QUANTITATIVE LINKAGES BETWEEN WATERSHED CONDITIONS AND MAINSTEM CHANNEL CHARACTERISITCS IN LAGUNITAS CREEK, NORTHERN CALIFORNIA

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CERTIFICATION OF APPROVAL

I certify that I have read *Quantitative linkages between watershed conditions and mainstem channel characteristics in Lagunitas Creek, Northern California* by James Alan Chayka, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the request for the degree: Master of Science in Geosciences at San Francisco State University.

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The Lagunitas Creek watershed provides critical habitat to endangered and threatened fish populations. Although much research has been conducted on the relationship between sediment particle size and habitat quality, it is not well known how watershed conditions may affect the bed texture variability along mainstem channels. I explore the relationship between watershed conditions and channel bed texture through a geomorphic landscape unit (GLU) framework which analyzes the spatial distribution of rock type, land cover, and surface gradients for selected subwatersheds. I found that channel slopes do not appear to correlate with variations in bed texture, but it is not immediately apparent that differences in subwatersheds can explain this variability. Individual subwatershed attributes—instead of combined GLUs—may be more appropriate for predicting bed texture. I suggest an adjusted GLU approach that is more sensitive to variability within each attribute category.

I certify that the abstract is a correct representation of the content of this thesis.

May 11, 2011

Chair, Thesis Committee | Date

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1. INTRODUCTION

1.1 The problem of understanding bed grain size distributions

Populations of coho salmon (*Oncorhynchus kisutch*) and steelhead (*O. mykiss*) have been delining in California for decades (Brown et al., 1994). Accurate adult steelhead population sizes for Lagunitas Creek and other Bay Area watersheds are currently unavailable, but statewide estimates suggest that the general steelhead population has decreased by roughly half since the 1960's (McEwan and Jackson, 1996).

Like many other coastal watersheds in Northern California, Lagunitas Creek watershed (Figure 1) has been altered by land-use activities such as cattle grazing and dam construction (Stillwater Sciences, 2008). These land-use changes have the potential to affect hydrology, sediment fluxes and biodiversity throughout the region (Lohse et al., 2008). In particular, elevated sediment supply and increased yields of fine sediment—particles smaller than 2mm in diameter—to streams are linked to degraded aquatic habitat and decreased fish populations (Heywood and Walling, 2007). Although gravel size requirements for salmonids differ with life cycle (Kondolf, 2000), excess fine sediment particles infiltrate redds and impede the emergence of fry (Heywood and Walling, 2007). This relationship between fine sediment production and declining fish populations has profound implications for salmonid species that continue to live in the Lagunitas Creek watershed.

While there is an increasing understanding of how sediment grain size can impact aquatic habitats (Cover et al., 2008), the reasons for sediment grain size variability are still incompletely understood. Can we detect the influence of local tributaries and subwatersheds on bed texture? Here I use the conceptual framework outlined by Montgomery (1999) to examine the effects of combined watershed attributes, also known as "process domains" or "geomorphic landscape units" (GLUs). Montgomery (1999) defined process domains as spatially identifiable areas characterized by distinct suites of geomorphic processes that one can expect to similarly influence riparian ecosystems. This framework implies that watersheds and channel networks can be divided into discrete regions that respond similarly to a watershed disturbance (Montgomery, 1999). For example, in wide u-shaped valleys filled with glacial sediments channels are often disconnected from hillslope disturbances such as landslides or avalanches, whereas in narrow v-shaped valleys channel processes are connected to—and are therefore more sensitive to—these types of landscape changes (Montgomery, 1999). The process domain concept also suggests that sediment supply to channels reflects the variability of geomorphic processes that drive erosion, and are related to patterns of natural disturbance and local land use activities within a watershed (Stillwater Sciences, 2007).

The process domain concept has important implications for land management. If watershed attributes have similar combined effects on habitat, we could interpret and steward these areas in ways that consider both the anthropogenic and natural conditions found throughout our watersheds. For example, excess fine sediment delivery to riverine systems can be caused by land use activities such as cattle grazing (Walling, 1999). While this activity can be regulated by land managers to reduce fine sediment supply, it is more difficult to manage watersheds that produce excess fine sediment in the absense of apparent anthropogenic causes. For example, tensile strength and erosion rates differ among rock types within watersheds (Sklar and Dietrich, 2001), which in turn can control the volume and grainsize distrubtion of sediment supplied to river networks (Dietrich et al., 2003). Given the potential for natural causes of excess fine sediment (e.g., certain rock types) it is important to explore discrete waterershed variables and the potential synergy between these variables. Can we identify those individual watershed variables, or combinations of watershed variables, that combine to provide beneficial or detrimental sources of sediment?

Here I explore whether the spatial variation in main-stem channel morphology and bed texture can be explained in terms of local watershed attributes in the tributary sub-watersheds draining to Lagunitas Creek. I focus on bar texture as a response variable, and test whether watershed attributes—such as gradient, landcover, and rock-type—can explain patterns in grain-size variability along the mainstem. I also test whether channel conditions such as channel slope correlate with bed texture. Is there a unique signature in mainstem Lagunitas Creek that reflects subwatershed differences? If so, what are the important watershed attributes that control variability in bed texture and channel morphology? Are there other watershed-scale variables that could account for the spatial variability in fine sediment? To what extent do potential watershed-scale variables control reach-scale attributes? Also, assuming that sediment supply at the subwatershed scale is responsible for spatial variability in bed texture along the mainstem, what role do channel processes have in influencing bed texture and channel morphology?

1.2 Lagunitas Creek environmental setting

The Lagunitas Creek watershed, which drains roughly 260 km^2 in West Marin County, is both the largest watershed draining to Tomales Bay (Birmingham and Weppner, 2007) and the largest watershed in Marin County. Lagunitas Creek originates on the northern slopes of Mt. Tamalpais in Marin County and flows approximately 40 km to its terminus at Tomales Bay (Figure 1). There are several dams located in the Lagunitas Creek watershed. Lagunitas Dam, Alpine Dam, Bon Tempe Dam, and Peters Dam impound water and sediment in the upper Lagunitas Creek Watershed (O'Connor and Rosser, 2006). Peters Dam, which forms Kent Lake, prevents the passage of anadromous fish into the upper watershed (Stillwater, 2008).

Major tributaries to this watershed include San Geronimo Creek, Devils Gulch, Nicasio Creek, and Olema Creek (Hecht and Glasner, 2002). San Geronimo Creek is the largest undammed tributary in the upper watershed; it drains approximately 23.8 km^2 before joining Lagunitas Creek just below Kent Lake (Hecht and Glasner, 2002). Devils Gulch is contributes flow and sediment from a 6.9 km^2 drainage area and joins Lagunitas Creek 5.6 km below Kent Lake. In the lower watershed, Nicasio Creek contributes flow and sediment from a drainage area of 93 km^2, which is the largest contributing drainage area in the greater watershed. However, Nicasio Dam is located approximately 1.6 km upstream of the confluence with Lagunitas Creek, impounding flow and sediment draining from the Nicasio Creek subwatershed (O'Connor and Rosser, 2006). Similarly, the Olema Creek watershed drains an area of 37.5 km^2 (SFRWQCB, 2002) but only joins Lagunitas Creek near the southern tip of Tomales Bay, resulting in a very weak influence on the hydrology and sediment delivery to most of Lagunitas Creek. Olema creek flows within the San Andreas Fault Zone (SAF), crossing the SAF at Five Brooks (RWQCB, 2002).

Nearly 60% of the land within the Lagunitas Creek watershed is publicly owned (RWQCB, 2002). Marin Municipal Water District (MMWD) is a public agency responsible for managing a 380 km^2 area of south and central Marin County, which includes the middle and upper portions of the Lagunitas Creek watershed, as well as smaller areas adjacent to Nicasio and Soulajule reservoirs in West Marin (mmwd website). Lagunitas Creek also flows through Samuel P. Taylor State Park, which is managed by the California Department of Parks and Recreation (DPR). The US Geological Survey (USGS) operates gauge station #11460400 within the State Park reach of Lagunitas Creek. The coastal portion of the watershed, including Olema Creek, is managed by the National Park Service as part of the Point Reyes National Seashore (O'Connor and Rosser, 2006)

Lagunitas Creek watershed is host to a number of anadramous fish species, including Coho salmon (*Oncorhynchus kisutch*), steelhead (*O. mykiss*), and Chinook salmon (*O. tshawytscha*) (O'Connor and Rosser, 2006). The coho salmon population in Lagunitas Creek belongs to the Central California Coast evolutionarily significant unit (ESU), and is federally listed as endangered under the Endangered Species Act (Stillwater, 2008). Steelhead in Lagunitas Creek also belong to the Central California Coast ESU, and have been federally listed as threatened under the Endangered Species Act (NMFS, 1997). Other aquatic species found within the watershed include freshwater bivalves, California freshwater shrimp, and California red-legged frog (Stillwater, 2008).

Geologic units within the Lagunitas Creek watershed (Figure 2) include Franciscan mélange, Quaternary alluvium, and portions of the San Bruno Mountain and Nicasio Reservoir terranes (Wahrhaftig and Wakabayashi, 1989). These rock types include lithic sandstone, shale, greenstone, and serpentine (O'Connor and Rosser, 2006).

Rainfall in the Lagunitas Creek watershed ranges from 122 cm per year in the upper watershed near Kent Lake to 89 cm in the downstream tributaries (Hecht and Glasner, 2002). The upper watershed near Kent Lake consists of dense forest communities that include Redwood, Douglas fir, coast live oak, bay, and alder trees (SFRWQCB, 2002). Grasslands dominate the uplands of San Geronimo and Nicasio valleys, with bay, alder and Douglas fir on the steeper southern slopes (SFRWQCB, 2002). The east-facing slopes of the lower watershed are mostly second-growth Douglas fir and chaparral (Stillwater, 2007). Riparian species along Lagunitas Creek include alder, willows, ash, maples, and dogwood (Stillwater, 2007).

1.3 Previous studies on watershed-channel linkages

The Lagunitas Creek watershed has been a region of intense research and public scrutiny. Driven by concerns for declining salmonid populations, local Marin County, as well as State and Federal agencies, have commissioned research projects focusing on sediment delivery mechanisms, habitat conditions, erosion prevention, and vegetation management (Birmingham and Weppner, 2007; Hecht and Glasner, 2002; Hecht et al., 2007; O'Connor and Rosser, 2006; Stillwater Sciences, 2007; Stillwater Sciences 2008).

Despite the abundance of research in this area, little is known about how watershed conditions influence channel morphology and sediment grain size. One study (Friend, 1992) examined the relationship between river morphology and sediment grain size, and found that the morphology of rivers may be locally controlled by mass wasting events that supply different sediment grain-sizes. For example, a major sediment influx to the mainstem can deflect flow toward the river banks, thereby eroding and mobilizing new sediment that can change the downstream sections of the main-river reach (Friend, 1992). Although this research makes a qualitative connection between sediment influx and channel morphology, little is known about how mainstem channel morphology can change due to changes in median sediment size—D50—of a given sediment influx. D50 is defined as the grain diameter at which 50% of the particles in a particular sample are finer.

A study by Rice (1998) examined the relationship between grain size and watershed conditions in British Columbia. This study revealed that certain basin parameters, such as area and slope, can disrupt the typical exponential downstream fining trend (Morris and Williams, 1999) found along mainstem rivers. Although these discrete basin variables seem to work independently to influence grain size, it is still unclear if the combination of these parameters can have an impact.

In one of the few studies to explore the relationships between sediment supply, stream channel conditions, and biological responses, Cover et al. (2008) determined that increased sediment supply in the Klamath Mountains is linked to elevated levels of stream-bed fine sediment for channels, which appears to adversely affect certain benthic macroinvertebrates that function as prey for salmonids. This relationship between sediment supply and biological response is important but the combination of watershed attributes that influence grain size remains uncertain.

Boggs (1969) found that rock type was an important control on the sediment grain-size of stream gravel bars. For gravel bars on the Sixes River in southwestern Oregon, pebble counts revealed that sandstone sedimentary rocks were consistently more abundant among finer gravel bars, whereas conglomerate, igneous, and metamorphic rock types were generally more abundant among coarser gravel bars (Boggs, 1969). Although the relative abundance of given rock types correlated with the mean grain size (D50) of the sample site, it remains unclear how watershed variables such as land use might control the influx of each rock type, thus altering the proportions of rock type for each sample population.

In a similar study, Sable and Wohl (2006) also found that rock type is one watershed attribute that clearly influences the amount of fine sediment deposited in streams. In comparing channels in the Oregon Coast Range underlain by sandstone or basalt, these researchers found that there is a positive correlation between sandstone drainages and relatively larger volumes of fines in pools (Sable and Wohl, 2006). Researchers intentionally held variables constant other than rock type—such as discharge, reach gradient, watershed area, and channel morphology—in order to isolate the influence of rock type on bed texture. While these results imply that rock type can influence the size of sediment particles transported to channel networks, it remains unclear how rock type may interact with other watershed and channel variables to influence bed texture.

1.4 Overview of next sections

In collaboration with Stillwater Sciences and the California State Regional Water Quality Control Board (RWQCB), I quantified the relationships among sediment grain size, channel morphology, and watershed attributes in Lagunitas Creek. As an intern with Stillwater Sciences in Summer 2008, I participated in channel and hillslope surveys in the Lagunitas Creek watershed. Funded by the RWQCB, these field efforts aided efforts by Stillwater Sciences to construct a sediment budget for the watershed and investigate sediment-transport dynamics for Lagunitas Creek (Stillwater Sciences, 2010). Stillwater applied the TUGS model (The Unified Gravel-Sand model) to analyze the transport of multiple particle sizes; the inputs for this model include channel longitudinal profile, bankfull channel width, water discharge, and sediment supply rate (Stillwater, 2010). Stillwater Sciences also used the GLU framework to calculate sediment inputs from subwatersheds within the Lagunitas Creek watershed. I sought to test whether the GLU framework might be useful for explaining bed texture variability along mainstem Lagunitas Creek. My project is an outgrowth of this sediment budget research, and builds on current knowledge about sediment delivery processes by exploring some of the watershed-scale and reach-scale variables that influence sediment grain sizes.

In the subsequent sections I describe channel characteristics, as well as attributes of the Lagunitas Creek watershed that I used to analyze differences among subwatersheds. I also describe my field and computer methods used to collect and calculate these data. The balance of this paper is dedicated to describing the results of channel and subwatershed analyses, and discussing potential implications for land management within the Lagunitas Creek watershed.

2. THE WATERSHED

My study area excludes the Nicasio Creek and upper Lagunitas Creek watersheds due to the presence of dams on these creeks, and the resulting effects on water and sediment flow to areas downstream of those dams. I have also excluded the Olema Creek subwatershed from my study area because it joins mainstem Lagunitas Creek near the outlet at Tomales Bay. I have analyzed my study area within the Lagunitas Creek watershed in terms of rock type, land cover, and slope. The following subsections describe these attributes using four rock types, four land cover categories, and three hillslope-gradient classes. Stillwater Sciences used these categories in constructing a sediment budget for the Lagunitas Creek watershed, and I used this convention to build upon that research and test the utility of a GLU framwork.

2.1 Geologic descriptions

The geology of the Lagunitas Creek watershed belongs to a group of rocks known as the Franciscan Complex. The Franciscan Complex is defined by its highly disrupted structural condition, and the amalgamation of various sedimentary rocks, igneous, and metamorphic rocks. The Franciscan Complex was formed in the mid-Jurassic when oceanic crust was subducted beneath the North American plate, resulting in the accretion of oceanic crustal rocks (mid-oceanic ridge basalt and underlying ultramafic igneous rocks) and overlying oceanic (primarily sandstone and radiolarian chert) sediments

(Wahrhaftig and Wakabayashi, 1989). The Franciscan Complex is divided into three northwest-trending belts. The Lagunitas Creek watershed is located within the Central Belt of the Franciscan Complex that consists mostly of mélange but also of large areas of relatively coherent rocks (Wahrhaftig and Wakabayashi, 1989). Franciscan mélange is a highly disrupted rock unit, where blocks of basalt, chert, limestone, gabbro, blueschist, eclogite, and amphibolite are isolated within highly sheared sections of shale, sandstone, or serpentinite (Wahrhaftig and Wakabayashi, 1989). Despite the fractured nature of the rocks in this region, there are coherent geologic bodies with similar structure, origins, and histories—known as tectonostratigraphic terranes—that are strikingly different from the mélange that dominates the watershed (Wahrhaftig and Wakabayashi, 1989). Other tectonostratigraphic terranes within the Lagunitas Creek watershed include the San Bruno Mountain terrane and the Nicasio Reservoir terrane (Wahrhaftig and Wakabayashi, 1989).

Figure 2 shows a geologic map indicating the location of four different rock-sediment units found within the watershed. Although all rocks within the watershed belong to the Franciscan Complex, this paper refers to "Franciscan" rocks as a mélange rock-sediment unit that is different from the aforementioned tectonostratigraphic terranes. Franciscan mélange rocks are found at the surface in 65% of the watershed (Figure 3a).

