each type of vegetation. At each transition point we also noted the vegetation height and the accompanying substrate, soil development, leaf litter abundance, and degree of canopy cover (Table 2). Although vegetation type and vegetation height are not strictly independent, they were separated because both short and tall communities of grasses and herbs were prevalent at some lowland reaches.

The surveys were made during baseflow conditions in June 2006. The elevation of each transition point along a transect was measured relative to the USGS stream gage datum, using a Sokkia Total Station and reflector prism. A total of 309 transition points were surveyed at the nine stream gages, or approximately 34 points per reach. Water surface slope was also surveyed in the field by surveying the height of the water level throughout the length of the reach.

Estimation of flow frequency

For the relative elevation of each of the surveyed transition points, the corresponding discharge was determined using the gage’s most current stage–discharge rating curve. The corresponding flow frequency of each discharge value was determined using two different metrics: flow duration and recurrence intervals. Flow duration is the amount of time that a given discharge threshold is met or exceeded and is a metric of the total duration that a surface is inundated by water. The recurrence interval is the average spacing between individual floods that exceed a threshold discharge, and indicates the timing between events. Both measures are needed to understand both the extent and regularity of high flows. Within this manuscript, flow frequency refers to flow duration, and corresponding recurrence intervals are given where applicable.

Flow-duration curves were constructed from the USGS approved discharge records for each gage. While both daily records and instantaneous (15-min) discharge records were available, the instantaneous data were used because they capture the magnitude and timing of peak flows in the flashy hydrologic regime of the Luquillo Mountains. The Log-Pearson Type III (LPIII) distribution was fit to the flow-duration curves in this analysis (Water Resources Council, 1981; Goodwin, 2004). The LPIII distribution is given by the following probability density function (pdf) and cumulative distribution functions (cdf):

$$\mathrm{pdf}(y) = \frac{\lambda^{\beta}(y-\varepsilon)^{\beta-1}}{\Gamma(\beta)}\exp(-\lambda(y-\varepsilon)) \tag{1}$$

$$\mathrm{cdf}(y) = \int_{\varepsilon}^{y} \frac{\lambda^{\beta}(y-\varepsilon)^{\beta-1}}{\Gamma(\beta)}\exp(-\lambda(y-\varepsilon))dy \tag{2}$$

where $y = \ln(Q)$, Q = discharge (m^3/s), Γ is the gamma function, and:

$$\lambda = \frac{\sqrt{\beta}}{\sigma_y} \tag{3}$$

$$\beta = \left(\frac{2}{C_y}\right)^2 \tag{4}$$

$$\varepsilon = \mu_y - \frac{\beta}{\lambda} \tag{5}$$

LPIII distribution parameters (λ, β, ε) for each gage were estimated from the sample mean (μ_y), standard deviation (σ_y), and skew coefficient (C_y) of the natural logarithm-transformed discharge records (Table 3).

Recurrence intervals were calculated using partial duration flood series (where the entire hydrograph is considered) rather than annual maximum series (one peak discharge value per year).

Table 3
The time span of the discharge record, the sample mean (μ), standard deviation (σ), and skew coefficient (C) of the natural logarithm-transformed discharge record (in m^3/s) used for the Log-Pearson Type III distribution, and the coefficients and exponents for at-station width (w) and depth (h) hydraulic geometry relationships of the form ($w = c_1Q^b$ and $h = c_2Q^f$).

			Distribution statistics (15-min data)			Hydraulic geometry			
			Moments			Coefficients		Exponents	
Gage name	Start	End	μ_y	σ_y	C_y	c_1	c_2	b	f
Rio Espiritu Santo nr Rio Grande	7/27/1994	8/20/2006	−0.21	0.94	1.24	11.4	0.36	0.28	0.35
Rio Fajardo nr Fajardo	10/1/1986	9/30/2006	−0.13	1.10	0.74	14.4	0.24	0.34	0.22
Rio Grande nr El Verde	8/16/1990	8/20/2006	−0.68	1.00	1.16	11.4	0.33	0.19	0.30
Rio Mameyes at Mameyes	8/1/1997	6/1/2006	0.23	0.94	1.04	15.4	0.32	0.17	0.24
Rio Mameyes nr Sabana	10/1/1990	6/1/2006	0.00	0.76	1.24	12.7	0.34	0.19	0.34
Rio Sabana at Sabana	10/1/1990	8/20/2006	−1.38	1.08	0.73	12.3	0.33	0.17	0.29
Quebrada Sonadora nr El Verde	10/1/1994	8/20/2006	−2.42	1.17	0.73	4.3	0.58	0.28	0.32
Quebrada Guaba nr Naguabo	6/23/1992	6/1/2006	−4.65	0.86	1.47	5.5	0.36	0.33	0.29
Rio Icacos nr Naguabo	7/21/1992	6/1/2006	−1.33	0.70	1.64	8.4	0.35	0.34	0.31

This approach was preferred because of the abundance of intra-annual floods that can modify riparian vegetation. Intra-annual floods were counted as long as they were independent events (i.e. not part of the same rainfall event or influenced by saturation from previous storms). We followed general guidelines for identifying independent peaks set forth by Lang et al. (1999), which suggest that independent flows must be separated by a minimum of 5 days and accompanied by a drop below 75% of the lower peak. However, due to the short duration of floods in these flashy streams, we considered events to be independent if they were separated by at least 24 h, and also had a 75% drop between peaks.

