AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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This study investigates patterns of physical structure organization in stream networks. In particular, it seeks to describe patterns of wood, boulders, pools and slope that are evident in stream channels and to determine whether patterns of these elements are influenced by network-level controls. The four in-stream parameters were combined to produce a metric of complexity, which was used to investigate differences in patters and organization of in-stream structure within and between watersheds.

Research was conducted in three Oregon Coast Range watersheds' Rogers Creek in the Northern Oregon Coast Range, and Turner and Elk Creeks in the South Central Oregon Coast Range. Rogers, Turner and Elk Creeks were $26km^2$, $12km^2$, and $17km^2$ respectively and fell into two distinct geologic regions, basalt geology in the north and sandstone geology in the south. Fifteen km of stream were surveyed in 60 meter segments for a total of 246 stream segments observations. There were 77, 70, and 99 study segments in Rogers, Turner and Elk Creeks respectively.

The network-level controls investigated were stream junctions, channel constraint, and debris flows. It was hypothesized that these network-level controls influence in-stream complexity by encouraging uneven distribution of large material

which in turn influences stream slope and pool abundance. Network-level controls where associated with differing patterns of complexity in each watershed. The influence of the network-level control was in part dependent on factors including: geologic setting, stream slope differences and difference in disturbance regimes. Stream junctions and constrained segments were found to be associated with some of the highest values of complexity, while recent debris flows were associated with lower complexity values.

Several of the hypotheses described in the Network Dynamics Hypothesis (Benda et al. 2004b) were investigated using a geographic information system (GIS) and data derived from a digital elevation model (DEM). The GIS was used to test for relationships between field measured complexity and stream network parameters that were developed using a program for DEM analysis. DEM derived data for the contributing area, junction angle and debris flow potential at sample points illustrated a weak relationship with complexity. By better understanding the influence of network level controls on complexity it may be possible to improve the understanding of how stream networks connect hillslope and riparian environments, thereby aiding watershed management and identifying locations of diverse habitat in the stream network.

A Study of In Stream Complexity in Three Oregon Coast Range Watersheds

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degree of

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APPROVED:

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Chair of the Department of Geosciences

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Paul Anderson, Author

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Introduction

Streams networks connect landscape components and route material and energy from the headwaters of watersheds to the sea. These networks interact with discrete and chronic disturbance events and material distribution in different ways depending on many factors including: geology, channel slope, vegetation, disturbance regime, and management history. In-stream physical structure is in part shaped by the interactions of these factors and the organization of the stream network itself. This study investigates patterns of physical structure organization in stream networks; in particular, it seeks to describe patterns, which are evident in streams channels and are described as "complexity", and to determine whether complexity can be explained by network level controls. One possible model for the influence of network level controls on complexity is offered in the network dynamics hypothesis (NDH). The NDH focuses on the shape of drainage networks, in particular the properties of stream junction environments. Several of the hypotheses presented in the NDH were investigated with data from this study.

Several key elements of in-stream structure were identified and grouped together to represent in-stream complexity. The term "complexity" has been defined differently in a number of studies depending on the management goals and scale of interest. To address complexity at the scale of the main channel in a stream network, several of the most commonly measured components of complexity were combined. The definition of complexity developed in this study focused on components that are useful in describing structural differences at the10s of meters scale: wood, boulders, pools and slope. Their abundance can lead to a more "complex" channel at the scale of the study. The focus of this study was on the main channel portion of stream networks in watersheds under 30 km^2.

The network level controls investigated include: stream junctions, valley width, and disturbance events. Disturbance events represent sources of material, while stream junction and constrained segments (smaller valley width) represent possible deposition environments. If network level controls influence complexity, as described in this study, areas of better habitat can be more easily identified. The significance of this study is that, by better understanding the influence of network level controls on complexity, it is possible to improve the understanding of how stream networks connect hillslope and riparian environments can be improved, thereby aiding watershed management.

In previous studies, complexity in streams has been defined as percent pool habitat, presence of large woody debris, hydraulic retention and substrate size (Kershner et al. 1997), hydraulic and structural diversity influenced by large wood (Sullivan et al.1987), complexity influenced by wood (Gurnell et al. 2002), and presence of large woody debris, which may trap sediment, affecting channel depth (Horan et al. 2000). Other studies refer to similar concepts as morphological heterogeneity, described as variation in gradient, presence of boulders, pools, and log jams (Benda et al. 2004); habitat complexity, described as large wood and boulders (Harvey et al.1999; Jackson and Sturm 2002); and habitat heterogeneity, described as wood, boulders, pools (Fausch et al. 2002). Complexity can be the amount of shelter in pools at a reach scale (Kershner et al. 1997) and complexity can encompass the valley floor at a watershed scale (Benda et al. 2004). These studies use a wide variety of methods and definitions for assessing complexity, making it difficult to draw general conclusions about channel complexity.

Importance of Complexity

Stream channel complexity is important for habitat quality, habitat diversity, and community structure. Channel complexity affects the size and stability of populations of aquatic organisms by providing refugia during high flows and by providing cover against predators (Horan et al. 2000). Complexity also improves survival rates of salmonids (Schlosser 1995; Quinn and Peterson 1996), community diversity due to a range of habitat types (Sullivan et al. 1987; O'Connor 1991) and structural diversity due to the presence large wood and boulders (Benda et al. 2005). Structural complexity of riverine habitat is also closely related to macroinvertebrate species richness (Downes et al, 1998).

Material sources and process that shape in-stream complexity

The processes that help shape in-stream complexity have been the focus of many studies in the Pacific Northwest, which include decades of data. The rich body of literature addressing debris flows, other material transport processes, interactions between these processes and in-stream structure, has served as a foundation for this study.

Physical complexity in channel networks is a function of the interaction of drainage basin morphology (i.e. watershed shape, stream network structure, channel constraint, stream junctions, and rock type) with dynamic watershed disturbances such as floods, landslides, and debris flows (Nakamura et al. 2000; Benda 2004b), and chronic landscape process such as earthflows, bank failures, and tree toppling (Benda and Dunne 1997; Benda et al. 2002; May and Gresswell 2002).

Persistent sources of sediment and wood include tree toppling, bank erosion, and earth flows, which contribute to physical complexity (May and Gresswell 2002; Gurnell et al. 2002). Streamside toes of earthflows are sources of sediment, boulders, and large wood to streams (Swanson and Lienkaemper 1987; Nakamura et al. 2000). Benda et al. (2002) found that high volumes of wood in their study streams in old growth forests in the Oregon Coast Range were due primarily to bank erosion and landslides. Other studies found that tree fall without bank erosion in unconfined valley floors were a major source of large wood to streams (Swanson and Lienkaemper 1987; May and Gresswell 2002).

Once wood, boulders and sediment are transferred to the stream channel via earthflows, toppling, and bank erosion, the material can be distributed in the stream network in several ways. Sediment can move downstream slowly through fluvial erosion or in pluses in a wave-like pattern, scouring the stream bed and depositing coarse grained alluvium on the banks before dispersing (Madej and Ozaik 1996; Benda and Miller 2000; Sutherland et al. 2002). Debris flows and earthflows can create debris dams which can fail during floods, causing storm surges, which collect and distribute wood and sediment downstream in the stream network (Nakamura et al. 2000; Grunell et al. 2002).

Landslides can move hillslope material directly to the main channel or, more often, to headwater channels of a stream network. Material delivered to headwater channels can subsequently reach the main channel as debris flows (Montgomery and Sullivan 1998). Debris flows result when landslides or in-channel failures cause rapid mobilization of soil, sediment, and large wood to move down a confined channel

(Varnes1978; Iverson et al. 1997). In a recent study Reeves et al. (2003) found that landslides and debris flows in some mountainous terrain may deliver most of the large wood that interacts with the active channel. Other studies have shown stream-side sources of material to have a greater role in material supply to main channels (Benda et al. 2004d).

Headwater channels, where debris flow activity usually initiates, comprise 60% to 80% of the cumulative length of drainage networks in steep unglaciated watersheds (Shreve 1969; Stock and Dietrich 2003; Benda 2005). Sediment can accumulate for centuries in headwater channels from chronic hillslope processes or landslides before being transferred downstream by debris flows (Benda and Dunne 1997, Lancaster et al. 2001, May and Gresswell 2004). The frequency of debris flow occurrence ranges from decadal to millennial in a single tributary (May 2002, Benda et al. 2005). Stock and Dietrich (2003) found that debris flow were major agents of erosion in unglaciated, Pacific Coast sandstone terrain. Everest and Meehan (1981) found that debris flows are important sources of large wood, boulders and sediment in steep terrain. Debris flows can also become part of a "disturbance cascade" in which material is transported from hillslopes as debris slides, then through headwater channels as debris flows, and finally to higher order channels, where the material can continue to flow down the stream channel as part of a flood surge (Nakamura et al. 2000). Recognition of this "cascade" of events aids the interpretation of the investigated patterns of large wood, boulders and complexity.

The volume and frequency of debris flows can be increased by specific management activities. Road-cuts and clear-cuts were found to increase debris flow activity in unstable areas in the HJ Andrews Forest in the Oregon Cascades relative to forested areas (Swanson and Dyrness 1975). Snyder (2000) found that debris flows were initiated from clearcuts 3-7 times more frequently than from forested areas, and road-associated debris flows occurred 11-50 times more frequently than those in forested areas in the HJ Andrews Forest in the Oregon Cascades. Wemple et al. (2001) noted that roads influence debris flow behavior in a series of events: roads concentrate runoff from inside ditches and deliver it to culverts, which in turn concentrates storm flow on road fill-slopes. Road fill-slopes may also fail and become landslides and then enter a confined channel finally becoming a debris flow (Wemple et al 2001). Therefore, each watershed is expected to have patterns of complexity that reflect the interaction of debris flow activity and management history.

Channel networks are hierarchical, branching systems, which concentrate stream flow, wood, and sediment movement along downstream gravitational flow pathways. Benda et al. (2004b) argue that this material can accumulate at stream junctions. Other studies have also found that sediment, wood, and boulders can accumulate in stream junctions at the intersection of low-order and higher-order streams (Swanson et al. 1987, Benda et al. 2005). Strahler (1964) and May (2002) found that in mountainous terrain, debris flows are a primary mechanism of material transport, from first and second order channels to fish-bearing streams. The volume and the runout length of the debris flows affect whether they reach a junction with a larger stream and, if they do, the amount of material input into the stream (Swanson et al. 1987, Benda and Cundy 1990, Benda et al. 2005). Several features of stream-junction environments exert a major influence on runout length and deposition of debris flows including: abrupt decrease in gradient, increased valley width, and potential for abrupt change in channel direction (Swanson et al. 1987, Benda and Cundy 1990, Benda et al. 2005). Similarly, alluvial fans at stream junctions can also lead to debris flow deposition due to decreased slope, increased width, and increased infiltration capacity of the bed material (Swanson et al. 1987).

In contrast, it is also thought that debris flows stop primarily because of coarse-grained flow fronts and margins, or snouts, that are sufficient to halt motion (Iverson 2003) and not particular network-level controls (e.g. intersection angles at stream junctions). In this model the constituent properties of debris flows at their snouts, determine the location of deposition, rather than network controls like junction angle or valley width. Incorporating a large wood component in to the equation can help reconcile the constituent property model and network-level control model. Lancaster et al. (2001) observed that debris flows with flow fronts that include large wood, may lose velocity at turns or stop in a collision with valley walls in contrast to debris flows without wood which move fluidly through bends with little loss of velocity. Consequently, debris flows may terminate at stream junctions or bends in the stream due to the constituents in the flow and network-level controls.

Watershed shape is a measure of the arrangement of proportionally small and large tributaries, which play a role in the size of debris flow volume. Large tributaries have the capacity to deliver greater volumes of material than small tributaries, and as a consequence stream junctions with larger contributing areas are expected to have larger debris flow volumes (Benda et al. 2004b). With increasing contributing area of the main channel, more debris flow volume will be required to influence patterns of complexity

(Benda et al. 2004b). Consequently, watershed shapes that support larger tributary formation should have higher complexity related to the stream junctions of larger tributaries (Benda et al 2004c). Watersheds with heart shapes or pear-shape drainage basins may include larger tributaries, while trellis or rectangular watersheds do not (Benda et al. 2004). Therefore, stream junctions with proportionally larger contributing areas are expected to have higher complexity.

The morphology of the valley floor affects the deposition locations of wood and sediment originating from hillslope and streamside sources. Material can be transferred to deposition sites through debris flows, sediment waves, flood peaks and flood surges. A flood surge occurs when water confined behind a barrier is suddenly released (Pritchard 2005). Constrained reaches may result in the creation of low-gradient, wide valley floors upstream (Swanson and James 1975; Swanson et al. 1985), where sediment and wood can be deposited. Channel constraint strongly influences channel response to floods and disturbance; large boulders rarely move but fine material may be entirely evacuated from constrained reaches (Montgomery 1998). Constrained reaches provide opportunities for accumulations of wood that can build mid-channel jams (Naiman 2002). Large wood and sediment that enter the main channel can be transported down-stream and be deposited in scattered levees along the channel or terminate in a debris jam (Nakamura et al. 2000). Constrained reaches force deposited material to interact with the active channel. Debris flow material that enters a higher-order channel can aggregate extensively in confined segments (Gomi et al. 2002) through deposition up stream from the confined point (Swanson et al. 1985) or by lodging long wood pieces against the valley walls. Therefore, constrained segments are expected to support higher complexity values in the stream network.

Watershed shape influences the hydrologic response to storm events: a circular watershed would be expected to result in runoff from various parts of the watershed reaching the outlet at the same time, causing a shorter time to concentration than in an elongated watershed. An elliptical watershed having the same area as the circular watershed would cause the runoff to be desynchronized, thus producing a smaller flood peak and longer time to concentration than that of the circular watershed (Figure 1) (Gordon 1992). The ability to entrain and transport material increases exponentially with discharge, so higher flood peaks transport more material from debris flows (O'Connor 2003). Therefore, circular watersheds are expected to have higher values of complexity, especially in the lower reaches of the main channel, compared to rectangular or trellis shaped watersheds.

The fate of debris flow material delivered to stream junctions is dependent on the valley floor configuration, the gradient of the main channel and position of the debris flow material relative to the main channel. Debris flow material delivered to stream junctions can either remain in place, be transported down the stream network, or both. Rock type and tectonic uplift rate influence the channel gradient, which in turn affect the energy environment in the stream (Hicks 2003). Less erosive rock types, such as basalt, and areas with relatively high uplift rates may have steeper channel gradient than areas with more erodible rock and lower uplift rates (Personius, 1995, Van Laningham 2003). The gradient has a major influence on the distance debris flows travel (Stock and Dietrich 2003). Therefore, debris flows are expected to move greater distances in watersheds with harder rock types and higher uplift rates.

Benda et al. (2004b) suggests that watershed shape, size and the configuration of stream networks can influence the distrubution of physical diversity in channel characterisitcs. The interaction between channel network structure and the local disturbance regime is cumaltively termed by Benda et al. (2004b) as the Network Dynamics Hypothesis. Several of the hypotheses discussed in the Network Dynamics Hypothesis are tested in relation to the metric of complexity developed for this study in conjunction with paramenters derived from Digital Elevation Model (DEM) analysis. These include the effect of tributary size on complexity at tributary junctions, the effect of stream junction angle on complexity, and the relation between watershed shape and complexity distribution in the stream network. A Geographic Information System (GIS) data-set was used to investigate the relation between complexity and contributing area, channel width and debris flow potential.

The general questions were: did stream junctions influence the complexity values in the main channel? If so, was there a correlation between larger contributing area of tributaries and higher complexity, as proposed in the NDH? Was there a relation between constrained segments and higher complexity? Did debris flow behavior differ in different geological and tectonic settings? The research consisted of three elements: field data collection, comparison of the field dataset and a digital dataset, and statistical analysis of the resulting data sets. The primary goal of the study was to investigate patterns of boulder deposits, large wood, pools and complexity, (a combination of wood, boulders, stream gradient and deep pools) in relation to the constrained reaches, stream junctions and debris flow influences; referred to collectively as network-level controls. Another goal was to determine if several of the hypotheses described in the Network Dynamics Hypothesis were evident in the complexity metric and linked to network-level controls measured in the study area.

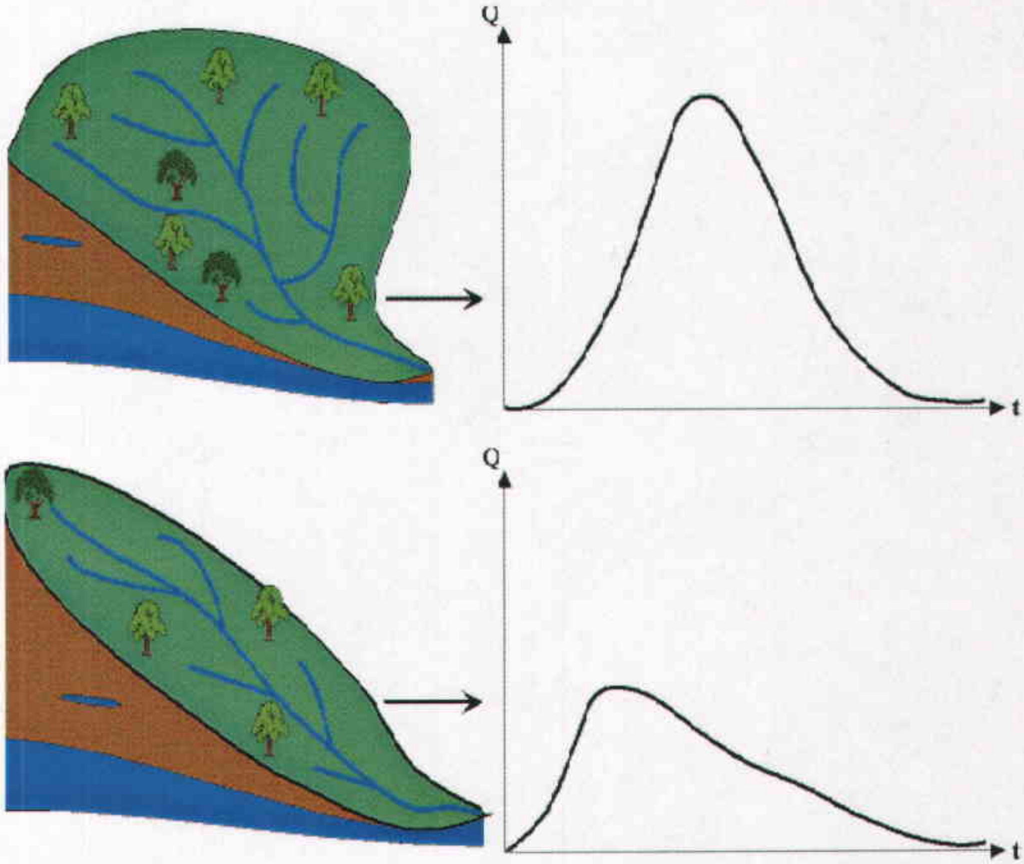

Figure 1: Watershed shape, effect on time to concentration and relative tributary size (after Musy 2001).

Methods

The study sites

The three watersheds are in the Oregon Coast Range, which has a maritime climate, characterized by wet, warm winters and dry summers. Normal annual precipitation in the Oregon Coast Range ranges from 1,650 mm to 2,230 mm, falling mostly as winter rain (Taylor 1997). Snowfall is minimal, with the majority of the area receiving only a few inches each winter. However, at higher elevations there can be a significant amount of snowfall, which can significantly influence floods and debris flows during rain on snow events (Taylor 1997).

The three sites were surveyed after the 1996 major storm event by the Oregon Department of Forestry (Robison et al. 1999) to ascertain the amount and extent of debris flows resulting from the storm. They were originally selected based on the high rate of geomorphic activity relative to the coast range as a whole. Rogers and Elk Creeks were completely surveyed in the 1999 ODF study, while only the upper half of Turner Creek was surveyed due to that surveys sample design. However, there was no evidence of recent (less than 10 year old) debris flows reaching the main channel in the lower half of Turner Creek during the current study.