Although Franciscan mélange is found throughout the watershed, the San Bruno Mountain terrrane is limited to the western side of the watershed between Lagunitas Creek and Olema Creek. This terrane consists mostly of submarine sandstone, with abundant detrital quartz and feldspar minerals. San Bruno Mountain terrane makes up 14% of the surface area of the Lagunitas Creek watershed.

The Nicasio Reservoir terrane is located primarily along the northeast side of Lagunitas Creek, in a large swath below Kent Lake and in the vicinity of Nicasio reservoir. This terrane consists mainly of pillow basalt, with some sandstone and underlying radiolarian chert (Wahrhaftig and Wakabayashi, 1989). Nicasio Reservoir terrane makes up 16% of the surface area of the Lagunitas Creek watershed.

Quaternary alluvium is found in valley bottoms and along portions of Lagunitas Creek. This rock-sediment unit contains loose, unconsolidated sediments that are transported by river processes.

2.2 Land-cover descriptions

In accordance with terminology used by Stillwater Sciences (Stillwater Sciences, 2007), the Lagunitas Creek watershed can be divided into four land-cover groups that account for both vegetation and land use (Figure 4). These categories—agricultural and herbaceous grasslands; conifer and hardwood forests; mixed shrubs; and urban or barren ground—were created by Stillwater Sciences using 30-m-resolution LANDSAT imagery in Geographic Informations Systems (GIS) software. This categorization reflects the potential for erosion due to differences in soil permeability and rainfall interception, canopy cover, and the effects of root strength and density (Stillwater Sciences, 2007).

Agricultural/herbaceous areas are those portions of the watershed that contain less than 50% tree canopy cover, and are dominated by agricultural or herbaceous grasslands. These areas also include permanent pastures, cultivated land, and orchards (Stillwater, 2007). Agricultural/herbaceous areas account for 36% of the land cover in the Lagunitas Creek watershed, excluding downstream drainages of Nicasio and Olema Creek subwatersheds (Figure 3b).

Shrub areas are those portions of the watershed that also have less than 50% tree canopy cover, but contain mixed shrub species such as chaparral, manzanita, and ceanothus (Stillwater, 2007). Forested areas include portions of the watershed that have greater than 50% tree canopy cover, composed mainly of hardwoods and conifers species such as redwood, Douglas fir, coast live oak, bay, and alder (SFRWQCB, 2002). Forested and shrub areas cover 43% and 17% the Lagunitas Creek watershed, respectively.

Urban or barren areas include homes or other residential units, impermeable surfaces such as roads or bedrock, and other urban structures that lack vegetation (Stillwater Sciences, 2007). Towns within the San Geronimo and Lagunitas valleys include Woodacre (population 1393) and Lagunitas-Forest Knolls (population 1835) (http://www.census.gov/), but smaller private inholdings adjacent to public land are scattered throughout the watershed. Urban or barren areas account for only 4% of land cover throughout the Lagunitas Creek watershed, excluding Nicasio and Olema Creek drainages.

2.3 Hillslope gradient

The Lagunitas Creek watershed contains a large percentage of hillslopes with a gradient greater than 30% (Figure 3c). Figure 5 shows a map of the watershed indicating the location of three different slope classes: (1) "gentle" slopes with a gradient between 0 and 5 percent; (2) "intermediate" slopes with a gradient between 5 and 30 percent; and (4) "steep" slopes with a gradient greater than 30 percent. More than half (59%) of the watershed is steep; intermediate and gentle slopes account for 35% and 6% of the watershed, respectively.

3. METHODS

My research questions grew out of fieldwork I conducted in 2008, which helped to create a sediment budget for the Lagunitas Creek watershed (Stillwater Sciences, 2010). I was interested in exploring the corrrelation between subwatershed conditions and channel bed texture. I therefore created an experimental design that would enable me to isolate and interpret different channel and watershed characteristics. While conducting a longitudinal profile survey of Lagunitas Creek, I noticed variations in bed texture and chose to measure this variability at different locations along the mainstem. I selected nine sites along San Geronimo and mainstem Lagunitas creek, with each site located just at a tributary confluence.

I hypothesized that variability in bed texture (i.e., grain size) at each site is directly related to differences in slope, rock type, and vegetation type for each subwatershed. Furthermore, I hypothesized that subwatersheds exert detectable influences on tributaries, and that these influences can be analyzed by amalgamating watershed conditions into discrete Geomorphic Landscape Units (GLU). GLUs are areas with shared, overlapping spatial attributes—such as rock type, slope, and land cover—and display similar processes and rates of erosion (Montgomery, 1999). I hypothesize that tributaries in the Lagunitas Creek watershed act primariliy as conduits of sediment, with variability in sediment size along the mainstem directly related to differences between subwatersheds.

3.1 Field work

I conducted a longitudinal profile from the confluence of Woodacre Creek (on San Geronimo mainstem) to Devils Gulch using a laser rangefinder and auto level. The laser range finder is a Countour XLRi manufactured by LaserCraft Inc. This rangefinder was aimed at a reflective target at the stadia location; it could then be used to display horizontal distances and vertical angles. Elevation changes were measured with a Topcon AT-B4 auto level by reading values on a stadia rod. All data points were entered into a field book, and then entered in Microsoft Excel for analysis.

I obtained the remaining longitudinal profile data (Devils Gulch to Highway 1 bridge; Figure 1) from Marin Municipal Water District (MMWD). These profile data were collected by the consulting firm Graham Matthews and Associates (GMA), and appear in my thesis courtesy of MMWD. The GMA survey was conducted in 2010, and was a continuation of the work I began with Stillwater Sciences in 2008 under a different contract with MMWD. I compiled the GMA and Stillwater surveys into a single Excel file, and plotted the entire longitudinal profile (Figure 6). This combined survey begins at Woodacre Creek in San Geronimo Valley and ends near the Highway 1 crossing on mainstem Lagunitas Creek.

I measured the bed texture of clasts in nine gravel bars along the longitudinal profile. I selected sampling sites that were located at tributary junctions, under the hypothesis that variability in bed texture at these locations reflect differences in the spatial attributes of subwatersheds draining to each bar. Depending on the size of the gravel bar, I subjectively divided each site into an upstream, middle, and downstream section. I conducted 100 pebble counts per section using the Wolman pebble-count method (Harrelson et al., 1994). Under this method, I walked random zig-zag transects at each gravel bar, and measured the intermediate axis of a single clast with every step. I selected each clast blindly by closing my eyes at each step, and pointing a pencil at a location in front of my foot. I then measured the diameter of the clast that was touching the end of my pencil, and recorded these data in a waterproof field book. I transferred these data into Excel in to examine the particle-size distribution—which describes the range and frequency of values—for each sampling site. I also measured the coordinates of each gravel bar location using a Garmin GPS60 global positioning system device, and stored these data in GIS and as text coordinates in Excel.

To examine the statistical differences in grain size among each of the gravel bars, I had to first construct a database in JMP ("JMP" is a powerful statistical software package) that could contain the nearly 3000 pebble counts, as well as information about the site location and section of gravel bar sampled. The appropriate statistical tool for comparing multiple sites is the ANOVA test, which depends on two assumptions. For ANOVA to be performed, the measurements at each site have to be normally distributed, and the amount of scatter at each site must be approximately the same (Helsel and Hirsch, 2002). I transformed the grain diameters using a logarithmic base-10 function in order to reduce the amount of scatter found in each plot, and to satisfy the second ANOVA condition mentioned above. Figures 7a and 7b show the differences in scatter and plots for transformed and untransformed grain sizes. Once both conditions for ANOVA were met, I was able to compare each bar in JMP using the "Analyze" drop-down menu, selecting "fit y by x", and choosing "Log10 particle size" for my y-variable, and "gravel bar" as the x-variable. Once I conducted this analysis, I was able to determine similarities and differences using both the "means/anova/t-test", and "compare means"→"tukey HSD" options in JMP.

In an effort to isolate channel conditions from subwatershed influences, I also examined channel slopes at each of my sampling sites. I used the longitudinal profile data to analyze bed elevations for approximately 150 m upstream and downstream at each site, which is equal to the length of approximately 20 channel widths. I focused on maximum elevations within each reach, and fit a linear trend to these elevation points to calculate slopes for each reach in Excel. Figure 8 demonstrates how I calculated these slopes using Gravel Bar #7 as an example.

3.2 Data mining

I conducted extensive searches for previous data collected within the Lagunitas Creek watershed. Although no previous longitudinal profile surveys exist for mainstem Lagunitas Creek, I obtained and incorporated streambed-monitoring data collected by Barry Hecht and others at Balance Hydrologics (Hecht et al., 2007). These data were collected from 1979 to 2008 at eight monitoring sites along mainstem Lagunitas Creek. Balance's monitoring sites were specifically selected at locations presumably away from the influence of tributary inputs (Hecht et al., 2007). I selected all of their data in PDF form, and imported it into Excel. I also transferred these data to JMP software, which contains spreadsheet formats but also allows for more advanced statistical analyses. I used JMP to analyze particle-size distributions for each of my sampling sites.

3.3 Geographic Information Systems (GIS)

There are large amounts of GIS data available to the public via the online "Marin Map" website (http://mmgis.marinmap.org/DNN/). I downloaded specific GIS layers—which are data and images that can be viewed simultaneously using GIS software—that included spatial information for the Lagunitas Creek watershed. These layers depict the greater Lagunitas Creek watershed boundary, coastline imagery for Tomales Bay and west Marin County, and river-path imagery for mainstem Lagunitas and San Geronimo Creeks.

I also obtained extensive amounts of GIS data from Stillwater Sciences to examine the GLUs for each subwatershed. Stillwater Sciences synthesized data from U.S. Geological Survey (USGS) with maps and other reports to create a single GIS file that depicts the rock type, land cover, slope, river network, and subwatershed boundaries for the entire Lagunitas Creek watershed (Stillwater Sciences, 2007). Stillwater Sciences combined 3-m USGS Digital Elevation Model (DEM) files to depict slope; a digitized geologic map of the San Francisco Bay region (Wentworth, 1997); and digitized LANDSAT vegetation imagery (USFS, 1998).

The combination of these three attributes (rock type, land cover, hillslope gradient) results in areas that share similar properties, but are spatially discontinuous throughout the watershed. Figure 9 shows how GIS layers of rock type, land cover, and slope overlap to create discrete GLUs.

To examine the spatial extent of GLUs for each of the subwatersheds draining to my gravel sites, I first had to separate each subwatershed from the greater Lagunitas Creek watershed. I created these separate shapefiles by exporting each subwatershed boundary (using the "select by attributes" function in the attribute table) from the original watershed map. Next, I used the "extract by mask" tool to integrate spatial information from the 3-m DEMs for Marin County into each subwatershed shapefile. This extraction enables the software to calculate the area of attributes within any defined boundary. Figure 10 shows an example of how this action is carried out within GIS.

With this approach, GIS subwatershed boundaries provided a spatial delineation to isolate attributes within a particular subwatershed. I converted the vegetation, rock type, and slope-category layers from vector data into raster data using the "polygon to raster" tool. This tool is found in the "conversion tools" toolbox within GIS. It was imperative to convert these layers into raster data so I could again use the mask function to assimilate vegetation, rock type, and slope data into the subwatershed files. Without first converting files from vector to raster data, GIS can over-calculate the spatial distribution of watershed attributes by including spatial data that overlap a masking boundary.

4. RESULTS

The following section describes the results of my pebble count analysis, subwatershed analysis, and exploration of potential linkages between bed texture and subwatershed conditions. First, I describe all data pertaining to bed texture, which includes pebble counts I conducted in 2008 and data collected by Balance Hydrologics for over twenty years. Next, I describe differences in subwatershed attributes for those areas draining to each of my gravel bars. Last, I examine similarities and differences of subwatersheds draining to statistically similar bars.

4.1 Channel findings

Plots of grain size distributions from my pebble counts show that the texture of my gravel bars vary significantly along the longitudinal profile, while maintaining a general downstream fining trend (Figure 11). An ANOVA test for the nine bars shows that there are statistically significant differences among some bars. I found that at the 95% confidence level the F ratio is 98.00, much greater than the "greater than 1" threshold required by ANOVA. See Table 1 for a summary of these statistics.

The next step involved determining which bars are statistically distinguishable from each other. I removed bars 8 and 9 from my analysis because they are upstream of the Lagunitas-San Geronimo confluence, and have different sediment supply characteristics due to the presence of Peters Dam. Similarly, I removed bars 4 and 5 from the analysis because they are not located at a tributary junction, and thus cannot be examined in terms of a corresponding subwatershed.

The appropriate test for determining whether the bars are statistically distinguishable is the Tukey HSD test. A few important findings emerged from this test. First, Gravel Bar #6—the coarsest gravel bar (D50 = 38.33 mm)—is statistically distinguishable from all other bars except Gravel Bar #2 (D50 = 35.5 mm). Second, the bars can be divided approximately in half, where one-half of the bars are statistically different from the other half. This relationship is best visually represented in Figure 12, using the comparison circles generated by the Tukey-Kramer plots. This plot shows that Bars 2 and 6 are a distinct population different from Bars 1, 3 and 7. Table 2 shows the comparisons for all pairs using Tukey-Kramer HSD.

To examine temporal changes in bed texture, I compared my pebble count data to data collected by Balance Hydrologics for years when they consistently monitored these sites. Since no other channel data exist for 2008 except for my pebble counts, I used data collected by Balance in 2007 for comparison purposes. These two years have similar average discharge as recorded by USGS gauge station #11460400: 23.1cfs and 29.8cfs in 2007 and 2008, respectively (Figure 13). I created a plot showing the median grain size of my 2008 gravel bars and the Balance sites from 2007 (Figure 14). This plot illustrates a slight downstream fining effect among all sites, when considering locations downstream of the confluence of San Geronimo and Lagunitas Creeks. This confluence is a useful delineation because sediment supply is different above and below this point, due to the presence of Peters Dam on Lagunitas Creek. Site KB is the upstream-most monitoring site on Lagunitas Creek and is the coarsest (D50 = 66.1 mm) among all sites for this year. Site KF is the downstream-most site monitored by Balance, and is upstream of Gravel Bars 1, 2, and 3. While KF (D50 = 22.9 mm) is not the finest bar among the grouped sites, the D50 for this site is among the finest of all sites and similar to other sites found in the same general downstream location. For example, Gravel Bar #4 (D50 = 28.0 mm) is located slightly upstream of KF, while Gravel Bar #3 and #2 are located downstream of KF with median grain sizes of 11.0 mm and 35.5 mm, respectively.

I also created a plot comparing my 2008 gravel bar data to Balance sites monitored in 2006 (Figure 15). The annual average discharge measured at USGS gauge station #11460400 in 2006 was 110.6 cfs, nearly four times greater than the discharge for 2007. Despite the large difference in discharge, the plot shows a similar relationships between the Balance sites and my data set, and a downstream fining effect. KB is again the coarsest among all sites, with a D50 of 77.1 mm, with the remaining downstream sites showing a slight downstream fining pattern.

I also plotted my 2008 gravel bar data together with data collected by Balance in 2002 (Figure 16). The annual average discharge measured by the USGS in 2002 is 45.0 cfs, which falls roughly between the previous years of 2006 (110.6 cfs) and 2007 (23.1 cfs). KB is again the coarsest site (88.4 mm), and the combined data illustrate a pronounced downstream fining effect. KF, the downstream-most site monitored by Balance, is the second finest site among Balance sites (D50 = 31.0 mm); it has a similar D50 to Gravel Bar #4 (28.0 mm), which is upstream approximately 30 m.

I combined my pebble count data (Table 3) with the data collected by Balance Hydrologics, and created a plot illustrating the time-averaged variations in grain size distribution at gravel bars along the mainstem (Figure 17). This data set includes all of the grain size monitoring data collected by Balance from 1981 to 2007 (Table 4). This plot illustrates a downstream fining trend among sites located downstream of the confluence of San Geronimo and Lagunitas Creeks, which is a general trend that is consistent with research conducted on rivers throughout the world (e.g. Morris and Williams, 1999; Rice, 1998). Nearly all of time-averaged Balance sites are coarser than the gravel bars that I measured in 2008, with only KL and KF (Balance's two downstream-most sites) grouped among my gravel bars. Site KH has the largest time-averaged D50 (65.9 mm) among all sites combined, and is the second site downstream of the confluence of San Geronimo and Lagunitas Creeks. Although KB is the upstream-most site, it has a D50 (57.5 mm) that is slightly smaller than KH; KB is located approximately 300 meters downstream of KB.

I also wanted to determine whether channel processes might appear to influence grain size at sampling sites, or whether it seemed that a sediment "signal" might be felt from the watersheds, trumping any influences of channel form and process. I calculated the slopes for each of my gravel bars and the Balance sites (Table 5), which revealed a wide range of channel slopes that do not appear to correlate with bed texture (Figure 18). When examining only my gravel bars I found a very weak correlation between median grain size and channel slope, with an R^2 value of only 0.008. (An R^2 value of 1.0 indicates a perfect predictability factor between variables.) This weak correlation between the D50 of my gravel bars and channel slope suggests that channel slope is not a good predictor for grain size, indicating that there are other likely factors influencing grain size. Similarly, I examined the slopes for the combined Balance sites and found an R^2 value of only 0.09, which also indicates an inadvisability of using channel slope as a predictor of grain size. I combined my gravel bars with the Balance sites to see if the grouped data might reveal a stronger correlation between D50 and channel slope. This grouped analysis revealed an R^2 value of only 0.053, also indicating a very weak connection between channel slope and D50.