Multivariate regression trees

Multivariate regression trees (MRT) are a statistical technique that can be used to predict relationships between a response variable and multiple environmental characteristics (De'ath, 2002). MRT forms clusters or groups by repeated splitting of the data, with each split defined by a simple rule based on the predictor variables. The splits are chosen to minimize the dissimilarity of data within clusters, or maximize the differences between clusters. The groups or clusters formed by MRT are defined by a simple splitting of one environmental variable at a time, generating an intuitive and easily interpreted decision tree. We used MRT to define groups, based on the environmental variables measured in the field (Table 2), that have different average flow frequencies. The flow frequency of each surveyed transition point was used as the response variable, after a logarithm-transformation was used to reduce skewness and achieve a normal distribution. Splits were based on the vegetation type, vegetation height, substrate size, soil development, leaf litter, canopy cover, and reach location. This procedure ultimately generated clusters of riparian features that occur at distinct flow frequencies.

Separate regression trees were performed for the data collected at the alluvial sites and the mid-elevation/steepland sites. One reach, Quebrada Guaba near Naguabo, was removed from the MRT analysis due to anomalous flow frequencies. Further supporting its removal from this analysis, this gage also has the smallest drainage area, a closed canopy that reduces the regeneration of channel-side herbs and grasses, the most flashy hydrograph, subsurface drainage through sandy substrate, and riparian features that occur above the boundary of apparent common floods.

Effective discharge

The effective discharge and its flow frequency, was estimated for the alluvial and mid-elevation reaches so that this frequency could be compared to frequencies of the clusters formed by MRT in the steepland channels. The effective discharge is defined as the discharge that transports the most sediment over time and is quantified as the discharge where the product of the frequency of discharge (probability density function) and the magnitude of sediment transport (the relative effectiveness curve) is a maximum (Wolman and Miller, 1960). Sediment transport here is quantified by the bed load discharge, because the gravel-, cobble-, and boulder-bedded channel form of steep mountain streams is fundamentally determined by the bed load rather than suspended sediment (Knighton, 1998). Bed load discharge is usually estimated using either a bed load sediment rating curve or similar threshold-based function of fluvial discharge (Emmett and Wolman, 2001; Torizzo and Pitlick, 2004). Empirical bed load transport formulas based on discharge have been shown to accurately predict sediment yields in these and other steepland drainages in Puerto Rico (Simon and Guzman-Rios, 1990).

The bed load sediment transport curve for each reach was estimated according to the Meyer-Peter and Muller (1948) relationship. The Meyer-Peter and Muller sediment transport equation relates sediment yield to channel width and excess bed shear stress applied by flowing water:

$$Q_s = w\rho_s \frac{8}{(s-1)g\rho^{3/2}}(\tau - \tau_c)^{3/2}, \quad \text{for } (\tau - \tau_c) > 0,$$
$$Q_s = 0 \text{ otherwise} \tag{6}$$

where Q_s = sediment yield (kg/s), w = channel width (m), ρ_s = specific weight of quartz sediment (2650 kg/m^3), s = sediment density ratio (dimensionless, 2.65), g = acceleration due to gravity (9.8 m/s^2), ρ = specific weight of water (1000 kg/m^3), τ = unit boundary shear stress (Pa), τ_c = critical boundary shear stress (Pa).

The unit boundary shear stress and critical boundary shear stress can be estimated according to the following relationships, assuming steady, uniform flow:

$$\tau = \rho gRS \quad \text{(depth-slope product)} \tag{7}$$
$$\tau_c = \tau_c^*(s-1)gd_{50} \tag{8}$$

where R = hydraulic radius or average depth (m), S = slope (m/m), τ_c^* = critical dimensionless shear stress (0.030 for alluvial streams, 0.045 for mid-elevation streams), following a positive relationship between slope and τ_c^* discussed in Mueller et al., 2005, d_{50} = median grain size (m).

Width and average depth of the wetted channel were estimated as power functions of discharge (Leopold and Maddock, 1953). The following power relationships were fitted for each gage, using width and depth measurements at varying discharges collected by the USGS:

