Assessment of Connectivity within a Recently Burned Basin

By

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Human populations have continued their unrelenting expansion into the wildland-urban interface and in locales which are prone to wildfire, the risk of secondary hazards associated with wildfires such as debris flows and flooding are increasing. While the implications of wildfire for the transport of sediment and surface runoff within burned areas are not agreed upon in consensus, many researchers believe an important, currently understudied aspect is the level of connectivity within the landscape. Connectivity refers to the extent to which water and sediment are or have the potential to be transferred within or between landscape compartments. The current study is designed to quantitatively capture transported sediment, assessing the level of (dis)connectivity within a recently burned basin.

Two surveys were conducted on 28-30 September 2008 (baseline topography pre-rainfall conditions) and 18-21 December 2008 (topography three days after 52mm of rainfall over a period of 22 hours) with the aid of a terrestrial laser scanner. Point clouds from the scanning sessions were used to produce 1 cm resolution DTM capturing pre- and post-rainfall topography. D-8 hydrologic networks were generated in Arc Map and used for the delineation of seven rill-gully threads (RGTs). The seven RGTs were analyzed for their pattern of deposition and erosion and their upslope contributing area sediment input.

Sediment transport was found to not be consistent for each of the RGTs and large depositional areas warranted labeling the RGTs as disconnective. We also concluded that hollows are a significant component for the connectivity of burned basins based on their importance for the routing and storage of dry ravel.

Functional and Structural Sediment Connectivity within a Recently Burned Basin

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INTRODUCTION

The threat of wildfires to human populations, infrastructure, and natural resources is a growing problem in fire prone areas, both in the United States and globally. Recent rapid development of residential areas in the wildland-urban interface has increased the risk for direct (fire) and secondary hazards (rockfall, and inundation by flooding, hyper-concentrated flow, and debris flow) associated with wildfires (Fig 1). Secondary hazards associated with wildfire are often a direct result of changes in the levels and patterns of sediment transport within recently burned watersheds. For instance, burning by wildfire reduces soil infiltration rates (Shakesby and Doerr, 2006). Lowering of soil infiltration rate increases overland flow, escalating the amount of sediment that can be progressively entrained and transported within and out of the burned basin. Enhanced overland flow also expands rill and gully networks. This increases the connection of various flow pathways, which provide a positive feedback mechanism leading to greater efficiencies of sediment removal and water transfer throughout a basin. These changes increase the risk for secondary hazards, which have the potential to produce significant loss of life and infrastructure (Cannon and Gartner, 2005).

Figure 1. An example of wildland-urban interface development in the greater Los Angeles area (left). Damage and inundation from a debris flow, La Canada Flintridge, California, winter of 2009-2010 (photo courtesy of Robert Leeper, USGS) (right).

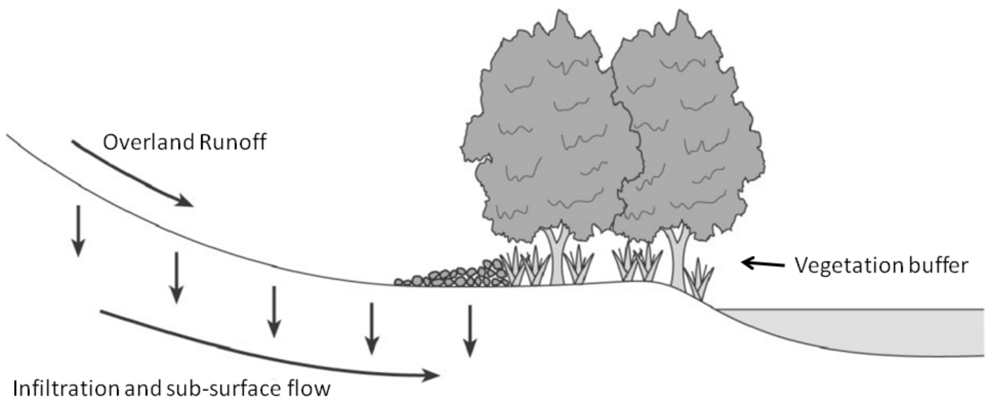


Figure 2. Example of a landscape where a riparian vegetation buffer limits sediment and overland water runoff connectivity. Adapted from Bracken and Croke (2007).

Vegetation represents a roughness component that intercepts rainfall within watershed. The roughness component limits sediment detachment, overland surface runoff and sediment transport, which ultimately limits connectivity (Fig. 2). Partial or total removal of vegetation within a watershed by wildfire, depending on burn severity, can significantly enhance surface runoff, sediment detachment, and sediment transport thereby increasing landscape connectivity and the potential for the initiation of secondary wildfire hazards (Shakesby and Doerr, 2006; Moody and Martin, 2009). Therefore, it is scientifically important to advance our understanding of landscape connectivity in recently burned watersheds and advance knowledge of how floods, hyperconcentrated flows, landslides, and debris flows initiate and propagate within and throughout recently burned basin systems. Findings from studies using connectivity as a research lens have potential applied merit as the scientific information can be integrated into the decision-making process of flood and debris flow early warning systems, thereby reducing the occurrence of false-positive warnings in communities located within the wildland-urban interface.

At present, no study has addressed the issue of connectivity within a recently burned watershed. In fact, the connectivity literature, from which this study finds its conceptual underpinnings, has yet to consider the measurement of connectivity within geomorphology by using appropriate real world datasets. Even so, connectivity has continued to grow as a concept; encompassing disciplines such as hydrology, geomorphology, and ecology. Research concerned with connectivity has mainly been devoted to developing and discussing a conceptual framework as well as promoting a common vocabulary to be used across a variety of disciplines. Recent examples and syntheses of connectivity are highlighted by the works of Turnbull et al. (2008), Ali and Roy (2009) and Wainwright et al. (2011). These articles are based on earlier attempts to define connectivity by developing common terminology and conceptual framework (Brierly et al., 2006; Bracken and Croke, 2007; Fryirs et al. 2007). Much like research within the broader field of connectivity, connectivity research within geomorphology has been limited to discussions of vocabulary and conceptual ideas of connectivity. Very few studies have developed concrete measures of connectivity from field experiments. This has hindered the validation of these conceptual models of landscape connectivity and disallowed an appropriate view of what landscape connectivity looks like in the real world.

The field-based studies described within this thesis examine a single component of connectivity, sedimentological connectivity within a recently burned basin with the aid of high resolution Digital Terrain Models (DTM) developed from terrestrial laser scanner surveys before and after the first major rainfall event. DTM differencing and other Geographical Information Systems (GIS) analyses provide specific insights to the spatial and temporal variation of sediment transport within and between the rills and gullies in a recently burned basin. Much of the conceptual understanding from previous research of the changes in recently burned basins is a synthesis of plot-scale research, field observations and/or coarse-scale sediment yield studies. The current study expands this knowledge by capturing detailed information on sediment transport along rills and gullies during the same event. This basin-wide analysis can help the scientific community by using accurate field evidence for sediment transport and begin to assess the conceptual understanding of connectivity.

Objectives

This research attempts to examine the spatial patterns of sedimentological connectivity within a recently burned watershed. A series of sub-basins will be used to determine the extent to which sediment transport varies spatially within and between the rills and gullies of a burned basin. Sedimentological connectivity will then be considered in the context of morphometric variations, contributing upslope sediment volumes, and sediment deposition and erosion along the drainage network. Items such as channel constrictions, channel confluences, channel expansion, knickpoints, dry ravel, variations in upslope contributing sediment, and the spatial patterns of deposition and erosion will be used to evaluate the role geomorphological variations in the level of sedimentological connectivity.

Significance

This research investigates a unique aspect of connectivity, which has not been investigated to date. The current study makes novel use of high resolution basin wide DTMs that capture topographic changes (erosion and deposition) after the basin has been recently burned and immediately after the first rain event. The first significant rain event in a recently burned basin presents the potential for large movements of sediment throughout a drainage basin and the most likely time for mass wasting events related to the fire to occur. The resolution and extent of the dataset not only provides a view of network feature from within each landscape compartment, but also the manner in which the landscape compartments are connected. This is a significant scientific advancement as it moves beyond the traditional point-based (plots or gauge sites) and cross-sectional analyses that have advanced our understanding of sediment transport in recently burned watersheds to date.

CHAPTER 1

Introduction

Recently, the term connectivity has gained traction within geomorphological research. Brierley et al. (2006) and Bracken and Croke (2007) have synthesized various aspects of this literature in an attempt to build succinct definitions, common terminology, and conceptual frameworks that encompass a wide range of geomorphic processes and environmental settings. The transfer of energy and matter between individual landscape compartments or within a system is commonly referred to as connectivity (Fryirs et al., 2007). Three types of connectivity are more commonly described in geomorphology and hydrology: (1) landscape connectivity (physical coupling of landforms [e.g. hillslope to channel] within a drainage basin); (2) hydrological connectivity (the passage of water from one part of the landscape to another and ultimately through the drainage basin); and (3) sedimentological connectivity (physical transfer of sediments through the drainage basin) (Bracken and Croke, 2007). However, recent evolution in connectivity discourse highlight the need for condensing connectivity approaches both within and between the disciplines of ecology, hydrology and geomorphology (Turnbull et al., 2008; Ali and Roy, 2009; Wainwright et al., 2011).

Wainwright et al. (2011) recently provided a broader interdisciplinary contextual framework for connectivity research. Structural and functional connectivity were proposed as universal terms in an attempt to communicate and discuss connectivity research within and between the fields of ecology, hydrology and geomorphology. Structural connectivity describes (at multiple spatial scales) the extent to which landscape units are linked. Functional connectivity accounts for the way in which the multiple structural characteristics of the system in question affect geomorphic, ecologic, and hydrologic processes. Here, the terms structural and functional connectivity are adopted to detail water and sediment transport (erosion and deposition) within and between landscape compartments of recently burned watersheds.

Scientific and Applied Significance of Connectivity to Recently Burned Basins

The threat of wildfires to human populations, infrastructure, and natural resources is a growing problem in fire prone areas in the United States and globally. Recent rapid development of residential areas within the wildland-urban interface has increased the risk for direct (fire) and secondary hazards (rockfall, and inundation by flooding, hyper-concentrated flow and debris flow) associated with wildfires (Cannon and Gartner, 2005). From a geomorphic perspective, many of the issues surrounding the understanding of secondary wildfire hazards center on the functional and structural connectivity of a burned landscape. In an unburned watershed, vegetation represents a roughness component that intercepts rainfall, reduces sediment detachment, decreases or slows surface runoff, and reduces sediment transport. Partial or total removal of vegetation (depending on burn severity) can significantly enhance surface runoff, sediment detachment, and sediment transport (Shakesby and Doerr, 2006; Moody and Martin, 2009). The potential for increased efficiency of water and sediment flow down and out of the basin can heighten the risk for inundation by flash flooding and mass wasting in areas downstream of burned basins. Therefore, it is scientifically important to enhance our understanding of landscape connectivity within recently burned watersheds to advance knowledge of how floods, hyperconcentrated flows, landslides, and debris flows initiate and propagate throughout the system. Scientific results can be integrated into the decision-making process of flood and debris flow early warning systems and reducing the number of false-positive warnings in communities located in the wildland-urban interface.

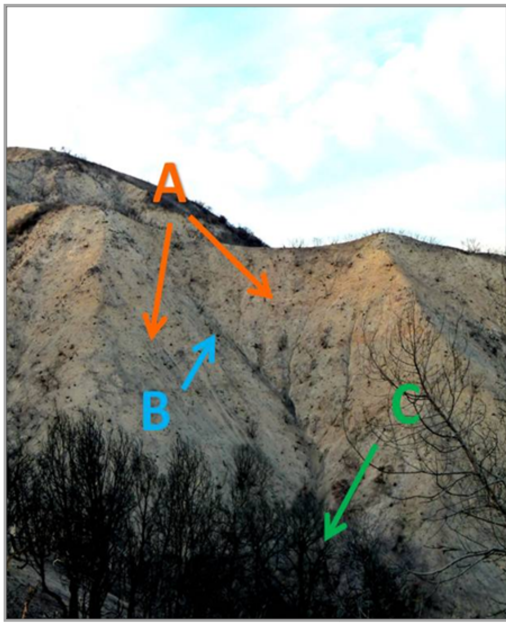
At present, no study has addressed connectivity within a recently burned watershed. The broader scientific community has focused on the development of conceptual ideas and common vocabularies associated with connectivity. The field experiments in recently burned basins have been limited to small plot based analyses within burned basins or coarse scale analyses that do not address the spatial dynamism of sediment transport or linkages between the two scales of analysis (Martin and Moody, 2001; Kinner and Moody, 2008; Moody et al., 2008). Studies at the plot-scale focus on a single landscape compartment that often offers only limited understanding of the overall connection that exists across the landscape compartment. Dynamism across the various landscape compartments often leads to large events that impact society and promote significant changes to the geomorphic system. Basin-scale studies frequently focus on sediment yields from an individual basin. Sediment yield studies tend to amalgamate the process-response within the landscape compartments, which limits the explanatory power of this type of approach. The previously described fine- and coarse-scale approaches to research in recently burned basins have hindered validation of conceptual models of debris flow initiation after wildfires and limited geomorphologist's and engineer's ability to comprehend basin-scale and regional emergent patterns of flood and sediment dynamics.

Objectives

The goal of this review paper is to place sediment transport and surface hydrology in recently burned watersheds into the context of the connectivity literature. This is accomplished in three parts. The critical review begins with an assessment of the functional and structural connectivity literature in unburned drainage basins. Next, a general review of impact of wildfires on the hydrologic and sedimentologic characteristics a drainage basin. Lastly, the connectivity literature from unburned basins and details from wildfire geomorphology literature are melded to provide a current understanding of functional and structural connectivity in recently burned basins. This endeavor will provide an important context for subsequent work related to ecologic, hydrologic, and geomorphologic research in recently burned basins.