4.2 Watershed and subwatershed findings

I calculated the spatial distribution of rock type, land cover, and slope for the entire Lagunitas Creek watershed (Figure 3, Table 6). In general, the watershed is a landscape that is mostly underlain by mélange with hillslopes greater than 30 percent gradient that are largely forested. However, the landscape attributes are more variable when examined at a subwatershed level (Figure 19). I analyzed the rock type, slope, land cover, and combined GLU for each of these subwatersheds (Table 7), and depicted these trends graphically in Figure 20.

Some interesting patterns emerge from examining the pie charts in Figure 20. Consistent with the overall "steep" characteristic of the Lagunitas Creek watershed, every subwatershed—except for the area draining to Gravel Bar #6—has at least 50% of its area consisting of hillslope gradients greater than 30 percent. Similarly, a very small portion of each subwatershed has a gentle gradient, with Gravel Bar #6 having the most expansive gentle area at only 6.25%.

While the Lagunitas Creek watershed consists largely of mélange overall, Figure 20 shows varying dominant rock types for each subwatershed draining to my gravel bars. Subwatersheds draining to Gravel Bars #1, #2, and #9 consist mostly of mélange (85.38%, 78.45%, and 87.0%, respectively), but each of the remaining subwatersheds has other dominant rock types. Subwatersheds draining to Gravel Bars #3 and #6 consist mostly of sandstone from the San Bruno Mountain terrane (95.46% and 89.73%, respectively), with mélange making up the small remaining area in each subwatershed. In contrast, subwatersheds draining to Gravel Bars #7 and #8 consist mostly of igneous rocks from the Nicasio Reservoir terrane (80.67% and 62.0%, respectively). Mélange makes up only 19.33% of the area draining to Gravel Bar #7, and the remaining 38% draining to Gravel Bar #8.

Subwatersheds appear most independent in terms of land cover. Figure 20 shows that each subwatershed draining to my gravel bars varies greatly in terms of the percentage of forested, shrub, and agricultural or herbaceous areas. For example, the subwatershed draining to Gravel Bar #3 is almost completely forested, with less than 1% of the area comprised of agricultural or herbaceous land cover. However, the subwatershed draining to Gravel Bar #6 has only 24.33% forested land cover. Shrub areas account for 45.17%

and 40.47% of the area draining to Gravel Bar #6 and #8, respectively. Only urban areas consistently account for very small portions of the subwatersheds draining to my gravel bars. Urban areas make up 4.29% of the subwatershed draining to Gravel Bar #8, and 0.95% of the area draining to Gravel Bar #9; the remaining subwatersheds do not have any urban or barren areas.

Figure 20 shows the distribution of GLUs for each of the subwatersheds draining to my gravel bars. Since there are a large number of possible GLUs throughout the Lagunitas Creek watershed (48 total), I chose to examine the top 3 GLUs for each of the subwaterhseds. There are 15 GLUs which make up the top 3 for each subwatershed; those GLUs that are not in the top 3 are combined into a category labeled "others" (Table 7). I created a GLU naming convention which uses the first letter of land cover type and geology—followed by the slope category—to refer to the GLU. For example, the code AF30 refers to a GLU with agricultural or herbaceous land cover, mélange, and slopes greater than 30%. The GLU pie charts in Figure 20 reveal subwatersheds that are not typically dominated by a single GLU. For example, only the subwatershed draining to Gravel Bar #3 has a top ranked GLU that accounts for more than 50% of the total area. Conversely, each of the top 3 GLUs draining to Gravel Bar #6 account for 28% or less of the total area, while the remaining combined GLUs for that subwatershed account for 35% of the total area. The subwatershed draining to Gravel Bar #2 also has a large spatial extent of GLUs that do not fall within the top 3. Although FF30 is the top ranked

GLU for this subwatershed—making up 31% of the area draining to Gravel Bar #2—34% of the total area is comprised of smaller GLUs not within the top 3.

4.3 Subwatershed attributes and median grain size

I explored similarities and differences of subwatersheds with similar grain size distributions. Subwatersheds draining to Gravel Bar #6 and #2 appear paired as anamolously coarse, while subwatersheds draining to Gravel Bar #7 and #3 appear paired as anamolously fine. Although Gravel Bar #6 and Gravel Bar #2 are not statistically distinguishable from each other (Figure 17), there are no subwatershed attributes that emerge as obvious explanatory variables linking these two gravel bars. The subwatershed draining to Gravel Bar #6 is predominantly underlain by San Bruno Mountain terrane (89.73%), while the subwatershed draining to Gravel Bar #2 has mostly mélange (78.45%). Due to the vast differences in rock type between these two subwatersheds, it does not appear that rock type alone can explain the coarseness in D50 for Gravel Bar #2 and #6 (D50=35.50 mm and 38.33 mm, respectively). Land cover also varies greatly between watersheds draining to Gravel Bar #6 and #2. The area draining to Gravel Bar #2 is roughly half forested and half agricultural or herbaceous. This differs from the area draining to Gravel Bar #6, which consists of 45.17% shrub cover. The remaining land cover for the area draining to Gravel Bar #2 is 24.33% forest and 30.50% agricultural or herbaceous land.

The dominant slope class for areas draining to Gravel Bar #2 and #6 is also different. Although both subwatersheds have large areas classified with slopes greater than 30 percent—consistent with the overall trend for the greater Lagunitas Creek watershed—this slope class is dominant for only Gravel Bar #2 (64.35%). The area draining to Gravel Bar #6 has five to thirty percent gradient as its top-ranked slope class (47.54%), followed by 46.21% area with "steep" slopes, and only 6.25% with a gradient less than five percent.

With such varying attributes among subwatersheds draining to Gravel Bar #2 and #6, it is not surprising that the GLUs for each subwatershed are likewise different. The top 3 GLUs draining to Gravel Bar #2 are completely different from the top 3 GLUs draining to Gravel Bar #6 (Table 7). Also, one-third of the area draining to each of these gravel bars are made up of GLUs that are not in the top 3. Similarly, the "dominant" GLU for Gravel Bar #2 (FF30) comprises only 31% of the total drainage area, while the dominant GLU draining to Gravel Bar #6 makes up only 28% of the total area.

Although Gravel Bar #7 and Gravel Bar #3—my anamolously fine bars—are also not statistically distinguishable from one another in terms of median grain size (D50=11.00 mm and 13.50 mm, respectively), I found striking similarities and differences among subwatersheds draining to these gravel bars. The dominant rock type underlying the subwatersheds draining to these two gravel bars are completely different. The subwatershed draining to Gravel Bar #7 is predominantly underlain by igneous rocks of the Nicasio terrane (80.67%), while 95.46% of the area draining to Gravel Bar #3 consists of sandstone rocks of the San Bruno terrane (Table 7). However, in terms of land cover these two subwatersheds do share an abundance of forested terrain. Nearly 100% of the subwatershed draining to Gravel Bar #3 is forested, while two-thirds of the area draining to Gravel Bar #7 has this land cover. Slope classes for these two subwatersheds are dominated by steep terrain, with 74.68% and 58.34% covering the area draining to Gravel Bars #3 and #7, respectively.

As was the case for my "coarse" gravel bars (#2 and #6), the top 3 GLUs for the areas draining to Gravel Bars #3 and #7 are completely different. However, the top 3 GLUs draining to Gravel Bar #3 make up 96% of the total area, with only 4% of the area consisting of GLUs not ranked in the top 3. Conversely, one-third of the area draining to Gravel Bar #7 consists of GLUs that are not ranked in the top 3; FN30 is the top ranked GLU at 44%.

5.0 DISCUSSION

Although my pebble count data show a general downstream fining trend (Figure 15), local deviations from this trend are not explained by channel slope. One would expect coarser median grain size along sections of the mainstem channel where there are relatively steeper channel gradients, but my data show very weak correlations when comparing D50 to channel slope (Figure 18). This general finding suggests that other variables are influencing bed texture along mainstem Lagunitas Creek. Differences among subwatersheds draining to my gravel bars may explain deviations in median grain size at gravel bars, but examining subwatersheds through the lens of overlapping attributes (GLUs) does not seem helpful. Similarly, isolating rock type, land cover, and hillslope gradients as separate variables also does not clearly explain variations in bed texture.

5.1 The complexity of GLU analysis

There are several reasons why GLUs are difficult to interpret in terms of their potential influence on bed texture. First, while the GLU approach effectively divides the landscape into sections with common attributes, the sizes of these sections are not equal and varies tremendously throughout the watershed. This is a result of rock type, land cover, and hillslope gradient occurring at vastly different scales. If all GLUs in the landscape were identical in size, it would be plausible to assume that differences in watershed conditions (e.g. erosion, sediment delivery) or bed texture are a result of the differences in "strength" of different GLUs. However, smaller GLUs in the Lagunitas Creek watershed may in fact exert a much stronger influence on channel conditons than larger GLUs. As indicated in Figure 19, GLUs that are not in the top 3 rank for each subwatershed often account for a significant amount of the drainage area. Perhaps it would be more revealing to depict a larger number of GLUs for each subwatershed, but the question of GLU strength would remain unanswered.

Another reason why GLUs are a difficult tool for interpreting variations in bed texture is that individual subwatershed attributes may also act disproportionately. For example, low gradient hillslopes account for a very small portion of each subwatershed. However, these areas are typically more suitable for grazing and other agricultural pursuits, resulting in increased erosion and sediment delivery to river channels. Similarly, a large portion of each subwatershed is characterized by steep gradients, which often results in more extreme mass wasting events (e.g. debris flows). Therefore, it is possible that subtle spatial changes in either of these slope classes could have a major impact on the size of sediment delivered to river channels. Without a way to quantify the potential impacts of these small changes, the GLU approach can obscure the effects of discrete subwatershed variables.

5.2 Watershed attributes as independent variables

While GLUs do not appear to explain deviations in bed texture along mainstem Lagunitas Creek, individual subwatershed attributes may help explain this variability. For example, subwatersheds draining to my finest gravel bars (#3 and #7) are both characterized by an abundance of forested land cover (Figure 20). These two subwatersheds also share a lack of underlying mélange. However, using these comparisons to explain bed texture variability may be misleading. The area draining to Gravel Bar #6—which is anomalously coarse—also is notable for its lack of mélange. Furthermore, the area draining to Gravel Bar #2—the other anomalously coarse bar—has nearly 50% of its area covered by forested terrain. Although the lack of mélange and the forested character of Gravel Bar #3 and Gravel Bar #7 may appear to correlate with fine bed texture, these subwatershed attributes are not unique among subwatersheds in my study area.

Another problem with using subwatershed attributes to analyze differences in bed texture is the inherent varability within each attribute. I have used categories for each watershed attribute that makes it easier to address similarities and differences over large areas of the landscape, but this approach may obscure variability within each attribute. For example, the geology of the Lagunitas Creek watershed is extremely complicated. Mélange within the watershed are a large mix of sediments that erode at different rates. One subwatershed that is categorized as "Franciscan" may consist solely of chert and blue schist, while another subwatershed with the same label could be underlain by a mix of sandstone, shale, and limestone. However, without extensive field efforts to map rock type at the subwatershed scale, it is impossible to predict how variability within Franciscan areas alone might influence bed texture throughout the greater Lagunitas Creek watershed.

Land cover is another watershed attribute that contains varability within its categories. For example, agricultural or herbaceous areas include land use activities such as grazing, crop production, and preserved open space. These distinct uses are bound to have an influence on the size of sediment delivered to the river network. Similarly, forested areas are also potentially different throughout the watershed. These areas are categorized as portions of the watershed that have greater than 50% canopy cover, but tree type, age, and health are not included here. Are large bay trees more resistant to tree throw—the tipping over of trees during storms, resulting in root upheaval and sediment production—than younger oak trees? If these forest communities are not equally resilient to storms, there is bound to be a difference in effects on the landscape. Non-homogeneity within subwatershed attributes is a potentially huge obstacle in comparing different subwatersheds, but it is difficult to determine what scale is both effective and efficient in exploring these spatial differences.

5.3 Channel processes and potential effects on bed texture

Although my data suggest that deviations in median grain size along mainstem Lagunitas Creek are not a result of channel slope (Figure 18), there may be other channel conditions that are influencing bed texture. Balance Hydrologics has reported that large woody debris and log jams have been responsible for mobilizing large volumes of coarse sediment along mainstem Lagunitas Creek, due to obstructed flows and subsequent bank erosion (Hecht et al., 2007). Although I did not observe any large woody debris or log jams in the vicinity of my gravel bars, these observations were not part of my experimental design and may have been overlooked in the field.

The tributaries supplying sediment to my gravel bars may also have characteristics that influence median grain size. Although I measured the channel slope of mainstem Lagunitas Creek up and downstream of this tributary confluence, I did not collect survey data in each corresponding tributary. It is possible that some tributaries are steeper than gradients at their Lagunitas Creek confluence, causing coarser sediment to be supplied to those respective gravel bars. Furthermore, I did not consider the potential impacts of large woody debris within tributaries, which could also influence bed texture for same reasons stated above.

Although I considered mean annual discharge when comparing my pebble count data to data collected by Balance Hydrologics during past years, this variable may be difficult to use as a comparison tool. For example, D50 for the Balance sites is quite similar in 2006 and 2007 (Figures 12 and 13), yet mean annual discharge was 23.1 cfs and 110.6 cfs, respectively. However, mean annual discharge for 2002 was 45.0 cfs, and median grain size for each of the Balance sites was coarser in this year than the D50 for both 2006 and 2007. This suggests that mean annual discharge does not directly correlate with bed texture, but a more detailed investigation of the hydrographs for these years is needed to explore these differences. It is possible that although 2006 and 2007 had drastically different mean annual discharges, the magnitude and frequency of rainfall—and thus, episodic discharge—had a stronger influence on bed texture.

5.4 Implications for land management

Through understanding the potential impacts that watershed variables may have on channel characteristics, land use managers can better plan for restoration projects intended to benefit endangered fish populations. However, my results suggest that it is difficult to analyze these landscape attributes at the watershed scale. Researchers in the Lagunitas Creek watershed have identified areas that produce large volumes of fine sediment (Stillwater, 2010), yet the exact reasons for these conditions are still unclear. It may be more cost effective and time efficient to focus future research on those subwatersheds that are already known to produce fine sediment. Although it is difficult to present clear linkages between watershed attributes and channel conditions using the GLU framework, this framework may be more useful if it incorporates more detailed data for each subwatershed. This adjusted framework would require the following data:

(1) Extensive geologic mapping for subwatersheds of concern. Although Franciscan mélange—as well as the other terranes found within the Lagunitas Creek watershed—are inherently complicated assembleges, more discrete mapping could help predict which areas of each geologic unit are more prone to weakening and erosion.

(2) Detailed land cover maps that include vegetation communities and land use activities. Land use activities have the greatest potential to alter the landscape and affect habitat quality within the Lagunitas Creek watershed. By mapping areas that are used for grazing or other agricultural pursuits, land use managers may better predict erosion rates and sediment supply to channels throughout the watershed. Similarly, research on erosion related to variations in forest communities and other vegetation could help create a model that predicts the size of sediment from those areas.

(3) Periodic mainstem and tributary channel surveys. These measurements could include elevation data and channel dimensions. These data would provide land managers with a baseline for future changes in channel form, and serve as a tool to track changes of areas with critical habitat.

6.0 CONCLUSION

Subwatersheds throughout the greater Lagunitas Creek watershed contain different types of vegetation, rock type, and hillslope gradients. The combinations of these attributes create Geomorphic Landscape Units (GLUs) that differ spatially among subwatersheds. I calculated the D50 at gravel bars along mainstem Lagunitas Creek, and used the GLU framework to explore possible linkages linkages between bed texture and subwatershed attributes.

My two coarsest gravel bars—Gravel Bar #2 and Gravel Bar #6—deviate from a downstream fining trend along mainstem Lagunitas Creek. Similarly, my two finest gravel bars—Gravel Bar #7 and Gravel Bar #3—also deviate from this trend. Although channel slope does not appear to be responsible for this variation in bed texture, it is not apparent whether watershed conditions are creating this variability. I analyzed the spatial extent of GLUs draining to each of my gravel bars, and ranked these GLUs in terms of their size. The top three (largest) GLUs for the areas draining to Gravel Bar #2 and Gravel Bar #6 are completely different from each other. This may suggest that the GLU approach is not an effective tool for analyzing differences in bed texture, or that certain smaller GLUs may exert a stronger influence than those GLUs that are more spatially dominant.

It may be more effective to examine bed texture in terms of individual subwatershed attributes, instead of the combined GLU approach. I calculated less forested area for the subwatersheds draining to Gravel Bar #2 and Gravel Bar #6 than compared to other subwatersheds draining to my gravel bars. However, it is unclear whether this single similarity can explain the coarseness of these two gravel bars. Each of the attributes—rock type, land cover, and hillslope gradient—that make up GLUs within the Lagunitas Creek watershed have inherent variability that confounds cross comparison. Also, the GLU approach to exploring variations in channel conditions relies on the assumption that spatially larger attributes and GLUs exert more influence than smaller ones.