$$w = c_1Q^b \tag{9}$$
$$R = c_2Q^f \tag{10}$$

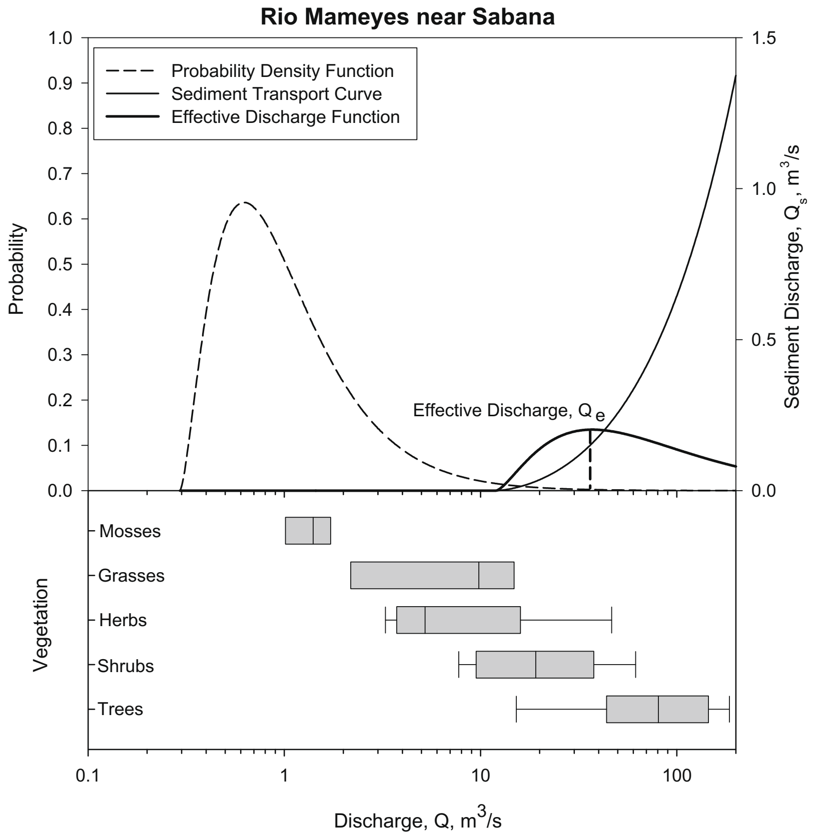


Fig. 4. The effective discharge occurs at the maximum of the relative effectiveness curve that is generated by multiplying the flow duration and sediment transport functions. In this illustration, using data from the Río Mameyes near Sabana gage, the effective discharge is roughly coincident with the presence of woody shrubs and trees.

where Q = discharge (m^3/s), and c_1, c_2, b, and f are coefficients and exponents empirically derived from a logarithm-transformed linear regression.

The relative effectiveness function, Φ, is the product of the probability density function (LP3 flow-duration curve), pdf(Q), and the bed load sediment transport curve, Q_s (Fig. 4). This relative effectiveness function represents the amount of sediment transported over time. The effective discharge is the discharge where this function is a maximum (i.e. derivative of the function is 0), such that:

$$\Phi = \mathrm{pdf}(Q) * Q_s \tag{11}$$

$$\left.\frac{d\Phi}{dQ}\right|^{Q_{\mathrm{effective}}} = 0 \tag{12}$$

The effective discharge was estimated for only the alluvial and mid-elevation streams because our initial analysis and other studies (Torizzo and Pitlick, 2004; Lenzi et al., 2006a) indicate these sediment transport equations were not considered appropriate for the steepest boulder-lined streams. Parameters used for each site in the calculation of the flow-duration curves, bed load sediment transport equation, and the relative effectiveness function are listed in Table 3.

Results

Riparian vegetation

The average elevation of the first occurrence of the different riparian vegetation types (mosses, grasses, herbs, shrubs, trees) are zonated with respect to elevation along the cross-sectional profile of the channel, as is illustrated for one of the sites in Fig. 3. Canopy cover, the abundance of leaf litter, and soil development also increase from the channel to the adjacent forest. Our surveys and observations in other streams in the region indicate that this zonation is best developed along channels that have open or partially open canopies where there is sufficient light for grasses and herbaceous vegetation to establish and also sufficient shade for the development of cushion mosses. While local environmental conditions (e.g. light, substrate, hydraulic shielding) can constrain the establishment of vegetation at any particular location, the average elevation of the first occurrence of different vegetation forms, litter cover, and soil development is consistently related to the frequency of flow inundation both within and between sites. Moreover, mosses, herbs, and grasses start establishing at elevations that are inundated weekly or monthly, and are slightly above the baseflow water level. Shrubs and trees are present at higher stages where they are inundated, at least briefly, several times a year.

The average elevation of the first occurrence of the different vegetation types is also related to sediment transporting flows and the effective discharge, as illustrated by data from the one of the Río Mameyes sites (Fig. 4). Mosses and short grasses dominate at a stage below the threshold of sediment transport but above the most frequent flows (the peak in the probability density function of discharge). That is, they first occur at stages that are frequently inundated by sub-effective flows. Herbs first occur at a stage associated with intermediate discharges that are around the threshold for sediment mobilization. Woody shrubs and trees establish at a less frequent discharge that is coincident with the effective discharge of bed load sediment. The greatest variation in the vegetation types occurs around the threshold for sediment mobilization, where grasses, herbs, shrubs, and trees commonly occur together.

Table 4
The median height above water table, unit discharge, flow frequency, and recurrence interval of each zone defined by the multivariate regression tree analysis. Zones A1–A4 are based on survey data points on the four alluvial stream gages, whereas zones S1–S4 are based on data from the four steepland gages.

Zone	Riparian features	# Survey points	# Gages	Height abv. baseflow (m)	Median unit Q (m^3/s/km^2)	Median frequency (% time)	Median recurrence (days)
A1	Short vegetation, coarse substrate	84	4	0.25	0.08	14.2	8
A2	Short vegetation, soil/clay	19	4	0.56	0.64	0.96	19
A3	Tall vegetation, coarse substrate	21	4	0.71	0.74	0.84	21
A4	Tall vegetation, soil/clay	29	4	0.99	1.41	0.30	39
S1	No soil, moss/herbs	79	4[a]	0.25	0.41	2.74	10
S2[b]	No soil, trees/shrubs	20	4[a]	0.80	2.01	0.21	41
S3	Soil, moss/herbs	18	4[a]	0.32	0.88	1.14	14
S4[b]	Soil, trees/shrubs	39	4[a]	0.92	2.51	0.13	55
Bankfull		4	4	1.27	2.29	0.16	50
Effective		4	4	1.20	1.61	0.20	39

[a] Data from Q. Guaba removed from analysis.

[b] Zone not significantly different from bankfull in alluvial channels based on a Tukey's HSD test, $a = .05$.