Rogers Creek

The 27 km^2 Rogers Creek watershed is in the Tillamook State Forest located in the northern portion of the Oregon Coast Range (Figures 2 and 3). A stream survey was conducted along 4.8 km of stream in Rogers Creek, and 8 debris flow deposits (also surveyed by Robinson et al. 1999) were investigated. There are 804 m of relief from the mouth of the watershed to the highest point. The watershed is underlain by basalt, tuff, and breccia (Robison et al. 1999). Hillsides generally have 60% to 100% slopes and soils are 0.3 to 2 m in depth, with the deepest soils in valley bottoms and in landslide deposits (Table 2) (Robison et al. 1999).

The entire Rogers Creek watershed was burnt in the Tillamook fire of 1933 and the Wilson River fire in 1945 and replanted between 1959 and 1962 (Mortensen 2005). There has been a small amount, 160 hectares, of commercial thinning in the watershed. No new roads were built after the 1950's, however road repair and maintenance was conducted after the 1996 storm season (Mortensen 2005).

Dense Douglas fir (*Pseudotsuga menziesii*) stands dominate the Rogers drainage, which was part of the Tillamook burns in the 1930s (Spies 2002). Red alder (*Alnus rubra*) is the dominant riparian vegetation while swordfern (*Polystichum munitum*), salal (*Gaultheria shallon*) and huckleberry (*Vaccinium parvifolium*) make up the majority of the understory vegetation.

Turner Creek

The 12.5 km^2 Turner Creek watershed is in the south central Oregon Coast Range, in the Veneta District of the Oregon Department of Forestry (ODF) located west of Eugene (Figures 2, 4). A stream survey was conducted along 4.2 km of stream in Turner Creek and 5 debris flows deposits (also measured Robison et al. 1999) were relocated and investigated.

There are 335 m of relief from the mouth of the watershed to the head of the drainage. The bedrock is gently dipping, usually under 10 degrees, and joints are typically widely spaced (Baldwin 1964). The soils are shallow, sandy gravels.

Hillslopes gradients are generally over 65% and in some cases exceed 100% (Table 2) (Robison et al. 1999). Forest management over the last 50 years has included clearcuts, valley bottom and upslope roads, and the addition of a paved road to part of the valley bottom. Clearcuts continue to be the dominant forest harvest method (McCoy 2005).

Elk Creek

Elk Creek is a 16.8 km^2 watershed in the Elliot State Forest, located in the southwestern portion of the Oregon Coast Range (Figure 2, 5). A stream survey was conducted along 5.8 km of stream in Elk Creek and 6-debris flow deposits measured in the 1996 ODF survey were relocated and investigated (Figure 5). There are 410 m of relief from the mouth of the watershed to the drainage head. Elk Creek watershed is underlain by thick sequence of sandstone beds with siltstone interbeds. The bedrock is gently dipping, usually under 10 degrees, and joints are typically widely spaced (Baldwin 1964). The soils are shallow, sandy gravels; hillslopes gradients are generally over 55% and in some cases exceed 100% (Table 2) (Robison et al. 1999). Forest management in Elk Creek has included clearcuts, valley bottom and upslope roads, and a well maintained and well used, rocked, valley bottom road. Clearcuts continue to be the dominant forest harvest method (McCoy 2005).

Vegetation in Turner and Elk Creeks

The overstory vegetation in the Turner and the Elk Creeks drainages is dominated by dense Douglas fir (*Pseudotsuga menziesii*) and Western hemlock (*Tsuga heterophylla*) forests (Franklin and Dyrness 1973). Red alder (*Alnus rubra*) is the dominant riparian vegetation and is also found in recently disturbed areas. The riparian understory is dominated by salmonberry (*Rubus spectabilis*) in the riparian areas while swordfern (*Polystichum munitum*), salal (*Gaultheria shallon*), and huckleberry (*Vaccinium parvifolium*) make up the majority of the upslope understory vegetation (May 2002).

Network-level controls and complexity

Network-level controls in this study are limited to constrained segments, stream junction segments, and recent debris flow segments. A constrained segment is defined as any 60 m segment that has at least one point at which the valley width is less than 15 m, measured from the top of the bankfull channel to the base of the valley wall (Figure 6). The fixed, 15 meter width used to identify constrained points was selected based on the valley floor widths observed in coast range streams and the size of large wood found in the sample areas. The 15 m width was a simple measurement that was straightforward to repeat and was used because this length is shorter than many of the key wood pieces in log jams and debris deposits. This absolute measure resulted in 15% to 27% of stream segments being rated constrained in the watersheds. A relative measure of valley constraint could have been used, such as one based on a set proportion valley floor width divided by the active channel width (Grant and Swanson 1995), however due to the similarity in active channel widths the absolute measure was selected. The sample segments were located in 4^{th} through 6^{th} order streams with valley widths ranging from over 100 m to less than 10 m. A "recent debris flow" segment is defined as any 60 m segment that includes at least one debris flow from a tributary within the past 10 years. A fixed 60-meter survey segment length was selected to facilitate comparison between complexity values while capturing channel variation.

Each complexity value was calculated from the same length of stream so each segment can be identified as more or less complex.

The data used in the study were collected from January through April of 2005, from three forested Oregon Coast Range drainage basins, all managed by the Oregon Department of Forestry: Elk Creek, near Scottsburg OR; Turner Creek, near Mapleton OR; Rogers Creek, near Lees Camp OR (Figure 2). The drainage basins selected represent a range of debris flow regimes and network structures. Rogers Creek is underlain by basalt, has a heart shaped drainage basin and experienced debris flows with long runout lengths compared to the other sample watersheds, on average of 181 m in length in the 1996 storm event (Tables 1, 2) (Robison et al. 1999). Turner Creek is underlain by Tyee sandstone, has a pear shaped drainage basin and experienced debris flows with short runout lengths compared to Rogers Creek, on average 73 m in length in the 1996 storm event (Tables 1, 2) (Robison et al. 1999). Elk Creek is underlain by Tyee sandstone, has a trellis shaped drainage basin and experienced debris flows with short runout lengths compared to Rogers Creek, on average 75 m in length in the 1996 storm event (Tables 1,2). Benda (2004; 2005) uses the drainage basin shapes, heart, pear and trellis, to convey a sense of the drainage network structure. All three sites have a history of high occurrences of debris flows in the Oregon Coast Range (Robison et al. 1999).

Data for this study were collected on large wood, boulders, pools, and valley floor characteristics in the winter of 2005. Debris flow deposits, broken into categories of recent (less than 10 years) and old, were investigated. The complete set of recent debris flow deposits was documented in a study of 1996 floods (Robison et al. 1999).

Comparisons and analyses were conducted on two spatial scales: within-watershed and between-watersheds. Analysis and comparisons were based upon data from field work, previous studies and GIS analysis.

Measures of wood, sediment, boulders, active valley floor parameters and network structure, were obtained in the field. A GIS was used to summarize watershed variables including: watershed area and relief and main channel length using descriptive statistics. Wood, boulders, pools, slope change, and the index of complexity were then grouped with network-level controls (stream junctions, constrained valley floor segments and debris flow termini mapped from the 1996 survey) to test the effects of the network structure on the patterns in the valley floor.

Sampling framework

During the winter of 2005, data were collected at Rogers, Turner and Elk Creeks. Field work included surveys of characteristics of the channel and channel margin including: large wood, boulders, finer sediments, network structure, and debris jams. In each study watershed, a continuous survey and a stratified random survey were completed to cover a maximum amount of variation in contributing area and determine the scale at which a pattern was discernable. The continuous survey consisted of surveying a least 1 km of stream by collecting observations in 60 m segments. The stratified survey segments were grouped into clusters of five, 60-meter study segments and distributed through the main channel. There were 8 clusters in Rogers and Turner Creeks and 9 in Elk Creek. The cumulative length of 300 m, i.e. 5 segments, was based on average distance between tributaries in the three study watersheds and selected to include at least one stream junction per cluster. The location of the continuous survey was selected to capture the highest quantity of recent geomorphic activity (Figures 2, 3, 4). The stratified-random design was chosen to detect spatial patterns in a variety of locations in the watershed with different contributing areas. The main channel was divided into 0.5-km segments and the sample segments were randomly located within the segments. In narrow, steep headwater stream segments, the sample segment length was decreased to 20 m due to the scale of the features and restrictions on visibility by vegetation. The 20 meter segments were reduced during data analysis to the standard 60 m segment length to allow for inter- and intra-site comparison. Field variables were either measured at the end point of the sample segment or aggregated over the entire segment (Table 3).

Study segment level variables

In each 60 m segment, variables were measured either over the entire segment or at its end. The following variables were tallied over the length of each study segment: boulders ≥ 1 m; large wood pieces with a diameter greater than 25 cm and length greater than 2 m that were at least partially in the channel; the presence or absence of bedrock and the proportion; constrained segments; percent bedrock on the channel bottom; stream junctions; the number of pools and their size class (small, less than half the channel width and less than 0.5 m deep or large, greater than half the channel width and < 0.5 m deep); the current status of debris flow deposits from the 1996 storm survey (Table 3). The debris flow deposits were recorded as persistent, partially dispersed or dispersed, based on the volume recorder in the Robinson et al. (1996). Field variables measured at the terminus of each 60 m segment include the percent slope (measured with a clinometer), the channel width at bankfull, and the channel depth at bankfull stage. Riparian vegetation was age-dated in at least five locations in each watershed in the study segments using an increment borer. This process also helped to age date debris flow deposit material and large wood and boulders in the channel. The age for the debris flow material and wood and boulders was estimated for each segment based on woody vegetation age.

Data analysis

Channel segments were binned by three categorical variables: "stream junction" or "non-stream junction"; "constrained" or "unconstrained"; and "debris flow" or "non-debris flow" terminus (Table 4). This designation was accomplished using field observations and previous studies. The majority of stream junctions in the study area have a history of functioning as outlet points for debris flows. The distinction between "recent debris flows" and "stream junctions" in this study area was set at 10 years. Locations of recent debris flow deposits in and near the study segments were obtained from the ODF 1996 debris flow survey (Robison et al. 1999) and investigated during the field survey. Study segments were assigned debris flow/ stream junction designation if they were within 60 m of a debris flow deposit or stream junction. The classification was used to determine the quantity of boulders, logs, pools or changes in slope that were significantly associated with either a stream junction, debris flow terminus or constrained segment. These attributes were combined to produce a measure of channel complexity, which was used to test for relationships with the stream junction, debris flow and constrained network-level control groupings.

A metric of in-channel physical complexity was developed based on pool density, slope change, large wood and boulder abundance. Since the absolute value ranges for each variable were non-uniform a Z-score was calculated for each variable (Weiss 1982). A Z-score is used to ensure that each variable is weighted equally. To calculate a Z-score the average of the population is subtracted from each value of the variable and the product is then divided by the standard deviation of the population, $((Z - \mu) / \sigma)$, where Z is the raw data point, μ is the mean for the population and σ is the standard deviation for the population. This produces a Z-score range that encompasses a value of zero. To assist in interpretation, the lower limit of each Z-score category was set to zero, $((Z - \mu) / \sigma) + X)$, where X is the value that sets the lower limit of the Z-score to zero. The Z-scores for each variable were added to create an index of complexity. Complexity is defined here as the incidence of non-uniform material distribution including boulders, large wood, as well as pool abundance and shifts in stream gradient over 60 m segments. Study segments with greater numbers of pools, boulders, large wood, slope change and combinations of these variables will have correspondingly higher complexity. Channel segments and their corresponding complexity index were ordered using binary network-level controls according to (1) proximity to stream junctions – within 60 m, (2) proximity to debris flow terminus - within 60 m and channel constraint – based on a valley width at one point in the segment less than 15 m; in order to determine how the network-level controls influenced complexity. Analysis of variance (ANOVA) was used to test for differences among groups of independent variables; stream junction, debris flow terminus and constrained segments and their related complexity indexes.

Hot spots and segment length influence

In order to identify and quantify large clusters of wood, boulders, pools, slope change, and complexity in the study watersheds, occurrences of variables equal to or greater than one standard deviation above the mean were identified. These locations were designated “hot spots”. Hot spots are defined as the largest accumulations of wood, boulders, pools, and complexity, and the largest changes in slope in each watershed and include the highest 16% of the data points. The numbers of hot spots that occurred at stream junctions, constrained segments, and debris flows was calculated. A Chi-squared test was used to test for significant association between the network-level controls and hot spot location.

To determine whether the network level control in selected stream segment also influenced the segment located downstream, the two segments were joined together and a new segment 120 m long was obtained. Segments immediately down stream of a stream junction, constrained segments and recent debris flow segments were each assigned to the respective upstream network level control designation. Analysis of variance was used to test for differences among the new groups of independent variables.

Between watershed analysis

Populations of channel segments were divided into subpopulations based on their designation as a stream junction, constrained segment or debris flow deposit segment. The subpopulations were tested using ANOVA to determine if similarly coded channel segments differed between watersheds.

GIS analysis

Several GIS data layers were developed using ESRI's ARCGIS 9.0. These included: roads, watershed boundaries, stream junction points, debris flow information, and georeferenced data points for each study segment. Shape files were developed for the locations of the study segments using a combination of network tools, GPS coordinates and field records, including locations of bridges and tributaries. Shape files for the watershed boundary and stream network were also created using Archydro and Arcedit tools. Preexisting shape files were downloaded from the Oregon geospatial data clearing house (GEO 2005) including roads and ownership layers. A set of network and node variables was created using Programs for DEM analysis, developed by Dan Miller and the CLAMS group (Miller, 2002), and were used to compare the DEM data to the field data comparisons. The network variables derived from the Programs for DEM Analysis were: slope change, tributary-to-main channel-area ratio, junction angle and debris flow potential variable. The debris flow potential value was based on estimating probability of the upslope susceptibility to debris-flow triggering landslides and the probability that a debris flow initiated up-slope would travel to the channel reach (Miller 2002).

All the DEM-derived variables were tested against the complexity index in individual regressions analyses. The linear regression was carried out between each of the DEM derived variables (width, contributing area, gradient and debris flow potential, junction angle, tributary-to-main channel-area ratio) and the index values for complexity for each watershed. DEM valley width was tested as a function of field measured valley width.

The study segments and DEM-derived data points and line segments were georectified by referencing field notes for locations of constraining features whose locations were known. These features were: road junctions, stream crossings, bridges, bends, and stream junctions. In the attribute tables of each layer, columns with unique identifier fields were added and attributed in order to be able to join rows of data between different layers.

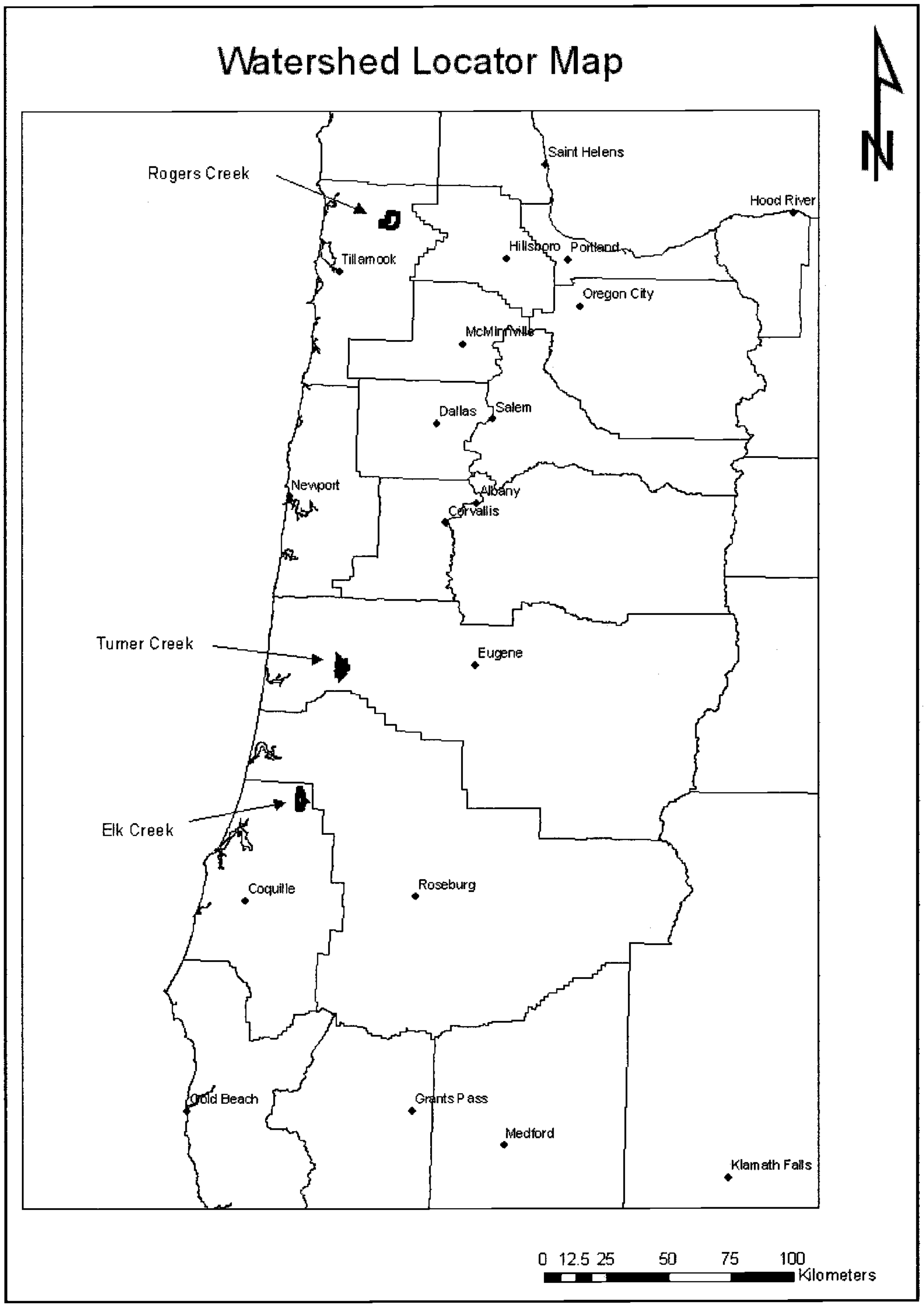

Figure 2: Site locations of Rogers, Turner and Elk Creeks in the Oregon Coast Range

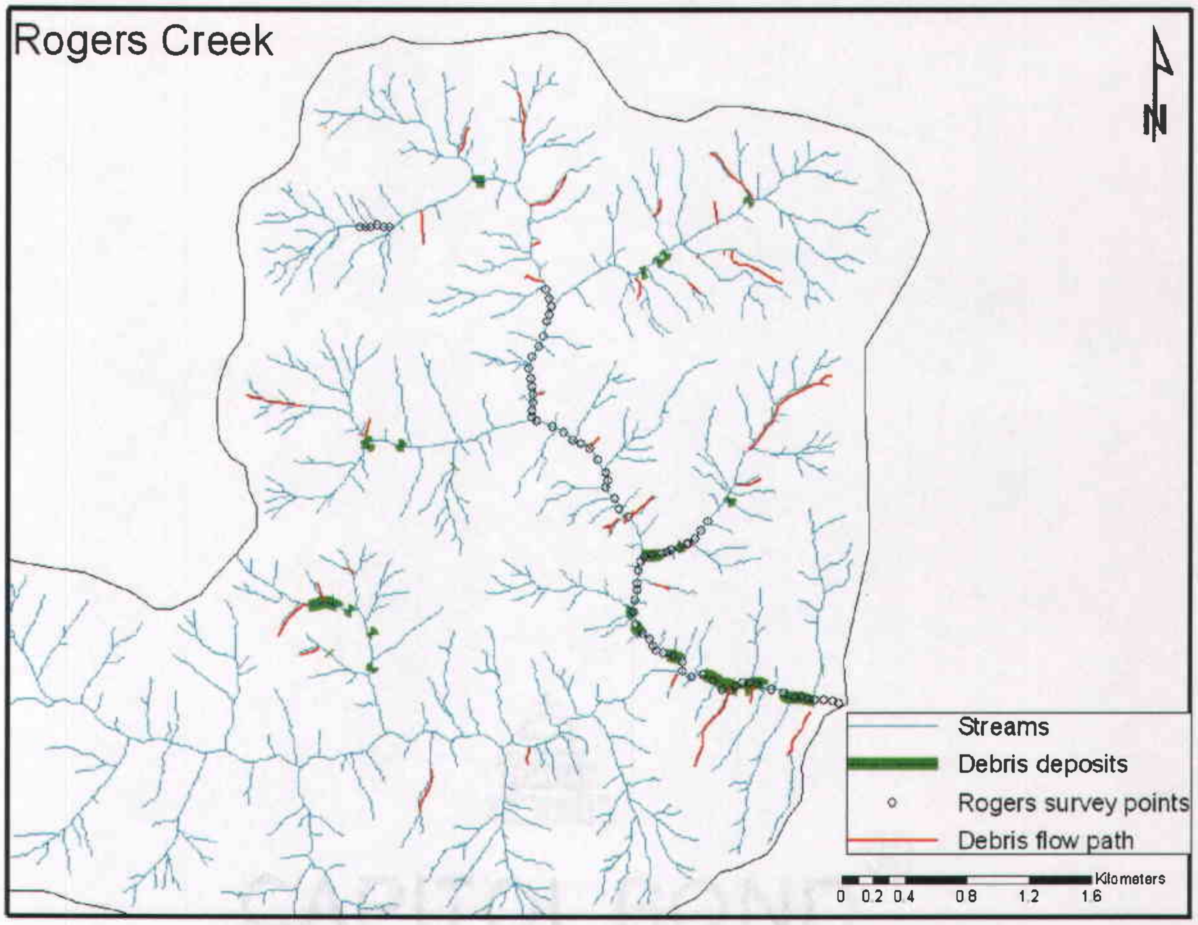

Figure 3: Study segment locations in Rogers Creek watershed. These include 60 segments 60 m long and 26 segments 20 m long surveyed in the winter of 2005. After degrading the 20 meter segments there were a total of seventy seven, 60 meter segments. A continuous 2700 meter section was surveyed consisting of sixth, fifth and fourth order stream segments and the remainder of the watershed was sampled as stratified random groups