Structural Connectivity within a drainage basin

Structural connectivity focuses on the extent to which landscape units are contiguous or physically linked to one another (With et al., 1997; Tischendorf and Fahrig, 2000; Turnbull et al., 2008; Wainwright et al., 2011). Structural connectivity in geomorphology has often been used to describe the configuration of a catchment and the coupling of landscape compartments. The vast majority of the research would not have specifically identified the term structural connectivity, but fits in the broader confines of the definitions provided in this manuscript. Within the context of recently burned basins in steep topography, the landscape can be divided into three distinct compartments: hillslope, hollow, and channel (Fig. 3).



Landscape Compartment	Features	Processes
A. Hillslope	Rill and interrill areas, flat or convex surfaces	Rainsplash, Infiltration, sediment detachment and transport, dry raveling, sediment deposition, gravity and wind induced grain flow.
B. Hollow	Gullies, shallow landslide scarp and deposit, colluvium deposits, dry ravel deposits	Gully erosion, sediment transport and deposition.
C. Channel	Knickpoints, Bedrock channel Confinement, step-pool features, colluvial and alluvial deposits	Channel erosion and deposition, sediment transport.

Figure 3. Conceptual model of structural (features) and functional (processes) connectivity within the three landscape compartments.

Structural Connectivity of the Hillslope

Structural connectivity is initiated at the drainage divide, but becomes more pronounced along rill networks, inter-rill locations, and planar hillslope surfaces. Beneath the drainage divide, planar hillslopes or rill networks connect surface and subsurface runoff as well as sediment transport. Planar hillslopes are often composed of thicker deposits of colluviums with relatively low surface roughness. Rills often exhibit parallel, sub-parallel, dendritic patterns, or a combination thereof. These broad morphological differences often lead to variations in rill density, geometry, confluence characteristics, and channel shapes, which are influenced by the angle and curvature of slopes (Schumm et al., 1987; Phillips and Schumm, 1987). Also, rill geometry likely varies by soil type, although no precise relationships have been shown to exist (Brunton and Bryan, 2000). Regardless of the features that exist within the hillslope (rills, planar surfaces, inter-rill), in particularly steep terrain, the hillslope may also be structurally connected via the overarching gradient found in the upper portion of the watershed. In this scenario, sediment transport along the features if often superseded by ravel processes that is independent of the underlying features.

Structural Connectivity of the Hollow

The coarse-scale form of a hollow is spoon shaped, which forces the convergence of colluvial material and water downslope (Dietrich et al., 1986). The convergent topography can consist of either an unchannelized surface or a gully that is connected to some combination of the hillslope features. Hollows represent transition areas between the hillslopes and channel compartments making them important components for the routing of sediment from the hillslope to the channel. Hollows in vegetated basins range in form from un-channelized concavities to more pronounced depressions that are prone to major landslide and debris flow events (Dietrich et al., 1986). Gullies are the predominant topographic features within hollows. Gullies are the direct result of concentrated runoff and erosion that can result from localized processes within the hollow, but often are connected to the rill networks within the hillslope compartment (Hyde et al., 2007). As the rill networks develop in the hillslope compartment, there is greater connectivity with the gully and this often results in the vertical and horizontal expansion of the gullies (Moody and Kinner, 2006). The rill-gully transition is either gradual or sharp, depending on the presence of a buried obstruction (Parrett et al., 2004). Gullies widen and deepen rapidly as a likely result of positive feedbacks between gully cross-sectional and profile characteristics. Much like rills, landscape position is also a factor in where gullies are located. Power-law relationships generally exist between gully head location and slope and contributing area (Gabet and Bookter, 2008).

Structural Connectivity of the Channel

The main channel reach within small basins can be defined as low order streams that are broadly classified as headwater streams (HWS). HWS channels are commonly bordered by steep slopes and rock walls. Steep side slopes adjacent to channels typically reflect high rates of stream incision, relative to surrounding topography (Kelsey, 1980). They may also contribute a significant amount of colluvial material to sections of the channel producing a reach that is dominated by colluvium (Wasklewicz and Hattanji, 2009). However, stream beds may also be bound by bedrock, which leads to episodes of cutting and filling during large runoff events and debris flows. Many HWS are characterized by some combination of alternating colluvium and bedrock reaches along the extent of the basin. HWS may also contain reaches that are solely colluvium dominated or bedrock dominated, depending on the environmental setting. Stepped-bed topography is a predominant feature of many HWS. The step or riser is often formed from bedrock, interlocked cobbles and boulders, or large woody debris. The steps vary as a function of sediment supply, larger substrate, exposed bedrock (kickpoints, bedrock confinement), and woody debris (Montgomery and Buffington 1998, Halwas and Church 2002, Gomi et al., 2002). Stepped-bed topography may be a fairly consistent feature along the extent of the HWS, existing as distinct, discontinuous knickpoints along the channel, or exhibiting a combination of the two (Hayakawa and Oguchi, 2009).

Functional Connectivity within a Drainage Basin

Functional connectivity is the interaction of the multiple structural characteristics of the system in question with geomorphic, ecologic and hydrologic processes (With et al., 1997; Tischendorf and Fahrig, 2000; Turnbull et al., 2008; Wainwright et al., 2011). In geomorphic research, functional connectivity has been defined as the individual processes that actively provide connectivity within or between landscape compartments. Functional connectivity is altered and being altered by the structural connectivity of the geomorphic system.

Functional Connectivity of the Hillslope

Functional connectivity within the hillslope compartment predominantly occurs along rill networks and is a result of slow slope processes and surface runoff. Slope steepness is often a factor contributing to rill growth and rill network evolution (Yao et al., 2008). Steeper hillslopes have greater surface roughness (Abrahams and Parsons, 1990). An increase in roughness promotes flow concentration, which in turn increases the velocity and transport capacity of surface runoff, thereby increasing the amount of erosion. Physical modeling experiments also indicate that steeper slopes generate higher flow velocities at the point of rill initiation (Yao et al., 2008). The higher rates of erosion associated with increases in slope, roughness, and velocity enhance connectivity. Both short- and long-term development of the rill networks further couple the hillslope to other landscape compartments and establish well developed rill networks within the hillslope compartment.

Rill network location within the hillslope represents another important aspect of functional connectivity. The spatial location of rill networks change as rills expand towards the drainage divide or connect with other rill networks via cross-grading. Location of the rill network on the hillslope is considered an important factor for the initiation of connectivity of matter within and out of the hillslope compartment. Rills located closer to the drainage divide do not receive as much overland flow. In this scenario, flow concentration is greatly reduced and sediment transport decreases as a result, which means the rill network is transport-limited (Bracken and Croke, 2007). Rills located farther from the drainage divide may have greater upslope contributing areas and steeper slopes allowing greater transport of overland flow and sediment into a hollow or directly into the channel.

In forested landscapes, slow slope processes provide a level of functional connectivity between rain events. Soil creep, debris creep, frost debris creep, frost heave, needle ice, slow solifluction, congeliflluction and biological slope processes provide the means for material to move downslope without the aid of overland flow (Young, 1972). In particularly steep or arid locations, the process of dry raveling may also provide additional precipitation independent sediment movement without precipitation (Gabet, 2003; Mayor et al., 2007). Dry raveling refers to the downslope movement of individual particles by sliding, rolling, or bouncing (Gabet, 2003). The majority of dry ravel begins as sediment located on steep slopes, which are often found in the hillslope compartment, making the sediment particularly vulnerable to mobilization by non-precipitation external forces. Factors contributing to mobilization of dry ravel include gravitational forces, wind, vibrations from external sources (e.g. vehicular traffic, airplanes), bioturbation, and impulsive loading from other transported particles (Gabet, 2003; Fu, 2004). Dry raveling initiated within the hillslope compartment can be deposited in the hillslope, hollow, or channel.

All of the factors discussed above can enhance the connectivity of the hillslope landscape compartment; however, in most basins vegetation acts as a basin-wide buffer inhibiting connectivity (Bracken and Croke, 2007). Vegetation improves soil stability, increases basin water storage capacity, provides sediment storage upslope of vegetation stems and trunks, and shields sediment mantled slopes from rain droplet impact (Florsheim et al., 1991; Moody and Martin, 2001; Shakesby and Doerr, 2006). In this way, overland flow and sediment instability is limited, thereby reducing the level of sediment and water connection within forested basins.

Functional Connectivity of the Hollow

Functionally, hollows experience slow, continuous movement of colluvium or soil via creep as well as rapid, discontinuous erosion via raveling, landslides, and/or debris flows (Hack and Goodlett, 1960; Dietrich and Dunne, 1978; Dietrich el al., 1986). Convergent surface topography promotes sediment deposition from both slow slope processes and dry raveling. As a result, the hollow tends to develop a thick mantel of colluvial deposits (Reneau et al., 1984; Dietrich et al., 1986).

The evacuation of sediment and establishment of functional connectivity within the hollow compartment occur when the resultant thick mantle of colluvium is evacuated by landslide, alluvium transported by surface runoff in the gully, and/or debris flow (Dietrich et al., 1986). Landslides occur most commonly within the hollow compartment. The frequency of landslides varies, but is generally thought to be controlled by the rate of colluvial accretion within the hollow. A landslide is more likely once sediment within the hollow reaches a threshold depth (Shimokawa, 1984). Revegetation on the landslide scar is important for reestablishing accumulation within the hollow (Lehre, 1982).

In addition to landsliding, gully erosion within the hollow can also establish functional connectivity by removing stored sediment within the hollow. Gullies are areas frequently impacted from debris flows, which can scour the hollow to bedrock (Dietrich et al., 1986). Debris flows can initiate from shallow landslides or might also develop from levee-lined rills (Reneau and Dietrich, 1987).

There are multiple interconnected processes and events that operate within the hollow. A strong linkage between the hollow and the hillslope compartment is evident. Gully morphometry is frequently modified by sediment transport from both surface runoff and mass wasting. The variety of events that modify hollows make this compartment particularly important to the (dis)connectivity of the landscape as a large portion of sediment is routed through and/or produced within this compartment.

Functional Connectivity of the Channel

The initiation of functional connectivity (erosion and transport) within low order HWS is largely contingent upon the amount and intensity of precipitation, the texture and depth of soil, the steepness of the slope, and the type and density of vegetation (May, 2007). When rainfall generates overland flow within a HWS, it becomes dominated by patterns of scour and fill. Scour and fill refer to the vertical fluctuations of alluvial stream-beds that occur in response to the entrainment (scour) and deposition (fill) of bed-material during flood events (Powell et al., 2007). Much of the variability in the magnitude of stream-bed scour can be accounted for by the magnitude of the flood (Lekach and Schick, 1983; Wohl et al., 2004; Powell et al., 2007). Although limited research has been conducted on the pattern of scour and fill in HWS, data collected by Leopold et al. (1966) suggests that the stream bed is scoured during the rising flood stages and that fill is initiated during the falling stages, thus maintaining an approximate balance.

Steep mountain HWS can be divided into cascade, step-pool and plane-bed channel morphologies (Grant et al., 1990; Montgomery and Buffington, 1997). Cascade morphologies are characterized by tumbling flow over individual randomly arranged clasts; step-pool channels have a consistent step and pool morphology; and plane-beds have no distinctive variations along the bed of the HWS (Montgomery and Buffington, 1997).

HWS reflect a mix of hillslope and channel processes because of their close proximity to sediment source areas originating within both the hillslope and hollow compartments (Benda et al., 2005). In the event of a mass movement, functional connectivity is established with the influx of sediment and woody debris from episodic landslides, debris flows and gully erosion, and this directly affects the morphological characteristics of HWS in steep mountainous regions (Dietrich and Dunne, 1978; Benda and Cundy, 1990; Whiting and Bradley, 1993; May, 2007). The initiation locations and deposition of landslide mass movements often both occur within headwater systems and this affects the accumulation and distribution of woody debris within the channel (Sidle et al. 1985). The cause of mass movements which impact HWS varies, but typically are a result of either shallow landslides which can mobilize into debris flows, or channelized alluvial erosion which progressively entrains sediment from the walls of the channel until it becomes either hyper-concentrated or a debris carrying flow.

The functional connectivity of the channel compartment is greatly dependent upon contributions from slopes above. Channel morphometry is often modified by the upslope input of surface runoff and sediment influx via relatively low frequency high magnitude mass movements. The functional connectivity of the channel compartment is of particular importance to the connectivity of the landscape as the channel represents a local maximum of sediment and surface runoff input.

Sedimentologic and Hydrologic Effects of Wildfire

Wildfires promote significant hydrologic and geomorphical landscape change (Shakesby, Doerr, 2006). Wildfires accelerate rock weathering (Shakesby and Dooer, 2006; Blackwelder, 1927), remove vegetation and litter cover (Shakesby and Dooer, 2006; Moody and Martin, 2001), produce changes in microbial and faunal activity (Shakesby and Dooer, 2006), and change the hydrological properties of soil (Shakesby and Dooer, 2006; DeBano, 1981). Typically, wildfires enhance hydrologic and sedimentologic change during a "window of disturbance," which begins immediately after the wildfire with the potential to last several years (Prosser and Williams, 1998). Moody and Martin (2001) measured 150-240-fold increases in sediment yield over four years on burned hillslopes in comparison to similar unburned slopes with 42 percent of the sediment yield coming in the first year after the wildfire. Of the physical disturbances brought on by wildfire, the greatest impact on sediment movement and hydrological variations are the removal of vegetation, litter cover and creation of soil water repellency.