Table 5
The discharge (Q, m^3/s), unit discharge (Unit Q, m^3/s/km^2), flow frequency (Freq., % time), and recurrence interval (Rec., days) associated with the bankfull stage (for alluvial sites), the effective discharge (for lowland and mid-elevation sites), and the reference stage (based on riparian features) that is defined in this paper.

Gage name	Bankfull				Effective					Bankfull analog			
	Q (m^3/s)	Unit Q (m^3/s/km^2)	Frequency (% time)	Recurrence (days)	Q (m^3/s)	Unit Q (m^3/s/km^2)	Frequency (% time)	Recurrence (days)	Zone	Q (m^3/s)	Unit Q (m^3/s/km^2)	Frequency (% time)	Recurrence (days)
Rio Espiritu Santo nr Rio Grande	61.5	2.7	0.14	42	25.7	1.1	0.51%	16	A4	33.7	1.5	0.34	26
Rio Fajardo nr Fajardo	96.9	2.5	0.08	90	65.3	1.7	0.16%	46	A4	55.4	1.4	0.21	43
Rio Grande nr El Verde	39.7	2.1	0.18	57	63.2	3.3	0.09%	98	A4	30.1	1.6	0.27	48
Rio Mameyes at Mameyes	46.2	1.3	0.31	27	54.0	1.5	0.24%	33	A4	38.0	1.1	0.42	30
Rio Mameyes nr Sabana	–	–	–	–	37.1	2.1	0.12%	50	S4	75.4	4.2	0.03	92
Rio Sabana at Sabana	–	–	–	–	6.9	0.7	0.70%	18	S4	23.4	2.3	0.09	48
Quebrada Sonadora nr El Verde	–	–	–	–	–	–	–	–	S4	6.7	2.6	0.27	40
Quebrada Guaba nr Naguabo	–	–	–	–	–	–	–	–	S4	2.0	6.6	0.03	346
Rio Icacos nr Naguabo	–	–	–	–	–	–	–	–	S4	9.2	2.8	0.16	50