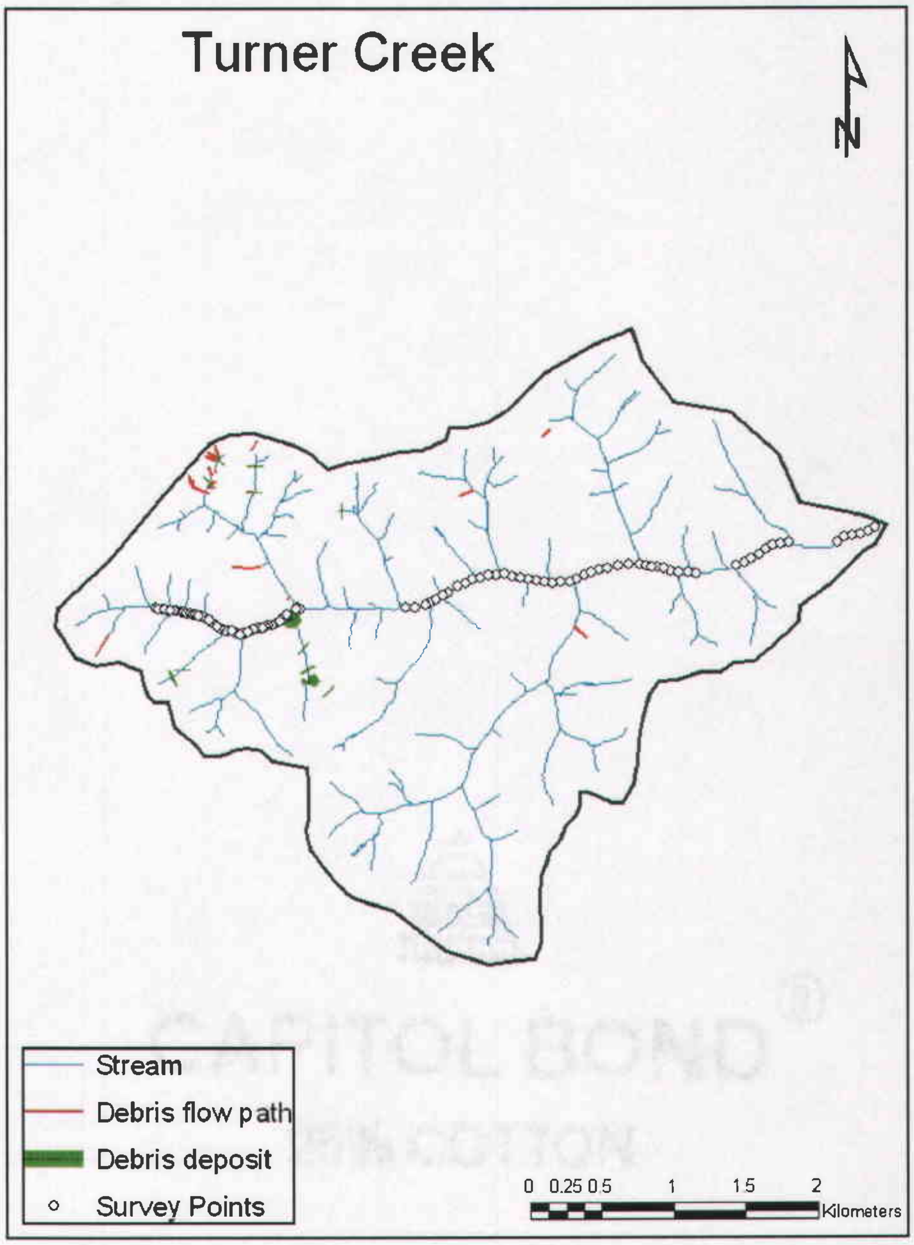

Figure 4: Study segments in Turner Creek watershed. These include 49 segments 60 m long and 52 segments 20 m long surveyed in the spring of 2005. After the 20 meter segments were degraded there were seventy, 60 meter segments. The upper 1000 meter section was surveyed as a continuous segment and the remainder of the watershed was sampled as stratified random groups.

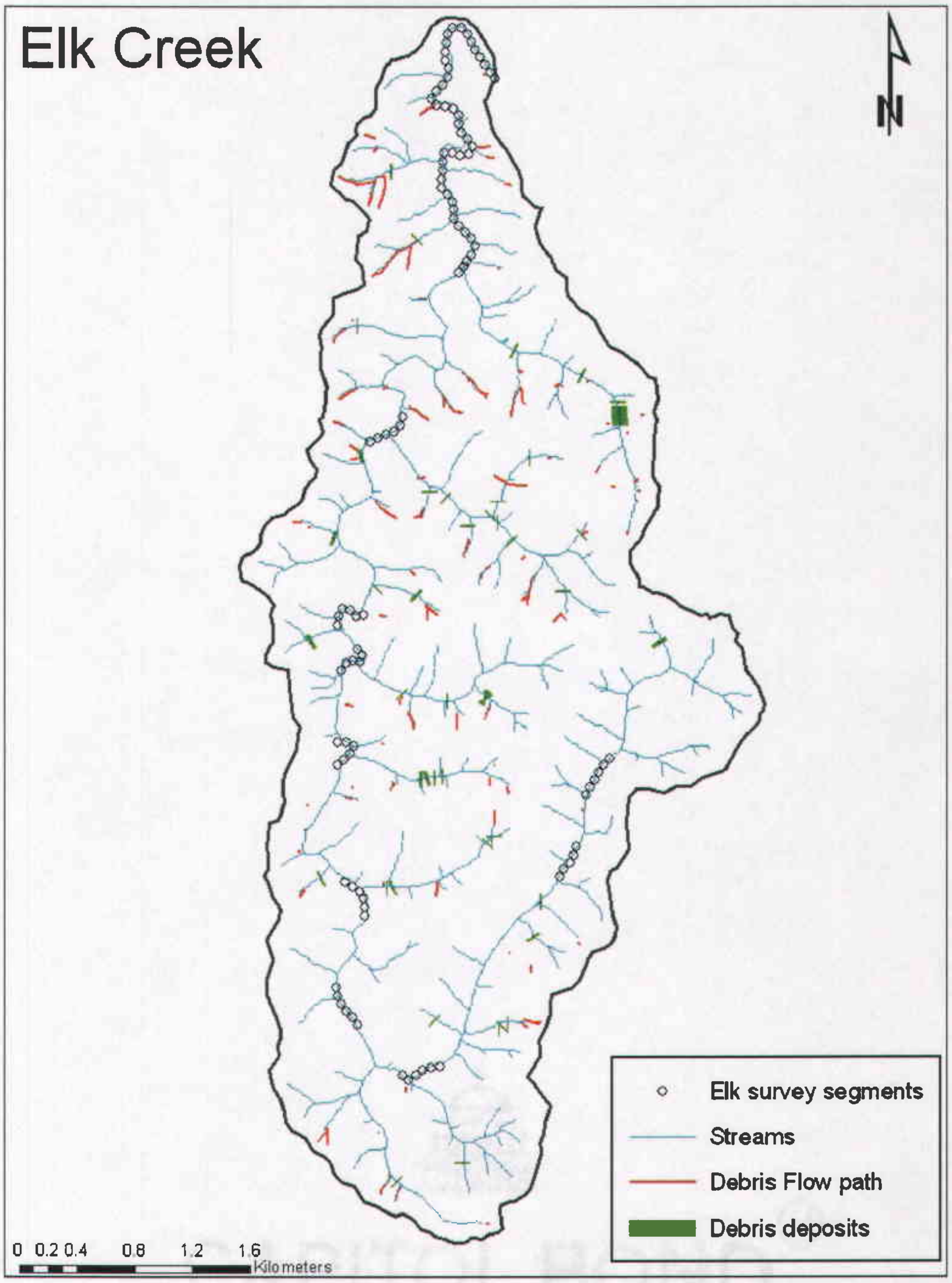

Figure 5: Elk Creek survey locations and watershed. These include 98 segments 60 m long surveyed in the spring of 2005. The lower 2400 meter section was surveyed as a continuous reach meanwhile the remainder of the watershed was sampled as stratified random groups.

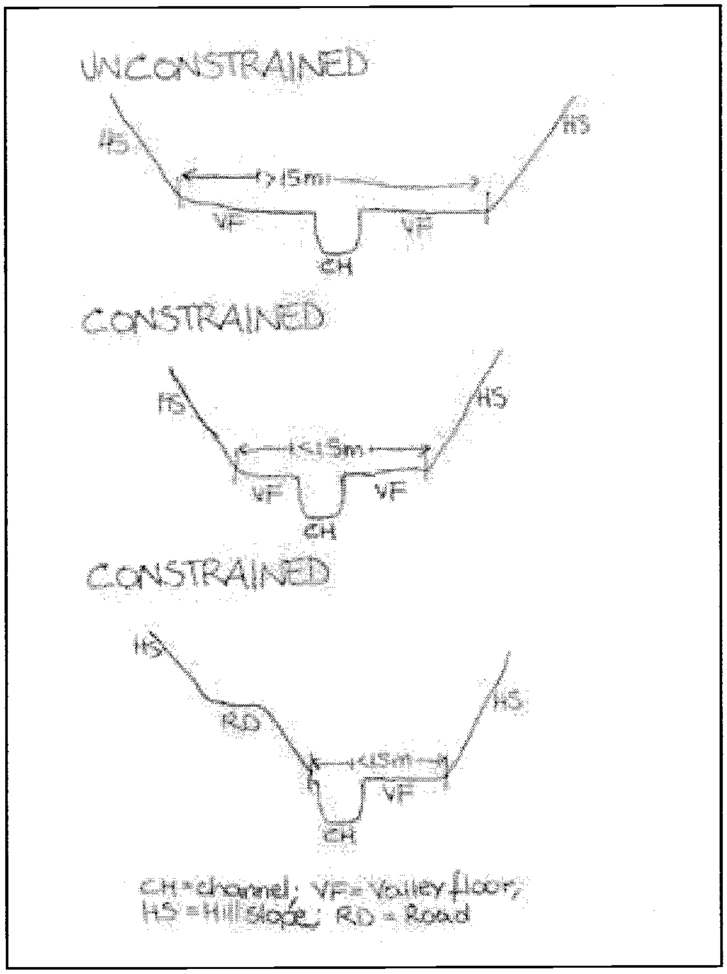

Figure 6: Constrained valley floor measurement examples from the field.

Table 1: Watershed statistics. Watershed shape, disturbance regime recent geomorphic activity, area, length of main stem and elongation ratio, average debris flow volume, average debris flow length, and uplift rates. Watershed shape from Benda et al. (2004). Debris flow information from Robison et al. (1999). Uplift rates from Personius (1995).

	Rogers Creek	Turner Creek	Elk Creek
Watersheds structure	Heart shaped	Pear shaped	Trellis shaped
Disturbance regime	Large debris flows	Small debris flows	Small debris flows
Number of debris flow < 10 years	64	19	112
Area km^2	26.6	12.5	16.8
Length of main channel m	6.98	6.0	14.5
Elongation ratio (dimensionless)	5.0	2.7	1.5
Mean Debris flow volume from 1999 storm survey m^3	519	145	250
Average debris flow length m	181	73	75
Average uplift rate mm/yr	0.6	0.2	0.2

Table 2: Physiography of Rogers, Turner and Elk Creek - Adapted from Robison, 1996

Physiography	Elk Creek	Turner Creek	Roger's Creek
Georegion	Coast Range	Coast Range	Coast Range
Geologic Map Units	Tyee Formation	Tyee Formation Mafic Intrusion	Subaerial flow basalt, tuff & breccia; Submarine flow basalt, tuff and breccia; Subaerial flow basalt; Landslide deposit
Lithologies	Thick sequence of 5-80 foot sandstone beds w/0.1 to 5 ft. thick siltstone interbeds. Gently dipping (usually under 10 degrees). Joints are typically widely spaced	Thick sequence of 5-80 foot sandstone beds w/0.1 to 5 ft. thick siltstone interbeds. Gently dipping (usually under 10 degrees). Joints are typically widely spaced	Commonly 10 to 30 ft. flows; highly sheared; often deeply weathered
Landform	Slopes are highly to extremely highly dissected, especially near ridgetops	Slopes are highly to extremely highly dissected, especially near ridgetops	Long slopes, slightly to moderately dissected, often irregular
Slope Steepness	Except near larger streams, most hillslopes exceed 55%, & some slopes are over 100%	Except near larger streams, most hillslopes exceed 65%, & some slopes are over 100%	Generally 60 to 100%
Soils	Shallow, sandy gravels with low plasticity in colluvial depressions, valley stage features, & in alluvial deposits around larger streams	Shallow, sandy gravels with low plasticity in colluvial depressions, valley stage features, & in alluvial deposits around larger streams	Less than 1 to 5 ft. in thickness, low plasticity, deeper in valley stage & landslide deposits
Channel Network	Dense dendritic	Dense dendritic	l dendritic, very steep

Table 3: Segment level variables – Every occurrence tallied over total segment or measured at the terminus

Field Measurement Variable	Units	End / Total
Location of tributaries – i.e., tributary junctions	Presence or absence, #	Total
Channel gradient	Percent slope	End
Channel width at bank full flow	m	End
Valley width – the width occupied by <=3 m high terraces;	m	End
Boulders	≥1 m diameter, #	Total
Large wood (LW), and origin	≥ 25cm diameter & ≥ 2 m in length	Total
The depth of incision from bankfull to thalweg.	m	End
Pools, broken into two size classes	> 0.5 m depth; > ½ channel width = large; < 0.5 depth; < ½ channel width = small	Total
Fate of debris flow deposit	Persistent, partially dispersed, dispersed	Total

Table 4: The number of segments by watershed and grouping variable

	Rogers Creek	Turner Creek	Elk Creek
Non-Stream J	46	43	75
Stream J	30	27	24
Non Constrained	54	55	62
Constrained	22	15	37
no Debris Flow	56	69	90
Debris Flow	20	1	9

Results

General patterns of large wood, boulders, and complexity were evident in each watershed; some patterns were unique to each basin while others were common among basins. Stream junctions, debris flows and constrained segments were related to patterns of complexity and channel characteristics in different ways in each watershed. Elk and Turner Creeks are underlain by Tyee sandstone and patterns of complexity strongly influenced by stream junctions, while patterns of complexity in Rogers Creek, underlain by Basalt, were correlated with constrained segments. Patterns of complexity were more closely related to recent debris flows in Rogers Creek than in Elk Creek, and not related in Turner Creek. The DEM-derived parameters (width, contributing area, gradient and debris flow potential) were moderately correlated with measures of in-stream complexity. Segments where debris flows occurred during the 1996 storm had, on average, lower counts of wood, sediment, and complexity.

Summary statistics

A total of 15.8 km of channel length, composed of two hundred and forty seven, 60 m segments were inventoried. Thousands of logs and boulders were tallied, along with valley and channel metrics including pools and changes in slope. On average, every 60 m of channel had 4.5 boulders, 4 pieces of large wood and 1.1 pools (Table 5). The highest average counts for complexity, large wood, and boulders were found in Rogers Creek (Table 5). The longitudinal profiles in Elk and Turner Creeks were similar while Rogers Creek had a steeper profile (Figure 7).

The geometry of the watersheds influences the dispersal and time to concentration of flows in streams. A useful way to define the geometry of a watershed is to use the elongation ratio (Re), Re= Dc/L, where Dc is the diameter of a circle with the same area as the basin and L is the maximum length of the basin along the main channel (Gordon 1992). The elongation ratios obtained for the watersheds were 1.5 for Elk Creek, 2.7 for Turner and 5.0 in Rogers (Table 1).

Descriptive results from sample watersheds

Major differences in riparian vegetation between the watersheds provide evidence for different disturbance dynamics. In both Turner and Elk Creeks mature red alder (*Alnus rubra*) grew on the margins of the channel. The alders sampled in Turner Creek had a narrow range of ages, from 32 to 39 and had little to no scarring of the lower boles by recent floods. Alders sampled in Elk Creek had a wider range of ages, 25 to 45, and scarring found on the boles of the alders on the stream-side indicated flood damage within the previous decade (Sigafoos 1964; Yanosky and Jarrett 2002). Scarred boles were noted in the lower reaches of the Elk Creek. The vegetation in the valley floor of Rogers Creek varied from 6 to 52 years old, including over a kilometer of valley floor compromised of a 6 to 9 year old cohort of red alder. Mature alder on the margins of the active valley floor showed evidence of multiple scarring events on the stream-side boles.

Debris flow deposits, large wood and boulders ages were bracketed using the age of woody vegetation as indicators of residence time. Using this method the majority of evident debris flow fans in Elk and Turner Creek were aged at greater than 25 years. In Elk Creek, about half of the large wood pieces and boulders in Elk Creek's evident debris flow fans in Elk and Turner Creek were aged at greater than 25 years. In Elk Creek, about half of the large wood pieces and boulders in Elk Creek's main channel were dated to be over 10 years old. In Turner Creek, only three quarters of the wood and boulders were dated to be over 10 years old. Rogers Creek had a wide range of ages of wood, boulders, and debris flow fans; about a quarter of the debris flow deposition fans were younger than a decade in this watershed.

The percent bedrock channel bottom in each study segment was also recorded. There was an obvious pattern of bedrock position in the watershed in each of the drainage basins. Bedrock channel bottoms dominate Elk and Turner Creeks lowest reaches, while Rogers Creek had exposed bedrock only in the highest study segments. From the mouth of Elk Creek, the first kilometer of stream bed was over 50% bedrock. That percentage dwindled to zero by the end of the second kilometer of stream. Beginning at the mouth of Turner Creek, the lower-most 500 m were over 50% bedrock and by 800 m bedrock was quite uncommon. In Rogers Creek only the uppermost 200 m, the furthest and steepest survey segments, had exposed bedrock. This was in large part to the different erosive properties of the geology in the watersheds. The sandstone found in Elk and Turner Creeks break down to gravel sand sized particles quickly and are mobilized by normal flows while in Rogers Creek the basalt bedrock resists erosion and was found to be cobble and stone sized particles in the main channel.

Uplift rates for the study areas are based on differential incision rates in western Oregon (Personius 1995). Both Elk and Turner Creeks had an uplift rate of about 0.2 mm/yr and the Rogers area had an uplift rate of about 0.6 mm/yr.