Fire severity is of initial importance as it acts as a control on the extent to which vegetation and litter is removed and the degree to which soil becomes water repellent (Rubio et al., 1997). Burn severity is a function of duration (length of time burning at a single point), intensity and the characteristics of the biomass, soil, terrain and local climate (Shakesby and Dooer, 2006). Both low to moderate fire severities typically burn ground fuels and shrubs of less than 4m in height whereas high to extreme fire severities typically consume all vegetation and woody debris up to 40m in height.

The consumption of vegetation and litter has a number of implications on basin hydrology and sediment movement. The removal of vegetation and ground litter leaves soils prone to raindrop impact. A rain drop impacting the exposed soil surface detaches soil particles and makes them susceptible to erosion via overland flow processes. In severely burned watersheds, rainsplash can play a significant role in the net down-slope migration of fine sediments (Shakesby et al., 2003). However, there is a greater propensity for overland flow (interrill erosion) and concentration of overland flow into rill networks which dominate the hillslope erosion processes. As the spatial extent and amount of surface runoff increases, the flux of water and sediment results in the longitudinal, lateral and vertical expansion of the pre-existing drainage network (Moody and Kinner, 2006).

Reductions in litter and vegetation cover also reduce the opportunities for rainfall storage, increasing the probability of erosive overland flow. Rainsplash soil detachment and the reduction of basin water storage capacity are considered by many researchers to be the most important factors for increased levels of post fire erosion (White and Wells, 1979; Wells, 1981; Dieckmann et al., 1992; Inbar et al., 1998). Other research, however, has pointed to the significance of dry ravel in sediment yields from burned slopes (Shakesby and Doerr, 2006). Before the wildfire, dry ravel can account for more than half of a basins sediment budget (Krammes, 1965; Rice, 1974). After the fire, the rate of dry ravel has been reported to increase 9 (Krammes, 1965) to 13 (Rice, 1974) fold. Typically, the consumption of vegetation stalks by wildfire initiates the downslope movement of the previously stored sediment, where it accumulates in irregularities in hillslopes and channels during dry conditions (Wondzell and King, 2003) and is transported downstream during subsequent overland flow producing rain events (DeBano and Conrad, 1976; Florsheim et al., 1991). In one example, two-thirds of the total yearly sediment budget was eroded as dry ravel within the first 24 hours after the fire (Bennett, 1982).

Wildfire also alters the infiltration rate of soil within recently burned basins in comparison with similar unburned areas (Martin and Moody, 2001). As stated previously, fire severity controls the extent to which litter and vegetation are consumed and removed from the surface, thus affecting the availability of water for overland flow. In areas of low fire severity, infiltration rates and water storage are relatively high in comparison with areas of high burn severity where vegetation and litter cover are more completely removed (Rubio et al., 1997). The reasons for the reduction of water infiltration vary. Researchers have cited: fusing of the soil surface and soil water repellency, sealing of pores by fine soil and ash particles (Campbell et al., 1977; Morin and Benyamini, 1977; Wells et al., 1979; Lavee et al., 1995; Neary et al., 1999), development of fungal crust (Lavee et al., 1995), rain droplet compaction (Wells et al., 1979) and increased seasonal soil freezing following wildfires (Campbell et al., 1977) as reasons for the measured reduction of water infiltration. More recently, water repellency via chemical changes to soil properties has been determined to be a main cause in the reduction of infiltration within recently burned basins (Moody and Martin, 2001; Shakesby and Doerr, 2006).

Structural and Functional Connectivity within a Recently Burned Basin

At present, no study has addressed the concepts of structural or functional connectivity within a recently burned basin. Numerous studies have examined components of hydrological, sedimentological, and landscape connectivity as highlighted in the previous review. The following section integrates findings from previous studies and field observations to present the current state of knowledge regarding functional and structural connectivity within the three previously described landscape compartments of a recently burned basin.

Structural Connectivity within a Recently Burned Basin

Structural Connectivity of the Hillslope

Wildfire alters significantly the structural connectivity of the hillslope landscape compartment. For both rill development and slow slope processes, the hillslope represents a transport surface with varying degrees of roughness depending on the drainage density, bedrock exposure, levels of vegetation and exposed particles on the surface. Slope impacts roughness and in turn impacts the transport efficiency of the surface. For slow slope processes, surface roughness is reduced in burned basins where vegetation is consumed by wildfire and this increases the potential for sediment to move between landscape compartments without rainfall or become more readily available for transport during rainfall.

Rill networks are instrumental for the transport of water and sediment within the hillslope compartment, and after a basin has been burned, extensive rill systems can develop (particularly on steep and water-repellent slopes) in response to the smallest of flow concentrations (Hyde et al., 2007; Doehring, 1968; Wells et al., 1987). Rills in burned basins have been observed to follow two spatial patterns; either draining planar surfaces in nearly a parallel pattern or by funneling water into a first order stream in groups of three to six converging rills (Moody and Kinner, 2006). Moreover, the increased flux of runoff and sediment within burned basins results in the longitudinal, lateral and vertical expansion of the pre-existing drainage network (Moody and Kinner, 2006).

After the wildfire, the expansion of rill networks within the hillslope increases the potential for water and sediment to be transported downslope and into the hollow and channel compartments. The extensive structural growth of rill networks increases the channelization of water and sediment on the hillslope, enhancing the structural connectedness between the hollow and channel compartments and their upslope contributing areas within the hillslope.

Structural Connectivity of the Hollow

The coupling of rill networks to a gully or previously un-channelized hollow is enhanced after a wildfire event (Gabet and Bookter, 2008). Moody and Kinner (2006) found that gullies in recently burned basins required less contributing area for gully initiation than in unburned conditions. This was primarily a result of an increase in rill-gully connectedness. Gullies are the direct result of concentrated runoff and erosion that can result from localized processes within the hollow, but often are connected to the rill networks within the hillslope compartment (Hyde et al., 2007). As the rill networks develop in the hillslope compartment, there is greater connectivity with the gully and this often results in the vertical and horizontal expansion of the gullies (Moody and Kinner, 2006). The rill-gully transition is either gradual or sharp if a buried obstruction is present (Parrett et al., 2004). Gullies widen and deepen rapidly after this point as result of positive feedbacks between gully cross-sectional and profile characteristics. Gullies in burned basins are often characterized by u-shaped cross-sections indicative of debris flows (Gabet and Bookter, 2008). Furthermore, gullies in burned basins typically expand their width:depth ratio since debris flows can accumulate mass by eroding the banks and bed of the gully.

Structural Connectivity of the Channel

Structurally, channels respond to wildfire disturbance mechanisms in a variety of ways (Shakeby and Doerr, 2006). The scale of the stream has a great deal to do with the response (Keller et al., 1997). Relatively little buffering exists between the hillslope and channel after a wildfire and the potential exists for episodically high sediment yields and substantial channel change (Wohl and Merritt, 2008). Channel changes related to the wildfire run the spectrum from channel aggradation or degradation (Florsheim et al., 1991), to channel narrowing (Germanski and Miller, 1995), to development of alluvial fans and tributary fans (Meyer and Wells, 1997). The wide range of responses are typical for coupled hillslope-channel systems where mass wasting events are interspersed with smaller fluvial events (Hattanji and Onda 2004; Golden and Springer 2006). Variations in the supply of sediment from tributary to trunk streams, as is typical in burned basins, alter the larger fluvial systems, and these changes are reverberated back through the tributaries (White and Wells, 1982).

While channels can experience significant deposition and erosion of material as a result wildfire disturbance, the coarser scale features of the channel (step-topography) change relatively little in response to the wildfire. In the event of large floods or debris flows, coarse material carried within the channel may result in slight bedrock modifications (Stock et al., 2005), but broad scale structural features typically remain intact.

Functional Connectivity within a Recently Burned Basin

Functional Connectivity of the Hillslope

The functional connectivity of rill networks, inter-rill locations, and the surfaces between the drainage divide and rills within the hillslope compartment can be heavily affected within recently burned basins. Of initial importance, immediately after the wildfire, is a dramatic increase in sediment flux rates, and dry raveling contributes substantially to this (Gabet, 2003; Shakesby and Doerr, 2006; Gabet and Sternberg, 2008). Dry ravel and other precipitation independent sediment movement takes place during and immediately following wildfire. Material stored in wedges upslope of trees and shrubs may be mobilized when the supporting vegetative mass is consumed (Florsheim et al., 1991; Gabet, 2003). Dry raveling may also be considered a product of the loss of soil cohesion, which occurs during wildfire (Gabet, 2003; Shakesby and Doerr, 2006). Decreases in soil cohesion have been attributed to losses in organic matter during wildfire, and changes in soil moisture content. Where slopes are steep, the decrease in soil cohesion makes particles vulnerable to mobilization from external forces.

Rain events often lead to overland flow in recently burned basins. Rills constitute the main hillslope fluvial feature conveying these flows. Pierson et al. (2008) have shown ground-cover reduction enhances the ability of overland flow to concentrate and form rills. Flow concentration often promotes headward migration, which leads to significant delivery of sediment from the hillslopes (Brunton and Bryan, 2000). Furthermore, Osborn et al. (1964) found rill production to be more likely on water repellent soils, similar to those found in burned basins.

In burned basins rill formation follows well defined stages. During rainfall, wettable soil becomes saturated resulting in soil failure and movement downslope in a miniature debris flow (eg. Wells, 1981; Gabet, 2003). Subsequently, adjacent overland flow is rerouted into the mini-debris flow scour where it further erodes sediment within the newly formed rill channel (Debano, 2000). Sediment transport rates frequently increase rapidly once the rills develop and as the rill network expands these rates continue to increase (Loch and Donnellan, 1983). Sediment and water conveyance as the rill network evolves is an important factor in initiating connectivity (Gabet and Bookter, 2008).

Functional Connectivity of the Hollow

The increased amount, rate, and timing of water and sediment transport from the hillslope compartment after a wildfire enhances connectivity within the hollow compartment. Functionally, hollows in burned basins receive increased levels of dry ravel deposits immediately following the wildfire and this can continue until vegetation reestablishes along the hillslopes. Sediment sources for the colluvial fill range from elevated levels of dry ravel during and after the burn (Gabet, 2003; Shakesby and Doerr, 2006; Gabet and Sternberg, 2008), to fine particles which are transported along the rill and gully networks and temporarily stored within the hollow (Moody and Kinner, 2006; Gabet and Bookter, 2008). The colluvial fill within the hollow is more readily available for transport after wildfire (Hyde et al., 2007).

Evacuation of stored sediment within the hollow may occur slowly by surface runoff within burned basins, but often debris flows remove large quantities of stored material quickly and act as an important means of delivering colluviums, which has been built up by dry ravel and other slow slope processes (Florshiem et al., 1991). Although debris flow processes in burned basins are complicated, variable, and not completely understood (Shakesby and Doerr, 2006) it is likely that the enhanced coupling of hillslope to hollow (rill to gully) found in burned basins promotes greater overland flow and erosion to the hollow compartment (Moody and Kinner, 2006). The enhanced flow and erosion permit channelized flows to gradually increase the amount of sediment in the hillslope runoff by scouring the bed and banks of the gully to a point where the dilute flow from the hillslope transforms into a debris flow (Gabet and Bookter, 2008). The influence of connectivity upon debris flows in recently burned watersheds is further highlighted within the functional connectivity of the channel compartment section.

Functional Connectivity of the Channel

Channels respond to wildfire disturbance mechanisms in a variety of ways, but are typically restrained by the characteristics of soil and vegetation, basins steepness, and burn severity (Shakeby and Doerr, 2006). Many of the hydrological studies conducted at the catchment-scale have focused on comparisons of the amount of discharge from burned versus unburned basins (Shakesby and Doerr, 2006). The majority of studies show significantly larger amounts of runoff from the burned basins, with peak-floods particularly sensitive to wildfire disturbances (Martin and Moody, 2001). Peak-flood magnitudes were greater and the response time shorter when compared with similar sized unburned basins (Robichaud et al., 2000). The effects of wildfire with regards to basin sedimentologic and hydrologic processes (detailed previously) coupled with greater connectedness of rill-gully network leads to the higher discharge rates.

Higher discharge rates are particularly important for functional channel connectivity because they are directly related to the amount and size of material that can be transported within the channel compartment. Runoff processes within the channel vary with underlying bedrock (Kelson and Wells, 1989; Ebizuka and Kondoh, 1990; Onda, 1992). A variety of processes act on channel sediments, but during floods bedload transport becomes the most significant for the functional connectivity of the channel. In particular, peak stream discharges show a direct relationship with bedload sediment transport (Hattanji and Onda, 2004). Suspended sediment levels are also elevated post fire. Helvey (1980) concluded in burned basins that during rising hydrograph conditions, large quantities of fresh loose sediment were available for transport but that in falling conditions the availability of sediment and the carrying capacity of the channel were both reduced. Similarly, Brown (1972) and Scott and Van Wyk (1990) have also recorded a substantial increase in suspended sediment yields in burned basin channels. This would suggest that the higher peak flow levels recorded within burned basins transport more sediment, enhancing the functional connectivity of the channel.