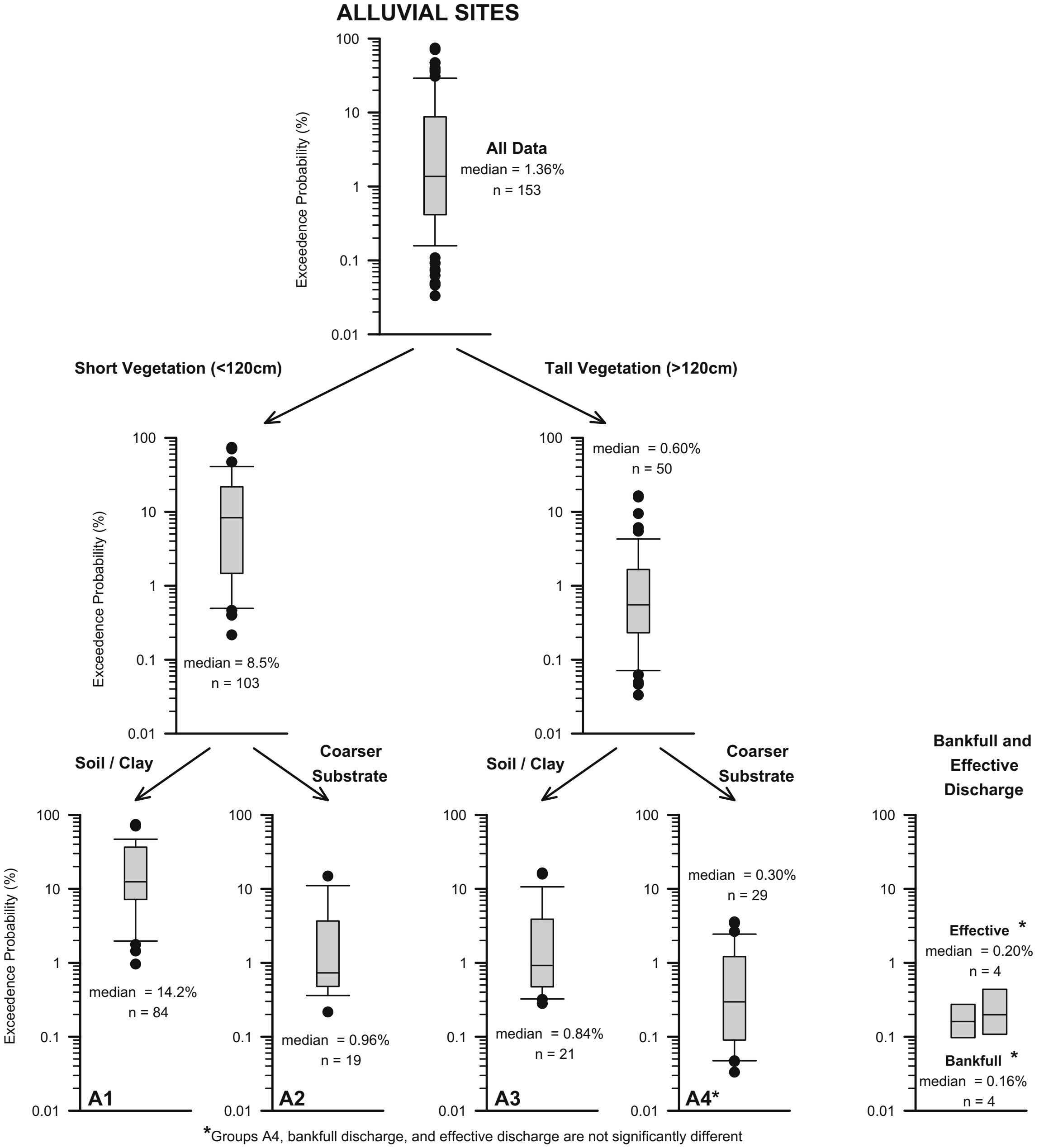
Bankfull and effective discharge

The median exceedance probability of the bankfull (morphologic) discharge at the four alluvial sites was found to be 0.16% and had a corresponding median recurrence interval of 50 days (Table 5). The median exceedance probability of the calculated effective discharges was 0.20% and had a corresponding median recurrence interval of 39 days. The average flow frequency of both bankfull discharge and effective discharge for the alluvial sites was not found to be significantly different (Student's *t*-test, $P > 0.1$). This confirms the assumption that the bankfull stage is coincident with the channel-forming discharge in this region. For comparison, the average flow frequency of the mean annual discharge among all sites is 23%; far more frequent than both the bankfull and effective discharge.

Multivariate regression trees

The data at the alluvial sites were first partitioned into two clusters: tall vegetation (120 cm in height or greater), and short vegetation (stature shorter than 120 cm) (Fig. 5). The cluster defined by short vegetation has a median exceedance probability of 8.5% and is inundated more frequently than the tall vegetation cluster (0.60%). Within both clusters, the data were further split into two divisions based on the same characteristics: clay sized substrate (including soil), and substrate coarser than clay. Thus, the data for alluvial sites were effectively divided into four clusters: (A1) short vegetation with coarse substrate (median exceedance probability = 14.2%), (A2) short vegetation with clay/soil (0.96%), (A3) tall vegetation with coarse substrate (0.84%), and (A4) tall vegetation with clay/soil (0.30%). Based on a comparison of means from logarithm-transformed data (using Tukey's HSD test), clusters A1 and A4 were found to be significantly different from each other and clusters A2 and A3 ($P < 0.01$). Clusters A2 and A3 were not significantly different from each other ($P > 0.1$). Similarly, the frequency of bankfull discharge, effective discharge, and the cluster defined by tall vegetation growing on soil or clay (A4) were not significantly different ($P > 0.1$). This suggests that in these alluvial streams, the morphologic bankfull stage and the effective channel-forming discharge is coincident with the presence of tall vegetation and soil development along the banks.

The vegetation and substrate data for the steepland sites separated into clusters that were based on similar factors as the data for alluvial sites (Fig. 6). The MRT analysis first split the data into two



*Groups A4, bankfull discharge, and effective discharge are not significantly different

Fig. 5. Box plots of the flow frequency for surveyed data points at alluvial sites that have been partitioned into clusters based on vegetation, substrate, and soil characteristics using a multivariate regression tree technique (see Section 'Results – Multivariate regression trees'). The means of the logarithm-transformed flow frequency data in cluster A4 (tall vegetation and soil), bankfull discharge, and effective discharge (all marked by an asterisk) are not significantly different.

clusters based on the presence of soil. Continuous and discontinuous soil formed one cluster (0.25%), and the absence of soil formed the other (1.73%). Moreover, the cluster with soil had a lower flow frequency than the cluster without soil. These two clusters were both further partitioned by vegetation type: presence of trees and shrubs, and presence of only herbs, mosses, and grasses. Hence, the data for steepland sites were divided into the following four clusters: (S1) no soil and herbs/mosses/grasses (2.74%), (S2) no soil and trees/shrubs (0.21%), (S3) soil and herbs/mosses/grasses (1.14%), and (S4) soil and trees/shrubs (0.13%). Further subdivision and partitioning in both models did not create additional clusters that were statistically different.

It is also important to acknowledge that the location of the reach was not chosen as a split within these models, therefore the clusters are applicable to all sites. The model coefficient of determination (r^2) for the MRT, based on cross-validation, for alluvial sites is 0.54, indicating that 54% of the variance among all surveyed points was explained by the division into these clusters. For steepland sites, the model r^2 is 0.45. However, at any given site, the division of data into these clusters accounted for a higher proportion of the variance (average at-site $r^2 = 0.63$). This indicates that although aggregating data between sites introduces error that is not necessarily present at a given site, the clusters can be compared among sites.

To determine the characteristic features of the steepland sites that mark a reference boundary with a flow frequency that is analogous to the bankfull stage in alluvial streams, the flow frequency of each of the steepland clusters (S1–S4) were systematically tested against the clusters developed for the bankfull flow frequency in the alluvial sites (Table 4). The comparison of means