Although the GLU approach did not yield a clear connection between watershed attributes and channel condition, this model may be effective by using a larger number of categories for each watershed attribute. This would require land managers to invest in more detailed geologic mapping, identifying areas with different landuse activities and vegetation communities, and collecting baseline channel surveys for Lagunitas Creek and tributaries throughout the Lagunitas Creek watershed.

REFERENCES

Birmingham, W., and E.W. Weppner (2007), Lagunitas Creek watershed assessment and erosion prevention planning project: Cheda Ranch, McIsaac Ranch, and Samuel P. Taylor State Park, Marin County, California, *Prepared for Marin Municipal Water District*, 22pp, Pacific Watershed Associates.

Boggs, S, Jr. (1969), Relationship of size and composition in pebble counts, *Journal of Sedimentary Petrology, 39*(3), 1243-1246.

Brown, L. R., P. B. Moyle, and R. M. Yoshiyama (1994), Historical decline and current status of coho salmon in California, *North American Journal of Fisheries Management, 14*, 237-261.

Cover, M.R., C.L. May, W.E. Dietrich, and V.H. Resh (2008), Quantitative linkages among sediment supply, streambed fine sediment, and benthic macroinvertebrates in northern California streams, *Journal of the North American Benthological Society, 27(1)*, 135-139.

Dietrich, W. E., D. G. Bellugi, L. S. Sklar, J. D. Stock, A. M. Heimsath, and J. J. Roering (2003), Geomorphic transport laws for predicting landscape form and dynamics. Pages 103-132 in P. R. Wilcock and R. M. Iverson (eds.) Prediction in geomorphology. American Geophysical Union, Washington, DC.

Friend, P. (1992), Control of river morphology by the grain-size of sediment supplied, *Sedimentary Geology, 85*, 171-177.

Harrelson, C. C., C. L. Rawlins, and J. P. Potyondy (1994), Stream channel reference sites: an illustrated field guide to field technique. General Technical Report RM-245, U.S. Department of Agriculture, Forest Service.

Hecht, B., and A. Glasner (2002), Interim analysis of streambed monitoring data: Lagunitas Creek sediment and riparian management plan, Marin County, California, *Prepared for Marin Municipal Water District*, 32 pp., Balance Hydrologics, Inc.

Hecht, B., M. Strudley, and S. Brown (2007), Lagunitas Creek sediment and riparian management plan, Marin County, California: Streambed monitoring report, 1995-2007, *Prepared for Marin Municipal Water District*, Balance Hydologics, Inc.

Helsel, D. R., and R. M. Hirsch (2002), Statistical methods in water resources, *Techniques of Water Resources Investigations, Book 4, chapter A3*, U.S. Geological Survey. 522 pages.

Heywood, M. J. T., and D. E. Walling (2007), The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content of intragravel water and embryo survival, *Hydrological Processes, 21*, 770-788, DOI: 10.1002/hyp.6266.

Kondolf, M. (2000), Assessing salmonid spawning gravel quality, *Transactions of the American Fisheries Society, 129*, 262-281.

Lohse, K. A., D. A. Newburn, J. J. Opperman, and A. M. Merenlender (2008), Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning, *Ecological Applications, 18*(2), 467-482.

McEwan, D., and T. A. Jackson (1996), Steelhead restoration and management plan for California, Management Report, California Department of Fish and Game, Inland Fisheries Division, Sacramento.

Montgomery, D.R., (1999), Process domains and the river continuum, *Journal of American Water Resources Association,* 35, 397-410.

Morris, P. H., and D. J. Williams (1999), A worldwide correlation for exponential bed particle size variation in subaerial aqueous flows, *Earth Surface Processes and Landforms, 24*, 835-847.

National Marine Fisheries Service (NMFS) (1997), Endangered and threatened species: threatened status for southern Oregon/northern California coast evolutionarily significant unit (ESU) of coho salmon, Federal Register 62: 24588-24609.

O'Connor, M., and B. Rosser (2006), Lagunitas creek fine sediment investigation, *Prepared for Marin Municipal Water District*, 70pp.

Rice, S. (1998), Which tributaries disrupt downstream fining along gravel-bed rivers?, *Geomorphology*, *22*, 39-56.

Sable, K.A., and E. Wohl (2006), The relationship of lithology and watershed characteristics to fine sediment deposition in streams of the Oregon Coast Range, *Environmental Management, 37*, 659-670.

San Francisco Regional Water Quality Control Board (2002), *Surface Water Ambient Monitoring Program (SWAMP), Final Workplan 2001-2002*, 57pp.

Sklar, L. S., and W. E. Dietrich (2001), Sediment and rock strength controls on river incision, *Geology, Dec. 2001.*

Stillwater Sciences (2007), Middle Lagunitas Creek watershed sediment delivery analysis, *Prepared for Department of Public Works, Marin County, California*, 49pp.

Stillwater Sciences (2008), Lagunitas limiting factors analysis: Limiting factors for Coho salmon and Steelhead, *Prepared for Marin Resource Conservation District*, 65pp.

Stillwater Sciences (2010), Taking action for clean water- Bay Area total maximum daily load implementation: Lagunitas Creek Sediment Budget, *Prepared for San Francisco Estuary Project / Association of Bay Area Governments*, 84pp.

U.S. Census Bureau wesite, http://www.census.gov

USFS (USDA Forest Service), 1998 CALVEG Database, http://www.fs.fed.us

Wahrhaftig, C., and J. Wakabayashi (1989), The Franciscan Complex, in *Geology of San Francisco and vincinity*, 28th International Geological Congress, Field Trip Guidebook T105, coordinated by C. Wahrhaftig, 69pp., AGU, Washington, D. C.

Walling, D. E. (1999), Linking landuse, erosion and sediment yields in river basins, *Hydrobiologia, 410*, 223-240, doi:10.1023/A:1003825813091.

Wentworth, C.M. 1997. General distribution of geologic materials in the San Francisco Bay region, California: A digital map database. U.S. Geological Survey Open-File Report OFR 97-744.

Table 1. Summary statistics for Oneway ANOVA

Oneway Analysis of log10(part.size) By Gravel Bar

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Gravel Bar	8	87.88022	10.985	98.0037	<.0001
Error	2306	258.47453	0.1121		
C. Total	2314	346.35475			

Means for Oneway Anova

Level	Number	Mean(mm)	Std Error	Lower 95%	Upper 95%
Bar#1	272	0.9593	0.0203	0.9195	0.9991
Bar#2	198	1.51367	0.02379	1.467	1.5603
Bar#3	193	1.03897	0.0241	0.9917	1.0862
Bar#4	297	1.4211	0.01943	1.383	1.4592
Bar#5	295	1.18061	0.01949	1.1424	1.2188
Bar#6	299	1.53115	0.01936	1.4932	1.5691
Bar#7	198	1.11432	0.02379	1.0677	1.161
Bar#8	267	1.2673	0.02049	1.2271	1.3075
Bar#9	296	1.40625	0.01946	1.3681	1.4444

Table 2. Summary statistics for comparisons of all pairs using Tukey-Kramer HSD

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.1047	0.05

Abs(Dif)-LSD	Bar#6	Bar#2	Bar#4	Bar#9	Bar#8	Bar#5	Bar#7	Bar#3	Bar#1
Bar#6	-0.08501	-0.07776	0.0249	0.03968	0.17633	0.26525	0.32159	0.3962	0.48475
Bar#2	-0.07776	-0.10447	-0.00279	0.01199	0.14889	0.23757	0.29488	0.36956	0.45727
Bar#4	0.0249	-0.00279	-0.0853	-0.07052	0.06614	0.15505	0.21141	0.28602	0.37456
Bar#9	0.03968	0.01199	-0.07052	-0.08544	0.05122	0.14013	0.1965	0.27111	0.35964
Bar#8	0.17633	0.14889	0.06614	0.05122	-0.08996	-0.00111	0.05549	0.13012	0.21845
Bar#5	0.26525	0.23757	0.15505	0.14013	-0.00111	-0.08559	-0.02921	0.0454	0.13393
Bar#7	0.32159	0.29488	0.21141	0.1965	0.05549	-0.02921	-0.10447	-0.02979	0.05792
Bar#3	0.3962	0.36956	0.28602	0.27111	0.13012	0.0454	-0.02979	-0.10581	-0.01816
Bar#1	0.48475	0.45727	0.37456	0.35964	0.21845	0.13393	0.05792	-0.01816	-0.08913

Positive values show pairs of means that are significantly different.

Level								Mean
Bar#6	A							1.5311516
Bar#2	A	B						1.513672
Bar#4		B	C					1.4210961
Bar#9			C					1.4062485
Bar#8				D				1.2672963
Bar#5				D	E			1.180606
Bar#7					E	F		1.1143208
Bar#3						F	G	1.0389704
Bar#1							G	0.9593031

Levels not connected by same letter are significantly different

Table 3. Pebble count data for gravel bars along mainstem Lagunitas Creek

Gravel Bar #	D50 (mm)
1 upstream section	11
1 mid section	13
1 downstream section	5
1whole	**9.67**
2 upstream section	41
2 downstream section	30
2whole	**35.50**
3 upstream section	11
3 downstream section	11
3whole	**11**
4 upstream section	30
4 mid section	26
4 downstream section	28
4whole	**28**
5 upstream section	20
5 mid section	16
5 downstream section	13.5
5whole	**16.5**
6 upstream section	49
6 mid section	35
6 downstream section	31
6whole	**38.33**
7 upstream section	15
7 downstream section	12
7 whole	**13.5**
8 upstream section	27
8 mid section	29
8 downstream section	6
8whole	**20.67**
9 upstream section	36
9 mid section	22
9 downstream section	25
9whole	**27.67**

Table 4a. Bed monitoring data collected by Balance Hydrologics (Balance 2008)

Site	Location	Segment	Year	Month	Day	Sample Size	D50 (mm)
(7) KF	Kelley's Tocaloma	Riffle	1980	12	16	64	43.3
(7) KF	Kelley's Tocaloma	Riffle	1981	2	24	68	46.6
(7) KF	Kelley's Tocaloma	Riffle	1981	8	12	72	39.9
(7) KF	Kelley's Tocaloma	Riffle	1982	7	21	134	40.3
(7) KF	Kelley's Tocaloma	Riffle	1991	11	1	136	30.6
(7) KF	Kelley's Tocaloma	Riffle	1993	10	19	146	28.3
(7) KF	Kelley's Tocaloma	Riffle	1995	10	27	96	30.5
(7) KF	Kelley's Tocaloma	Riffle	1996	10	31	115	28.7
(7) KF	Kelley's Tocaloma	Riffle	1997	9	3	100	19.0
(7) KF	Kelley's Tocaloma	Riffle	1998	9	3	92	33.1
(7) KF	Kelley's Tocaloma	Riffle	1999	9	1	84	25.8
(7) KF	Kelley's Tocaloma	Riffle	2000	7	6	106	28.2
(7) KF	Kelley's Tocaloma	Riffle	2001	6	22	118	35.7
(7) KF	Kelley's Tocaloma	Riffle	2002	6	4	111	31.0
(7) KF	Kelley's Tocaloma	Riffle	2003	9	11	110	30.8
(7) KF	Kelley's Tocaloma	Riffle	2004	6	2	138	25.9
(7) KF	Kelley's Tocaloma	Riffle	2006	5	16	154	26.9
(7) KF	Kelley's Tocaloma	Riffle	2007	5	23	130	22.9
(6) KL	Cheda Ranch Road	Riffle	1981	2	24	126	25.1
(6) KL	Cheda Ranch Road	Riffle	1981	8	3	185	28.9
(6) KL	Cheda Ranch Road	Riffle	1982	7	30	156	33.3
(6) KL	Cheda Ranch Road	Riffle	1991	11	8	118	31.7
(6) KL	Cheda Ranch Road	Riffle	1993	10	15	170	24.3
(6) KL	Cheda Ranch Road	Riffle	1995	11	3	116	18.4
(6) KL	Cheda Ranch Road	Riffle	1996	11	15	105	51.1
(6) KL	Cheda Ranch Road	Riffle	1997	9	5	60	26.5
(6) KL	Cheda Ranch Road	Riffle	1998	9	4	84	28.5
(6) KL	Cheda Ranch Road	Riffle	1999	9	8		27.5
(6) KL	Cheda Ranch Road	Riffle	2000	7	6	66	36.6
(6) KL	Cheda Ranch Road	Riffle	2001	7	8	62	32.0
(6) KL	Cheda Ranch Road	Riffle	2002	6	5	96	27.6
(6) KL	Cheda Ranch Road	Riffle	2003	9	11	112	25.8
(6) KL	Cheda Ranch Road	Riffle	2004	6	2	81	14.8
(6) KL	Cheda Ranch Road	Riffle	2006	5	18	123	25.2
(6) KL	Cheda Ranch Road	Riffle	2007	5	24	144	21.3
(5) KD	Big Bend	Riffle	1980	12	16	95	67.0
(5) KD	Big Bend	Riffle	1981	2	25	158	59.4
(5) KD	Big Bend	Riffle	1981	7	29	197	58.5
(5) KD	Big Bend	Riffle	1982	9	15	101	61.2
(5) KD	Big Bend	Riffle	1993	10	12	117	72.7
(5) KD	Big Bend	Riffle	1995	11	3	148	63.1
(5) KD	Big Bend	Riffle	1996	11	5	143	73.3
(5) KD	Big Bend	Riffle	1997	9	5	102	34.4
(5) KD	Big Bend	Riffle	1998	6	4	97	49.0
(5) KD	Big Bend	Riffle	1999	9	8	136	70.8
(5) KD	Big Bend	Riffle	2000	6	14	128	59.8
(5) KD	Big Bend	Riffle	2001	8	7	95	56.7
(5) KD	Big Bend	Riffle	2002	5	22	121	57.9
(5) KD	Big Bend	Riffle	2003	5	21	94	47.9
(5) KD	Big Bend	Riffle	2004	5	25	100	47.4
(5) KD	Big Bend	Riffle	2006	5	18	128	25.0
(5) KD	Big Bend	Riffle	2007	5	24	166	28.3

Table 4b. Bed monitoring data collected by Balance Hydrologics (Balance 2008)

Site	Location	Segment	Year	Month	Da y	Sampl e Size	D50 (mm)
(4) KJ	Big Rock	Riffle	1980	12	12	80	45.0
(4) KJ	Big Rock	Riffle	1981	2	25	79	54.5
(4) KJ	Big Rock	Riffle	1981	7	27	154	53.8
(4) KJ	Big Rock	Riffle	1982	7	23	119	46.1
(4) KJ	Big Rock	Riffle	1991	11	11	152	55.8
(4) KJ	Big Rock	Riffle	1993	10	8	135	38.9
(4) KJ	Big Rock	Riffle	1995	11	1	118	44.2
(4) KJ	Big Rock	Riffle	1996	11	5	122	46.5
(4) KJ	Big Rock	Riffle	1997	9	3	124	48.5
(4) KJ	Big Rock	Riffle	1998	9	3	155	69.2
(4) KJ	Big Rock	Riffle	1999	9	1	70	42.1
(4) KJ	Big Rock	Riffle	2000	7	6	124	45.6
(4) KJ	Big Rock	Riffle	2001	6	22	122	53.5
(4) KJ	Big Rock	Riffle	2002	5	21	161	39.7
(4) KJ	Big Rock	Riffle	2003	9	16	126	44.7
(4) KJ	Big Rock	Riffle	2006	5	18	126	29.9
(4) KJ	Big Rock	Riffle	2007	5	24	122	18.2
(3) KC	Samuel P. Taylor State Park	Riffle	1980	3	25	126	47.9
(3) KC	Samuel P. Taylor State Park	Riffle	1980	7	23	181	37.1
(3) KC	Samuel P. Taylor State Park	Riffle	1980	12	16	130	58.1
(3) KC	Samuel P. Taylor State Park	Riffle	1981	2	27	135	49.2
(3) KC	Samuel P. Taylor State Park	Riffle	1981	7	24	138	59.2
(3) KC	Samuel P. Taylor State Park	Riffle	1982	7	9	148	41.5
(3) KC	Samuel P. Taylor State Park	Riffle	1993	10	12	124	41.6
(3) KC	Samuel P. Taylor State Park	Riffle	1995	11	3	138	57.0
(3) KC	Samuel P. Taylor State Park	Riffle	1996	10	29	156	46.6
(3) KC	Samuel P. Taylor State Park	Riffle	1997	9	3	135	35.2
(3) KC	Samuel P. Taylor State Park	Riffle	1998	6	4	130	55.6
(3) KC	Samuel P. Taylor State Park	Riffle	1999	9	1	113	61.7
(3) KC	Samuel P. Taylor State Park	Riffle	2000	6	4	122	52.2
(3) KC	Samuel P. Taylor State Park	Riffle	2001	9	21	131	62.9
(3) KC	Samuel P. Taylor State Park	Riffle	2002	5	22	154	68.6
(3) KC	Samuel P. Taylor State Park	Riffle	2004	5	27	72	26.9
(3) KC	Samuel P. Taylor State Park	Riffle	2004	5	27	105	20.4
(3) KC	Samuel P. Taylor State Park	Riffle	2006	5	23	120	29.2
(3) KC	Samuel P. Taylor State Park	Riffle	2007	5	16	139	28.1
(2a) KX	Above Irving Bridge	Riffle	2002	11	4	123	52.3
(2a) KX	Above Irving Bridge	Riffle	2003	5	21	127	46.8
(2a) KX	Above Irving Bridge	Riffle	2004	5	25	140	42.6
(2a) KX	Above Irving Bridge	Riffle	2006	5	16	162	44.1
(2a) KX	Above Irving Bridge	Riffle	2007	5	16	135	38.1