A component (in some cases the major source) of the channel sediment delivery is supplied by debris flows. Debris-flow initiation results from a variety of processes that include shallow landsliding, impulsive loading, entrainment of dry ravel in channels, and progressive bulking (Costa, 1984; Johnson and Rodine, 1984; Cannon et al., 2003; Gabet and Bookter, 2008). Debris flows in burned areas are typically a product of the progressive bulking of sediments in response to moderate to high-intensity precipitation events (Cannon et al., 2003; Blijenber, 2007; Gabet and Bookter, 2008). Surface runoff from a rainfall event erodes sediments from hillslope and channels until sufficient material is entrained, relative to runoff volume, for a debris flow to be generated (Cannon et al., 2003). An abundance of fine particles from loose soil, dry raveling, and a layer of fine ash on the surface make burned areas particularly susceptible to this process (Gabet and Bookter, 2008). Fine particle entrainment may increase flow transport capacity and shear stress, permitting mobilization of coarser channel sediments (Costa, 1984). Therefore, functional connectivity within the channel is both reliant on bedload transport during flood conditions and episodic debris flows. Ideally, water flowing along the channel would entrain sediment (dry ravel deposits, alluvial fill) from within the channel resulting in bedload transport. Flowing downstream, the bedload flow would progressively erode sediment from the banks of the channel or channel colluvial or alluvial fill whereby a debris flow would form.

Synopsis of Connectivity within Burned Basins

A review of the impact of wildfire on the sedimentologic and hydrologic response of a recent burned basin as well as a similar review of connectivity research lead to the conclusion that recently burned basins exhibit increased structural and functional connectivity. As a result of wildfire, the hillslope compartment of a recently burned basin should see growth of its rill network and a greater proportion of the rill network should become connected with downslope landscape compartments, thereby more efficiently transporting sediment and water out of the hillslope compartment, and initiating or enhancing functional connective system. Hollows should receive an elevated amount of colluvial material via dry ravel processes. Water and sediment transport increase are associated with greater connectivity from the rills in the hillslope compartment. The vertical and lateral extents of gullies often enlarge with the increased connectivity of the rill network. The increase in stored colluvium and greater amounts of overland flow from upslope rill networks elevates the potential for shallow landsliding and gully scouring via debris flows. In the event of a landslide or debris flow, functional connectivity is established when the stored colluvial material is evacuated, transported along the gully and into the channel where it is either deposited or continues to progressively bulk downstream.

Within the channel, bedload transport processes benefit from the increased discharge from greater connectedness with the hillslope. Increased bedload capacity during floods aids in the erosion of stored sediment within the channel and once sediment is entrained the potential exists for progressive bulking and eventual debris flow initiation. Wildfire increases the occurrence of dry ravel and the transportation of fines along rill and gully networks. Often these sediments are deposited within the channel reach and constitute an increased level of functional connectivity as a response to wildfire disturbance.

After reviewing the current literature regarding connectivity within the geomorphic environment and reviewing current burned basin research, there are a number of important issues that need to be resolved with respect to researching connectivity within burned basins and also with regard to connectivity research in general.

Of the greatest initial importance, further connectivity research should aim to test the current principles of connectivity by using real world datasets. More specifically, field-based sampling techniques should be used to quantitatively analyze how connectivity is enhanced by wildfire. Field research should incorporate both the monitoring of process (e.g. pore pressure, discharge at several locations) as well as the measurement of structure and contributing structures and their movement overtime. Since the study of connectivity includes the movement of sediment and water across all parts of the basin, basin monitoring should be intensive and not merely the extrapolation from a few points of data. Analyses of quantitative field monitoring should incorporate varying scales of connectivity assessment, and an assessment of connectivity or disconnection within a system.

Currently, the conceptions of connectivity are in a fledgling state and are based on literature reviews and qualitative observations. If connectivity is interrogated by using field research designed to study the connection of a landscape, then conceptions of connectivity can be honed, resulting in more realistic measures of connectivity. Moreover, the greatest need exists currently for a methodology of connectivity assessment. More specifically, there is no current term for determining the relative connection or disconnection of any rill, gully, hollow, hillslope or basin. It is important for the advancement of connectivity research to detail a quantitative real world example of functional and structural connectivity. We propose however, a smaller step first. The quantitative observation of a system, where it is assessed to be either connected or disconnected, and the method and variable for this assessment should be outlined. In this way, connectivity research can begin to reflect real world transfers of sediment and water instead of conceptually based models of connection

CHAPTER 2

Introduction

Urban sprawl continues to increase the number of human inhabitants in the wildland-urban interface. These same locales are also experiencing a rise in the number and the magnitude of wildfires. The increased frequency and size of wildfires have also led to greater potential for secondary hazards associated with wildfire such as debris flows, hyper-concentrated flows, and flooding. The full implications of the changes in the number and magnitude debris flows, hyperconcentrated flows, and flooding are generally not agreed upon. The precise timing and causal mechanisms have still not been completely worked out or agreed upon. A greater understanding of the spatial variations in sediment transport during and after rainfall events following fires are required in order to develop a broader consensus of the timing and initiation of secondary wildfire hazards (e.g. floods and debris flows). This work must not only rely solely on numerical models for results, but should integrate and corroborate these findings with field measurements. Furthermore, this type research also requires the development of field experiments that test the hypotheses developed from modeled results.

An important factor when considering the timing and initiation of any secondary wildfire hazards is the level of connectivity within the landscape. Connectivity refers to the extent to which water and sediment are transferred, or have the potential to be transferred, within or between landscape compartments. Connectivity research to date has made significant conceptual progress, outlining terms and definitions to be used for describing the relative (dis)connection of any system. However, there is a general lack of field experimental designs, and field and numerical modeled data to examine these conceptual ideas. None of the connectivity research to date has considered recently burned basins.

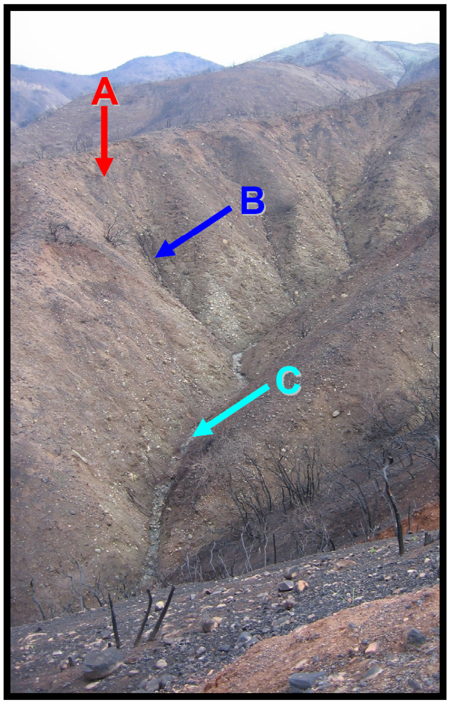
Recently burned basins have been documented to undertake great changes along hydrologic networks as well as precipitation-independent sediment pathways. Precipitation-independent erosion and sediment transfer is induced primarily by dry raveling processes (Gabet, 2003;

Mayor et al., 2007). Dry raveling refers to the downslope movement of individual particles by sliding, rolling, or bouncing. Dry raveling represents an important means of sediment transport in semi-arid and arid environments (Gabet, 2003).

Wildfires also increase basin sediment flux by reducing sediment cohesion and increasing overland flow (Shakesby and Doerr, 2006). These physical effects of wildfire increase the connection of the sediment and water transport hydrologic networks (rills, gullies, channel) and along precipitation-independent pathways associated with gravity dependent processes along hillslopes (dry raveling). This makes recently burned basins an ideal “test-bed” for connectivity research since changes that would otherwise require decades, can occur within several months after a basin is burned during the first precipitation event.

Literature Review: Connectivity within Recently Burned Basins

A recently burned basin can be divided into three distinct landscape compartments; the hillslope, hollow, and channel compartments (Fig. 4). The connection of sediment and water movement within and between these landscape compartments can be termed as either structurally or functionally connective (Wainwright et al., 2011). Structural connectivity focuses on the extent to which landscape units are contiguous or physically linked to one another. Functional connectivity considers the individual processes that actively provide connectivity within or between landscape compartments.



Compartments	Structures	Processes
A. Hillslopes	Flat Planar or Convex Surfaces, Rills and Interrill Areas, Shallow Landslides	Rainsplash, Infiltration, Runoff Generation, Detachment, Sediment Transport, Dry Raveling, Sediment Deposition, Grain Flows
B. Hollow	Gully Network, Colluvial Wedge, Dry Ravel Deposits, Shallow Landslides	Gully Erosion, Sediment Transport, Sediment Deposition
C. Channel	Morphological features such as knickpoints, step-pool features, bedrock-confined reaches, and pre-existing channel deposits	Channel Erosion and Deposition, Sediment Transport

Figure 4. Landscape compartment diagram and their structures (structural) and processes (functional) in a recently burned basin.

Hillslope Compartment

Infiltration is critical to understanding structural and functional connectivity because it is linked to runoff, which is important to rill development as well as water and sediment transfer along the hillslope and rill network (Bracken and Croke, 2007). Reduced infiltration rates have been linked to a number of factors: fire severity and the amount of vegetation removed (Bailey and Copeland, 1961), sealing of pores by fine soil and ash particles (Campbell et al., 1977), compaction by raindrop impact (Wells et al., 1979), and soil hydrophobicity (DeBano, 1971). Regardless of the cause, the reduction in infiltration capacity increases surface runoff in burned basins when compared to similar unburned basins (Prosser, 1990) and background levels. The increase is significantly higher during early rainfall events and then declines toward background levels within one to two years (Shakesby and Doerr, 2006).

Structural connectivity within a recently burned basin can change significantly from the enhanced runoff present in recently burned basins. Rill networks are instrumental for the transport of water and sediment within the hillslope compartment, and after a basin has been burned, extensive rill systems, particularly on steep and water-repellent slopes, can develop in response to the smallest of flow concentrations (Hyde et al., 2007; e.g. Doehring, 1968; Wells et al., 1987). Rills in burned basins have been observed to follow two spatial patterns; either draining planar surfaces in nearly a parallel pattern or they drain a critical area funneling water into a first order stream in groups of three to six converging rills (Moody and Kinner, 2006). Moreover, the increased flux of runoff and sediment within burned basins results in the longitudinal, lateral, and vertical expansion of the pre-existing drainage network (Moody and Kinner, 2006). As the rill network evolves, increasing levels of sediment and water are conveyed by headward incision, and this increases the functional connectivity of the basin (Gabet and Bookter, 2008).

Recently burned hillslopes are also comprised of significant precipitation-independent sediment sources. There is a dramatic increase in sediment flux rates immediately following wildfire and dry raveling contributes substantially to this (Gabet, 2003; Shakesby and Doerr, 2006; Gabet and Sternberg, 2008). Functional connectivity is enhanced when material mobilized by dry raveling processes is transported to gullies and channels, thereby increasing the amount of debris potentially eroded during subsequent runoff events. Dry ravel also represents a significant colluvial sediment source to the hollow and channel compartments.

Hollow Compartment

The hollow landscape compartment is important for both the routing of sediment and overland flow. A significant amount of colluvium is often stored within the hollow. Connectivity is established when stored sediment is transported downslope by a debris flow, slope failure, surface runoff, or some combination of the three.

In recently burned basins, hollows receive and capture large quantities of colluvium. Sediment sources for the colluvial fill range from elevated levels of dry ravel during and after the burn

(Gabet, 2003; Shakesby and Doerr, 2006; Gabet and Sternberg, 2008), to fine particles which are transported along the rill and gully networks and temporarily stored within the hollow, to creep processes (Moody and Kinner, 2006; Gabet and Bookter, 2008). Hollows typically capture dry ravel, which increases the level of sediment within the hollow. The functional connectivity of the hollow is then arrested until the occurrence of a debris flow, slope failure and/or surface runoff is able to remove the stored material.

Gullies commonly initiate and dominate the channel network found within hollows. The evolution of rill networks in the hillslope compartment increases the area contributing sediment and water into the hollow, and this often leads to an increase in the structural connectivity of the gully, through its vertical and horizontal expansion (Moody and Kinner, 2006). Functionally, water based gully erosion increases as a result of wildfire related increases in overland water flow, greater connection to upslope rill networks and also because of an increase in the amount of available easily erodible sediment (deposits of dry ravel) within the gully (Hyde et al., 2007).

Channel Compartment

Channels respond to wildfire disturbance mechanisms in a variety of ways, but these responses are often constrained by the characteristics of soil and vegetation, basins steepness, and burn severity (Shakeby and Doerr, 2006). Structurally, enhance connectivity within the channel with upslope areas is dependent upon the level of riparian vegetation consumption during the wildfire. If vegetation around the channel is consumed, then there is an increased connection with adjacent hillslopes, as the loss of the riparian buffer would increase hillslope-channel coupling. Burned basins also have higher rates of discharge and a quicker response to rainfall, which indicates a greater level of upslope structural connectivity after the fire (Neary et al., 1999; Moody and Martin, 2001; Neary et al., 2003).

Functionally, channel response to wildfire variation includes; aggradatration or degradation (Florsheim et al., 1991), channel narrowing (Germanski and Miller, 1995), and development of alluvial fans and tributary fans (Meyer and Wells, 1997). Suspended sediment levels are also elevated post fire. Helvey (1980) concluded in burned basins that during rising hydrograph and high flow conditions large quantities of fresh loose sediment are transported, but that as flow decreases the availability of sediment and the carrying capacity of the channel are both reduced. Similarly, Brown (1972) and Scott and Van Wyk (1990) have also recorded a substantial increase in suspended sediment yields in burned basin channels. This suggests that burned basin channels have substantially higher functional connectivity (ability to move channel sediments) than in unburned basins.