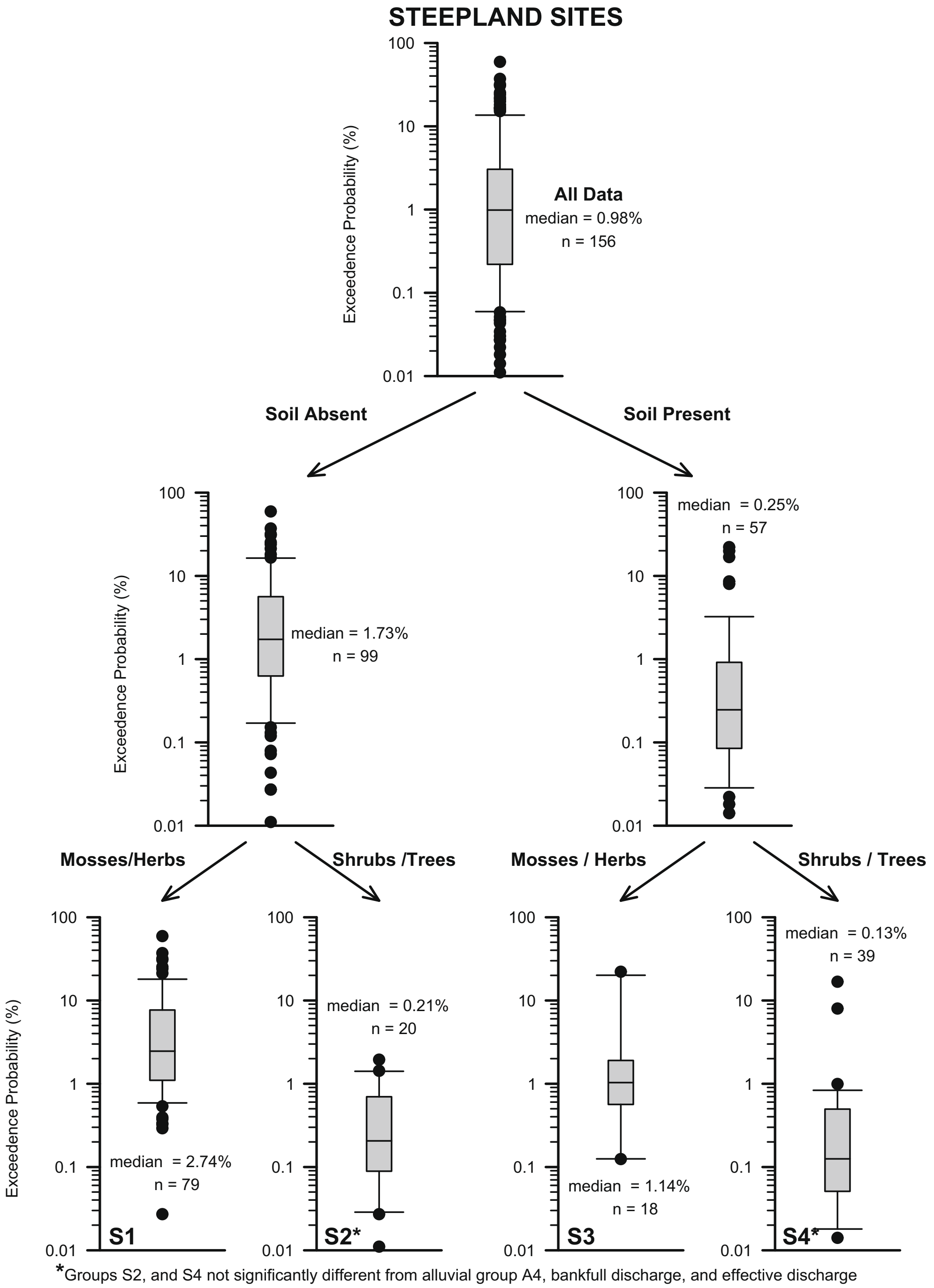


Fig. 6. Box plots of the flow frequency for surveyed data points at mid-elevation and steepland sites that have been partitioned into clusters based on vegetation, substrate, and soil characteristics using a multivariate regression tree technique. Based on a comparison of flow frequency, the means of the logarithm-transformed data in clusters S2 (soil absent/shrubs and trees), and S4 (soil present/shrubs and trees) are not significantly different from the means of logarithm-transformed data in clusters A4 (tall vegetation and soil), bankfull discharge, and effective discharge (all marked by asterisk) at adjacent alluvial sites that are shown in Fig. 5.

of the logarithm-transformed flow frequency between each zone using Tukey's HSD test indicated that the steepland zone S2 (no soil, trees/shrubs), zone S4 (soil, trees/shrubs), zone A4 (tall vegetation and clay/soil, for alluvial sites), bankfull discharge, and effective discharge are not significantly different ($P > 0.1$). On the basis of flow frequency, the zone defined by soil development and the presence of woody shrubs and trees in steepland sites (zone S4) was most analogous to the bankfull stage in alluvial streams. The bankfull stage for the alluvial streams occurs on average 1.3 m (±0.09 m, 1 S.D.) above the baseflow water level, has a corresponding unit discharge of 2.3 $m^3/s/km^2$ (±0.62), a flow frequency of 0.16% (±0.09), and an average recurrence interval of 50 days (±0.31). The analogous steepland channel boundary that is marked by the first occurrence of soil and woody vegetation occurs on average 0.92 m (±0.31) above the baseflow water level, has a corresponding unit discharge of 2.5 $m^3/s/km^2$ (±0.85), a flow frequency of 0.13% (±0.10), and an average recurrence interval of 55 days (±23).

The corresponding flow frequency of this channel boundary was compared across all the sites its consistency throughout the stream network (Table 5). For eight of the nine gaged channels, this boundary marks a flow frequency ranging from 0.03% and 0.42%

(median = 0.24%), with a recurrence interval between 26 and 92 days (median = 46 days). There was no significant relationship between drainage area and flow frequency of this boundary ($r^2 = 0.15$, $P > 0.1$), suggesting that it does not vary systematically with area throughout the stream network. The only site that is dramatically different in terms of flow frequency is Quebrada Guaba, where the occurrence of soil and woody vegetation correspond to a flow frequency of 0.03% and a recurrence interval of 346 days—a much less frequent flow than other reaches. This is also the smallest stream, and suggests that the technique of flow frequency estimation based on riparian features may not work for the 1st order channels. However, as evidenced by the other eight reaches, the channel-boundary marker is consistent in flow frequency throughout the stream network, albeit some local variation.