Scatter plot interpretations

Scatter plots were used to graphically explore how wood, boulders, slope change, pool abundance and complexity varied within and between watersheds (Figures 8 – 17). The data points were coded in three categories defined by the presence or absence of a stream junction, debris flow termini and constrained segment. The field variables were plotted in pairs: pool abundance was plotted as a function of large wood pieces; boulder accumulation was plotted as a function of percent slope change; and complexity was plotted as a function of percent slope. Scatter plots were created with each of the pairs of field variables combined with the three network-level controls and all three watersheds, resulting in nine scatter graphs. The scatter diagrams with all three watersheds were next distinguished into single watersheds and plotted on a log-log scale resulting in 36 graphs. The visual analysis focused on three questions each graph was used to address: was there a relation between wood and pool numbers, slope change and boulders or complexity and segment slope? Did the relationship between the field variables differ by watershed? Did the relationship vary by the network-level controls (stream junctions, constrained segments and debris flow segments)?

There was no apparent relationship between boulder accumulations and percent slope-change between segments. Elk and Rogers Creeks exhibited no obvious relationship between slope and boulders but in both watersheds the highest boulder values and slope changes were inversely related to each other. Turner Creek also had no visually obvious relationship between boulders and slope (Figures 8, 9, 10).

The effect of stream junctions on slope change and boulder accumulation in the study watersheds was negligible; the lowest and highest values in both Rogers and Elk Creeks were associated with segments without stream junction (non-stream junction segments). In Turner Creek the highest values of slope change were associated with stream junctions and there was a slightly positive relationship between slope and boulders in stream junction segments (Figure 8). Elk and Rogers Creeks had their highest boulder abundance values in constrained segments and Rogers Creek also had its largest slope change value in a constrained segment. Constrained segments in Turner Creek had lower slope change and boulder values than non-constrained segments (Figure 9). Debris flow termini segments had lower boulder and slope change values when compared to non-debris flow segments in all cases, with only Rogers Creek having a few sites with moderately high slope change values associated with debris flow termini (Figure 10). There was no strong association between slope change and boulders in any of the watersheds.

Pool abundance as a function of large wood accumulations was found to have an inconsistent relationship between watersheds and network-level controls. Rogers Creek had the highest large wood and pool numbers, while Elk Creek had the lowest values for both variables. Relationships between pools and wood abundance were negligible in all three watersheds (Figures 11, 12, 13).

In Elk Creek, the largest wood clusters were associated with stream junctions while the largest pool abundance values were associated with non-stream junction segments. The opposite was observed in Rogers Creek where high wood abundance was associated with non-stream junction segments. Turner Creek's stream junctions exhibited a slight positive relationship between wood and pool abundance when grouped by junction segments (Figure 11). There was no obvious pattern of pools and wood when grouped by constrained segments (Figure 12). Recent debris flow segments exhibited no clear pattern to wood or pool abundance in the study watersheds (Figure 13). In all cases recent debris flows deposit locations had lower pool and wood abundance.

Complexity as a function of channel slope had a slight positive association in the Rogers and Turner Creeks. Turner and Rogers Creek exhibited increasing complexity in concert with increasing slope, while there was no obvious relationship in Elk Creek (Figures 14, 15, 16).

There appeared to be a positive correlation among stream junction segments, slope and complexity in Rogers Creek. There is a weaker but similar trend in the stream junction segments in Turner Creek, but not in Elk Creek (Figure 14). Constrained segments in Rogers Creek exhibited a positive relationship and had larger slope and complexity values than Turner and Elk Creeks. Turner Creek showed a similar, but weaker, positive relationship between slope and complexity while grouped by constrained segments. In Elk Creek, constrained segments tended to have large complexity values and there was no correlation with increases in slope values (Figure 15). In Rogers Creek recent debris flow segments exhibited a positive pattern between higher slopes and complexity. Recent debris flow segments tended to have lower slope and complexity values in Elk and Turner Creeks (Figure 16).

Scatter plots were used to visually explore relationships between DEM-derived data and field data. The data points were coded by the presence or absence of a debris flow terminus. The DEM-derived debris flow potential was plotted as a function of field measured complexity. Field measured valley width was plotted as a function of the DEM-derived width. Each plot was used to answer two questions: was there a relation between debris flow potential (DFP) and complexity or DEM-width and field width? Did the relationship between the field variables differ by watershed?

There appeared to be a positive relationship between DFP and complexity. Rogers Creek had the most unambiguous pattern of DFP correlated to complexity, but Turner and Elk Creeks exhibited the pattern as well. In Rogers Creek debris flow termini show a positive relationship between DFP and complexity (Figure 17, 18). The debris flow termini segments in Elk Creek also exhibited a positive relationship. However, the values of complexity and DFP were an order of magnitude smaller in Elk Creek than in Rogers Creek (Figure 17, 18). No trend in debris flow segments in Turner Creek appeared due to the low number of segments.

The three study watersheds, exhibit a general positive relationship between DEM calculated valley width and field measured valley width. However, there was a trend in Rogers Creek for the calculated DEM width to underestimate the larger valley widths, while calculated DEM widths in Turner and Elk Creeks were generally overestimated (Figure 18).

Network-level controls

Roughly one third of sampled segments were within 60 m of stream junctions, proportions ranged slightly between basins. On average about one-quarter of sampled stream segments were constrained but proportion varied from one-fifth at Turner Creek to greater than one-third at Elk Creek. Percentages of segments in the deposition zone of a 1996 debris flow, ranged from 25% in Rogers Creek to less than 1% in Turner Creek (Table 4).

The majority of segments in all three watersheds were either not adjacent to stream junctions, and those that were adjacent to stream junctions, they were neither constrained nor contained debris flow termini. Only 9 % of stream junctions segments were constrained. Over 40% of all study segments were coded as non-stream junction, unconstrained, and non-debris flow (Table 7).

Statistical analysis

Influence of Network Level Control

The parameters used to describe complexity (pool abundance, wood, boulders and slope change) showed significant difference between the means in a minority of cases, when grouped by network level controls (Table 8). Pool abundance means were significantly different when grouped by debris flow termini in Rogers and Elk Creeks, with higher values in not-debris flow segments. Wood abundance showed significant difference only in Elk Creek when grouped by stream junction segments, with stream junctions having higher values than no stream junctions; there were no significant differences in any other grouping by network level controls. Boulder abundance still showed significant difference only in Elk Creek when grouped by stream junction segments, with stream junctions having higher values than no stream junctions; there were no significant differences in any other grouping by network level controls. Slope change showed significant difference only in Turner Creek when grouped by stream junction segments, with stream junctions having higher values than no stream junctions; there were no significant differences in any other grouping by network level controls.

Average complexity when grouped by network-level controls differed significantly in three cases. In Rogers Creek the average complexity values differed when grouped by constrain and unconstrained segments (with higher values found in constrained segments) and debris flow and non-debris flow segments (with higher values in non-debris flow segments). In Turner Creek the average complexity values were significantly different when grouped by stream junction and no-stream junction segments (with higher values associated with stream junction segments). In Elk Creek there were no significant differences in average complexity values regardless of the network-level controls.

Influence of segment length

The influence of segment length was investigated by grouping adjacent, downstream segments with the assigned upstream network-level controls. One hundred and twenty meter segments were tested with ANOVA to determine if the network-level controls exerted influence over two joined segments (120 m).

The lowest complexity values in Rogers Creek, when grouped in 60 m segments, occurred in stream segments that were designated as debris flow termini (2.28) and the highest complexity recoded was in constrained segments (5.04) (Table 8). Similar results were obtained when the influence of the network-level controls was assessed over 120 m. Debris flow termini segments had the lowest value (2.52), and were significantly smaller than the non-debris flow termini segments (4.27), which is the same pattern as in the 60 m segments (Table 9). The highest values were in constrained segments (4.58), however they were no longer significantly larger than the unconstrained segments (2.88) (Table 9). Complexity in Turner Creek showed no relationship with any of the network-level controls at the 120 meter length (Figure 9, 10).

The lowest complexity values in Tuner Creek, when grouped in 60 m segments, occurred in stream segments that were designated as non-stream junctions (2.00) and the highest complexity recoded was in segments designated stream junctions (3.40). When the influence of the network-level controls was assessed over a distance of 120 m down stream the pattern differed. Debris flow termini segments had the lowest complexity values (1.49), whereas complexity values averaged by non-debris flow termini segments were larger (2.59). The highest values were in constrained segments (2.93), which differed from the pattern in the 60 m segments (Table 8, 9).

The lowest complexity values in Elk Creek when grouped in 60 m segments occurred in stream segments that were designated as debris flow termini (1.75) and the highest complexity recoded was in stream junction segments (3.21). When the influence of the network-level controls was extended 120 m down stream the pattern was slightly different. Non-stream junction segments had the lowest average values (2.05), whereas the stream junction segments (3.21), which were the largest complexity values, on average, in Elk Creek (Table 8, 9).

Hot Spots

In Rogers Creek, 11 cases of complexity values and 8 cases of slope changes were greater than one standard deviation above the mean. Of these, 6 of the complexity values and 3 of slope changes cases were associated with stream junction segments. Also, 6 of the 8 cases of slope changes and 6 of the 11 cases of complexity values were associated with constrained segments (Table 10).

In Turner Creek, 12 cases of complexity values were above one standard deviation, of which 9 were associated with stream junction segments. Stream junctions were associated with pool 5 of 9 cases, with slope changes in all 4 cases and with wood in 6 out of 10 cases (Table 10).

In Elk Creek, high complexity values were associated with constrained segments in 5 of 6 instances. Stream junction influenced segments were found associated with high complexity values in 3 of 6 instances, large wood clusters in 7 of 10 instances and boulder accumulations in 4 of 5 instances (Table 10).

Chi-squared tests for Rogers Creek, demonstrated that stream junctions had greater than expected numbers of hot spots, wood, pool abundance, and complexity. Constrained segments had greater than expected values of wood, slope change and complexity. Only one in ten of the hot spots in Rogers Creek were found in unconstrained, non-stream junction segments with no recent history of debris flows.

In Turner Creek, chi-squared tests demonstrated that stream junction segments had greater than expected values of slope change, wood, pool abundance, boulders and complexity. Constrained segments had greater than expected values of wood, pool abundance and complexity. Sixteen percent of the hot spots in Turner Creek were found in unconstrained, non-stream junction segments with no recent history of debris flows.

In Elk Creek, chi-squared tests demonstrated that stream junction hot spots had greater than expected values of wood, boulder abundance, and complexity. Constrained segments had greater than expected values of complexity. All hot spots in Elk Creek were found either in constrained segments, stream junction segments or segments with a recent history of debris flows or a combination of these channel morphology variables.

Spatial patterns of network-level controls between watersheds

The mean values of complexity did not differ significantly between watersheds when complexity was coded by stream junctions, non-stream junctions, debris flow termini, non-debris flow termini, and unconstrained segments. However, complexity index values in constrained segments in Rogers Creek had a significantly larger mean values (5.04), than Turner (2.97) and Elk Creeks (2.84) (Table 11). Elk Creek had more channel length associated with constrained segments than Rogers (8% more length) and Turner Creeks (16% more length) (Table 12). There was lower average complexity in Elk Creek stream junction segments (2.21), compared to Rogers (3.40) and Turner Creeks (3.40) (Table 11) and also 15% less stream length associated with stream junctions in Elk Creek than in the other two watersheds (Table 12). Population means grouped by two and/or all three of the network-level controls were not significantly different between watersheds.

Patterns of complexity in relation to GIS variables

When the field observations were compared to the DEM-derived parameters, four of the seven relationships tested had at least some significant difference. The variables with the strongest relationship to empirical observations were: contributing area, total valley width, gradient, and debris flow potential (Figures 20 - 23). Junction angle, change in slope from tributary to main channel, and main channel to tributary area ratio did not differ significantly among watersheds.

At Rogers Creek the complexity index decreased (weakly) with increasing contributing area ($r^2 = 0.26$), declined with decreasing valley floor width ($r^2 = 0.36$), increased with rising stream gradient ($r^2 = 0.34$) and did not vary with debris flow potential ($r^2 = 0.04$) (Figure 20).

At Turner Creek the complexity index decreased (weakly) with increasing contributing area ($r^2 = 0.16$), declined with decreasing valley width ($r^2 = .15$), increased with increasing stream gradient ($r^2 = 0.13$) and did not vary with debris flow potential ($r^2 = 0.08$) (Figure 21).

At Elk Creek the complexity index seemed to be unrelated to contributing area ($r^2 = 0.02$), did not vary with valley floor width ($r^2 = .08$), was not associated with stream gradient ($r^2 = 0.05$) and was weakly, positively related to debris flow potential ($r^2 = 0.11$) (Figure 22).

The implications of watershed shape were addressed by comparing Turner to Elk Creek, excluding Rogers Creek due to major geologic differences. Complexity did not vary significantly between Turner and Elk Creeks when grouped by network-level controls or cumulatively. The differences in contributing area of tributaries did not appear to influence complexity values in either Turner or Elk Creeks. There was no apparent effect of tributary contributing area within Rogers Creek. Since Rogers Creek was not paired with another basalt basin, the effect of watershed shape and tributary size was not tested.

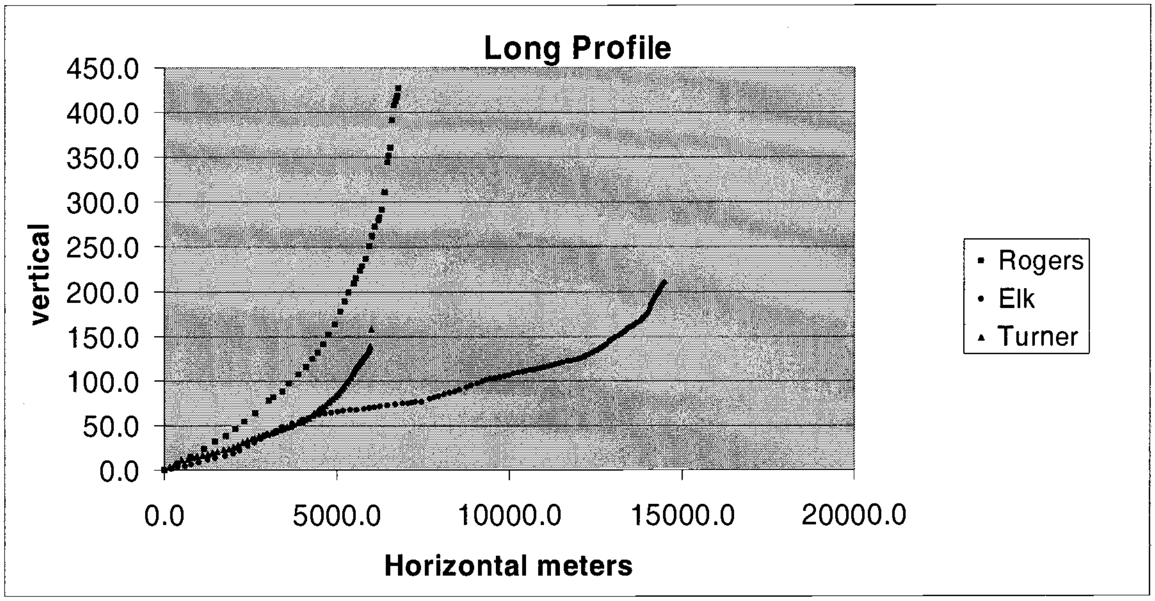

Figure 7: Longitudinal profile of Rogers, Elk and Turner Creeks

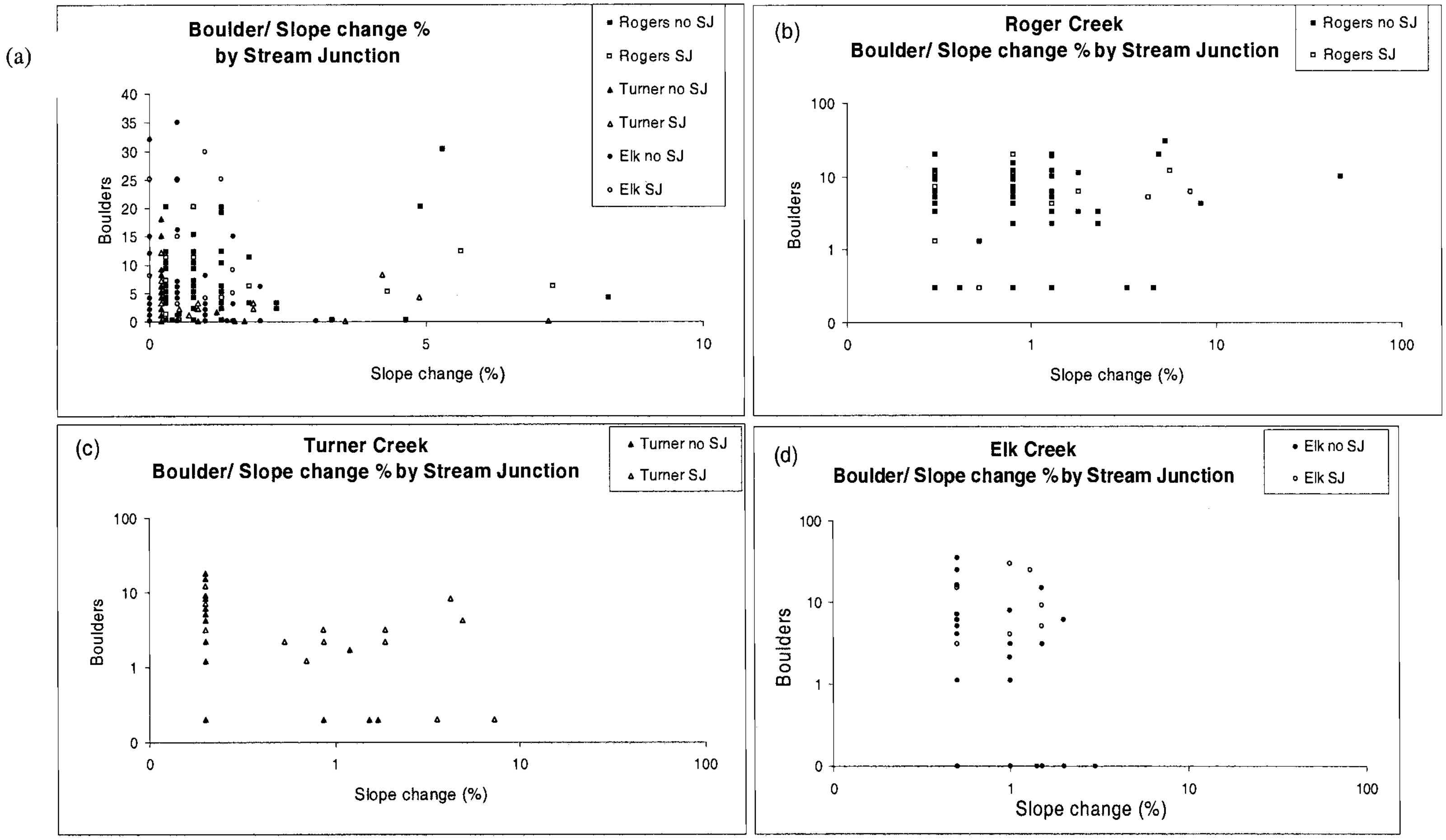

Figure 8: Scatter plot of observed boulders as a function of slope change, grouped by presence of stream junctions per 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a stream junction in the 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