Table 4c. Bed monitoring data collected by Balance Hydrologics (Balance 2008)

Site	Location	Segment	Year	Month	Da y	Sample Size	D50 (mm)
(2) KH	Kelley's Upper	Riffle	1980	12	1	132	60.3
(2) KH	Kelley's Upper	Riffle	1981	2	23	130	73.8
(2) KH	Kelley's Upper	Riffle	1981	7	28	182	72.5
(2) KH	Kelley's Upper	Riffle	1982	7	23	137	72.2
(2) KH	Kelley's Upper	Riffle	1991	11	27	109	60.2
(2) KH	Kelley's Upper	Riffle	1993	10	1	114	62.6
(2) KH	Kelley's Upper	Riffle	1995	10	27	102	71.3
(2) KH	Kelley's Upper	Riffle	1996	10	30	128	68.0
(2) KH	Kelley's Upper	Riffle	1997	8	5	113	57.9
(2) KH	Kelley's Upper	Riffle	1998	9	3	126	80.3
(2) KH	Kelley's Upper	Riffle	1999	9	8	134	73.6
(2) KH	Kelley's Upper	Riffle	2000	7	13	130	83.9
(2) KH	Kelley's Upper	Riffle	2001	5	23	104	82.5
(2) KH	Kelley's Upper	Riffle	2002	6	4	110	55.5
(2) KH	Kelley's Upper	Riffle	2003	9	16	132	57.1
(2) KH	Kelley's Upper	Riffle	2004	6	2	120	64.0
(2) KH	Kelley's Upper	Riffle	2006	5	23	120	50.0
(2) KH	Kelley's Upper	Riffle	2007	5	23	140	42.1
(1) KB	Below Shafter	Riffle	1981	2	23	103	69.8
(1) KB	Below Shafter	Riffle	1981	7	24	157	89.1
(1) KB	Below Shafter	Riffle	1982	7	30	118	30.8
(1) KB	Below Shafter	Riffle	1991	11	26	153	20.4
(1) KB	Below Shafter	Riffle	1993	10	15	111	22.8
(1) KB	Below Shafter	Riffle	1995	11	1	108	37.6
(1) KB	Below Shafter	Riffle	1996	10	31	130	29.5
(1) KB	Below Shafter	Riffle	1997	9	5	145	50.8
(1) KB	Below Shafter	Riffle	1998	9	4	145	35.9
(1) KB	Below Shafter	Riffle	1999	9	8	78	77.8
(1) KB	Below Shafter	Riffle	2000	7	13	120	60.6
(1) KB	Below Shafter	Riffle	2001	8	7	127	71.8
(1) KB	Below Shafter	Riffle	2002	5	22	119	88.4
(1) KB	Below Shafter	Riffle	2003	9	16	140	77.3
(1) KB	Below Shafter	Riffle	2004	5	27	140	72.0
(1) KB	Below Shafter	Riffle	2006	5	23	122	77.1
(1) KB	Below Shafter	Riffle	2007	5	23	137	66.1

Table 5. Chanel-reach slope summaries for my gravel bars and Balance sites.

Site	Cum dist (m) from Woodacre Cr	Slope (using linear trend at bar tops)	My Bars D50 (mm)	Balance sites D50 (mm)	All sites D50 (mm)
1	20052.03	0.005	9.67		9.67
2	15640.13	0.001	35.50		35.50
3	14755.51	0.001	11.00		11.00
4	13272.55	0.003	28.00		28.00
5	13104.86	0.003	16.50		16.50
6	11709.00	0.005	38.33		38.33
7	10615.86	0.002	13.50		13.50
KB	7300.87	0.005		66.10	66.10
KC	9425.16	0.001		28.10	28.10
KD	11301.86	0.003		28.30	28.30
KF	13921.76	0.001		22.90	22.90
KH	7628.23	0.002		42.10	42.10
KJ	10099.08	0.004		18.20	18.20
KL	12376.86	0.005		21.30	21.30
KX	8212.75	0.004		38.10	38.10

Table 6. Spatial distribution of geology, slope class, and land cover for the Lagunitas Creek watershed.

Attribute	Sub-attribute	Area (km^2)	Percent total
Rock unit	melange	133.3	64.4%
	Nicasio	33.3	16.1%
	Quat. alluv.	10.8	5.2%
	San Bruno	29.4	14.2%
Slope class	0-5	13.9	6.5%
	5-30	73.6	34.5%
	>30	125.7	59.0%
Land cover	ag/herb	76.6	35.9%
	forested	92.3	43.3%
	shrub	35.5	16.7%
	urban	8.8	4.1%

Table 7. Distribution of subwatershed attributes for areas draining to my gravel bars.

Gravel Bar info	Gravel Bar #	1	2	3	6	7	8	9
	D50 (mm)	9.67	35.5	11	38.33	13.5	20.67	27.67
	location dst (m)	20057.16	15644.13	14759.29	11712	10618.58	5171.87	2559.93
Subwatershed	Area (km^2)	4.51	6.35	1.92	5.96	9.59	1.09	5.39
Geology	Franciscan	85.38%	78.45%	4.54%	10.27%	19.33%	38.00%	87.00%
	Nicasio	9.34%	21.55%	0.00%	0.00%	80.67%	62.00%	0.00%
	San Bruno	4.16%	0.00%	95.46%	89.73%	0.00%	0.00%	0.00%
	Quat Alluv	1.12%	0.00%	0.00%	0.00%	0.00%	0.00%	13.00%
Land Cover	Ag/Herb	29.16%	50.55%	0.35%	30.50%	32.79%	8.15%	53.23%
	Forested	66.37%	48.50%	99.65%	24.33%	63.97%	47.09%	42.31%
	Shrub	4.48%	0.95%	0.00%	45.17%	3.24%	40.47%	3.51%
	Urban/Barren	0.00%	0.00%	0.00%	0.00%	0.00%	4.29%	0.95%
Slope Class (%)	0-5	1.79%	2.22%	5.38%	6.25%	0.90%	1.11%	4.81%
	5-30	42.88%	33.42%	36.28%	47.54%	24.42%	30.56%	38.86%
	>30	55.33%	64.35%	58.34%	46.21%	74.68%	68.33%	56.34%
GLU rank	GLU 1	FF30 (39%)	FF30 (31%)	FS30 (58%)	SS30 (28%)	FN30 (44%)	FN30(28%)	AF30 (27%)
	GLU 2	FF530 (19%)	AF530 (19%)	FS530 (33%)	AS530 (20%)	AN30 (15%)	SN30 (19%)	FF30 (27%)
	GLU 3	AF530 (14%)	AF30 (16%)	FS05 (5%)	SS530 (17%)	AN530 (10%)	SF530 (10%)	AF530 (16%)
	GLU 4	others (28%)	others (34%)	others (4%)	others (35%)	others (31%)	others (43%)	others (30%)

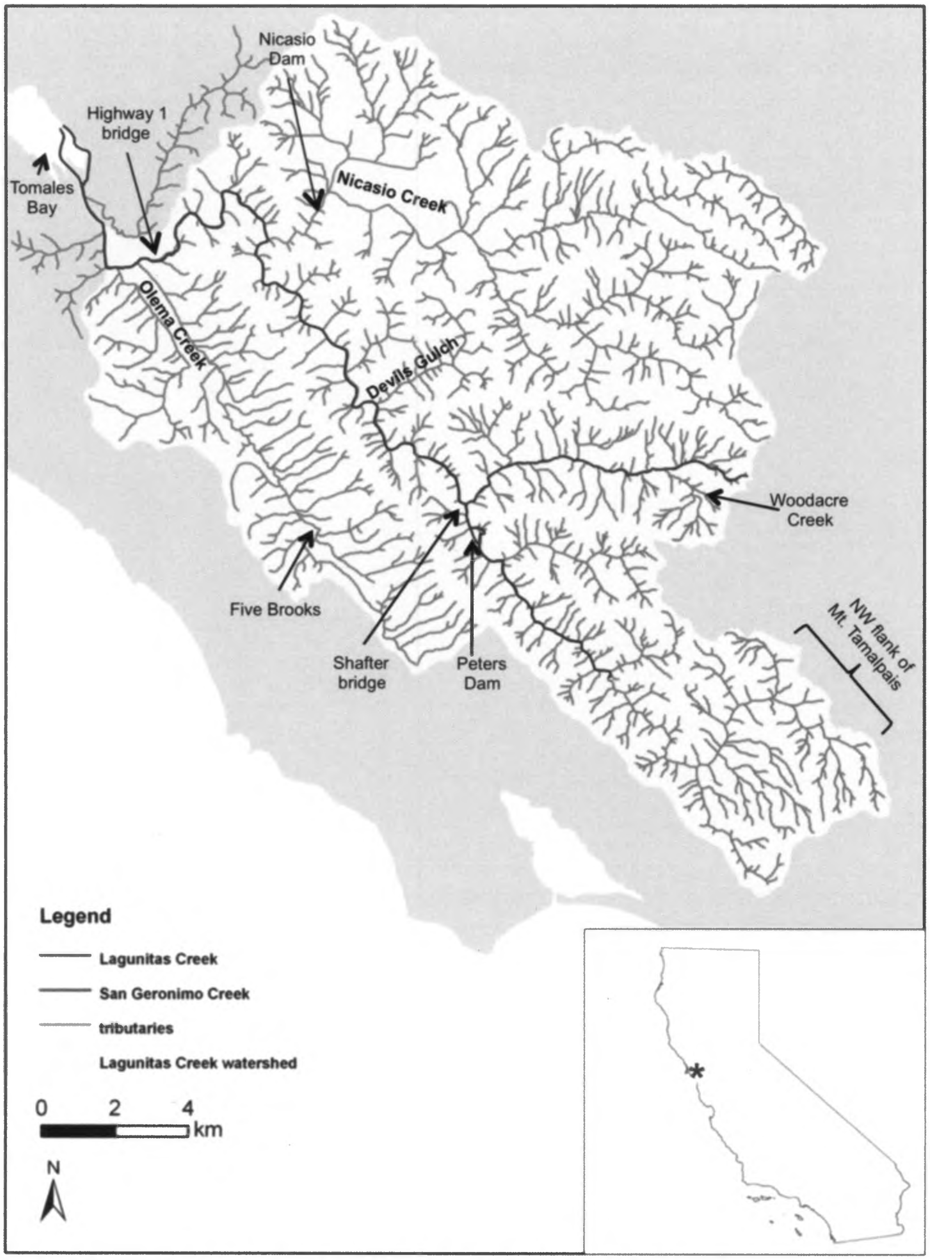


Figure 1. The greater Lagunitas Creek watershed.
Mainstem Lagunitas Creek, depicted in red, flows northwest into Tomales Bay. San Geronimo Creek, the major tributary, is shown in purple and flows west. The inset map shows the border of California, with a red star indicating the approximate location of the Lagunitas Creek watershed.

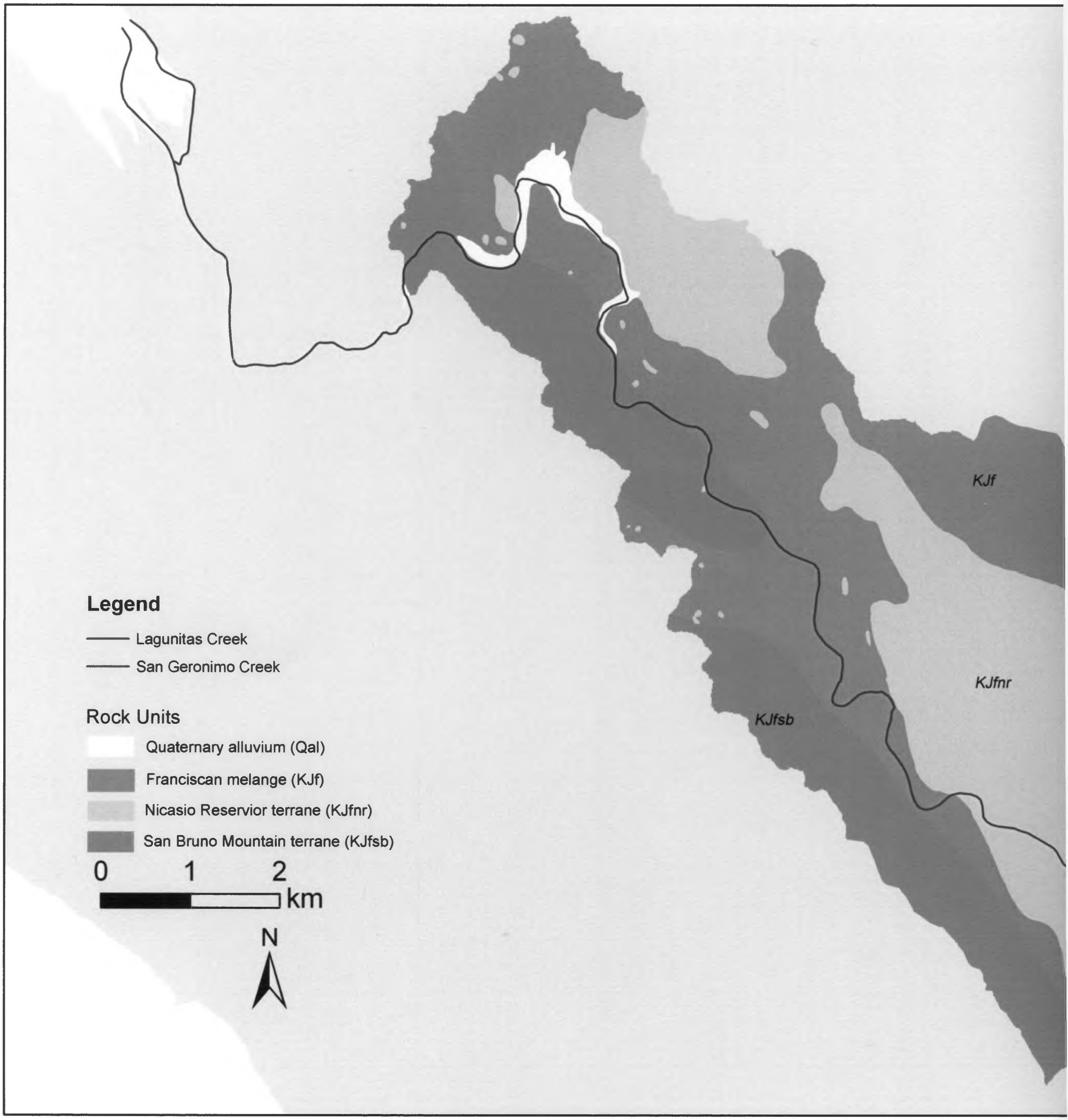
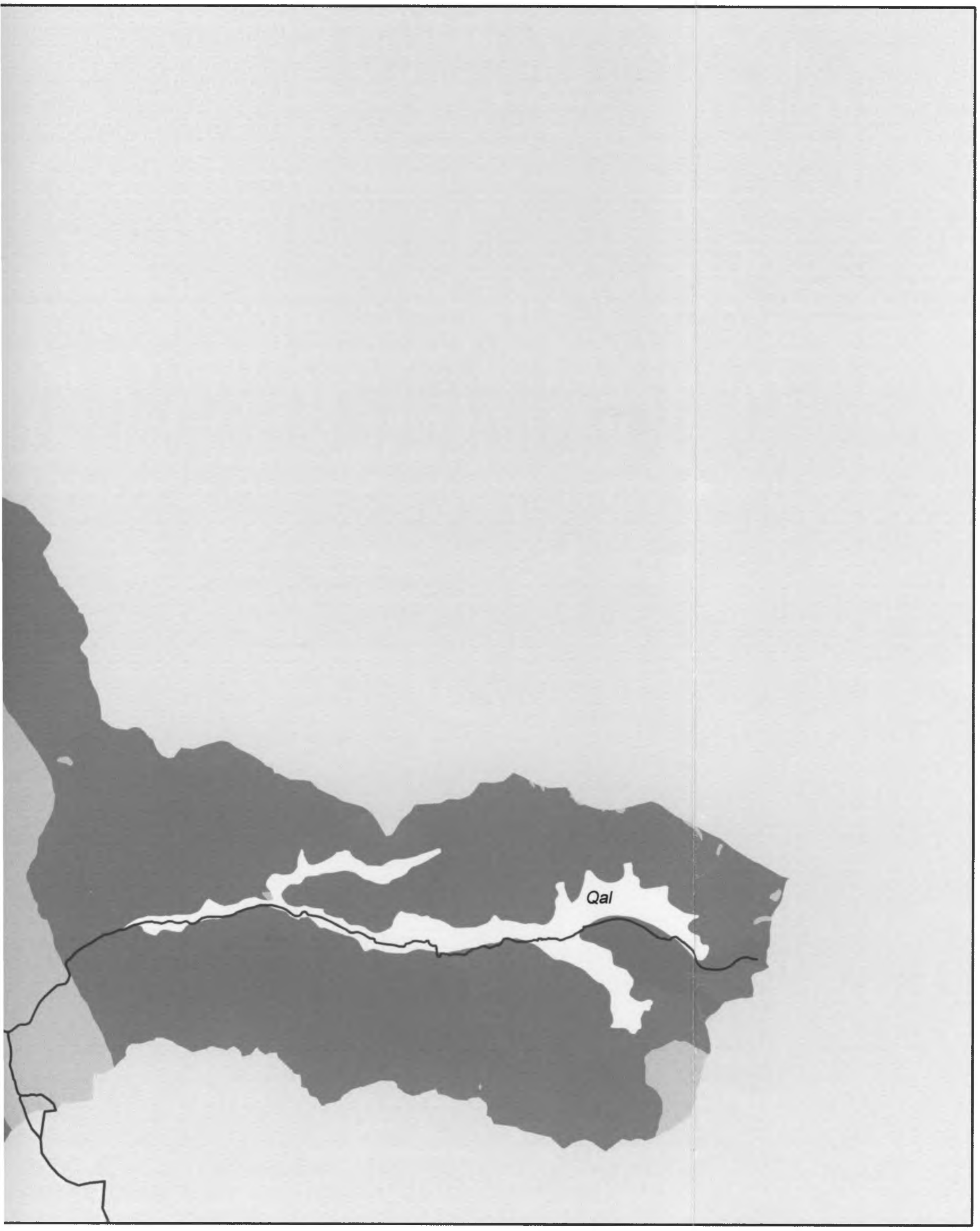


Figure 2. Rock units within the Lagunitas Creek watershed.
There are four distinct rock units found within part of the Lagunitas Creek Watershed. (1) amphibolite combined with sheared sections of shale, sandstone, or serpentinite. (2) Nicas radiolarian chert. (3) San Bruno Mountain terrane, represented in green, consists mostly o yellow, consists of loose, unconsolidated soil and sediments which have been transported



anciscan mélange, represented in light purple, is a mix of basalt, chert, limestone, blueschist, eclogite, and Reservoir terrane, represented in grey, consists mainly of pillow basalt, with some sandstone and underlying bmarine sandstone, with abundant quartz, feldspar and other lithics. (4) Quaternary alluvium, represented in :iver processes (Wahrhaftig and Wakabayashi, 1989).