In some burned basins, debris flow events provide sediment delivery to the channel, thus initiating a functional connectivity relationship between the channel and the originating location of the flow. Functionally, debris-flow initiation results from a variety of processes that include shallow landsliding, impulsive loading, entrainment of dry ravel in channels, and progressive bulking (Costa, 1984; Johnson and Rodine, 1984;Cannon et al., 2003; Gabet and Bookter, 2008). Debris flows in burned areas are typically a product of the progressive bulking of sediments in response to moderate to high-intensity precipitation events (Cannon et al., 2003; Blijenber, 2007; Gabet and Bookter, 2008).

Research Hypotheses

The previous review chapter provided a conceptual framework for enhanced connectivity within recently burned watersheds. The current research is an attempt to validate this conceptual evidence through a series of questions related to the functional connectivity of rills and gullies. Data gathered from field-based sampling techniques are used to quantitatively analyze how connectivity is enhanced by addressing the following research hypotheses:

H1 : Functional connectivity is prevalent along rill-gully threads within a recently burned sub-basin after the first significant rainfall event.

H2 : Functional connectivity is prevalent along rill-gully threads between recently burned sub-basins after the first significant rainfall event.

H3 : There are no significant differences in functional connectivity with the scale of analysis in a recently burned drainage basin.

Study Site

In early July, 2008 the Gap Fire burned 28 km^2 of steep, predominately chapparal terrain near Santa Barbara, California (Fig. 5). A 7000m^2 sub-basin located within Wylie Canyon was chosen as the study site based on its lack of vegetation and its predicted ability (qualitative) to produce high levels of sediment flux following the first major rain event. The site was initially chosen by researcher scientists from the USGS Landslide Hazards Program for their annual Intensive Research Area. The unnamed sub-basin is an ephemeral headwater stream of San Pedro Creek. The basin is underlain by an interbedded unit of conglomerate, sandstone, and mudstone, which weather (physical and chemical) into a wide variety of particle sizes ranging from clays to large (greater than 50 cm) boulders. There is wide variation in hillslope forms across the watershed, which includes smoother, less steep, smaller particle size and steeper, more rugged mixed particle size slopes. Across the watershed, partially burned vegetation stems and trunks are commonly found and range in size from 10 cm to 2 m.

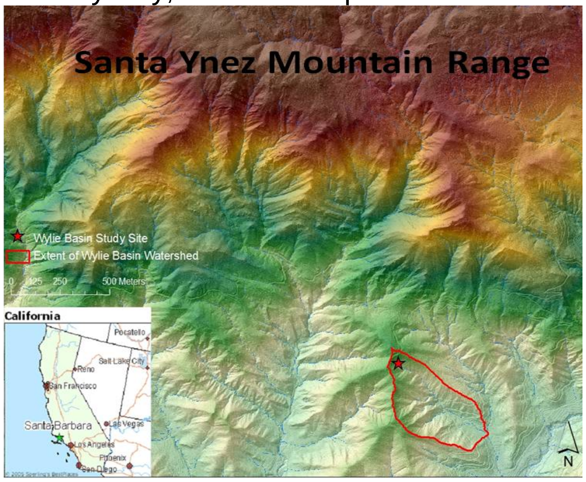


Figure 5. Map of Wylie basin study site.

Figure 6. Scanner Setup at the top of Wylie basin. Leica Geosystems Scan Station 2, ruggedized Dell laptop, and 1000 watt Honda generator.

In addition to the smooth and rough topographical surfaces, some areas contain bedrock outcroppings, which either act as a nick point in a gully or create breaks in slope along the hillslope compartment or adjacent to the channel.

A rainstorm occurred on December 14 and 15, 2008. A maximum 15-min rainfall intensity of 20.8 mm/hr and a total of 52 cm over 14 hours were recorded at the study site basin. This resulted in surface runoff within all of the basins, but no evidence of debris flow or hyper-concentrated flows was apparent in both video taken at the site or from post-rainfall field observations.

Methods

Terrestrial Laser Scanning

A Leica Geosystems HDS ScanStation 2 terrestrial laser scanner (TLS) was used to survey the Wylie basin (Fig. 6, 7). A TLS is a tripod mounted system that uses pulsed laser light to scan a field of view (360° x 270° up to 200m) for the prod uction of a 3D cloud of elevation points. Each point irradiated by the laser is recorded on a laptop computer and referenced within a 3D Cartesian coordinates system (x, y, and z based on where the laser light is emitted within the scanner). The scanner also records both digital imagery through an onboard digital camera (recorded as rgb color values) and intensity (amount energy from the laser beam returned to the scanner given the reflectivity of the surface). Both intensity and imagery data can be overlaid on the point cloud for the visualization of the features within a point cloud.

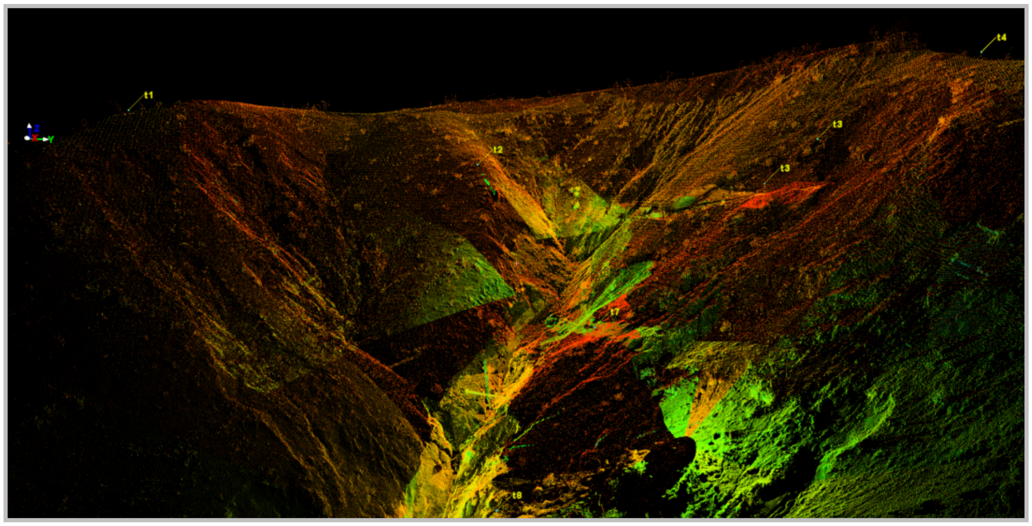


Figure 7. Point cloud of Wylie basin study site. The points are colored with intensity ("i") values which represent the energy of the laser light at its return to the laser scanner. The Intensity of the laser light is influenced by the reflectivity of the surface and distance from the scanner to an object. The small yellow t1,t2, etc... are the locations of the seven control points.

Two surveys were conducted: 28-30 September 2008 to establish baseline pre-rainfall conditions, and 18-21 December 2008, three days after the rainfall event. Seven control points (Leica Geosystems High Definition Survey targets) were established for redundancy, greater flexibility in scan locations and the use of a common Cartesian coordinates linking each of the scan locations. For repeat surveys, each control point was established on top of a permanent monument consisting of a single 50 cm length of rebar driven into the ground and cemented into place. Both surveys required fourteen separate scan locations positioned across the basin. Multiple scan locations reduce "shadowing effects" and allowed scanning of areas larger than the Leica Geosystems ScanStation 2 range of 200 m. The number of scan locations is a function of (in decreasing importance): complexity of topography, required resolution of final product, and size of the basin.

Point Cloud Workflow

Fourteen point clouds were generated from 14 scan locations and registered in Leica Geosystems Cyclone software. The registration process joins the scans by using the targets as common control points. The data were registered to Cartesian coordinates originating from the location of the first survey location. Cartesian coordinates were selected because they are: more accurate (reduced error associated with surveying the control points); more efficient in the field as there is no need to conduct a surveying campaign, and also further reduces disturbance of the landscape compartment while traversing to conduct the surveying of the control points. Average point spacing from both surveys across the extent of the watershed after registration is less than or equal to 1cm. The mean absolute registration error for x, y, and z data in both surveys is 3 mm.

GIS Workflow

The TLS point cloud was exported as an x, y, and z three column text file from Cyclone and imported to ArcGIS. A Triangulated Irregular Network (TIN) was constructed in Spatial Analyst. The TIN was converted to a 1cm raster file via linear interpolation (Wheaton, 2008). Vegetation filtering was conducted across the entire DEM to remove charred plant remains and newly sprouted vegetation from the surveys. Vegetation was identified based upon a signature of high topographic complexity relative to bare-earth surfaces, and removed from the point cloud data with a morphological filter (Vosselman, 2000; Pfeifer and Mandlburger, 2009) to create a DTM containing only those points where the laser recorded a bare earth surface.

In ArcGIS, a hydrologic network (flow paths) was developed for both DTM's using Spatial Analyst hydrology tools (Fig. 8a, 8b). The procedures for hydrologic flow network delineation were constructed using the Deterministic 8 (D8) model for flow over a 1 cm DTM. The D8 method produces a single flow direction towards the steepest slope of one of the eight grid cells neighboring the initial center cell (O'Callahan and Mark, 1984; Tarboton, 2003). The D8 method was chosen for its simplicity and widespread use in hydrologic terrain analysis (Kiss, 2004).

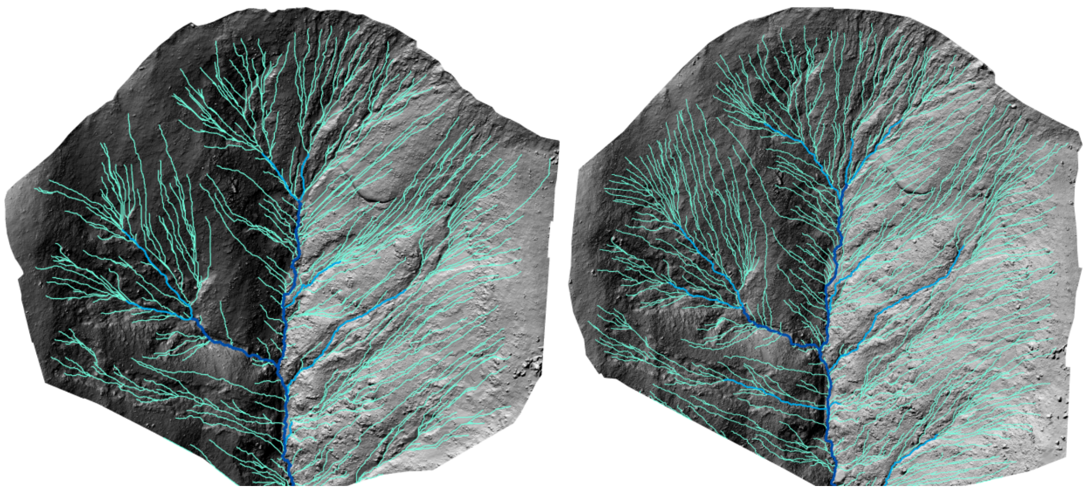


Figure 8a, 8b. Image of D8 hydrologic networks from the first survey (left) and second survey (right). Rills (turquoise), gullies (light blue), channel (dark blue).

The hydrologic networks were used to classify and locate the rills, gullies, and channels within Wylie basin based on the stream order assigned by the D-8 algorithm. Seven contiguous rill-gully threads (RGTs) were identified within the Wylie basin (Fig. 9).

The RGTs begin at varying distances down from the drainage divide. RGTs were extracted manually by generating unique watersheds at each point on the RGT where a significant D8 stream order enters into the chosen RGT (Fig. 10a). A polygon shape file was then created using the extents of the watersheds as the boundaries for each of the RGTs. This results in many overlapping polygon files, which were joined in “union” to form a contiguous border, delineating the RGT (Fig. 10b).

A DTM of Difference (DOD [DTM after the rainfall minus DTM prior to rainfall]) was created using the raster calculator in ArcGIS. Differencing the DTM’s produced a map of elevation changes. Elevation differences were used in the calculation of both areal and volumetric budgets of erosion and deposition (Wheaton, 2008). DOD surfaces and elevation surfaces were extracted for each of the seven RGT polygon shape files with the aid of analysis masks in ArcMap Spatial Analyst.