Discussion

Riparian features

The multiple regression trees developed for both the alluvial and steepland sites generated several statistically significant clusters of points, based on the first occurrence of riparian features, that have different average flow frequencies. Data for the alluvial sites were partitioned on the basis of vegetation height (tall vs. short), and substrate size (soil/clay vs. coarser substrate). Data for the steepland sites were partitioned on the basis of soil development (present or absent) and vegetation type (moss, herbs, grass, shrubs, trees). The partitioning of data for both upland and alluvial sites suggests that the first occurrence of short-stature vegetation (herbs, mosses, and grasses) occurs on coarse substrates and in areas that are inundated by flows of moderate frequency and intensity. Moreover, the zones defined by these features are associated with the mean annual discharge and sub-effective flows. In contrast, tall, mature, woody vegetation and soil development are related to less frequent flows of higher magnitude that approximate the effective discharge. Furthermore, these features are related to the bankfull and effective flows of alluvial streams and can be used to identify an analogous marker in steepland streams. Because this reference marker occurs at a relatively constant flow frequency throughout the stream network, it can be used to determine channel boundaries at ungaged reaches in the region.

The characteristics of the two zones that are based on riparian features that estimate bankfull discharges at both the alluvial and steepland sites are remarkably similar. In the alluvial sites, bankfull stage is associated with the first occurrence of tall vegetation (shrubs, trees and some grasses) and clay substrate/soil. In the steepland sites, the reference stage is also marked by the first occurrence of woody shrubs/trees and soil development. However, the MRT analysis indicates that in the alluvial sites, vegetation height was found to be more important than vegetation type in the cluster divisions. Conversely, in the steepland sites, vegetation type was more important than vegetation height. This difference is due to the large proportion of different grass species found at open alluvial sites. Despite being all considered the same vegetation type, the grasses differ in height (some greater than 120 cm) and composition according to their proximity to the channel, so that vegetation height more strongly reflects flow frequency than does vegetation type. In contrast, the type of vegetation was more important in forming clusters for steepland sites because there is less dominance of one vegetation type over the rest at these sites. This difference in vegetation between alluvial and steepland reaches is driven by the fact that the alluvial reaches are higher order streams, lower in elevation, have greater incident light, and are generally surrounded by non-forest land use (mostly pastures and rural development areas).

However, these riparian vegetation and substrate features do not mark the same magnitude and frequency of flows in the smallest, closed-canopy streams in the study area. In these small channels, the riparian features are more influenced by local factors than by fluvial disturbance. It should also be noted that there is a large amount of variability within any given zone defined by riparian features. Flow frequencies within a cluster can span an order or two of magnitude, which represent drastically different flood magnitudes. The large degree of natural variability is responsible for this variance. Although the first occurrence of vegetation that was surveyed along each transect is primarily influenced by the frequency of flooding, the exact stage where the vegetation grows relative to the stream channel is also influenced by local factors such as hydraulic shielding by boulders, differences in light, and substrate stability. These small differences in height can translate into a larger difference in flow frequency and generate a large degree of natural noise. Fortunately, the repeated measure of different vegetation types in a reach reduces this variation and provides a reliable estimate of the corresponding flow frequency. This analysis also indicates that it is valid to identify the high-flow riparian features at gaging stations using the techniques identified in this paper and then identifying them at non-gaged reaches, much like bankfull morphology is identified in alluvial reaches. Field identification at non-gaged sites is acceptably accurate and precise because the first occurrence of woody vegetation and soil is easily recognizable.

Bankfull and effective discharge

The recurrence intervals that are associated with both the bankfull discharge in alluvial channels and the analogous reference boundary in steepland channels are between 40 and 90 days. This range is significantly more frequent than commonly reported values of 1–3 years (Wolman and Miller, 1960; Dunne and Leopold, 1978; Rosgen, 1994; Knighton, 1998). The difference is due both to the methodology used and the flashy nature of these streams. Recurrence intervals presented here were calculated according to a partial duration series analysis using 15-min instantaneous discharge data, rather than an annual maximum series and/or daily discharge records used in many studies. By definition, the annual maximum series used in these classic publications is drawn from one annual peak per year, thus forcing recurrence intervals greater than or equal to 1 year. While annual maximum series analysis may be pertinent for large temperate basins, it fails to capture the intra-annual flows that are responsible for structuring the vegetation in and adjacent to the channels in these flashy and relatively small streams. Although some of these publications acknowledge that bankfull discharge can be observed 'several times per year' (Rosgen, 1994) in many rivers, little guidance is given to assess the recurrence interval of multiple flows per year. A partial duration series captures the many flow events over the bankfull threshold found in these flashy streams because it allows for multiple floods each year. Had an annual maximum series been used in this study, bankfull stage would be exceeded by the peak flow in every year (recurrence interval of 1 year). Furthermore, if daily discharge data (rather than 15-min data) had been used in this study to calculate recurrence intervals (using partial duration series), the frequent short-lived peaks would be damped such that only one or two events per year would have exceeded the bankfull threshold (recurrence interval of 0.5–1 year).