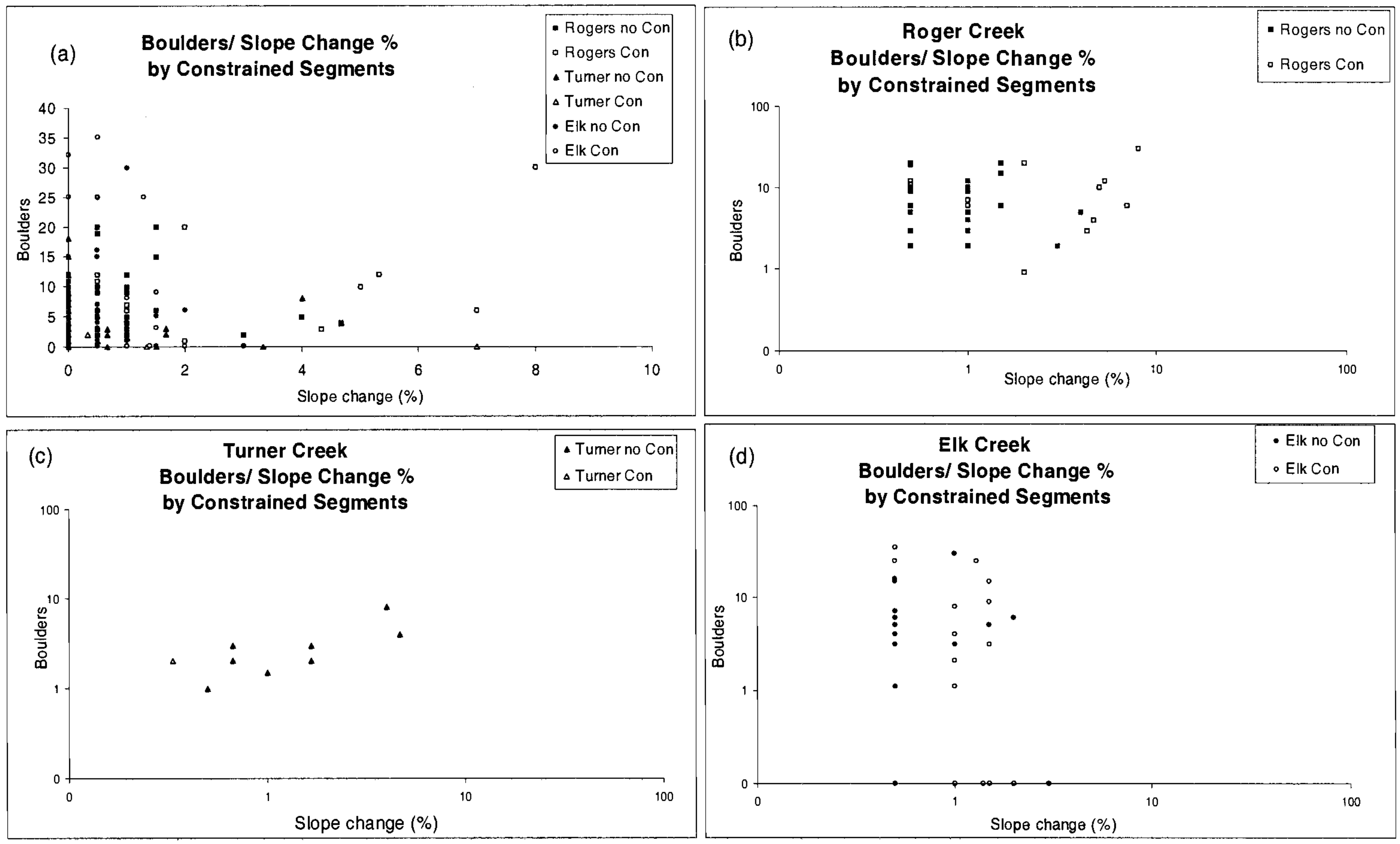

Figure 9: Scatter plots of observed boulders as a function of slope change, grouped by presence of constrained 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a constrained 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

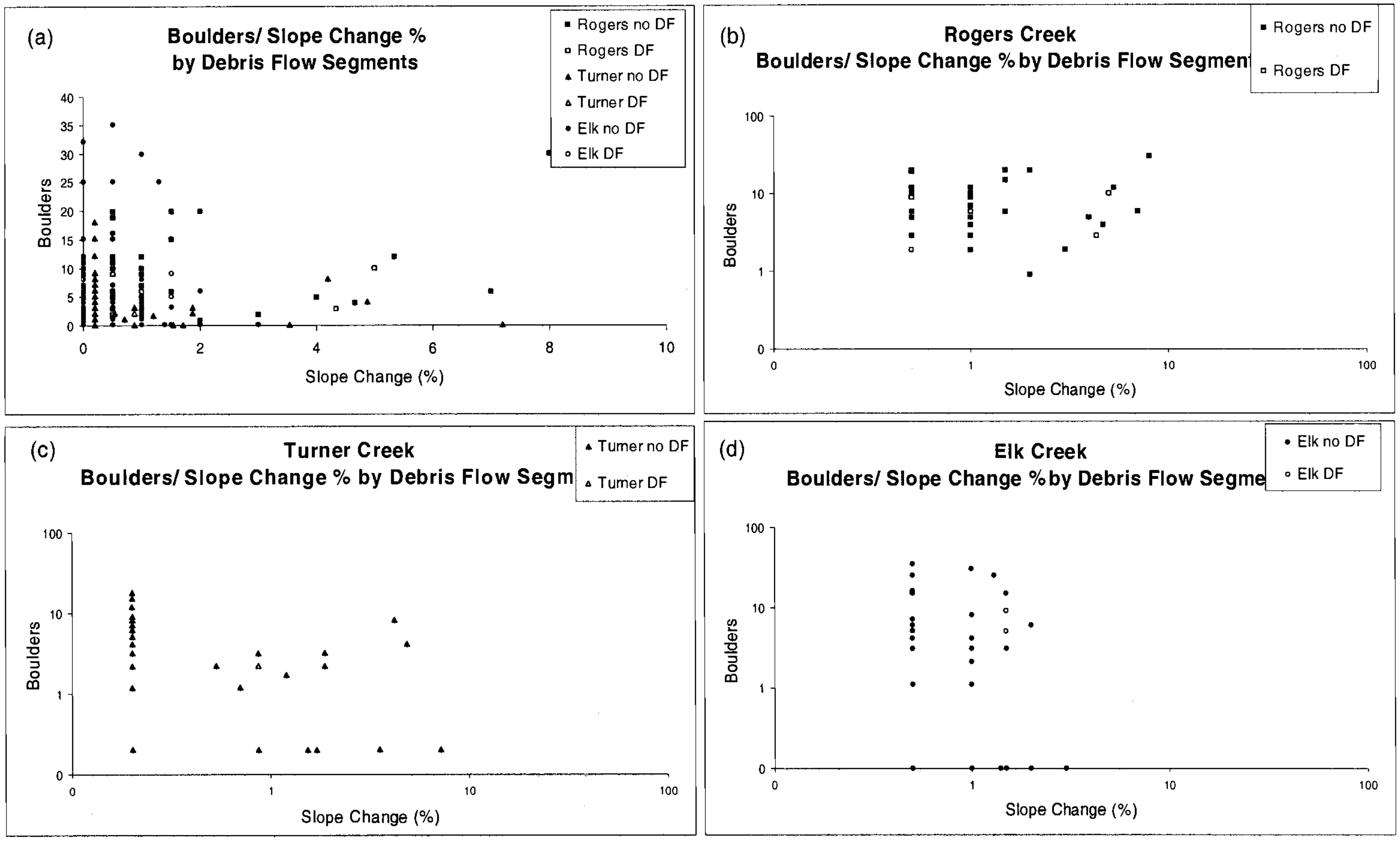

Figure 10: Scatter plots of boulders as a function of slope changes, grouped by presence of debris flow termini per 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a debris flow termini 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

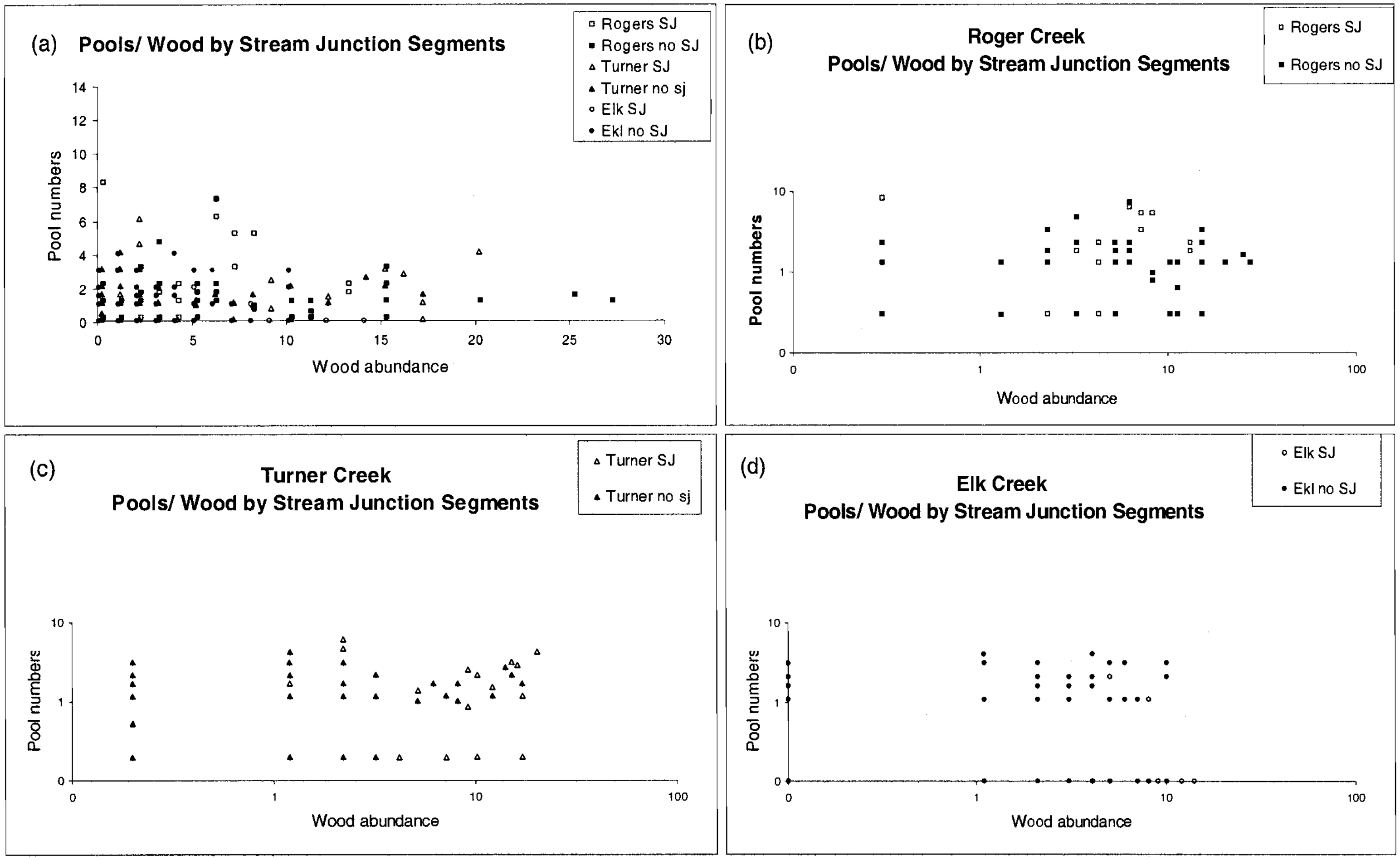

Figure 11: Scatter plots of pool numbers as a function of wood abundance, grouped by presence of stream junction per 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a debris flow termini 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

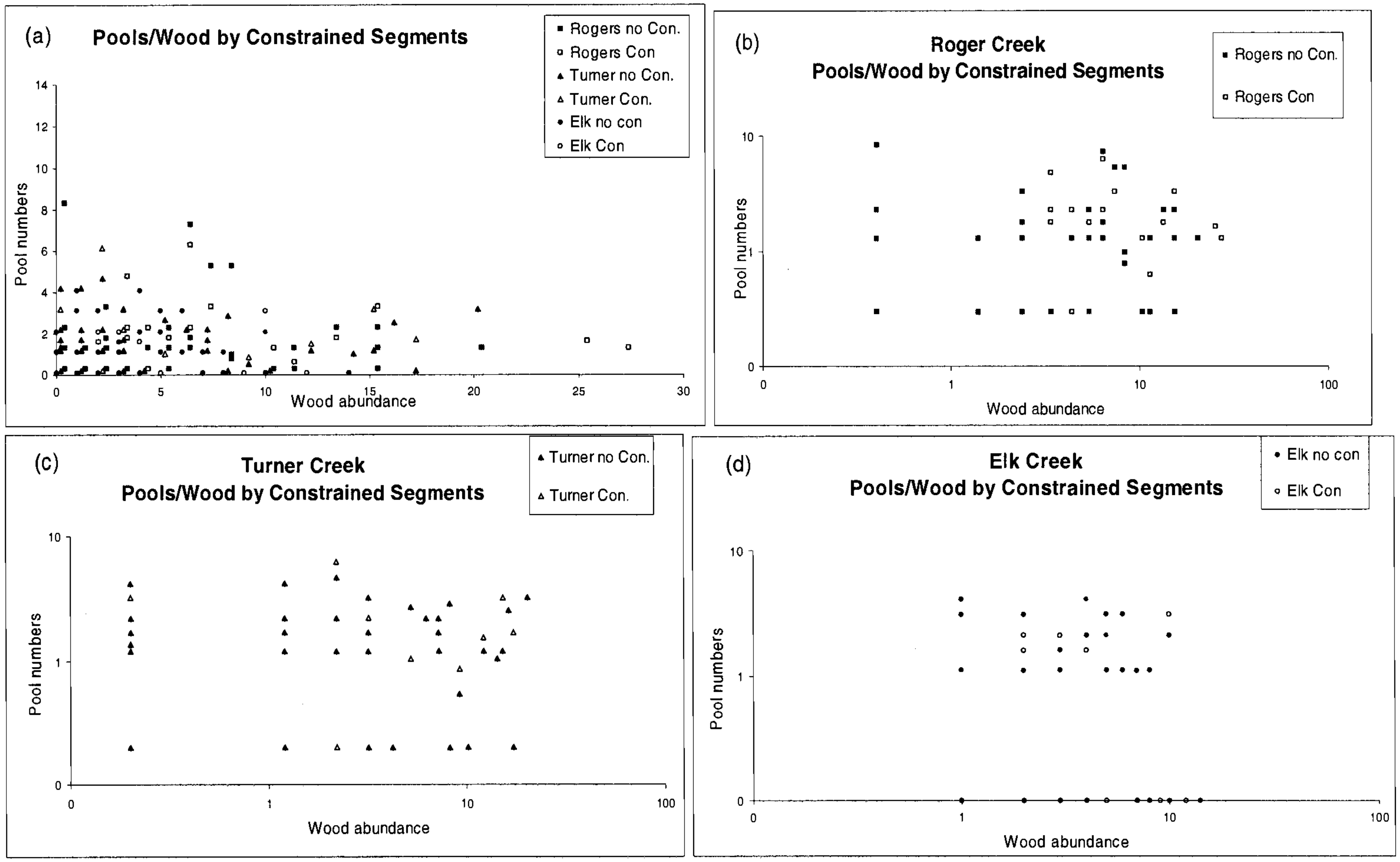

Figure 12: Scatter plot of observed pool numbers as a function of wood abundance, grouped by presence of constrained, 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a constrained 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

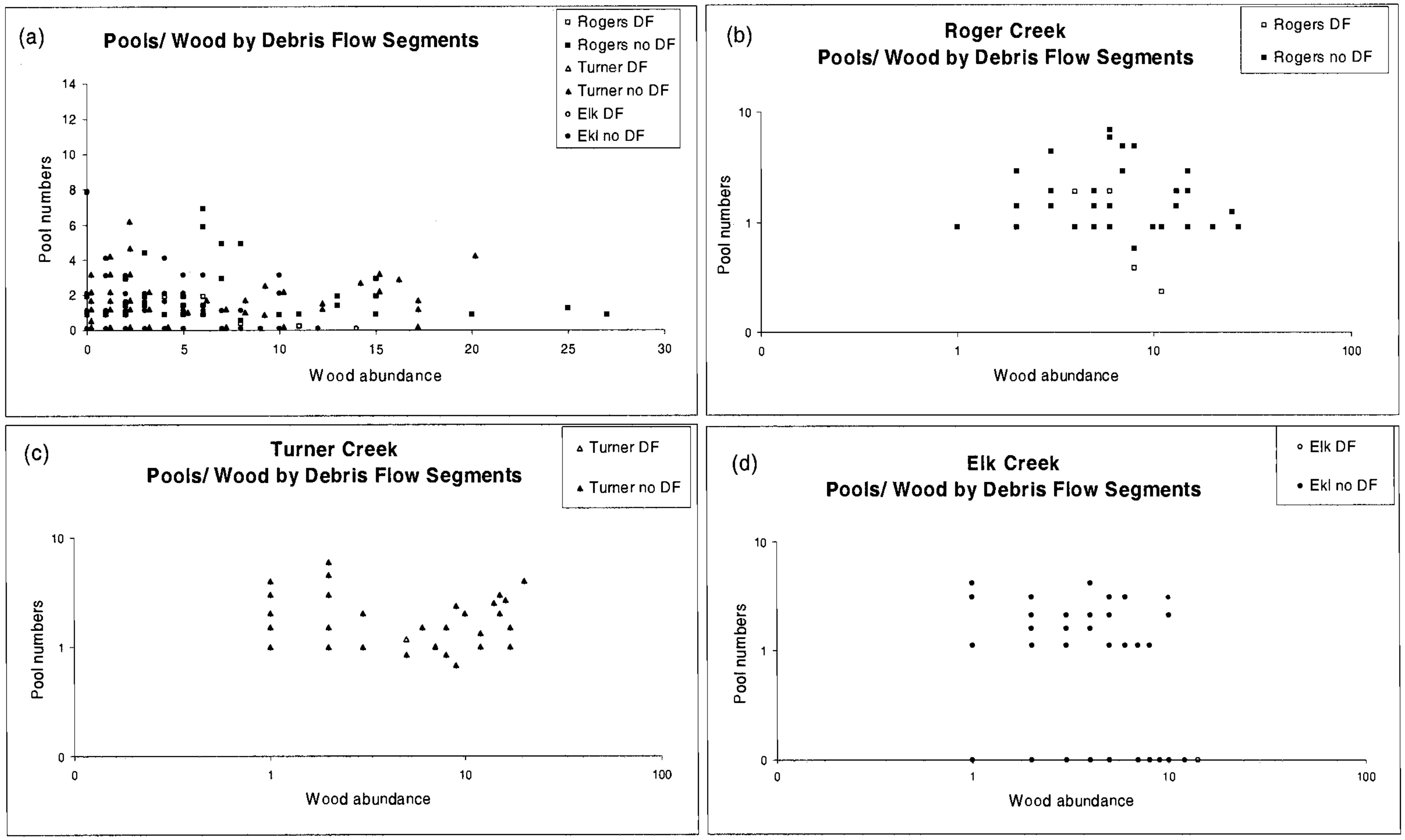

Figure 13: Scatter plot of observed pool numbers as a function of wood abundance, grouped by presence of debris flow termini per 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a debris flow termini 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