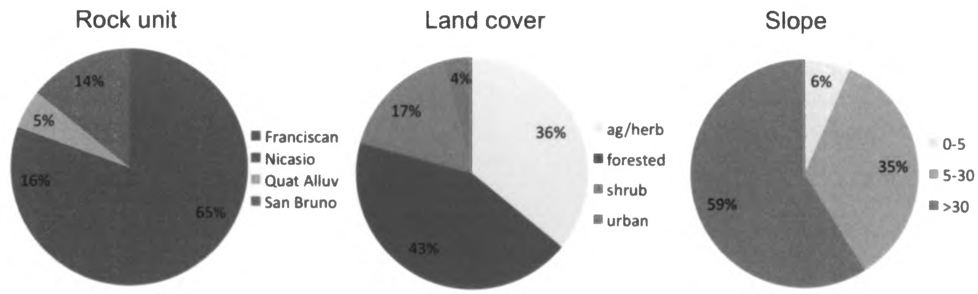


Figure 3a, 3b, 3c. (left to right) Watershed attributes and their distributions throughout the Lagunitas Creek watershed.

Figure 3a. There are four geologic units at the surface within the Lagunitas Creek watershed. These include Franciscan mélange, Nicasio Reservoir terrane, San Bruno Mountain terrane, and Quaternary alluvium.

Figure 3b. The four land cover categories within the Lagunitas Creek watershed include (1) agricultural and herbaceous areas;
(2) forested areas, which have greater than 50% canopy cover;
(3) shrub areas, which have less than 50% canopy cover;
(4) urban or barren areas containing roads, structures, or other impervious surfaces.

Figure 3c. I have grouped hillslope gradients into three slope classes. These classes include (1) slopes less than 5%; (2) slopes ranging between 5 and 30%; (3) slopes with a gradient greater than 30%.

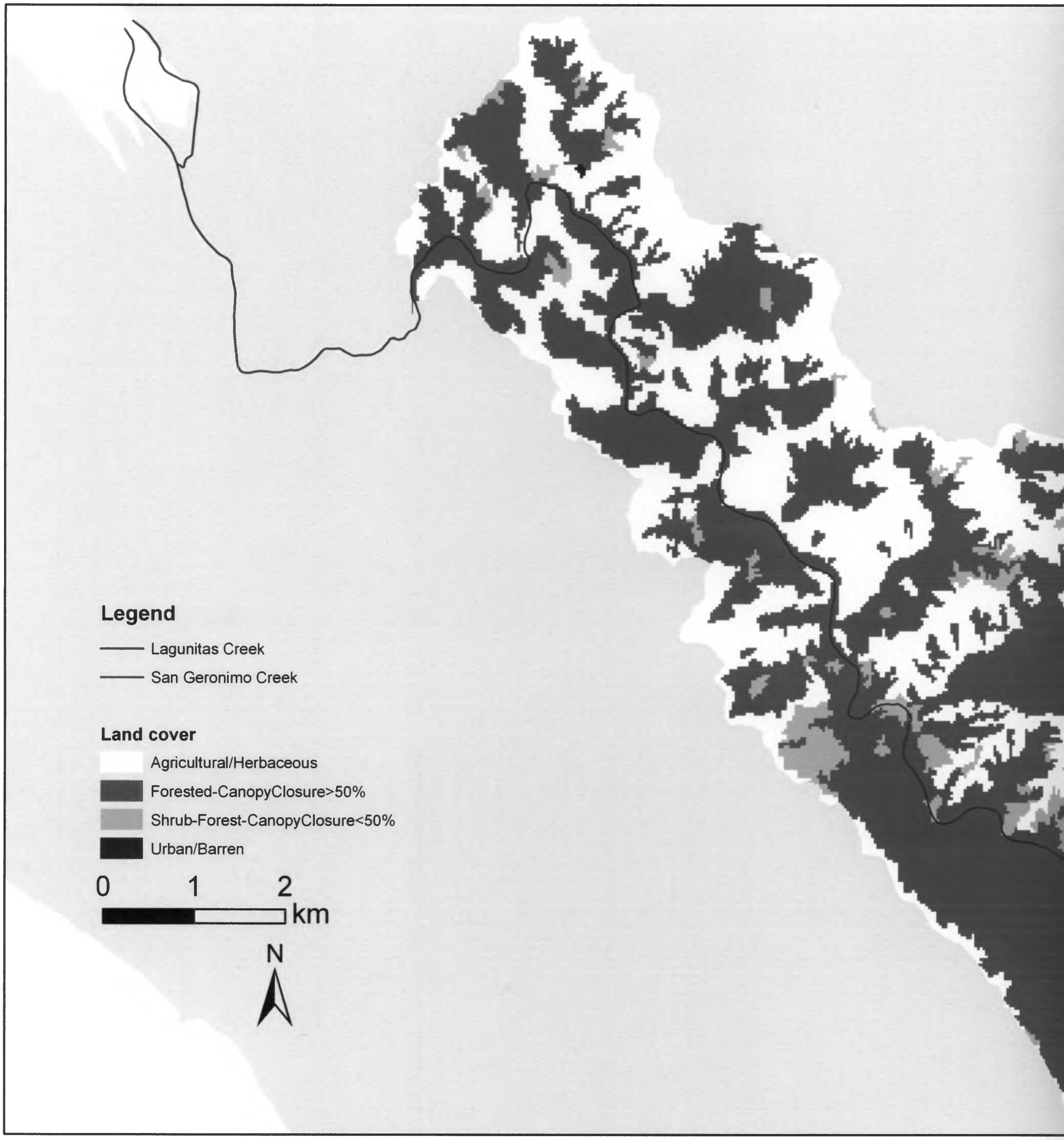


Figure 4. Land cover within the Lagunitas Creek watershed.
I have used four land cover categories to depict vegetation and landuse throughout the wat
(2) Forested areas, depicted in dark green, are areas with greater than 50% canopy cover.
(4) Urban/barren areas, depicted in dark red, contain roads, structures, or other impervious

rshed. (1) Agricultural/herbaceous areas, depicted in yellow, contain grazing, crops or grassland.
3) Shrub areas, depicted in light green, are areas with low growing trees and less than 50% canopy cover.
surfaces.

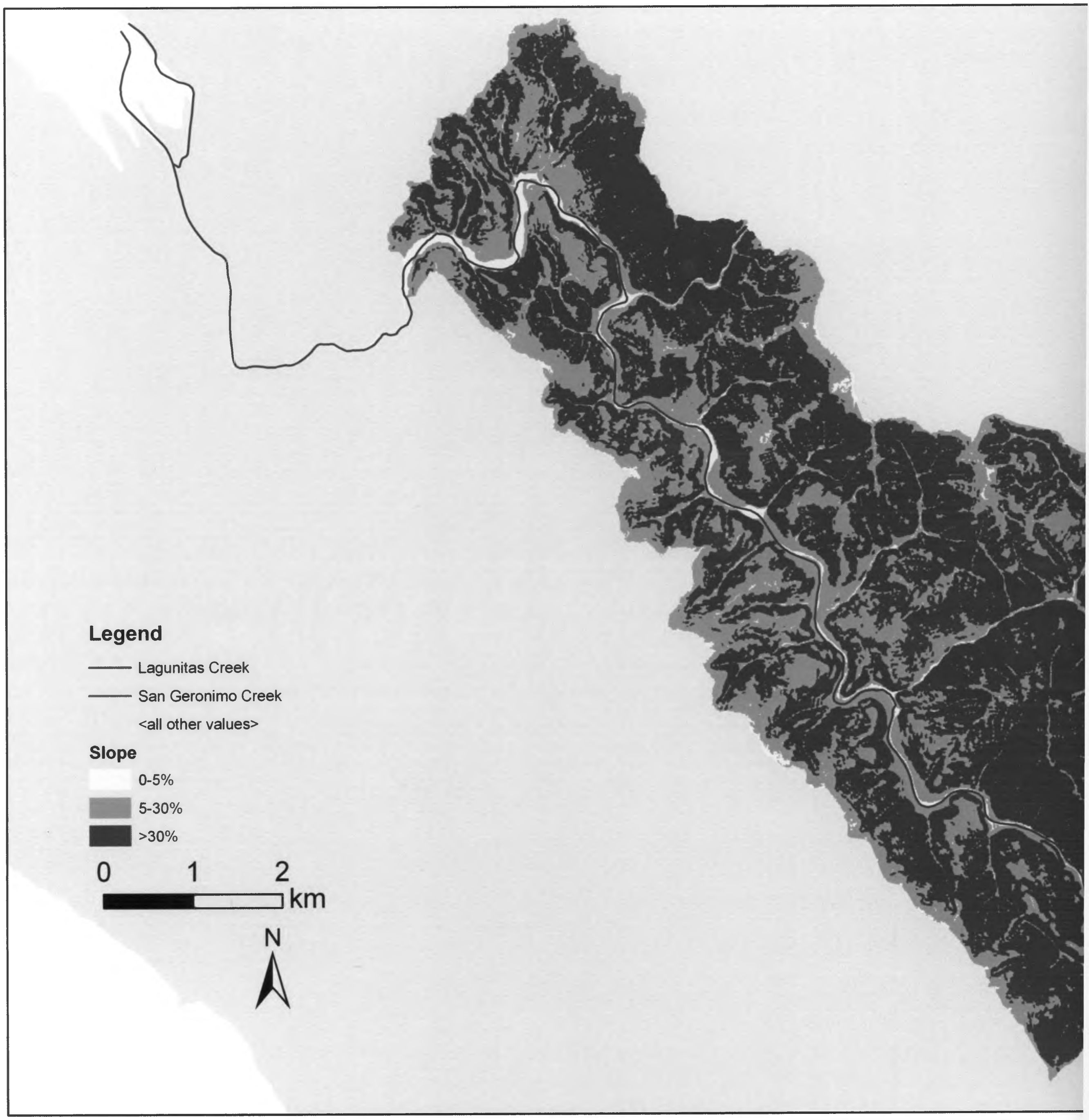
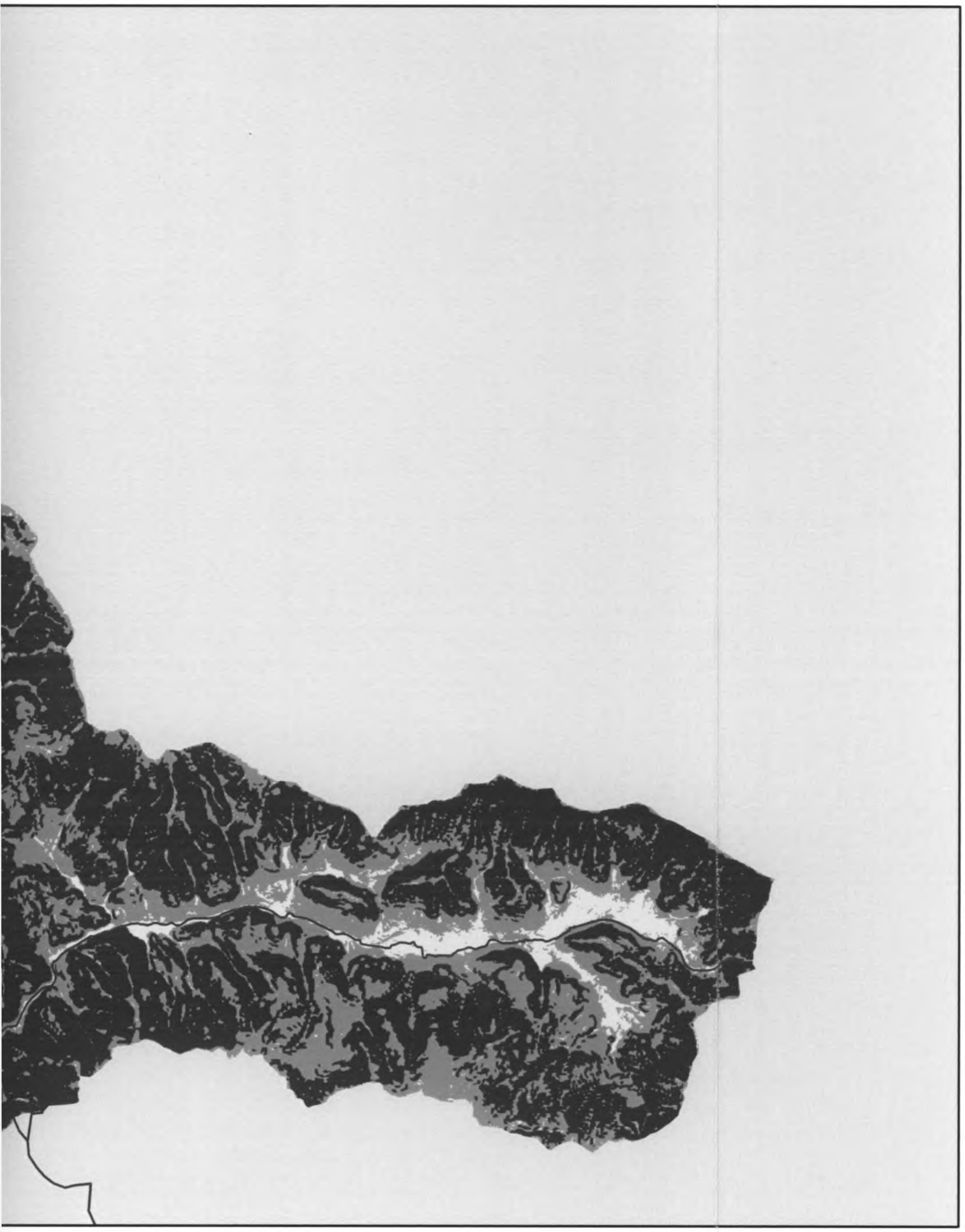


Figure 5. Slope classes within the Lagunitas Creek watershed.
This map depicts four distinct slope classes within the Lagunitas Creek watershed. More
Intermediate sloeps (5-30% gradient) are depicted in orange and account for 35% of the
and account for only 6% of the watershed.



an half the watershed consists of slopes with a gradient greater than 30% (red areas).
ershed. Yellow areas represent low gradients, found typically on hilltops and valley bottoms,

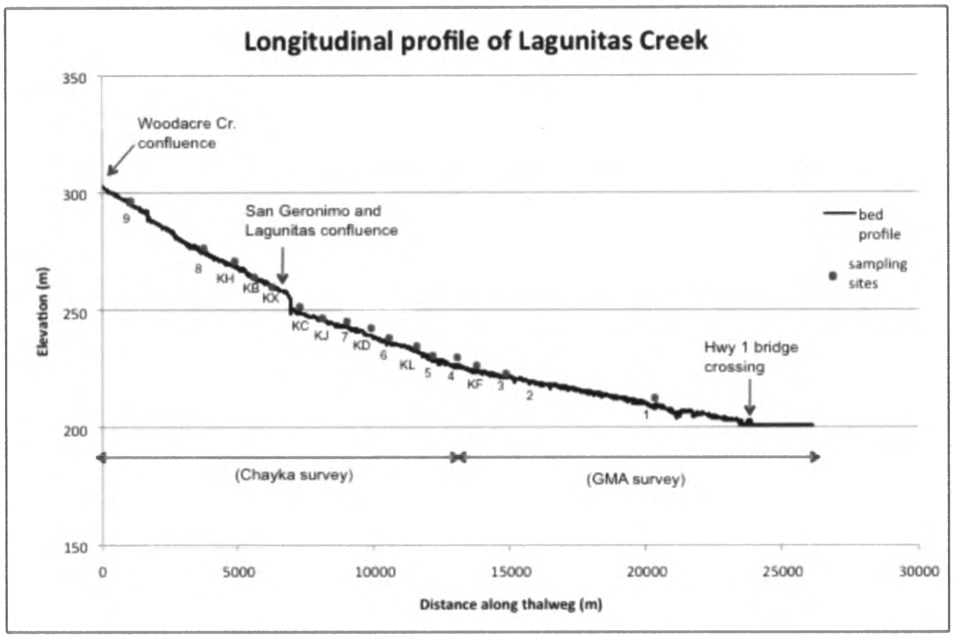
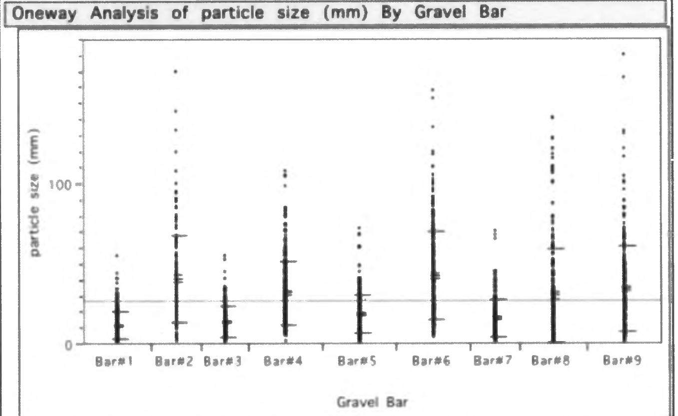


Figure 6. Longitudinal profile survey of mainstem Lagunitas Creek. The upstream portion of the survey begins on San Geronimo Creek at the confluence of Woodacre Creek, and ends approximately 25 km downstream near the Highway 1 bridge crossing. Since the survey did not tie in to verified benchmarks, elevations are relative and do not refer to distance above sea level.