A fishnet was developed in ArcMap at the dimensions of one column 25 m wide and rows 0.05 m in length to aid in the extraction of sediment transport rates within the extent to the RGT (Fig. 11). To account for the meandering nature of the RGT's, a polygon analysis mask was created

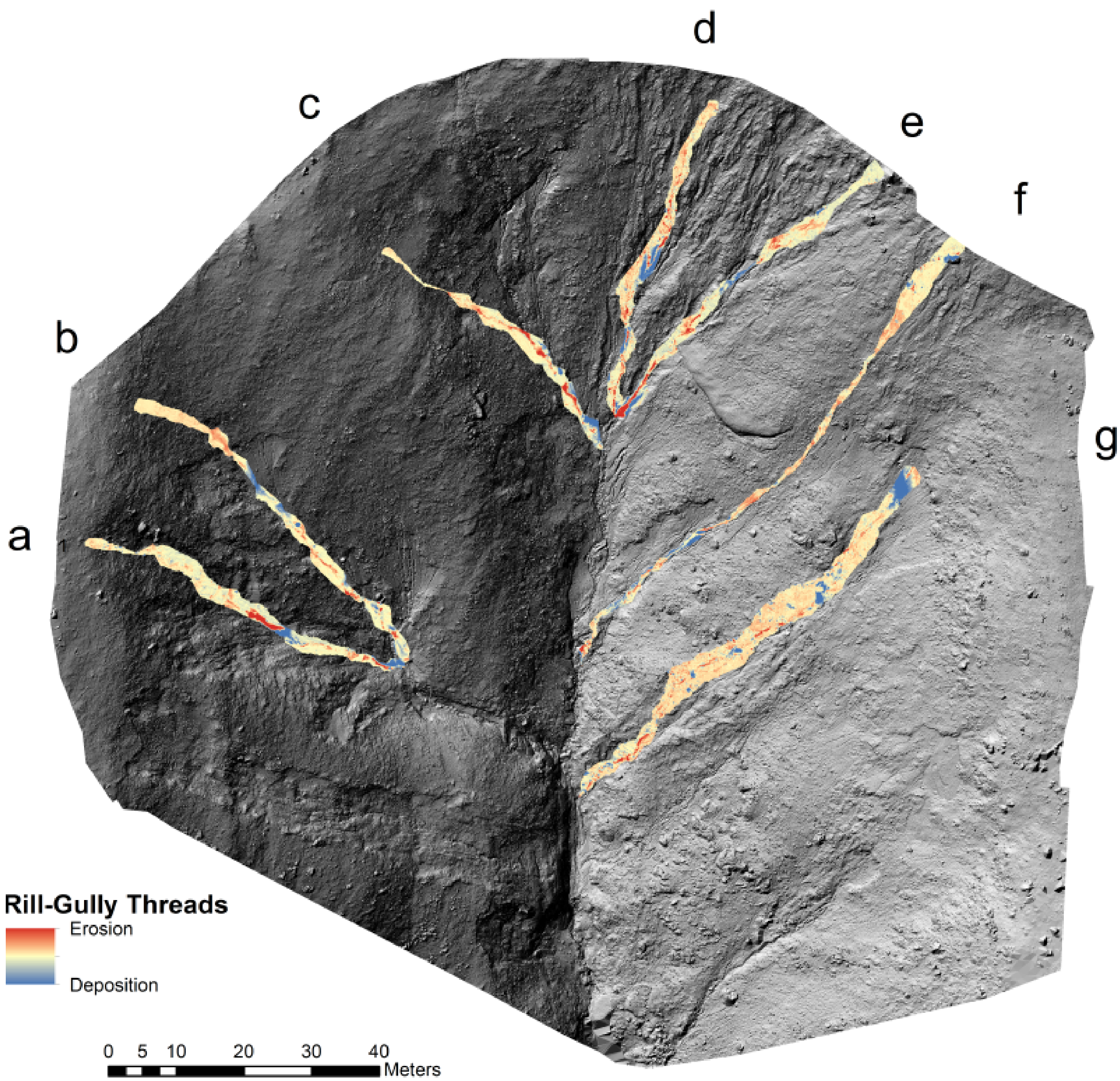


Figure 9. Location of the seven RGTs. RGT-a, RGT-b, etc…

that separated the RGT into linear sections. This allows for the fishnet to remain perpendicular to the thread along the entire length of the RGT. Spatial analysis zonal statistics were employed in the calculation of rill-gully width (calculated from count) and sediment change (total of all DTM of Difference cell values). The values were exported into Microsoft Excel where sediment budgets and deposition/erosion charts were assembled. The fishnet cross sections provided cross-sectional measures and sediment connectivity in the context of variations in width and magnitude of sediment deposition or erosion at the scale of the rill beginning at the top of the rill. A second scale of sediment transport was also considered in the analyses. Total upslope sediment yield (total deposition – total erosion) was estimated every centimeter down each of the seven RGTs. Total upslope sediment yield was based upon a weighted flow accumulation algorithm from the difference surface and a D8 flow direction algorithm, as performed in ArcGIS. For the upslope sediment grid, the product of the weighted flow accumulation algorithm was multiplied by the cell resolution (0.01m x 0.01m) to convert the weighted topographic differences

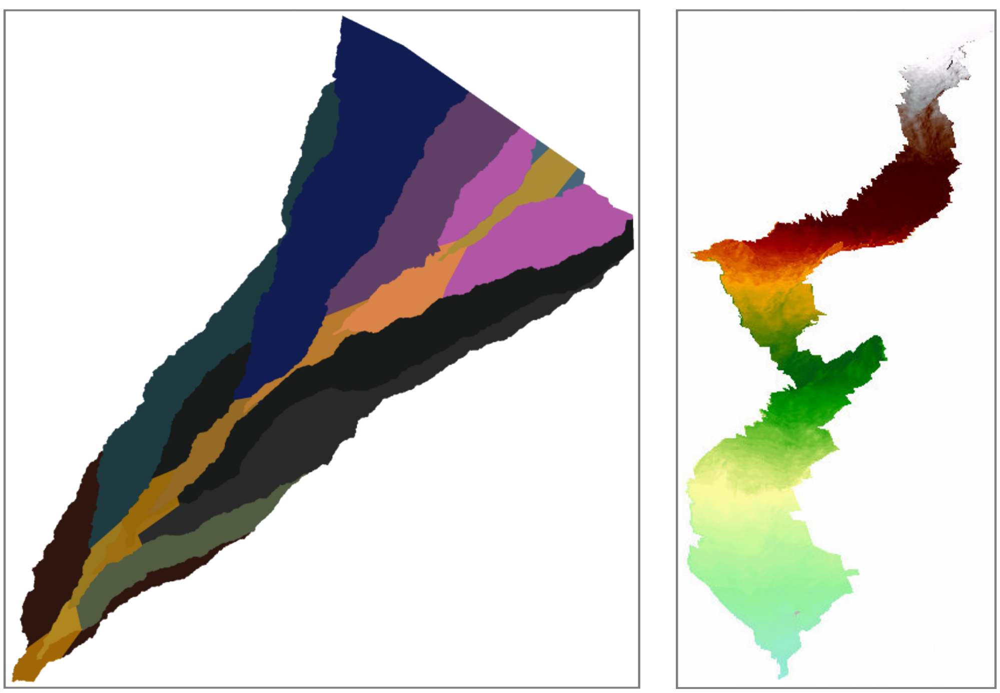


Figure 10a. (left) Unique watersheds along RGT f, with shaded orange representing the extent of the delineated RGT.
Figure 10b. (Right) 3D ArcScene visualization of RGT d. Color represents relative elevation.

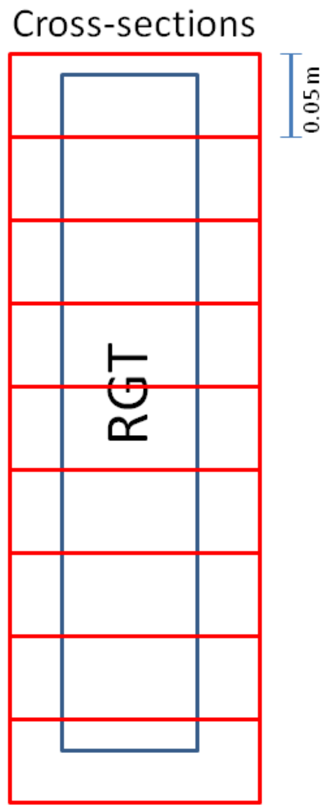


Figure 11. Cartoon depiction of 0.05m cross-sections (red) overlaid on top of a RGT (red).

to volume (in m^3). The entire difference surface was used as the weight grid for the calculation. This grid represents the total amount of material removed from the area upslope of each cell in the basin.

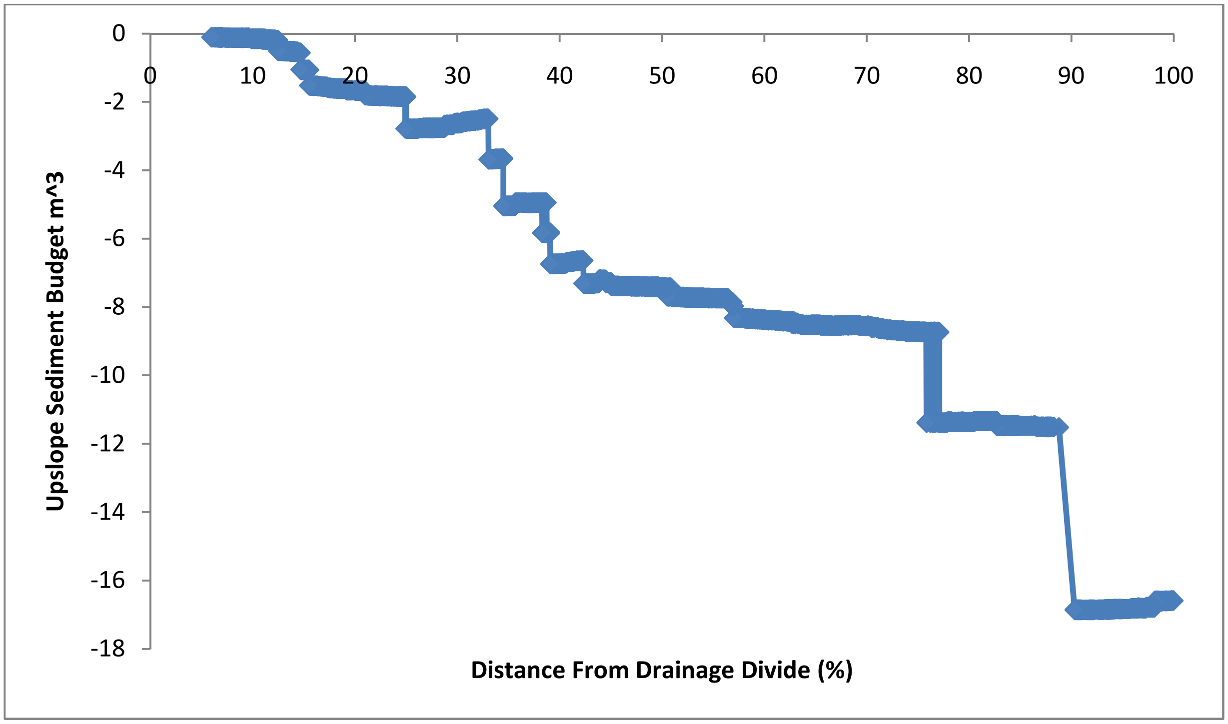
Analysis Workflow

Locally, functional connectivity was assessed via analysis of the downslope order of erosion or deposition along each of the RGTs. Erosion and deposition was expressed in cm^3 per cm^2, which standardizes the data to make comparisons between fishnet areas of variable size along the RGT. As a visual aid, a simplified graph of areas of erosion and deposition along the RGT was produced to easily determine the general pattern of sediment transport. To accomplish this, the RGT fishnet values were assigned a value of either 10 (deposition) or -10 (erosion) and plotted against distance from the drainage divide. This simplification provided a count of erosion and depositional areas, which can be used for comparisons between threads. Analyzing functional connectivity from a coarser scale, connectivity along the RGTs was assessed via the total upslope contributing area sediment yields. For comparison between RGTs and between analyses, distance down the RGTs were standardized as percentage down from the drainage divide (not always the top of the RGT) to the confluence of the gully and channel.

Results

Upslope Contributing Area Sediment Budgets

The upslope contributing area sediment budgets show a consistent pattern of erosion along a majority of the RGTs. The removal of sediment from the upslope contributing areas indicates a functionally connective landscape. Five of the RGT never exhibit a positive upslope sediment budget where total erosion was greater than total deposition. RGT a,b,c have significantly more erosion than deposition in comparison to RGTs d,e,f,g where deposition and erosion are approximately equal. RGT b shows the largest upslope contributing area sediment deficit at a given point along the RGT, which is estimated at $-17m^3$. RGT f has the largest upslope surplus, estimated at $0.5m^3$.



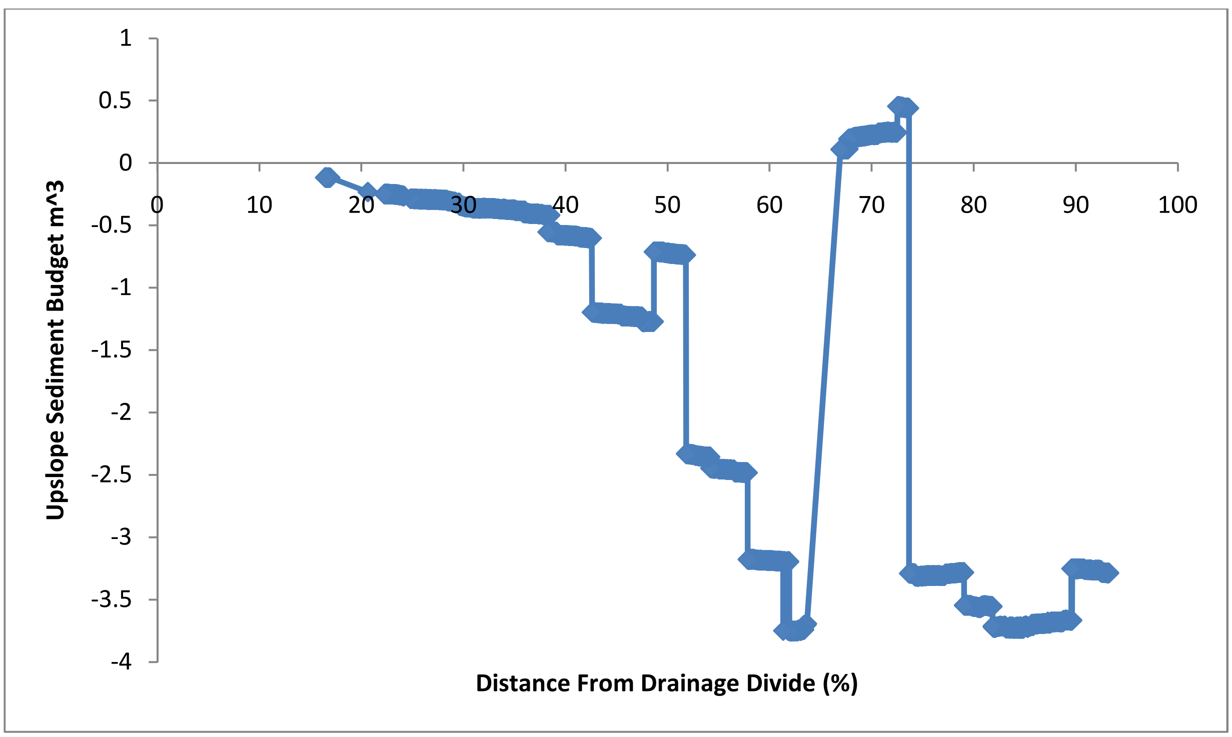


Figure 12a (top), 12b (below). Upslope sediment budgets are a cumulative assessment of sediment gained or eroded in the watershed area above discrete points along the main flow path of the RGT. Fig. 12a is representative of a connective upslope area (consistent erosion), while Fig. 12b is representative of disconnection (inconsistent erosion).