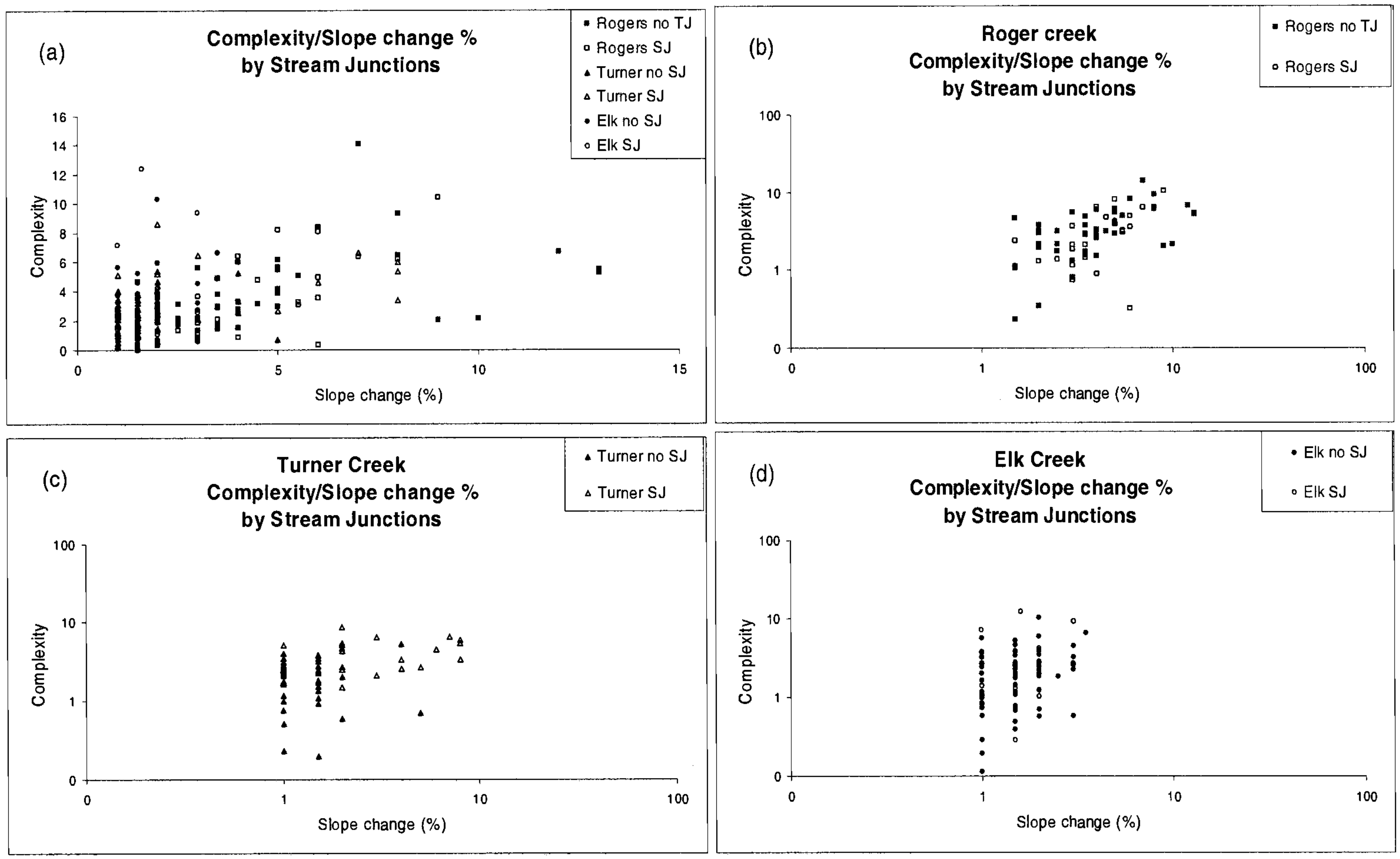

Figure 14: Scatter plot of complexity as a function of percent slope, grouped by presence of stream junctions per 60 meter segment. Watersheds are differentiated by the symbol shape. The presence of a stream junction in the 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

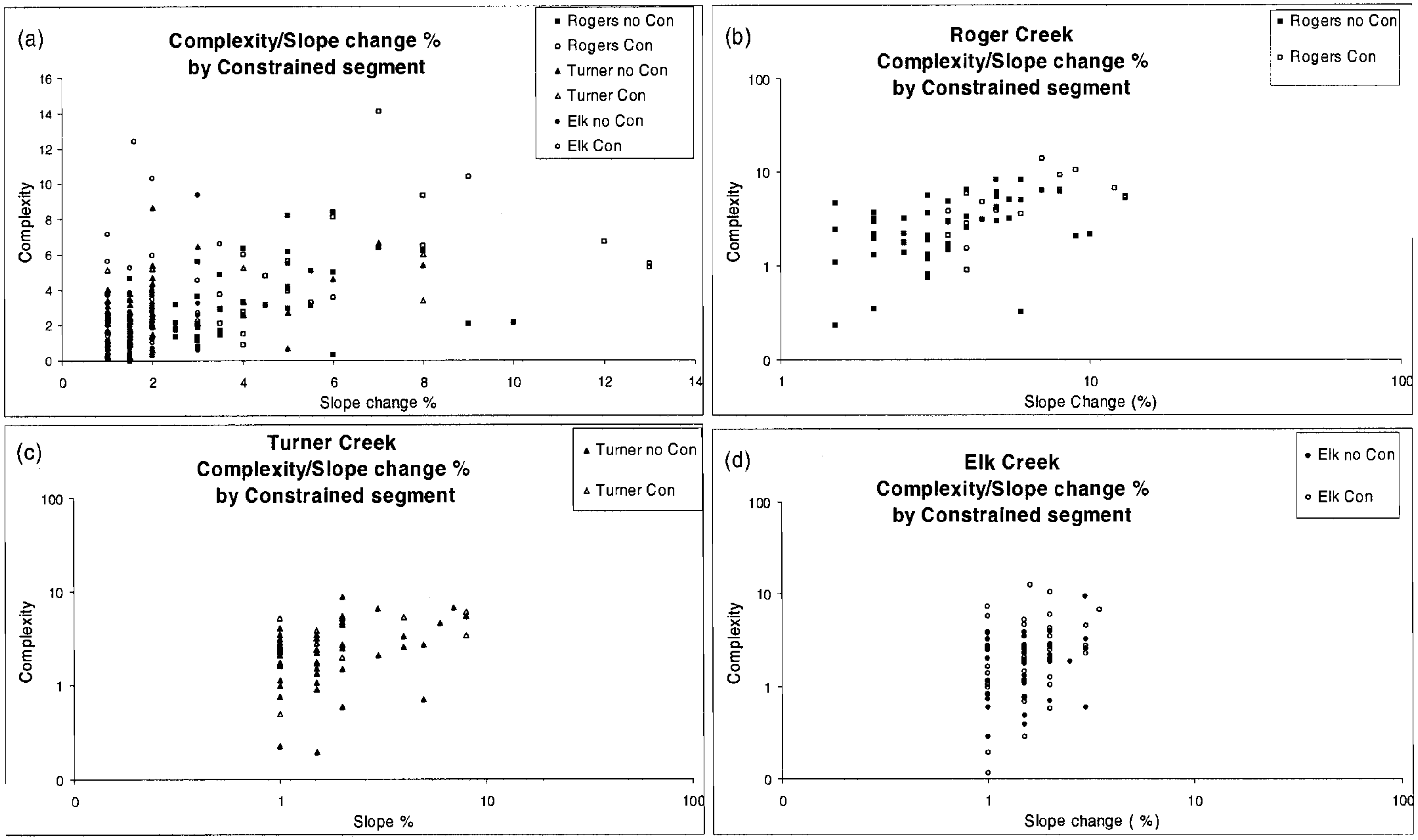

Figure 15: Scatter plot of complexity as a function percent slope, grouped by presence of constrained 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a constrained, 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

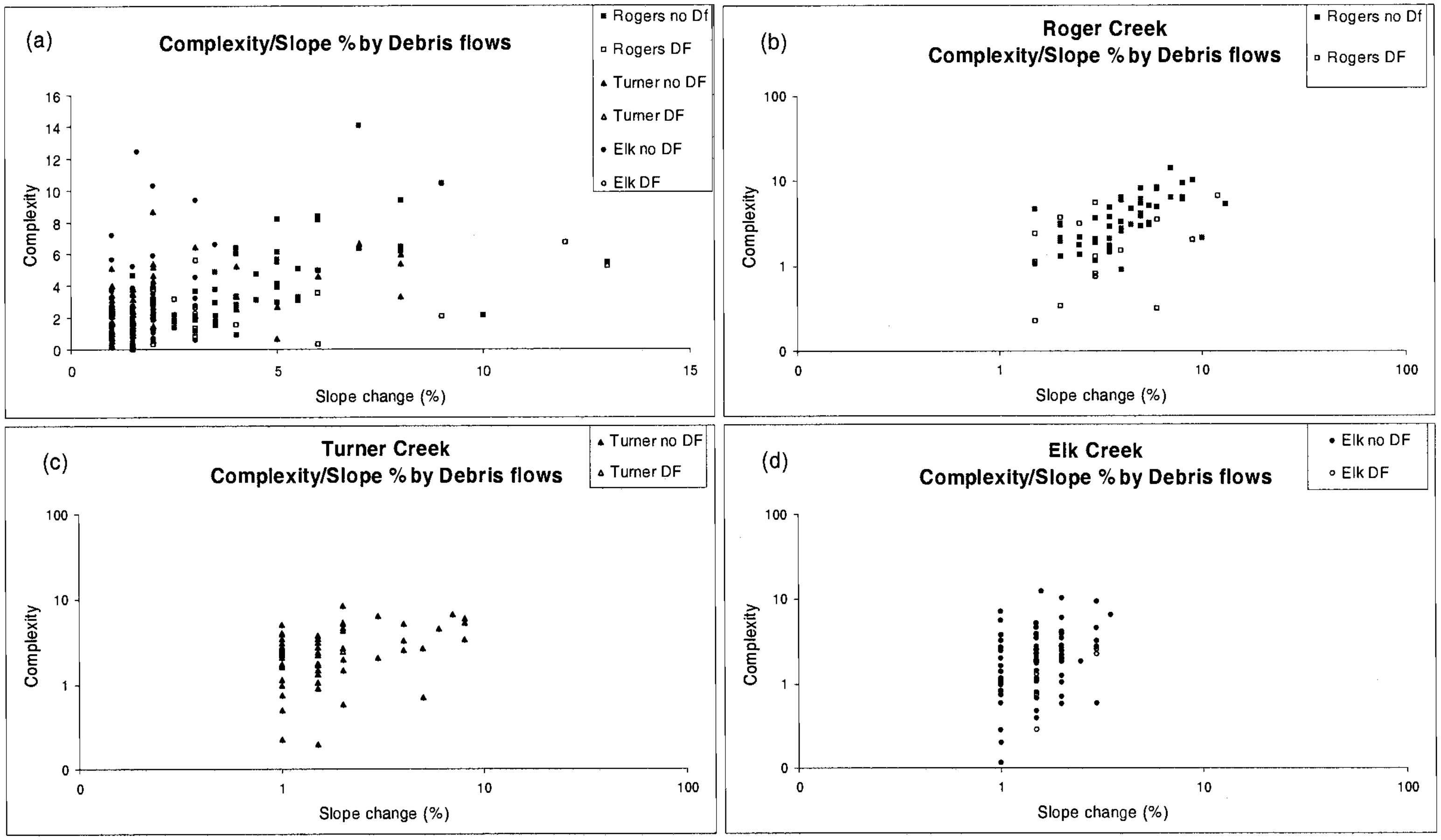

Figure 16: Scatter plot of observed complexity as a function of percent slope, grouped by presence of debris flow termini per 60 meter segments. Watersheds are differentiated by the symbol shape. The presence of a debris flow termini 60 meter segment is indicated by a hollow symbol. Data from graph (a) includes all watersheds, while graphs (b), (c) and (d) represent data in log space for each watershed.

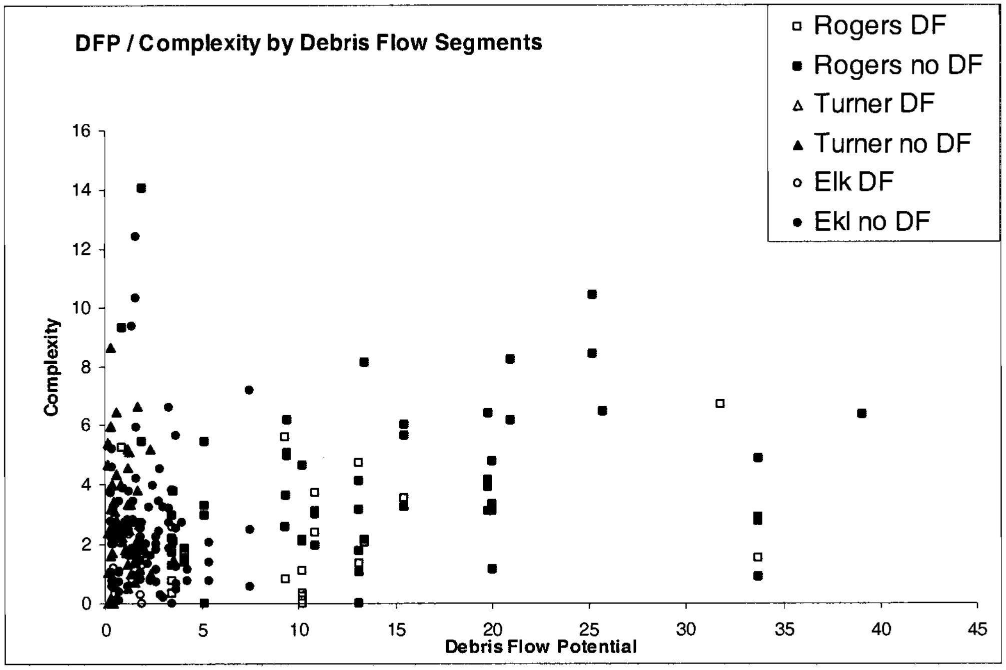

Figure 17: Scatter plot of calculated debris flow potential as a function of complexity, grouped by presence of debris flow termini per 60 meter segments

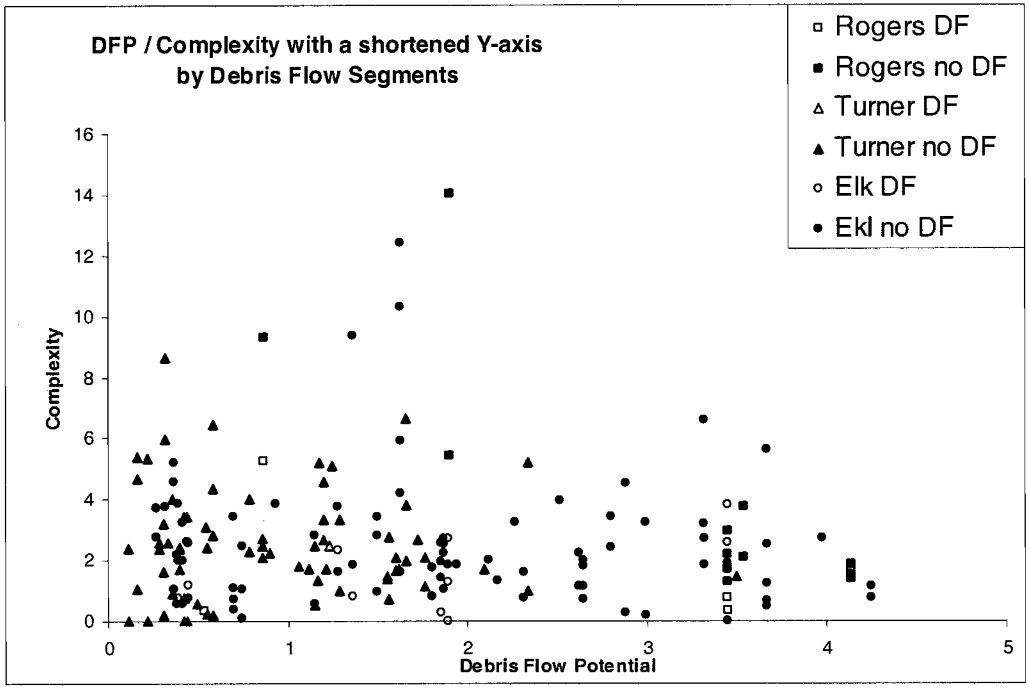

Figure 18: Scatter plot of calculated debris flow potential as a function of complexity, grouped by presence of debris flow termini per 60 meter segments. Figure 15 is the same data in figure 14 with the Y-axis truncated to values between 0 and 5.

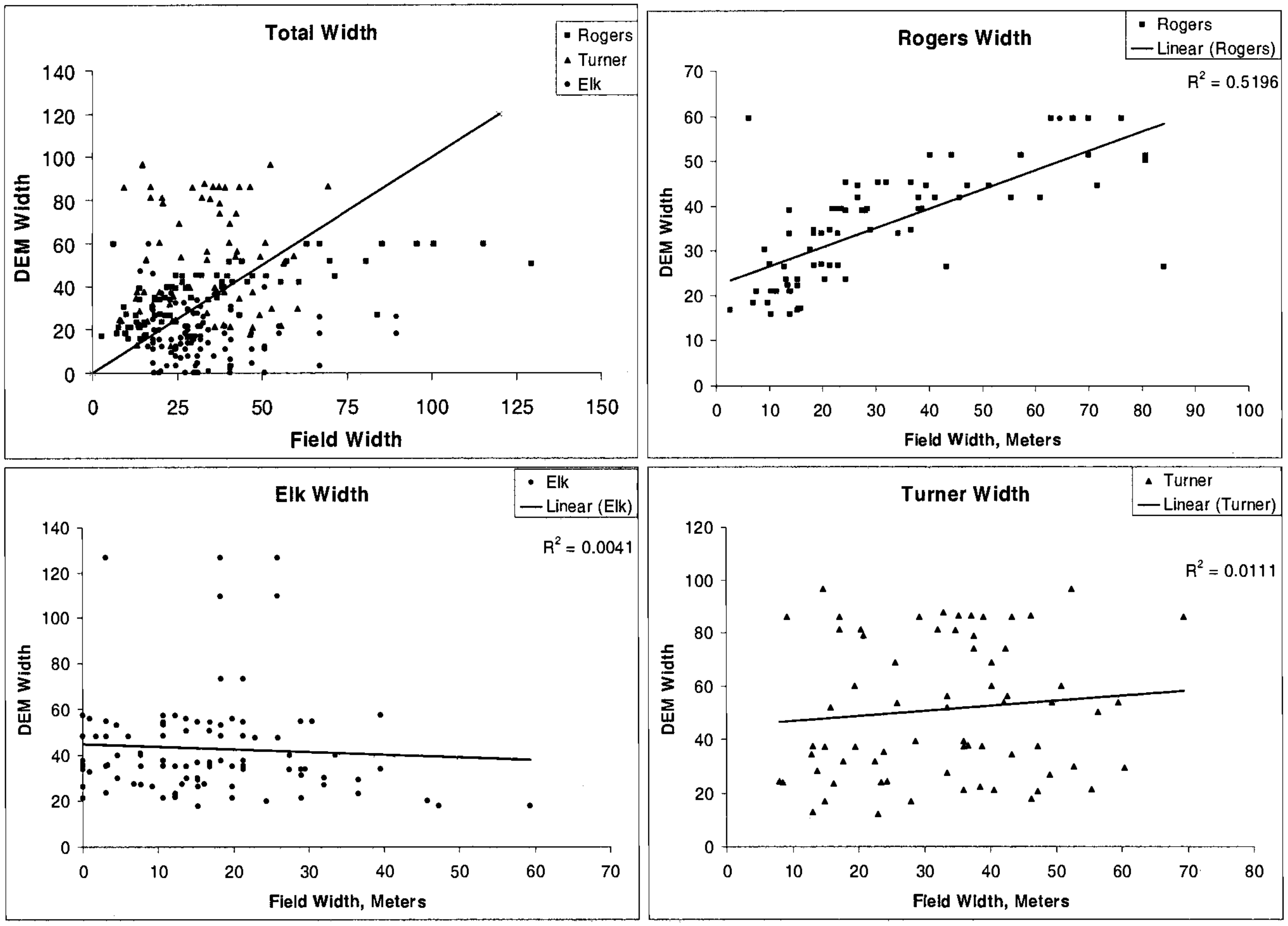

Figure 19: Scatter plot of field measured valley width as a function of calculated DEM width per 60 meter segment. Watersheds are differentiated by the symbol shape. Individual watershed scatter plots of field measured width as a function of DEM-derived width a, b, c. Also shown is a simple linear regression and R^2 value (upper right hand corner).