Figure 7a. Untransformed pebble count data for each of the nine study areas. The scatter at each site is not approximately the same, violating the conditions for ANOVA testing.

Oneway Analysis of particle size (mm) By Gravel Bar

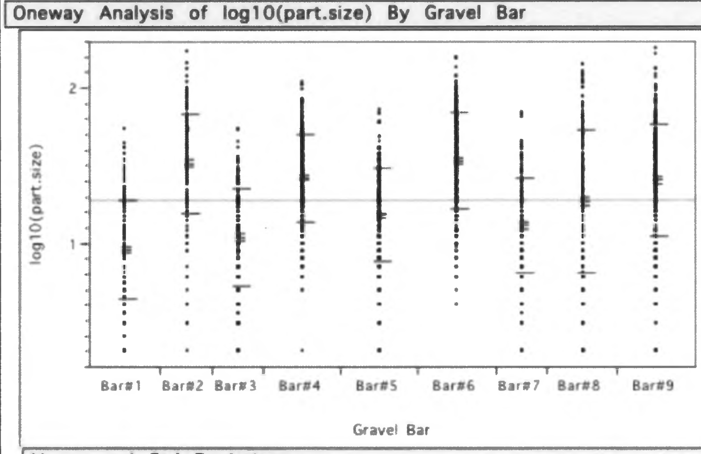


Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Bar#1	272	11.7371	8.5176	0.5165	10.720	12.754
Bar#2	198	41.0025	27.2180	1.9343	37.188	44.817
Bar#3	193	13.9119	9.7119	0.6991	12.533	15.291
Bar#4	297	32.0067	19.9423	1.1572	29.729	34.284
Bar#5	295	18.7203	12.1675	0.7084	17.326	20.115
Bar#6	299	42.4699	27.5205	1.5916	39.338	45.602
Bar#7	198	16.4520	11.7878	0.8377	14.800	18.104
Bar#8	267	30.1273	29.5986	1.8114	26.561	33.694
Bar#9	296	34.3885	26.7476	1.5547	31.329	37.448

Figure 7b. Transformed pebble count data, using the Log10 transformation.

Oneway Analysis of log10(part.size) By Gravel Bar



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Bar#1	272	0.95930	0.318371	0.01930	0.9213	0.9973
Bar#2	198	1.51367	0.320332	0.02276	1.4688	1.5586
Bar#3	193	1.03897	0.314606	0.02265	0.9943	1.0836
Bar#4	297	1.42110	0.281836	0.01635	1.3889	1.4533
Bar#5	295	1.18061	0.299703	0.01745	1.1463	1.2149
Bar#6	299	1.53115	0.305968	0.01769	1.4963	1.5660
Bar#7	198	1.11432	0.308100	0.02190	1.0711	1.1575
Bar#8	267	1.26730	0.461541	0.02825	1.2117	1.3229
Bar#9	296	1.40625	0.361761	0.02103	1.3649	1.4476

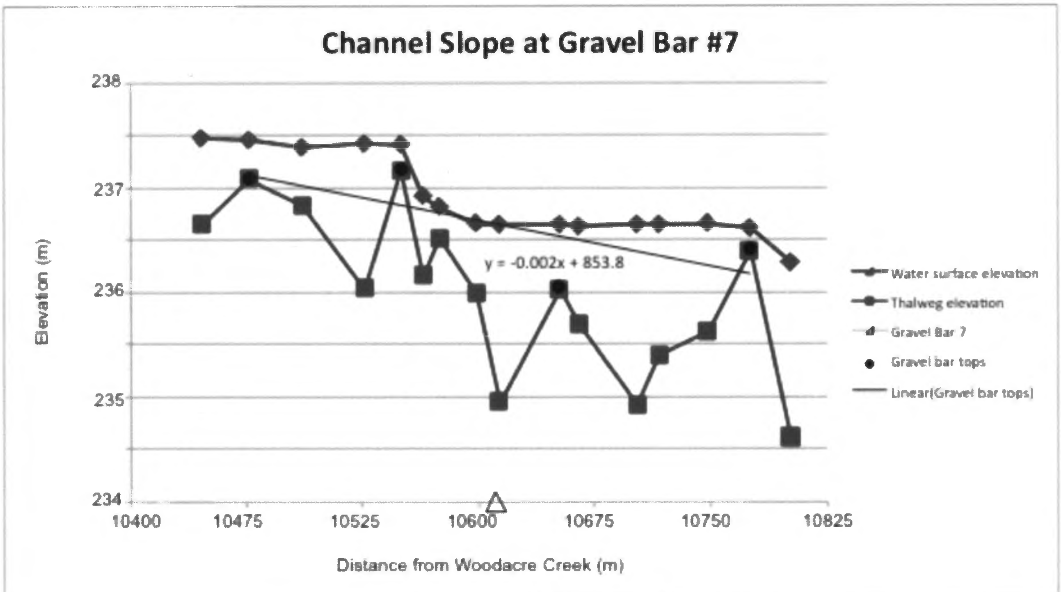


Figure 8. Channel slope measurement for Lagunitas Creek.
This figure uses Gravel Bar #7 to illustrate how I calculated channel slope for a single reach. The peaks in the thalweg elevation (red data set) represent various gravel bars up and downstream of Gravel Bar #7. I fit a trend line to these peak elevations to determine channel slope for the reach representing Gravel Bar #7. I calculated a channel gradient of 0.002 for this reach of Lagunitas Creek.

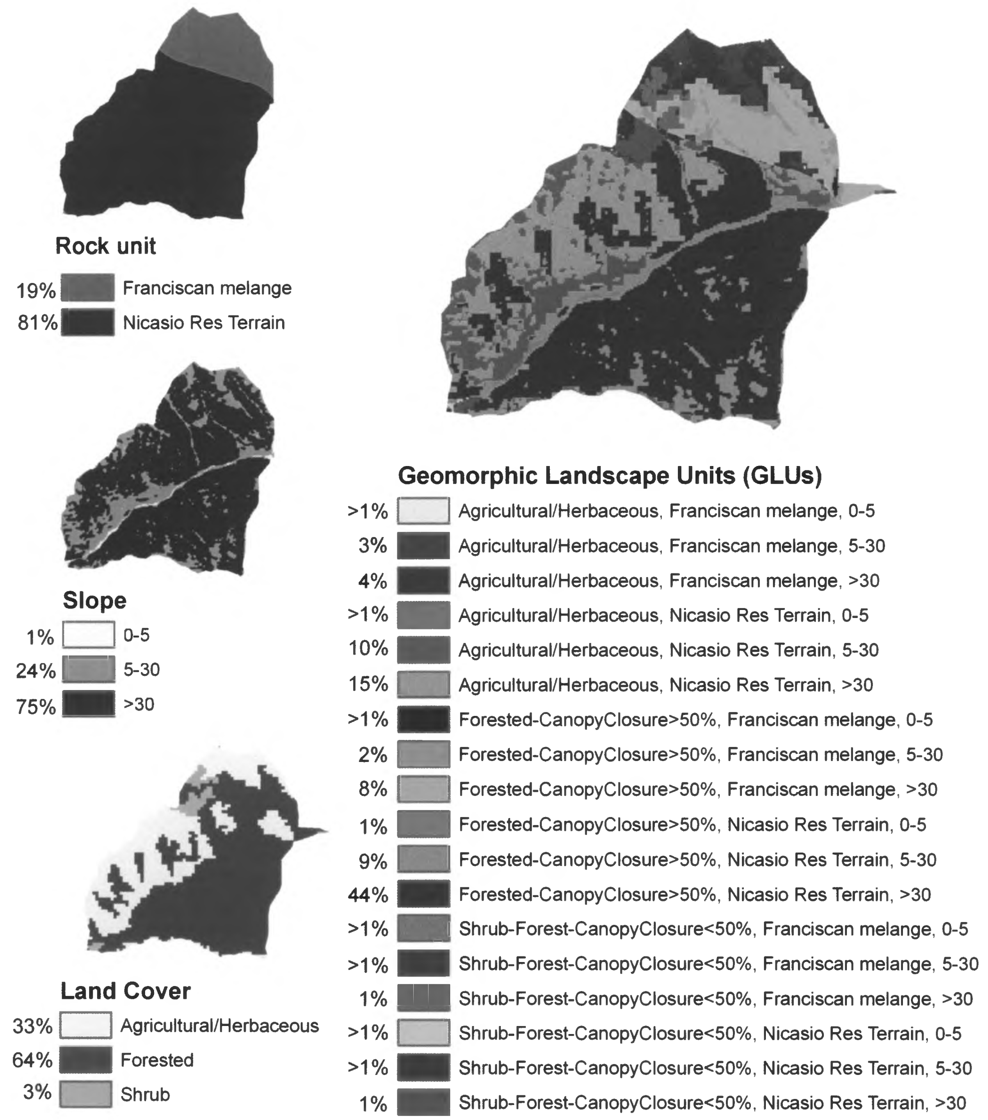


Figure 9. Creating a Geomorphic Landscape Unit (GLU)
This figure uses a subwatershed within the Lagunitas Creek watershed to illustrate how subwatershed attributes overlap to create a GLU. First examine the left column of subwatersheds: The upper right portion of this subwatershed is entirely melange (blue), has mostly steep slopes (red), and is a mix of forested (green) and agricultural (yellow) land cover. These layers overlap to create a uniue GLU (Forested/melange/Slopes >30) depicted in light blue in the subwatershed in the right column. The percentage of each attribute and combined GLU is listed to the left of the color boxes in each legend. For example, 8% of this subwatershed is characterized by a "Forested/melange/Slope >30" GLU, represented in light blue.

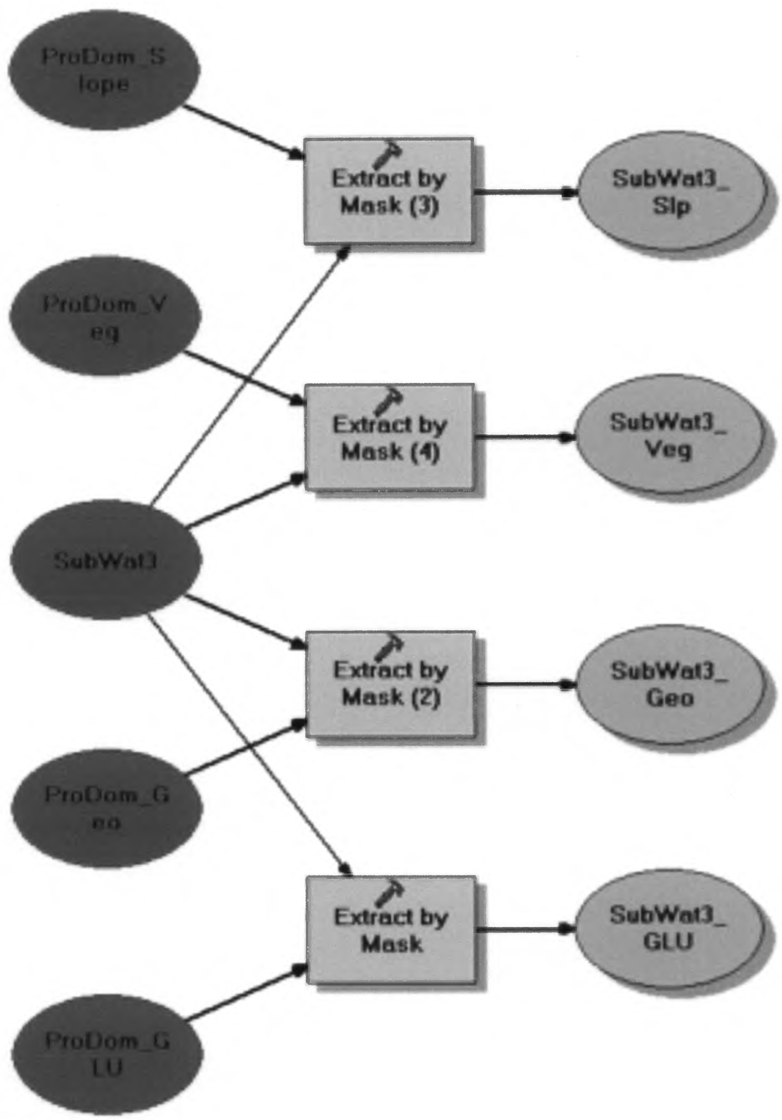


Figure 10. Using the "Extract by Mask" tool to create attribute layers. This model takes larger spatial layers (represented by blue ovals) and applies an extraction tool (yellow boxes) to calculate the spatial distribution of geology, slope, and land cover for a single subwatershed. The green ovals represent these new layer outputs.

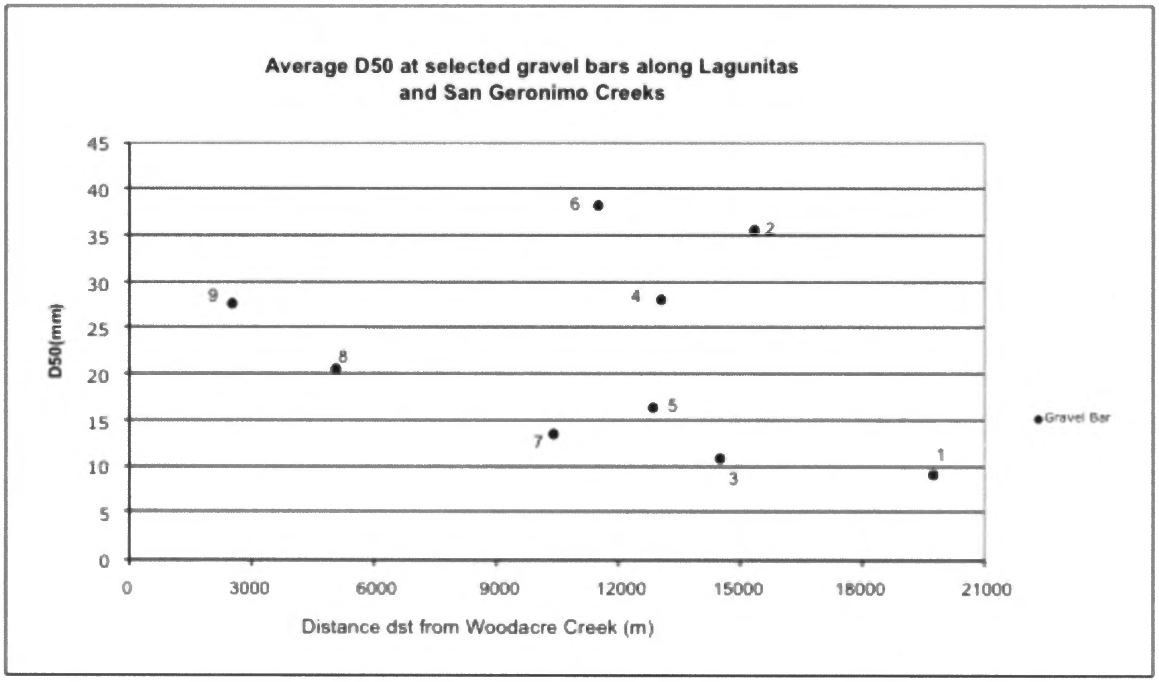


Figure 11. A plot of D50 for nine gravel bars along San Geronimo creek and mainstem Lagunitas Creek. This plot shows a slight downstream fining trend, with gravel bars on the left side of the graph generally coarser than those on the right side of the graph. However, gravel bar #6, #4, #2 appear to deviate from this trend.