Patterns of Deposition and Erosion

All of the RGTs include an alternating pattern of depositional as well as erosional areas (Fig. 13). Deposition along the channel is indicative of disconnectivity and therefore, we can reject our H1 hypothesis. None of the seven RGTs shows either uniform erosion or deposition throughout the study site. However, a few of the RGT's contain significant distances where erosion or depositional is continuous over a larger extent of the RGT. RGT c shows only erosion from between 37% to 93% of the total thread length, accounting for 2030 cm of continuous erosion. The longest continuous extent of deposition is recorded from 7% to 17.5% of the total thread length along RGT e accounting for 480 cm of continuous net deposition. Along the RGTs the calculated deposition and erosion show large variations in magnitude. The largest depositional event recorded within the seven RGT's is 48.5% down RGT-b, and yielded an accretion of 22.9 cm^3/cm^2. The largest amount of erosion is recorded 61% down RGT e, and yielded a loss of 28.3 cm^3/cm^2.

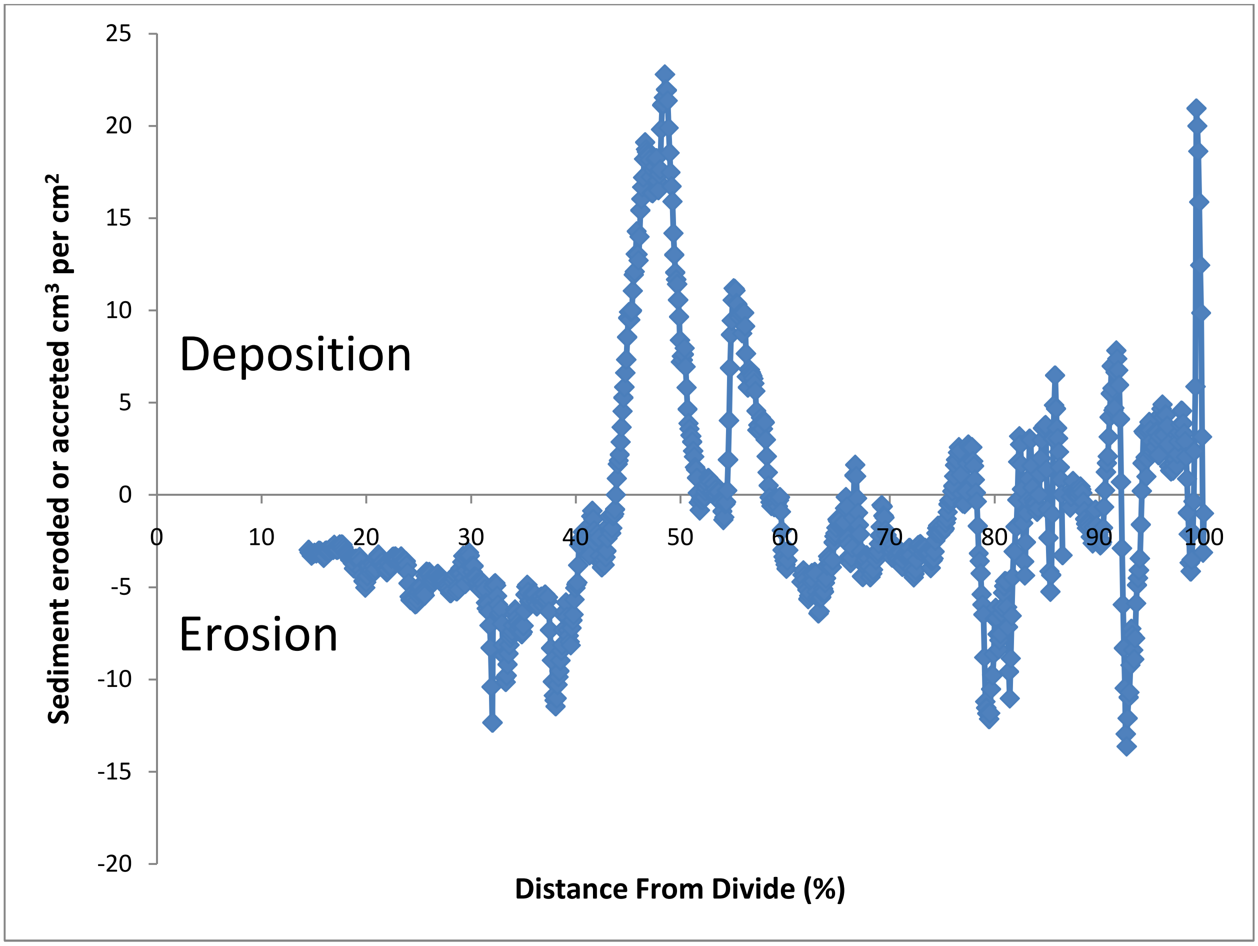


Figure 13. Pattern of deposition and erosion (cm^3 per cm_2) along RGT b. Blue markers show the amount of sediment deposited or eroded at each cross-section down through the rill-gully. Deposition = disconnectivity, Erosion = connectivity.

Cumulative Sediment Budgets

The cumulative sediment budgets indicate a largely erosional trend along the RGT as is evident from a majority of the RGTs' negatively sloping graphs. However, the cumulative budgets are interspersed with depositional sections, which are indicated by brief areas of positive slope. This would suggest a disconnected system.

The cumulative sediment budgets allow a general view of connectivity. For example, if more sediment is removed than deposited at any point, then connectivity may be assumed. With the exception of RGT g, the RGT's cumulative sediment budgets reveal that erosion dominated much of the thread length. Six of the seven RGT's have a net loss of sediment along their individual reaches. Of the six that contain net erosion, four never exhibit a positive sediment budget. RGT has the largest sediment deficit, reaching a maxima of ~37 m^3 eroded cumulatively at 4600 cm down the RGT. RGT d contains the largest sediment amount of sediment deposited, with ~10 m^3 deposited cumulatively at 4700 cm down the RGT.

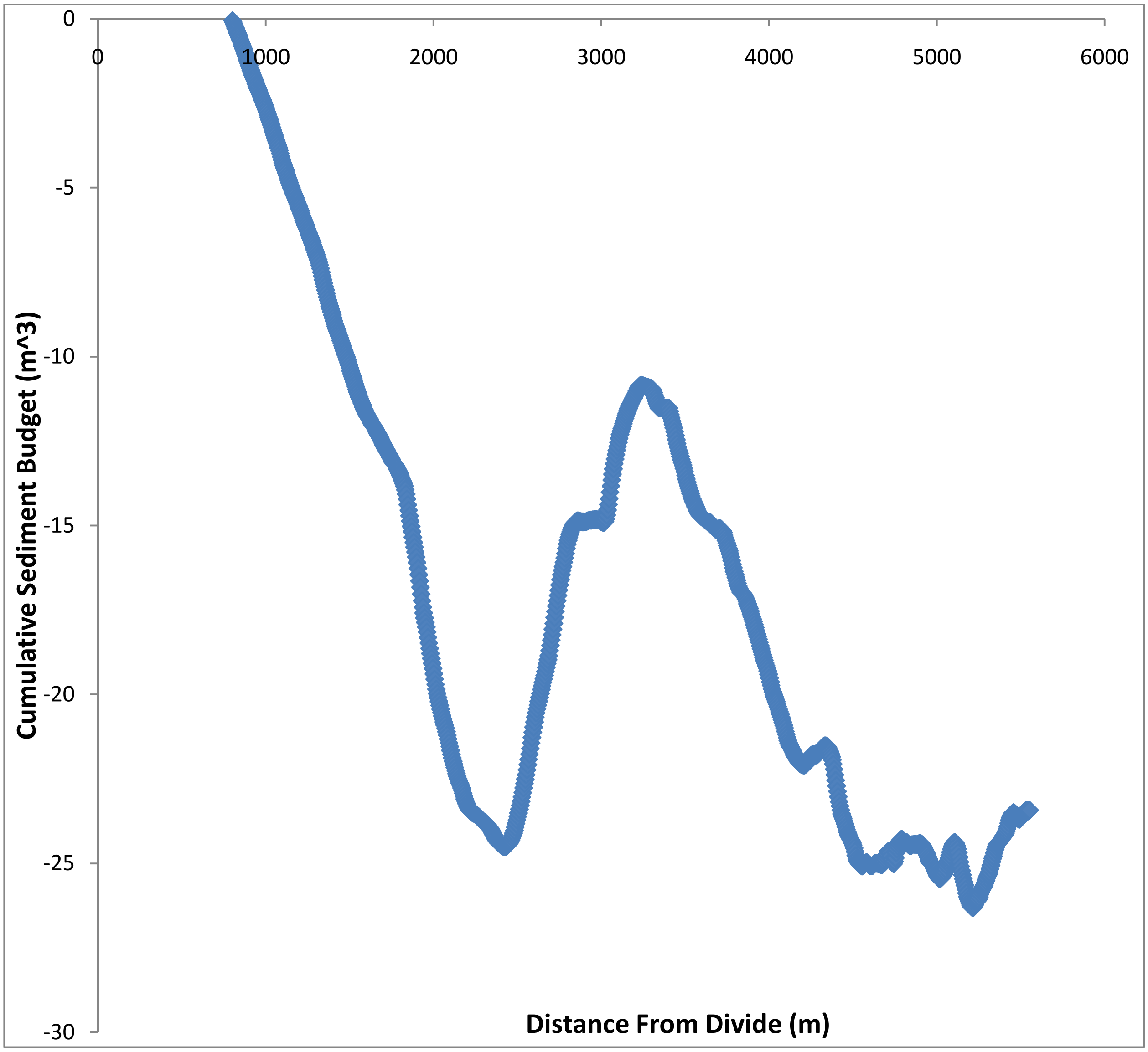


Figure 14. Cumulative sediment budget for RGT b. RGT b represents a similar pattern of deposition and erosion as seen in the six other RGTs. From any point on the graph; Positive slope = deposition, negative slope = erosion.

Simplified Deposition and Erosion Comparison

The simplified count of deposition and erosion areas provides a comparable measurement of sediment connectivity between the RGTs (Fig. 15). While it does leave out the spatial patterns of deposition and erosion, it shows the total area of deposition and erosion between threads. RGT f contains the most depositional and erosion areas and it is also the longest of the seven RGTs. RGT c has the smallest count number of deposition and erosion areas and it is also the shortest in length.