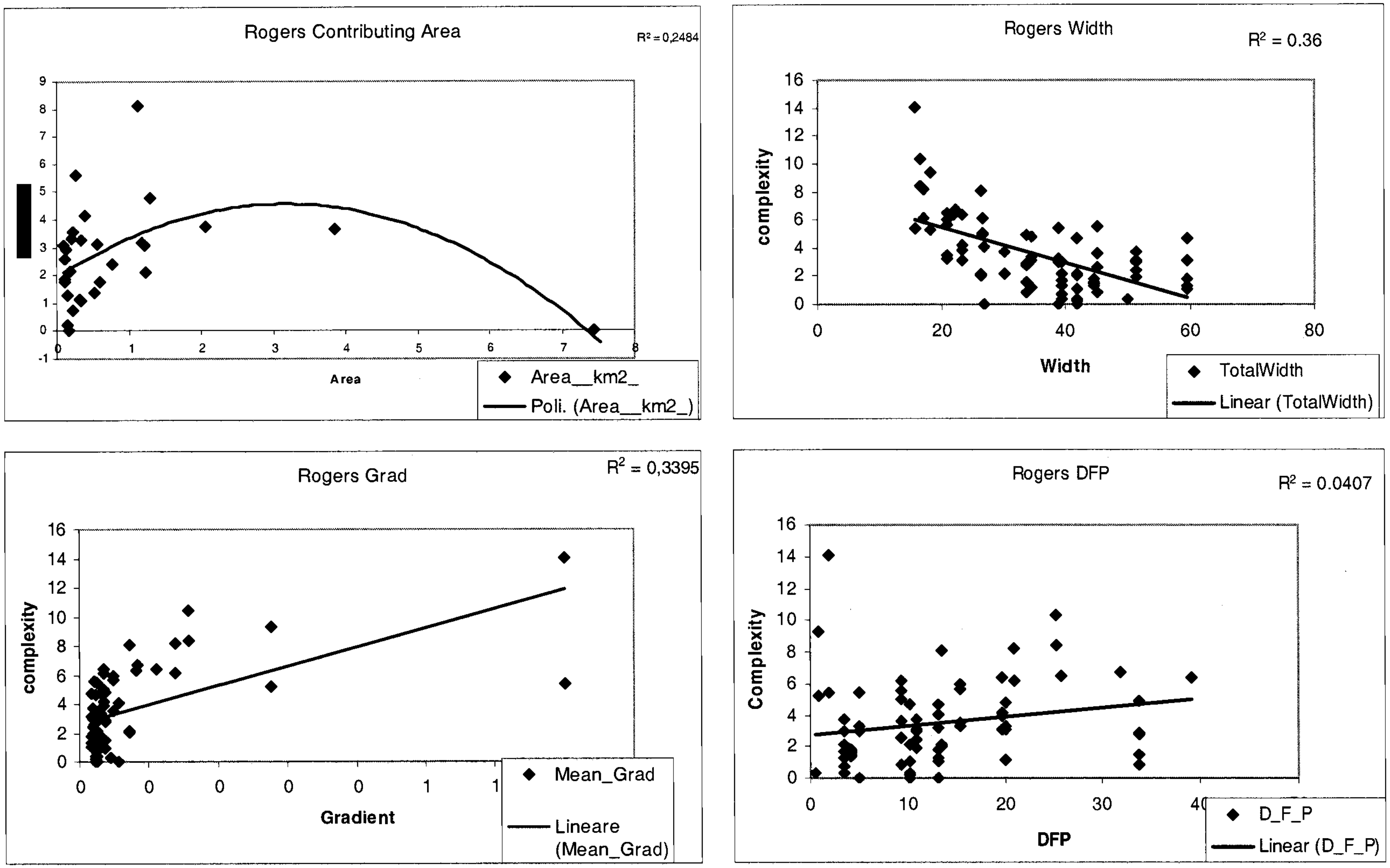

Figure 20: Rogers scatter plots of GIS derived parameters: valley width, tributary contributing area, main stem gradient, debris flow potential – plotted against complexity. Also shown is a simple linear regression line and R^2 value.

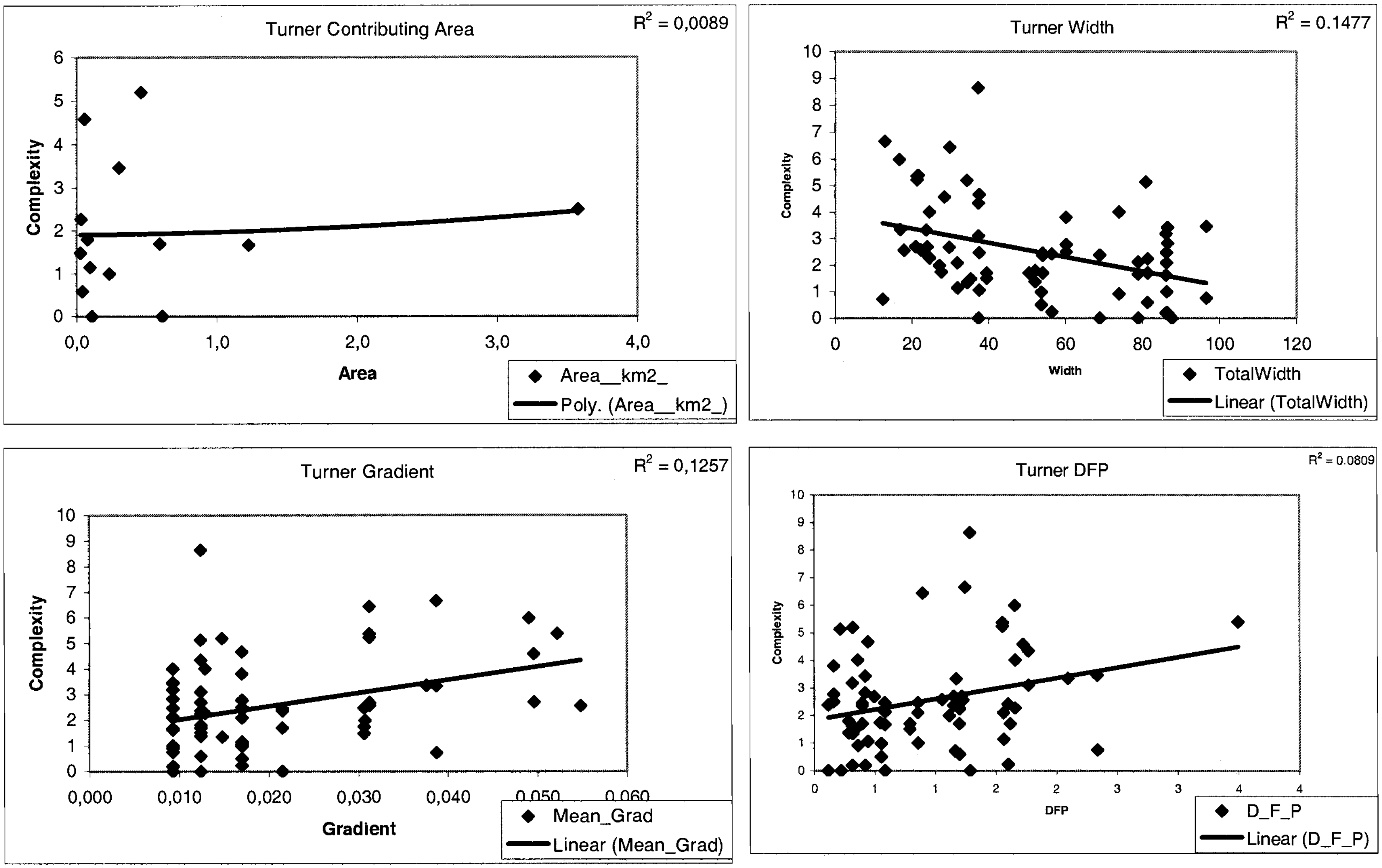

Figure 21: Turner scatter plots of GIS derived parameters: valley width, tributary contributing area, main stem gradient, debris flow potential – plotted against complexity. Also shown is a simple linear regression line and R^2 value.

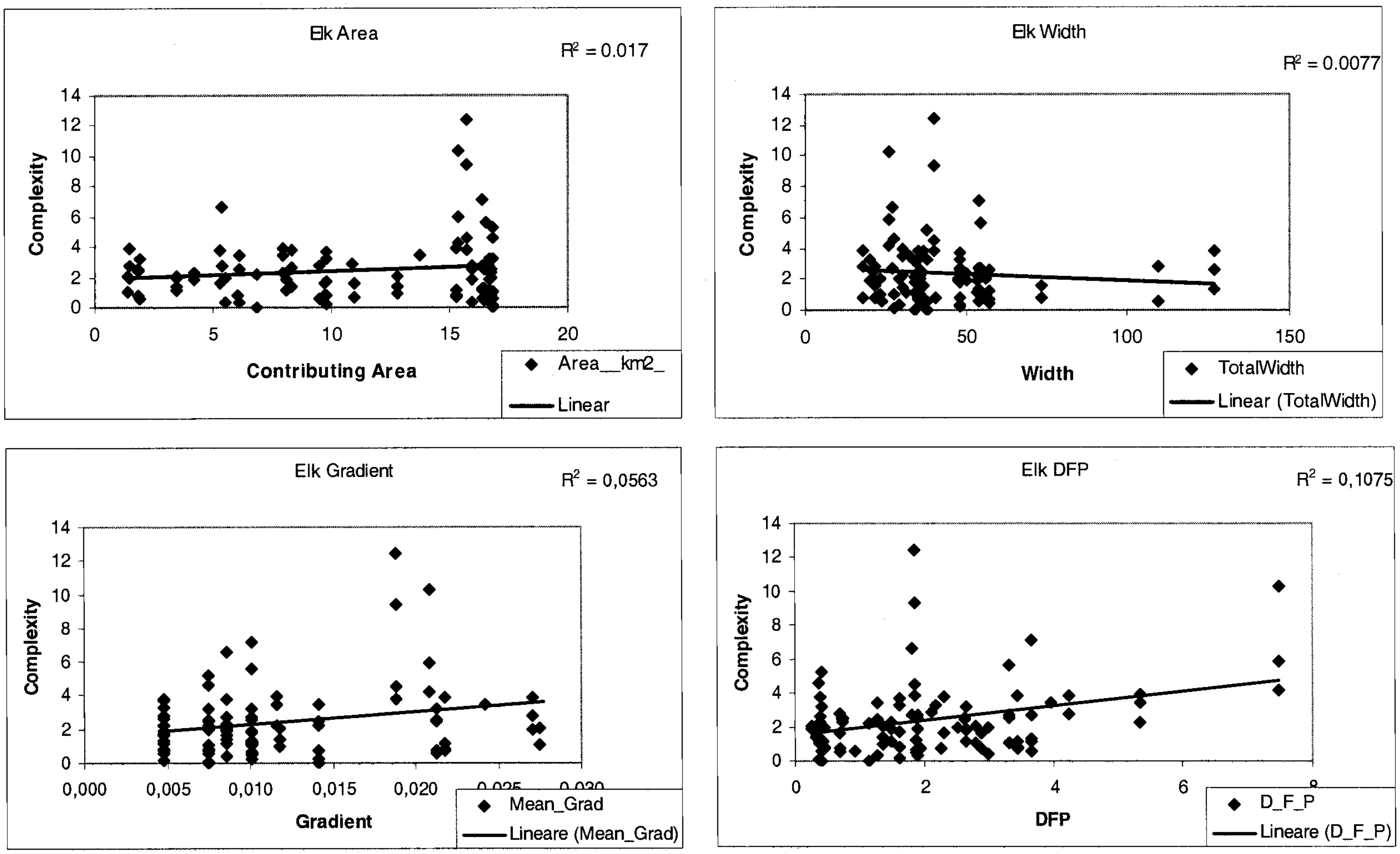

Figure 22: Elk scatter plots of GIS derived parameters: valley width, tributary contributing area, main stem gradient, debris flow potential – plotted against complexity. Also shown is a simple linear regression line and R^2 value.

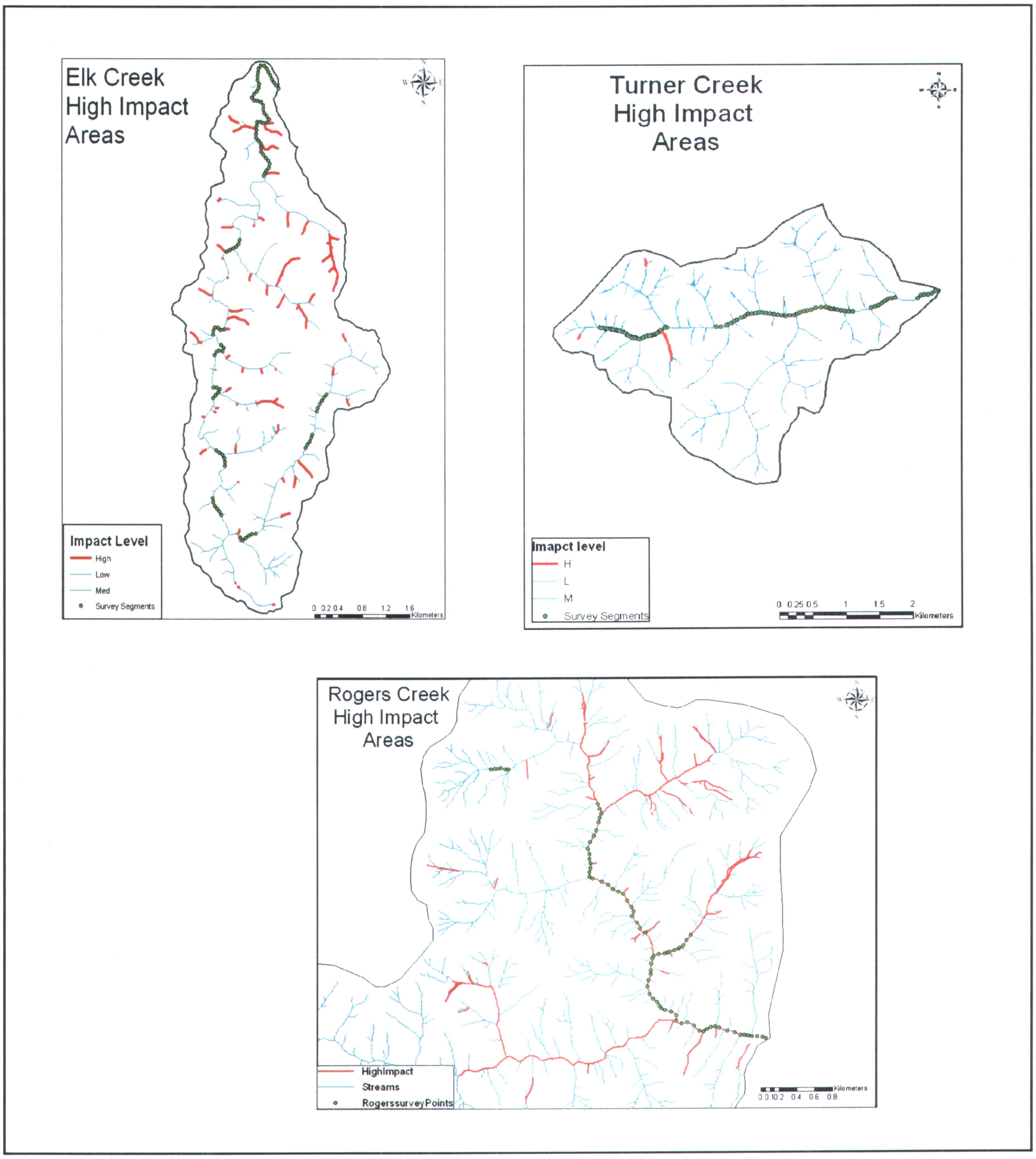

Figure 23: The type of impacts that occurred during the 1996 storms was delineated. A highly impacted channel, delineated in red, was characterized by massive scour and/or fill and overturn of sediments along with considerable damage to the vegetation along the edge of the channel. In order to have this level of impact, a debris flow, debris torrent, or debris flood would have to occur. Green dots represent the study segments, blue lines are the drainage network

Table 5: Summary statistics of raw data for individual watersheds. Wood and boulders columns are counts of number of individual pieces, pools are a weighted average of small and large pools, slope change is the percent change between 60 meter segments

	Roger Creek Complexity		Turner Creek Complexity		Elk Creek Complexity	
	mean	n	mean	n	mean	n
Complexity	3.53	76	2.58	69	2.42	98
Pool Abundance	1.35	74	1.54	65	1.15	89
Slope Change, %	1.12	68	0.51	64	0.87	82
Wood ≥ 25cm D, ≥ 2m L	6.29	73	4.77	65	3.59	90
Boulder ≥ 1m diameter	7.22	73	3.10	65	5.60	88

Table 6: Numbers of 60 meter stream segments by type of coding variable and watershed. The percent of the segments grouped by the coding variable is recorded in the upper right hand comer of the cell.

	Stream Junction		Non-Stream Junction		Confined		Unconfined		Debris Flow		Non-debris Flow		Total	%
	n	%	n	%	n	%	n	%	n	%	n	%		
Rogers Creek	30	40	47	60	22	29	55	71	20	26	57	74	77	28
Turner Creek	27	39	43	61	15	21	55	79	1	2	69	99	70	25
Elk Creek	24	25	75	75	37	37	62	63	9	13	90	90	99	37
Total	81		165		74		172		30		216		246	
Total (%)	30		70		27		73		11		89		100	

Table 7: Interactions between 60 meter stream segments by stream junction, constrained segment and recent debris flow termini segment. The percent of the segments grouped by each permutation coding variable is reported in the bottom of the table.

	Stream Junction				Non Stream Junction				
	Constrained		Unconstrained		Constrained		Unconstrained		
Watershed	Debris Flow	No DF	Debris Flow	No DF	Debris Flow	No DF	Debris Flow	No DF	Total
Rogers	1	7	6	16	3	12	11	21	77
Turner	0	6	1	20	0	9	0	34	70
Elk	2	11	6	5	1	23	0	51	99
Total	3	24	13	41	4	61	11	106	276
Percent%	1	9	5	17	2	18	4	43	100

Table 8: Average pool density, large wood, boulder abundance, slope change between segments and complexity values by watershed; broken up by pair wise comparisons by rows of stream junctions, constrained segments, and debris flows. Mean values represent average of all 60 meter segments for the population. Paired group means in the same column (ex. stream junction / non- stream junction) followed by "*" indicate a significant difference within the watershed at a 95% confidence interval. Group means in the same column followed by an "a" indicate they are significantly different from group means followed by an "b" at a 95% confidence interval. Values followed by "b" are not statistically different than other values followed by another "b".

		Pool Abundance, #		Wood ≥ 25cm D, ≥ 2m L		Boulder ≥ 1m diameter		Slope Change, %		Complexity	
		Mean	n	Mean	n	Mean	n	Mean	n	Mean	N
Rogers	No Stream J	1.14	45	7.16	44	7.84	44	1.09	44	3.62	46
	Stream J	1.67	29	4.97	29	6.28	29	1.19	24	3.4	30
Turner	No Stream J	1.46	40	3.46	39	2.59	40	0.17*	39	2.00*	43
	Stream J	1.67	25	6.73	26	3.92	25	1.05*	25	3.40*	27
Elk	No Stream J	1.17	45	2.67*	48	4.76*	45	0.9	44	2.15	52
	Stream J	0.96	24	4.09*	23	9.92*	24	1.11	22	3.21	24
Rogers	Unconstrained	1.16	53	5.25	52	6.67	52	0.69	47	2.91*	54
	Constrained	1.82	21	8.86a	21	8.57	21	2.09	21	5.04*a	22
Turner	Unconstrained	1.48	51	4.46	52	3.05	51	0.47	50	2.42	55
	Constrained	1.77	14	6	13	3.29	14	0.67	14	2.97b	15
Elk	Unconstrained	1.07	35	3.76b	37	4.39	36	0.51	34	2.14	39
	Constrained	1.12	34	2.44	34	8.91	33	1.45	32	2.84b	37
Rogers	no Debris Flow	1.63*	55	6.94	54	7.85	54	1.19	50	3.98*	56
	Debris Flow	0.54*	19	4.42	19	5.42	19	0.93	18	2.28*	20
Turner	no Debris Flow	1.55	64	4.77	64	3.12	64	0.51	63	2.54	69
	Debris Flow	1.17	1	5	1	2	1	0.67	1	2.47	1
Elk	no Debris Flow	1.19*	60	3.11	62	6.97	60	1.03	57	2.58	67
	Debris Flow	0.44*	9	3.22	9	3.78	9	0.61	9	1.75	9

Table 9: Results of down stream grouping by 120 meter segments. Paired group means (ex. stream junction / non- stream junction) followed by a"*" indicates they are significantly different from each other at a 0.95% confidence interval.