Despite differences in recurrence intervals between this study and others, the flow-duration values of bankfull reported in this study are comparable to other studies. We report average bankfull flow durations of $\sim$0.27%, or approximately 1 day of inundation per year. For comparison, the bankfull duration of streams in England and Wales is reported to be 0.60% (2 days per year) (Nixon, 1959), and between 0.4% and 3.0% (1.5–11 days per year) in mountain streams in Colorado and Wyoming (Andrews, 1980). Dunne and Leopold (1978) asserted that bankfull flow duration often varies between 1.3% and 4.5%, with an average of 2.1% (8 days per year). The bankfull stage here is inundated slightly *less* total time than the rivers mentioned in these other studies, although there are *more* floods of bankfull magnitude per year. This suggests that bankfull formation among these different rivers may be related more to the total amount of time bankfull stage is exceeded rather than the timing between floods.

This similarity of bankfull exceedence (on the basis of flow duration) between this study and others may be related to the flashy nature of the floods in this tropical montane environment. Flood peaks in these streams and many mountain streams are brief (hours in duration) and strong, reflecting rapid movement of water down steep hillslopes and channels (Swanson et al., 1998). While these floods are intense, they are short-lived so that several events of bankfull magnitude each year may be required for channel and riparian zone maintenance. In contrast, floods in large lowland basins often inundate the flood plain for up to several days, but may only occur once a year. Consequently, the overall effectiveness of frequent short-duration floods in these mountain streams may be similar to floods in other basins that are more rare and longer in duration.

The same flows that are geomorphically effective are also responsible for maintaining riparian vegetation patterns, as evidenced by the relationship between the effective discharge in alluvial and mid-elevation channels and the boundary of woody vegetation in this study. The effective discharge based on bed load transport is at the same magnitude as the threshold for woody vegetation, as both are apparently influenced by similar periodic flows. Thus, the boundary marked by vegetation and substrate features can be used as an indicator of effective flows in mid-elevation and alluvial reaches. This has implications for studying the downstream hydraulic geometry of the stream network, which requires that the bankfull and effective discharge occur at a constant frequency throughout a basin (Leopold and Maddock, 1953). Because the reference stage defined in this study marks a flood of equal flow frequency and is also consistent with the supposed channel-forming/maintaining discharge, it can be used as a channel-boundary marker for downstream hydraulic geometry studies to compare channel cross-sectional morphology.

However, it should be cautioned that that the supposed geomorphically effective flows, as defined by bedload transport, are not necessarily channel-forming in the steepland boulder- and bedrock-lined reaches in this study. Carling (1988) argues that the effective discharge concept only applies well to alluvial channels that are free to adjust their boundaries, and not to channels that are constrained by coarse sediment and immobile beds. In fact, the channel-forming discharge in bedrock mountain streams may be higher than the effective discharge of sediment transport due to the high threshold of stream power required for bedrock incision and movement of large boulders (Costa and O'Connor, 1995). There is also discussion in the literature that the effective discharge is not necessarily a discrete value, but rather a range of flow events that are responsible for the greatest amount of geomorphic work (Goodwin, 2004). Here we are only using effective discharge as a general guide to the magnitude of channel-altering flows and not as a rigid measure of geomorphic work performed on the channel. Some researchers have even posited that there are two dominant discharge ranges for steep mountain rivers: a relatively frequent flow responsible for maintaining channel forms, and a more infrequent high flow responsible for large-scale channel shaping (Lenzi et al., 2006b). On this note, it seems plausible that although rare floods occurring every several years may be responsible for bedrock incision and mass sediment movement, it is the more frequent flows (on the order of the effective discharge) that influence riparian vegetation patterns and maintain the general characteristic form of the channel in thus study area.

Applicability to other stream systems

The results of this study are directly applicable to streams in the Luquillo region of Puerto Rico. However, the techniques of quantifying flow frequencies associated with different types of vegetation and riparian features used here should be applicable in a range of environments. It is also expected that mountainous streams with both a similar flashy flow regime and a humid tropical climate with analogous vegetation types will have relationships between riparian field indicators and flow frequencies that are consistent with those determined in this study. Areas with the requisite combinations of geological, tectonic, and climatic conditions are known in East Asia, the Indian subcontinent, coastal Africa, northern Australia, and the neotropics (Gupta, 1988).

Riparian features have also been noted as robust indicators of flow frequencies in a variety of temperate montane systems, including the South Island of New Zealand (Wohl and Wilcox, 2005), the Rocky Mountains (Wohl et al., 2004), the Pacific Northwest (Montgomery and Gran, 2001), and the alpine region of Poland (Radecki-Pawlik, 2002). Because these areas are in different physiographic provinces with different vegetation patterns, it would be spurious to assume that the reference features that approximate bankfull found in this study occur at the same flow frequency as those in temperate mountain streams. However, it is likely that similar features based on soil, substrate, and vegetation can act as reference features in other systems and that local/regional flow frequency zones can be identified in a physiographic region using techniques outlined here.

Conclusions

In the study area of the Luquillo Mountains, we used a network of stream gages to determine a reference boundary of constant flow frequency, based on riparian features, in steepland streams where a bankfull stage was absent. The results indicated that in the steepland streams, the reference discharge associated with the average first occurrence of soil and woody vegetation has the same flow frequency as the bankfull discharge of adjacent alluvial streams. Likewise, the stage associated with the first occurrence of woody vegetation in alluvial streams can be similarly used to estimate bankfull. The results also indicate that bankfull stage, effective discharge, and presence of tall vegetation and a clayey substrate all occur at a stage associated with a reference discharge that has a similar flow frequency. Thus, throughout the stream network, high-flow riparian features can provide a common benchmark of flow frequency. Furthermore, the general approach of surveying the first occurrence of riparian features and using multivariate statistical analysis linking these occurrences to 15-min flow duration can provide an internally consistent framework for identifying reference flow frequencies within a region.

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