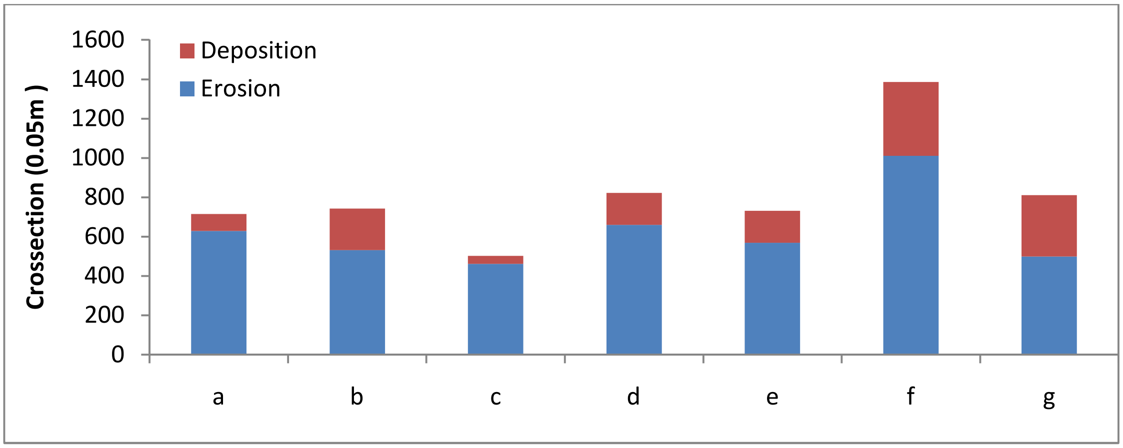
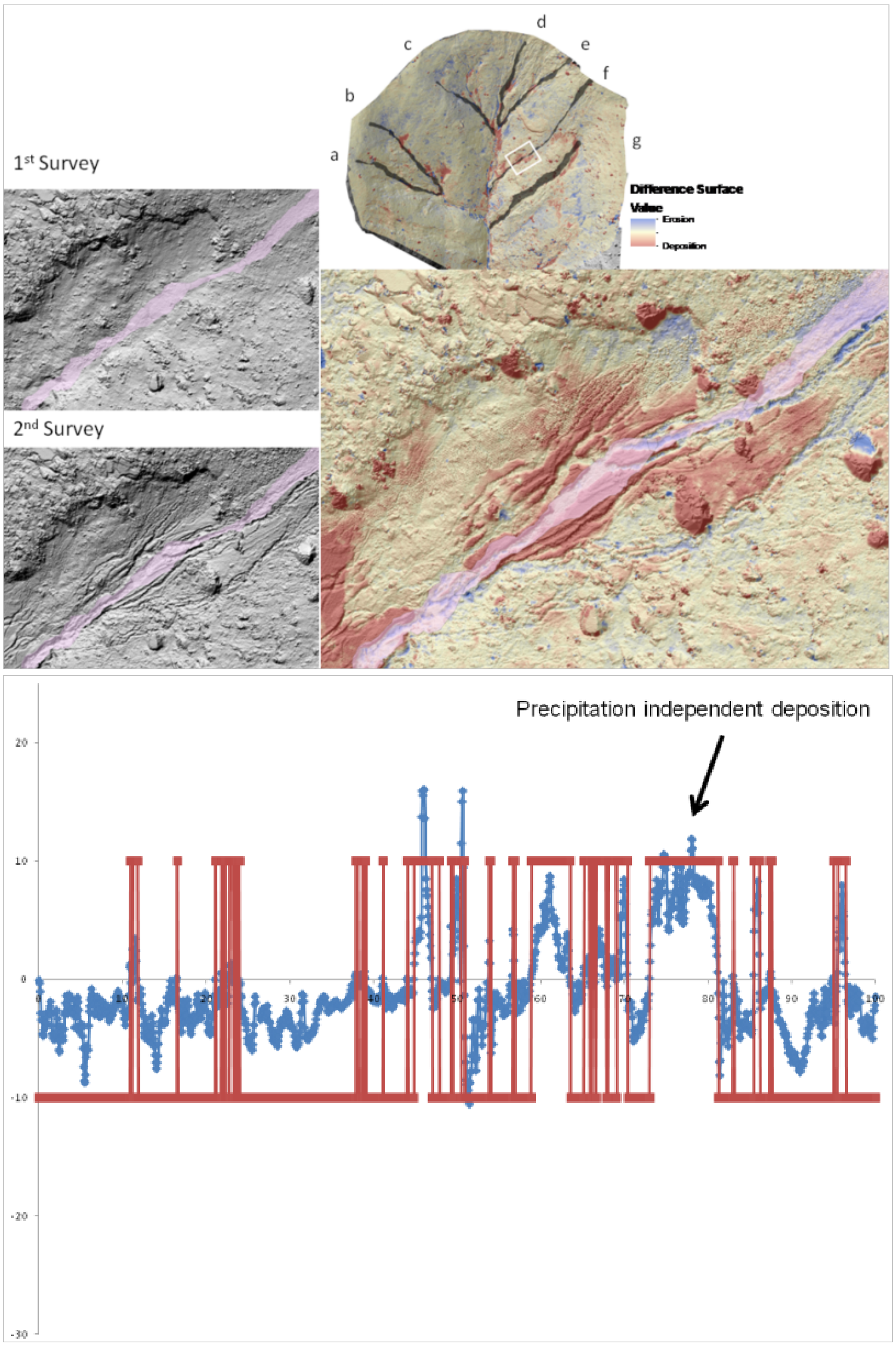


Figure 15. A simplified count of deposition areas to erosion areas. The count also provides a length measurement for each of the RGTs. Length in centimeters for each RGT is deposition+erosion count * 5.

Discussion

Each of the RGTs displayed functional disconnectivity after the occurrence of two small rainfall events. Therefore, *H1* is rejected because the movement of sediment along each of the RGTs is not consistently erosion. The RGT extents that show erosion (connection) are highly disconnected by interspersed deposits of sediment and this is reflected in the RGT charts of deposition and erosion. *H2* could not be rejected as the functional disconnectivity did not display consistent spatial patterns amongst the seven RGTs. A highly varied pattern of disconnectivity between the RGT showed that erosion and deposition along each RGT was quite non-linear. This would account for the lack of a pattern in the functional connectivity away from the drainage divide. Dry ravel deposits located along the RGTs are likely the main source of the functional disconnectivity. Surface runoff along the RGTs did not possess the capacity to remove the dry ravel deposits, which led to an erosion pattern through these deposits that



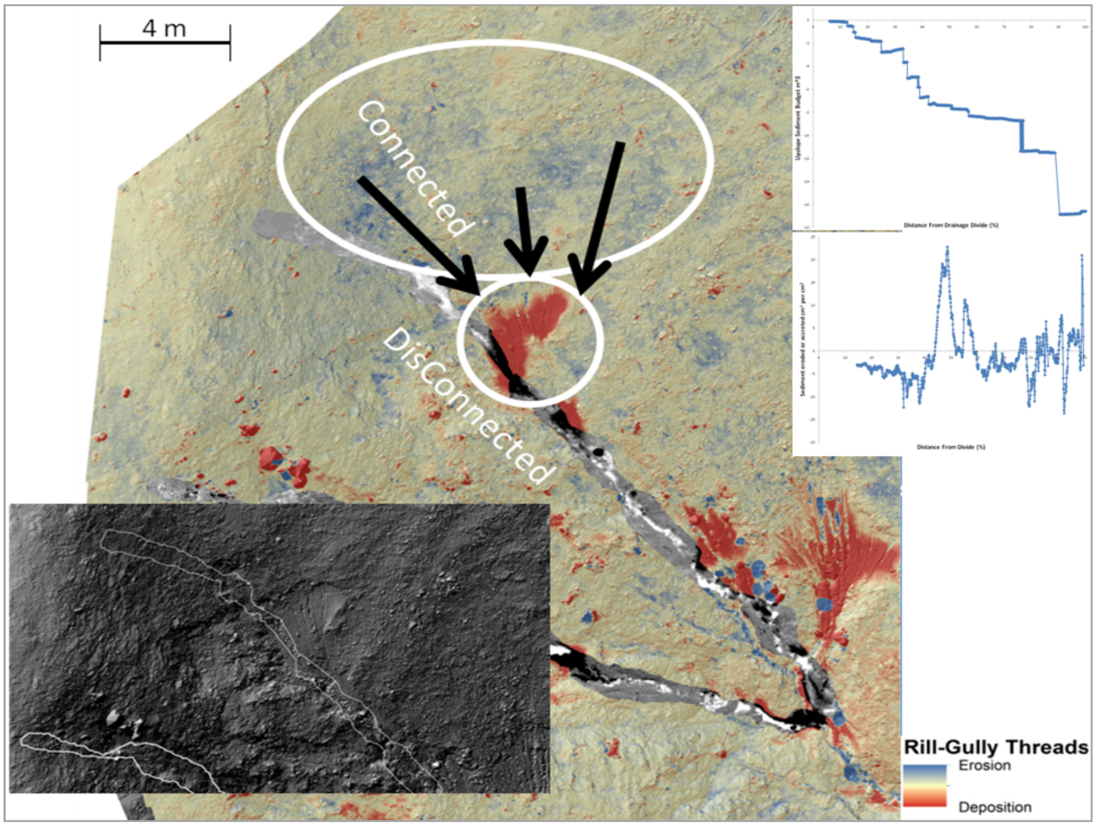


Figure 16a, 16b, 16c. Fig. 16a (top) is a compilation of images depicting the accumulation of precipitation-independent sediment movements and its partial erosion by rill and gully alluvial processes. Fig. 16c (middle) shows the location of these deposits on our graph. Fig. 16b (bottom) shows the upslope connection of dry ravel movement and its storage within a small hollow. The upslope connection and disconnection along the RGT as a consequence is clearly indicated within our graphs.

exhibited an anatomosing pattern (Fig. 16a).

While erosion was present, the bulk of the dry ravel deposits remained in place after the runoff event and this is reflected by a positive trend along the RGT sediment budgets (Fig. 16c). Short sections of functional connectivity were present and located along sections of the RGT that had undergone incision via surface runoff along the width of the thread. The incision resulted in the localized removal of sediment. An overwhelming share of deposition occurred within the hollow landscape compartment, and this is consistent with previous hollow research, which identifies an increase in the amount of dry ravel deposition within hollows immediately after a fire (Gabet, 2003; Shakesby and Doerr, 2006; Gabet and Sternberg, 2008). Our field observations and results indicate that the concavity of the rill and gully serve as a break-in-slope from the adjacent hillslopes and permits the collection of dry ravel.

Qualitative conceptual models of hollows indicate episodic slow accumulation and rapid evacuation of sediment (Dietrich et al., 1986). Rapid evacuation of sediment in the Wylie basin did not occur because the flows within the gully did not possess the capacity to remove the ravel and therefore functional connectivity was not achieved within the RGT. Several studies have reported that the rapid evacuation of sediment was more likely immediately after a wildfire (Shakesby and Doerr, 2006; Hyde et al., 2007). What is not typically recited is the role of the hollow when there is no rapid evacuation of sediment. The hollow restricted functional connectivity by capturing and preventing the movement of sediment downslope as was evident from the results in Wylie Basin. Structural connectivity is also restricted within the hollow since the gully remains full of colluvial fill, which limits the transport of sediment downslope and the structurally disconnected nature of the hollow is signaled by our quantitative measures of functional connectivity. Concordantly, in the event of greater rainfall (amount or intensity), a debris flow could occur. If a debris flow did occur there would be greater potential for the hollow to be rapidly remove a large portion of the stored sediment (Hack and Goodlett, 1960; Dietrich and Dunne, 1978; Dietrich el al., 1986; Parrett, 1987; Wells, 1987; Meyer and Wells; 1997; Cannon and Reneau, 2000; Cannon, 2001; Gabet and Bookter, 2008). The scouring of the hollow by debris flow would momentarily cause the hollow to be functionally connected thus relieving the bottleneck of stored sediment, creating a functionally connective RGT. In the instance of a debris flow, the structural connectivity of the gully would also be increased as it would have been scoured.

Altering the scale of analysis, the upslope contributing areas along each of the seven RGTs reveal a consistent pattern of erosion. Therefore, we can reject the H3 hypothesis since scale has an influence on connectivity. From the coarser scale of the upslope contributing areas, five of the seven RGTs never reveal a decrease in the total upslope sediment eroded. This is interpreted as consistent, continuous erosion from the contributing area of each cell along the entire length of the RGT. The uninterrupted erosion from the contributing area of each cell is indicative of functional connectivity. Net erosion within a majority of the contributing areas resulted from ravel and surface runoff erosion.

A major inference from the previous findings is that functional (dis)connectivity with recently burned basin is highly dependent on dry raveling. RGT experience net erosion at the scale of the contributing area for each cell, while at the scale of rill and gully features the magnitude of dry ravel contribution is large enough to certain parts of these features that surface runoff cannot evacuate this nonlocal source of sediment. Therefore, functional connectivity displays distinct differences with scale after the small rainfall events.

Conclusion

Functional connectivity was assessed along seven rill-gully threads (RGTs) located within a recently burned basin. At the scale of the RGTs, all seven threads were found to be functionally disconnected. Functional disconnectivity of the RGTs was reflected as deposition/accretion recorded at multiple locations along each of the RGTs. Dry ravel deposition from the hillslope and hollow compartments led to a nonlocal input of sediment that impacted the local sediment transport. The nonlocal sediment source was functionally connective and created a structurally disconnective scenario as the low magnitude and intensity rainfall did not possess the energy to remove the dry ravel. Further analysis at the coarser scale of the upslope contributing areas indicated a more consistently erosive pattern of sediment movement above each cross-section of the rill and gully. The erosive pattern of sediment movement within the contributing areas, coupled with the inconsistent pattern of sediment transport along the RGTs, seems to indicate functional connectivity in sediment movement from the upslope areas (via dry ravel and surface runoff) and functionally disconnectivity in sediment transport within the rill-gully systems.

A majority of the research on recently burned basins infers that there is a high level of functional connectivity within and between various landscape compartments. This assumption would seem to hold true in scenarios where larger magnitude or higher intensity rainfall events lead to flooding or debris flows. However, the current study clearly provides evidence for disconnectivity that results from lower intensity and smaller rainfall events. Small events are an important component of the sequence of events that potentially lead to larger more catastrophic events after wildfire. Further research is required to assess broader applicability of the scalar variability in functional connectivity associated with small rainfall events. This will require greater spatial and temporal monitoring of recently burned basins in order to fully assess the triggering mechanisms of large catastrophic events. The sequence of events is more important than a single event.

CONCLUDING REMARKS

Recently, the term connectivity has gained popularity within geomorphological research. Even so, currently no field-based research of geomorphologic-related landscape connectivity has been considucted. Furthermore, recently burned basins, where the transport of sediment and water undergo great changes as a result of burning, has yet to be analyzed by measuring the basin's ability to transfer water and sediment (connectedness) within and between the landscape compartments of the basin.

An extensive literary basis for what we would expect to find regarding the connection of landscape compartments within a recently burned basin was first developed in order to make a case for functional and structural connecitivity. Then, using the literature review as a basis for our connectivity analyses, we developed a method whereby seven rill-gully threads (RGT) were delineated based on the D-8 hydrologic network algorithm. Then the amount and pattern of sediment transport (deposition and erosion) and the upslope contributing area sediment input were estimated along the threads, providing our measure of connectivity.

All of the threads were found to be disconnective and this was represented by patches of significant deposition along each of the RGTs. However, at the scale of the upslope contributing areas, erosion dominated, and this suggested a level of connectivity. A majority of the large depositional events along the RGTs were a result of dry ravel which filled a hollow or gully after the fire, but before the first rain event occurred. Quantitatively, this is supported by the upslope contributing areas sediment yields. Dry ravel, which originated within the hillslope compartment, was deposited along the hollow compartments of the RGTs creating a connective upslope area but disconnected RGT. With this result, we were able to conclude that hollows are a significant component related to the connectivity of water and sediment within recently burned basins.

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