	Rogers Creek Complexity		Turner Creek Complexity		Elk Creek Complexity	
	mean	n	mean	n	mean	n
Stream J	3.41	52	2.84	40	2.83	47
Non-Stream J	3.79	24	2.14	30	2.05	51
Constrained	4.58	29	2.93	26	2.51	69
Unconstrained	2.88	47	2.31	44	2.21	29
Debris Flow	2.52*	32	1.49	3	2.57	17
No Debris Flow	4.27*	44	2.59	67	2.39	81

Table 10: Displays the number of large groupings (greater than one standard deviation over the mean) associated with stream junctions, constrained segments and debris flow termini in each watershed. An "*" indicates that the variable had greater than expected numbers of extreme values based Chi squared test.# Seg = number of segment above 1 standard deviation, SJ = Stream Junction, Con = Constrained, DF = Debris flow

	Rogers Creek				Turner Creek				Elk Creek			
	# Seg	SJ	Con	DF	# Seg	SJ	Con	DF	# Seg	SJ	Con	DF
Pool	6/77	4*	2	0	9/70	5*	3*	0	12/99	1	5	0
Slope	8/77	3	6*	2	4/70	4*	1	0	2/99	1	2	0
LW	13/77	4*	6	2	10/70	6*	3*	0	10/99	7*	5	2
Boulder	7/77	1	2	1	9/70	4*	2	0	5/99	4*	4	0
Complex	11/77	6*	6*	1	12/70	9*	4*	0	6/99	3*	5*	0

Table 11: Complexity index for stream segments. Group means in the same column followed by an "a" indicate they are significantly different from group means followed by an "ab" at a 95% confidence interval. Values followed by "b" are not statistically different than other values followed by another "b".

	Rogers Creek		Turner Creek		Elk Creek	
	mean	n	mean	n	mean	n
Stream Junction	3.4	30	3.4	27	2.21	24
Non-Stream Junction	3.62	46	2.00	43	2.15	75
Constrained	5.04a	22	2.97ab	15	2.84ab	37
Non Constrained	2.91	54	2.42	55	2.14	62
Debris Flow	2.28	20	2.47	1	1.75	9
Non Debris Flow	3.98	56	2.54	69	2.58	90

Table 12: Length of segments in meters and proportion of each coding variable by watershed

	Rogers Creek		Turner Creek		Elk Creek	
	Length (m)	as %	Length (m)	as %	Length (m)	as %
Stream Junction	1800	39	1620	39	1440	24
Non-Stream Junction	2760	61	2580	61	4500	76
Constrained	1320	29	900	21	2220	37
Non Constrained	3240	71	3300	79	3720	63
Debris Flow	1200	26	60	1	540	9
No Debris Flow	3360	74	4140	99	5400	91
Total	4560	100	4200	100	5940	100

Discussion

Results from this study provide evidence that complexity, pools, wood, boulders and slope change, were related to network-level controls. However, the relationship was specific to each watershed, and was not consistent between watersheds for all network-level controls (Table 13). This finding was supported by the complexity values at stream junctions in Turner Creek and at constrained and debris flow segments in Rogers Creek. The hot spot analysis results also added evidence to the relationship between the network-level controls and complexity (Table 10). About 90% of the hot-spot values of complexity were associated with stream junctions, constrained segments or both. The majority of the high complexity values were associated with small, less than 2 km^2 tributaries. Recent debris flow deposition zones appeared to have a slightly negative affect on complexity, depending on the watershed: in Rogers Creeks, pools were filled and logs were subsequently transported away from the deposition zone, whereas in Turner and Elk Creek, logs and boulders were generally not delivered to the mean channel.

Hypotheses

Stream junctions had higher complexity values than non-stream junction segments in the two low-gradient watersheds (Turner and Elk), regardless of contributing area. The hypothesis that stream junctions, with a high tributary to main channel contributing area ratio, would have proportionately larger affects on complexity (Benda et al. 2004b) was not supported by these results. However, small tributaries, less than two km^2 in size, which are steep enough to deliver debris flow material in this environment, did show a relationship with higher complexity. An additional clause regarding an upper size limit for tributaries may enhance the hypothesis. For example, stream junctions, with higher tributary to main channel contributing area ratio up to two km^2, will have proportionately larger affects on complexity, fits better with this dataset.

Constrained stream segments were found to have higher complexity than non-constrained segments in all watersheds. Over half of the highest complexity values (hot spots) were found in constrained segments. This supports the hypothesis that constrained segments influence the distribution of complexity. Constrained points created a depositional zone directly upstream, where wood and boulders could be deposited and pools could formed in relation to the deposited material. The narrowing of the valley at the constrained point also causes slope to increase, combining all the parameters used to describe complexity and therefore increasing the values of complexity.

The effect of watershed shape on complexity was tested only between Turner and Elk Creeks due to their geologic similarity and their different shapes. If watershed shape did influence complexity, then the pattern and values should demonstrated a difference. Complexity values and patterns did not vary significantly between Elk and Turner Creeks and therefore the study results do not support the hypothesis that watershed shape influences complexity.

Stream segments that experienced recent debris flow deposits had lower complexity in all watersheds. In Rogers Creek, many recent debris flow deposits transported into the main channel have been repositioned with time by fluvial processes. In Turner and Elk Creeks, recent debris flows tended to terminate in tributary channels either on top of coalescing debris flow complexes (Lancaster and Grant 2005), on old debris flow fans, or on road beds that decreased the gradient and confinement, thereby weakening the debris flow before it reached the main channel. However, the higher complexity at stream junction segments in Turner and Elk Creeks was likely due to re-exposed coarse debris flow material. The main channels of Turner and Elk Creeks are low energy environment as indicated by the lowest reaches where sufficient stream flow energy can expose the bedrock floor. The low energy flow takes many years to exhume the "bones" of the old debris flows, that usually accumulate in stream junctions, which is why high complexity is associated with width old deposits. The findings from this study support the hypothesis that each watershed has a pattern of complexity that reflects unique debris flow activity.

The basalt geology and slightly higher uplift rates (0.6 mm/yr) in Rogers Creek may have led to longer sustained steeper slopes that led to longer average runout lengths for debris flows (181 m). Both Elk and Turner Creeks had Tyee sandstone geology and lower (0.2 mm/yr) uplift rates that may have led to shorter sustained steep slopes and therefore shorter average debris flow lengths (75 m and 73 m respectively). This appears to support the hypothesis that debris flows travel longer distances in watersheds with harder rock types and faster uplift rates. Geology was likely responsible for the locations of exposed bedrock in the channel bottom: bedrock was not exposed rock in Roger Creek since basalt weathers to cobbles and stones, which are not easily entertained by fluvial processes and therefore dominate and cover the channel bottom; in contrast, the Tyee sandstone in Turner and Elk Creeks weathers to smaller particles (i.e. sand), which are more easily transported as fluvial power increases.

The differences in management histories may also help explain some of the difference between the watersheds. There is a more homogenous aged stand of timber in Rogers Creek due to the fires in the first half of the century and more patchy forest cover in Elk and Turner Creeks due to the current and past harvest practices. Roads in the three watersheds have been managed and maintained in different ways, with a paved road added in the lower Turner Creek and other valley bottom roads in the upper watershed were abandoned. Both Rogers and Elk Creek have well-maintained, rocked valley bottom roads. Debris flows appeared to incorporate valley bottom road fill into their volume in Rogers Creek, while debris flows in Elk and Turner Creeks appeared to lose power and stop on valley bottom roads. Wood was more abundant in the active channel in Rogers Creek than Elk and Turner, perhaps in part due to the systematic removal of large wood during harvest in the two southern sites and the cull from the fire salvage in the northern site. The level of acceptable defect in logs has increased over the last 50 years so it is conceivable that wood that would be removed today was left on site after the fires in Rogers Creek watershed, thereby creating an environment where there was more large wood available to be transported to the main channel by disturbance events like debris flows.

Influence of network-level controls on complexity

Constrained segments had higher average complexity in all three watersheds compared to unconstrained segments. There are two probable explanations for this difference, depended on the watershed involved: constrained segments may drive upstream deposition of material in Rogers Creek; or the higher energy environments in constrained segments in Turner and Elk Creeks may exhume larger material previously deposited in floods than other locations in the same watersheds.

In Rogers Creek, lower energy environments immediately upstream of constrained points may have resulted in upstream material accumulations leading to higher complexity values associated with constrained reaches. These locations can also be wide and accumulate fine sediments however in the active channel the fines are evacuated and the larger pieces remain thereby increasing complexity. Logjams in constrained reaches may have increased complexity as well. The local base level can be raised by constrained reaches thereby leading aggregation upstream of the constraint (Swanson et al. 1985). Constrained segments also influence where wood pieces become lodged between valley walls to create log jams (Figure 24).

In Turner and Elk Creek, the main channels may have lacked the capability to evacuate the material delivered in debris flows. This concept was supported by the observation that bedrock streambeds were observed only in the lowest portions of Elk and Turner Creeks. Due to the larger contributing area, there may be more stream energy in the lower reaches as well as in the constrained reaches, which would explain the prevalence of bedrock streambeds only in the lowest portions of the stream. The sandstone geology weathers to sand which can be more easily entrained by normal flows than the cobbles and stones in basaltic Rogers Creek. In constrained reaches in both Elk and Turner Creeks, the energy of the water column may have been sufficient to evacuate the fine sediments and exhume buried wood and boulders that added to complexity.

Stream junction segments in Turner and Elk Creeks had higher complexity values than non-stream junction segments. Turner Creek had statistically significant higher values while Elk Creek tended to have larger values associated with stream junctions. Rogers Creek had lower complexity associated with stream junctions. The differences between the influences of stream junctions in the watersheds may best be explained by the slope of the main channel in each of the watersheds and the residence time of debris flow deposits. This supports the hypothesis that complexity is organized at stream junctions based on stream slope at the junction and the constituent properties of the debris flow.

Material deposited by debris flows also appears to have remained stable on the valley floor longer in Turner and Elk Creeks than Rogers Creek. Ages of vegetation growing on debris deposits, including logs and boulders, were six to eight years old in some segments of Rogers Creek. The majority Elk and Turner Creek's riparian vegetation was over 25 years old, which supports the hypothesis that valley floor material was more stable in these watersheds. The difference between Elk and Turner Creeks and Rogers Creek may be that the gradual slope, and desynchronized flood flows in Turner and Elk Creeks generate less fluvial energy to transport debris flow deposited material than Rogers Creek. The water energy in Elk and Turner Creeks appears to be sufficient to scour fine sediments, such as the sand produced from the tyee sandstone erosion, away from larger objects like wood and boulders which appear to remain in place and function as complexity components. In Rogers Creek, the gradient of the streambed and apparent synchronized flood flows appear to route large debris material down stream during and after major storm events. The younger vegetation associated with stream junctions and down stream segments in Rogers Creeks indicates a "disturbance cascade" effect (Nakamura et al. 2000). The vegetation was uniformly aged suggesting that it grew as a single cohort, post disturbance. There is little evidence of recent "disturbance cascades" (Nakamura et al. 2000) in Elk or Turner Creeks based on vegetation age and depth of incision into the valley fill.

Debris flow termini segments had lower average complexity values in all three watersheds than non-debris flow termini segments. The lower values likely arise from the different debris flows runout lengths and deposition locations in each watershed.

The debris flows in Rogers Creek tended to terminate in the main channel while those in Elk and Turner Creeks tended to terminate in tributary channels on top of coalescing debris flow complexes or on old debris flow fans that allowed the flow to spread and thin on the wider surface, thereby increasing the resistance to flow. Since the majority of debris flows in Elk and Turner Creeks terminated in tributary channels, the only apparent affect was an increased load of fine sediment. These increased loads may partial fill pools and bury wood and boulders, thereby decreasing complexity. In Rogers Creek debris flow material may have been deposited directly in the main channel, filling pools and also becoming incorporated into flood flows that redistribute wood and sediment downstream. The areas heavily impacted in each watershed by debris flows in 1996 are shown in Figure 24.

Roads

Roads affect debris flows runout paths in two major ways: by providing sources of material when they fail and become incorporated into landslides or debris flows; and by slowing or stopping debris flow material due to the break in slope on the road surface (Jones et al. 2000, Wemple et al 2001). Debris flows in Rogers Creek generally by-passed or incorporated material from valley bottom roads before reaching the main channel. Valley floor roads in Elk and Turner Creeks appeared to slow or stop debris flows before they reached the main channel. The differing affects of valley floor roads may be partially explained by the lower volumes of debris flows in Elk and Turner Creeks (145 m^3 and 250 m^3), than Rogers Creek (519m^3) (Table 1). Debris flow volume may be positively correlated to runout length. This is supported by debris flow information compiled by Iverson (1997), which showed a strong positive relationship between debris flow volume and runout length. This relates well to the smaller debris flows in Elk and Turner Creeks terminating after shorter travel distances than debris flows in Rogers Creek.

Rogers Creek

Evidence such as boulder berms, sidewall scaring, and distinct accumulations of wood, suggests that recent debris flows in Rogers Creek intersected the main channel at stream junctions and continued down stream as flood surges or rafts of wood. The six to eight year old vegetation growing in the valley floor and the bole scaring on surviving large alders also support the hypothesis that flood surges and rafts of wood may have traversed parts of the main channel valley floor during the 1996 storms. This is consistent with the interpretation, as suggested by Benda (2004), that the heart shaped drainage basin of Rogers Creek watershed may cause runoff from various parts of the watershed to reach the outlet in a narrow time interval, resulting in a high flood peak. This may have led to debris flow material reaching the main channel concurrent with, or prior to full flood stage. In Rogers Creek the timing of mass movements, the main channel gradient and the watershed shape, may have led to a "cascade" of disturbance, as described in Nakamura et al. (2000). The consequence of this disturbance cascade is that material may have been transported from the active valley floor at stream junctions and then deposited in constrained segments and floodplains. This helps explain the higher complexity in constrained segments and lower complexity at stream junctions.

Turner Creek

Stream junction segments in Turner Creek exhibited significantly higher values of complexity than non-stream junction segments. The majority of the deposited material appeared to have persisted in place for decades based on adjacent vegetation ages. The major storm in 1964 may explain this phenomenon. After forest harvests in the 1950's and the historic December 1964 rain on snow event, described as "undoubtedly the most severe rainstorm to ever occur over central Oregon," may have led to substantial slope failure and subsequent debris flows (NOAA 2004; McCoy 2005). Based on the homogeneous age of the vegetation in the main stem, the 1964 event appeared to be the cause of the debris flows and subsequent new cohort of riparian vegetation. Effects of the 1964 disturbance were evident in three main ways: the depth of the coalescing debris flow complexes - three m in depth in some tributaries; logging chokers and logs with cut ends that were partially exposed in the valley fill; the homogenous age of the valley floor vegetation. The large volume of sediment in the tributaries may have led to decreased potential energy for debris flows due to a widening of the valley floor. There was little evidence for major debris flows entering the main channel in the intervening 40 years since the 1964 storms. However, there has been significant geomorphic activity, including 19 debris flows in the Turner Creek watershed recorded after the 1996 El Nino storm event (Robins et al. 1999), which is not a compleat tally since the 1999 study only included the upper half of Turner Creek. The deposits investigated during fieldwork in 2005 were stable and remained in the locations mapped in 1996 (Robins et al. 1999).

Elk Creek

Elk Creek showed no significant differences in complexity values associated with constrained segments, debris flow termini or stream junctions. There 6 hot spots in Elk Creek, 5 of which were associated with constrained segments and 3 of which were associated with stream junction segments (Table 10). The higher energy created by confined flows in constrained segments may have exhumed buried wood and boulders, thereby increasing the complexity values.

Elk Creek is an elliptical watershed having the outlet at one end of the major axis. This may cause the runoff peaks to be desynchronized over time (Benda 2004b), thus producing a smaller flood peak than a circular watershed. A smaller flood peak would produce less energy to move valley floor material. The size of debris flows in the drainage network and the valley floor roads may be responsible for keeping recent debris flow deposits away from active channel and the overall complexity values low.

Management implications

In steep Coast Range watersheds where large wood recruitment, boulder recruitment, and pool and gradient diversity are desired qualities, managing the watershed as a whole to take advantage of disturbance events is recommended.

Understanding of network-level control can be used to enhance complexity: the majority of high complexity values associated with stream junction segments in this study were related to small, less than 2 km^2 tributaries; debris flows can act as a mechanism to transport hillslope material to small tributaries and than main channels; channel constrained segments were associated with higher complexity in all watersheds. Consequently, small, steep tributaries, less the 2 km^2 in size and adjacent to narrow points in the valley floor, would be ideal locations to recruit large wood by creating larger stream protection zones and headwall retention zones. Since these tributaries are prone to debris flows and landslides, and since material delivered to the main channel has been shown to accumulate at stream junctions and/or constrained segments, they provide an opportunity to use disturbance events as a mechanism to increase in-stream complexity.

Sources of error

All the debris flows in the "recent" category were generated by the1996 storm. The storm influenced a specific set of debris flows in the three watersheds and it was a unique event in time and space. Therefore, while complexity may have a persistent relationship with debris flows, the use of the debris flows from a single storm cannot fully address this relationship. To investigate the influence of the debris flow on complexity, a longer temporal explicit dataset of the debris flow regime may result more useful than a single dataset base on one storm event.

Roads and forest harvesting have been shown to have an impact on debris flow behavior and the disturbance regime in streams (Swanson and Dyrness 1975, Snyder 2000, Jones et al. 2000, Wemple et al. 2001). A detailed analysis of road and clearcut interactions with debris flows would add to an overall understanding of hillslope/stream- complexity interactions.

There were both upslope and bottom valley roads in all three watershed whose influence was not taken into account in the study. These roads undoubtedly affected the run out volume and termination point for debris flows. Forest harvest practices in Rogers Creek differed from Elk and Turner Creeks. Rogers has been lightly managed, while both Elk and Turner Creek had regular forest harvest.

Problems with complexity

The use of the complexity metric introduces uncertainty into the results. Due to relative definition of complexity, it is difficult to compare the results to other studies since it was based on characteristics of three watersheds which may or may not be representative of the region. The locally normalized value of complexity does not allow the metric to be readily transferred to other areas. The choice of the particular field variables, the equal weighting assigned to each one and the way they were quantified determines the complexity values and causes the complexity metric to be sensitive to any changes in field data collection such as the length of the segment. A change in the segments length over which the variables were measured or even the units in which slope was recorded would change the value of complexity. Complexity is a site specific, relative metric, based on variables that may be more or less important in different regions. For example, in basalt watersheds like Rogers Creek or in much of the Cascades, boulders and steeper slopes will be much more common than in sandstone watersheds, and those variables will take on more or less relative importance. Likewise, in heavily logged forest, in-stream large wood may be relatively scarce compared to unmanaged forests and take on a greater importance in complexity and habitat.

The difficulty defining and using a metric of complexity reflects the multiple ways that complexity has been described in the literature (Sullivan et al.1987, Kershner et al. 1997, Harvey et al.1999, Horan et al. 2000, Fausch et al. 2002, Gurnell et al. 2002, Jackson and Sturm 2002, Benda et al. 2004). It is not obvious from the literature what complexity is and consequently the definition used in this study, while recognizing its flaws, is just one approach to define and use the term.

A definition of complexity using hydraulic components such as speed of flow and depth may be more easily repeatable and therefore more easily transferred to other study areas. The hydraulic parameters were not used in the definition of complexity developed for this study to maintain the simplicity of the observations and their direct function as habitat elements. A hydraulic measure of complexity may improve the definition of complexity in future studies.

Figure 24: Confined segment illustrating CWD and boulder accumulations due to the valley constraint.

Table 13: Hypothesized controls on complexity by watershed. The "√" indicates the average values of complexity were statistically from the remainder of the population.

	Stream Junction	Constrained	Debris Flow Termini
Rogers	-	√	√
Turner	√	-	-
Elk	-	-	-

Conclusion

This study provides insight in to how network-level controls influence in-stream complexity in the Oregon Coast Range. This study is novel in that it attempts to relate stream junctions, channel constraint, and debris flows to a new metric of in-stream complexity developed for this study. Patterns of complexity affected by channel constraint, stream junctions and debris flows vary between watersheds, however the highest complexity values tend to be associated with stream junctions and constrained segments. Differing geology may affect which network control influences complexity the most; in the basalt watershed, complexity was influenced most strongly by constrained segments while in sandstone watersheds complexity is more likely to be influenced by stream junctions. While the definition of complexity is sensitive to changes in the relative abundance of its components, the significance of network-level controls on in-stream patterns of wood, pools and boulders is relevant to other watersheds in this region. In areas where debris flows are a dominant disturbance process, channel constraint and stream junction environments are important locations for structural diversity and habitat complexity.

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