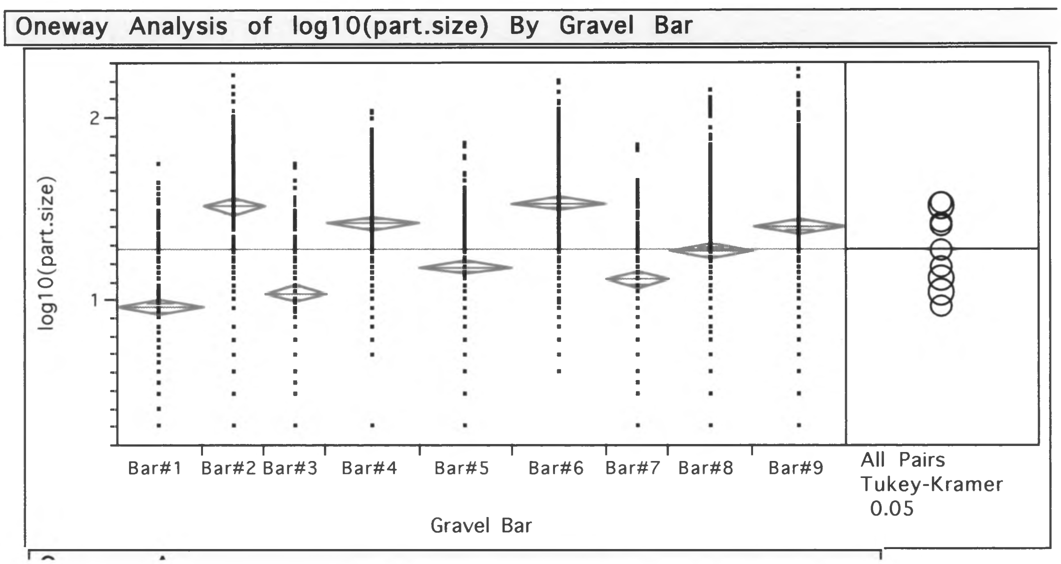


Figure 12. Tukey-Kramer plots for my nine gravel bars.
The scatter above each gravel bar label (x-axis) represents the range in pebble sizes for counts conducted at each location. The green diamonds indicate the location of the mean particle size for each gravel bar. The results for the Tukey-Kramer analysis are shown in the box at the right side of this figure. Each circle represents a different gravel bar, and overlapping circles suggest that the populations are not statistically distinguishable from one another. These rings are grouped into two statistically distinct populations. Gravel bars 2, 4, 6, and 9 are grouped together in the top of the box, while gravel bars 1, 3, 5, 7, and 8 are grouped in the lower part of the box.

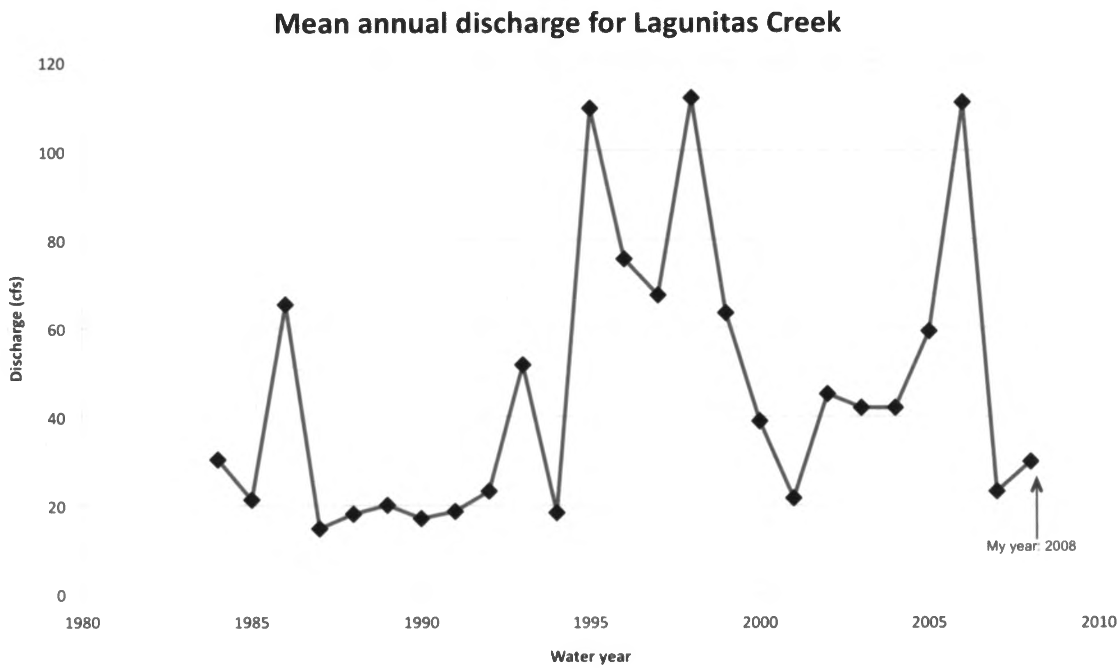


Figure 13. Mean annual discharge for Lagunitas Creek.
This plot uses gauge data from USGS stream gauge #11460400—located near Shafter Bridge on mainstem Lagunitas Creek—to illustrate changes in mean annual discharge from 1983 to 2008. I collected pebble count data along mainstem Lagunitas Creek in 2008, which had a mean annual discharge of 29.8 cfs.

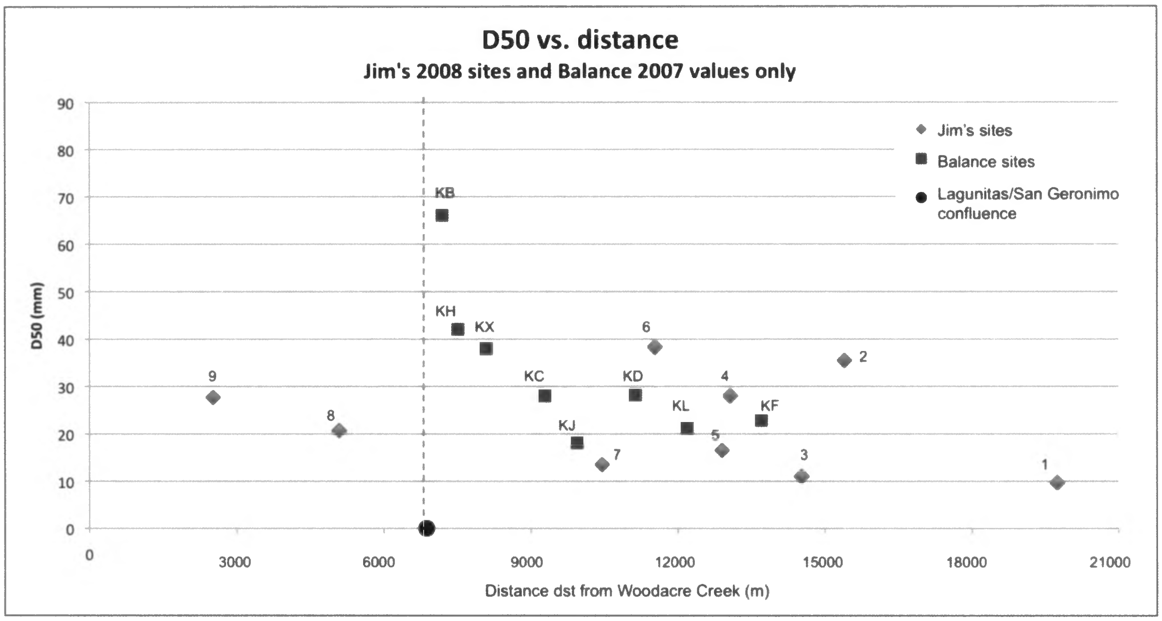


Figure 14. D50 vs. Distance for bed texture sampling sites along mainstem Lagunitas Creek. The blue diamonds indicate gravel bars where I conducted pebble counts in 2008. The red squares are sites monitored by Balance Hydrologics, representing values from 2007 only. I've used a dashed line to divide the plot at the Lagunitas-San Geronimo confluence (black circle on x-axis). The mean annual discharge for 2007 and 2008 was 23.1 cfs and 29.8 cfs, respectively.

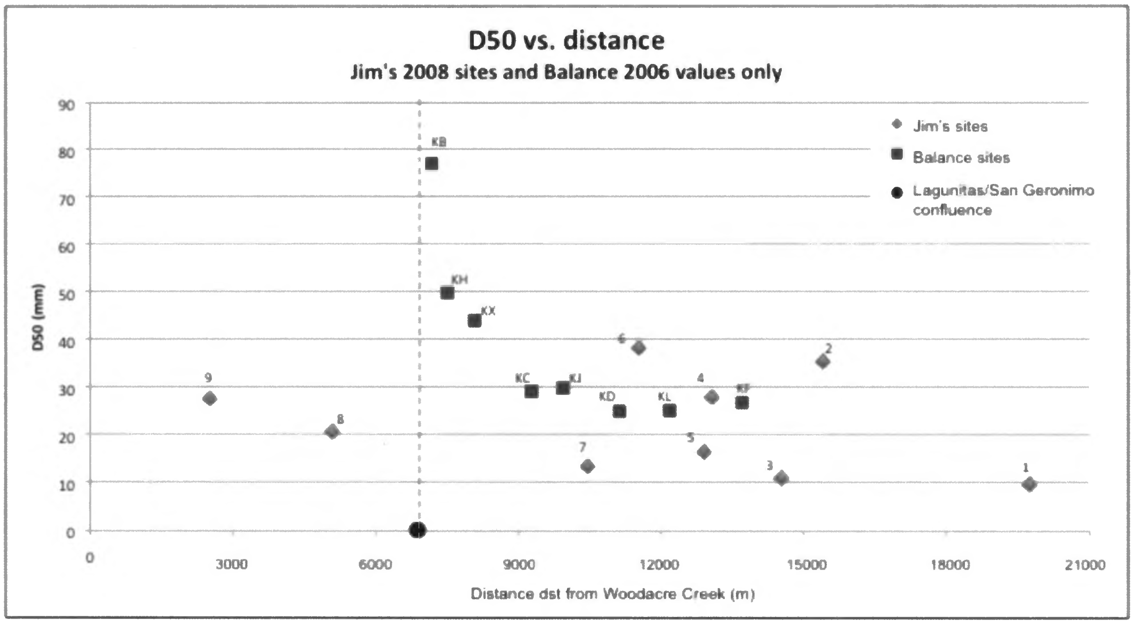


Figure 15. D50 vs. Distance for bed texture sampling sites along mainstem Lagunitas Creek. The blue diamonds indicate gravel bars where I conducted pebble counts in 2008. The red squares are sites monitored by Balance Hydrologics, representing values from 2006 only. I've used a dashed line to divide the plot at the Lagunitas-San Geronimo confluence (black circle on x-axis). The mean annual discharge for 2006 was 110.6 cfs.

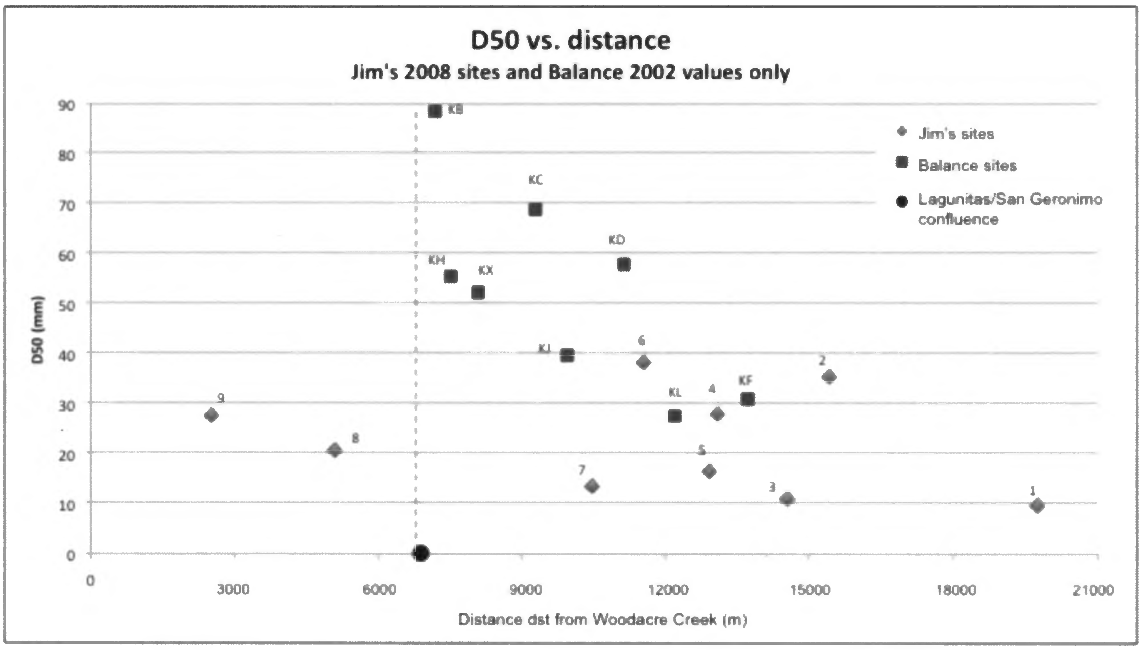


Figure 16. D50 vs. Distance for bed texture sampling sites along mainstem Lagunitas Creek. The blue diamonds indicate gravel bars I conducted pebble counts in 2008. The red squares are sites monitored by Balance Hydrologics, representing values from 2002 only. I've used a dashed line to divide the plot at the Lagunitas-San Geronimo confluence (black circle on x-axis). The mean annual discharge for 2002 was 45.0 cfs.

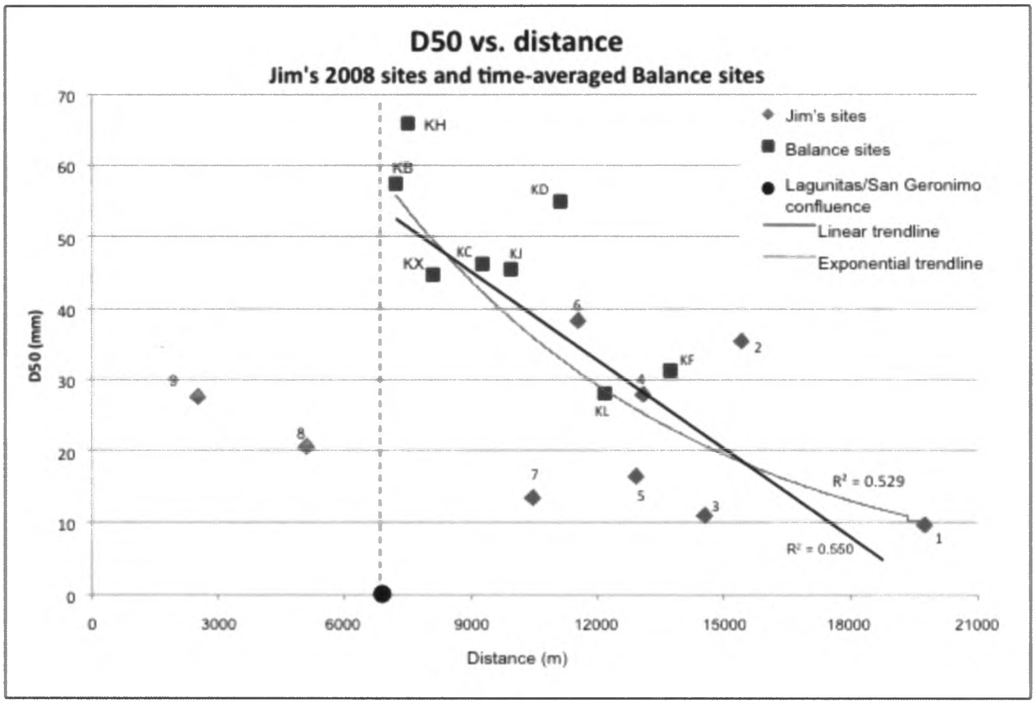


Figure 17. D50 vs. Distance for bed texture sampling sites along mainstem Lagunitas Creek. The blue diamonds indicate gravel bars I conducted pebble counts in 2008. The red squares are sites monitored by Balance Hydrologics, representing time-averaged values from 1983 to 2007. I've used a dashed line to divide the plot at the Lagunitas-San Geronimo confluence (black circle on x-axis). The black linear trendline shows an R2 value of 0.550, while the green exponential trendline shows an R2 value of 0.529, indicating a downstream fining trend for monitoring sites along mainstem Lagunitas Creek.

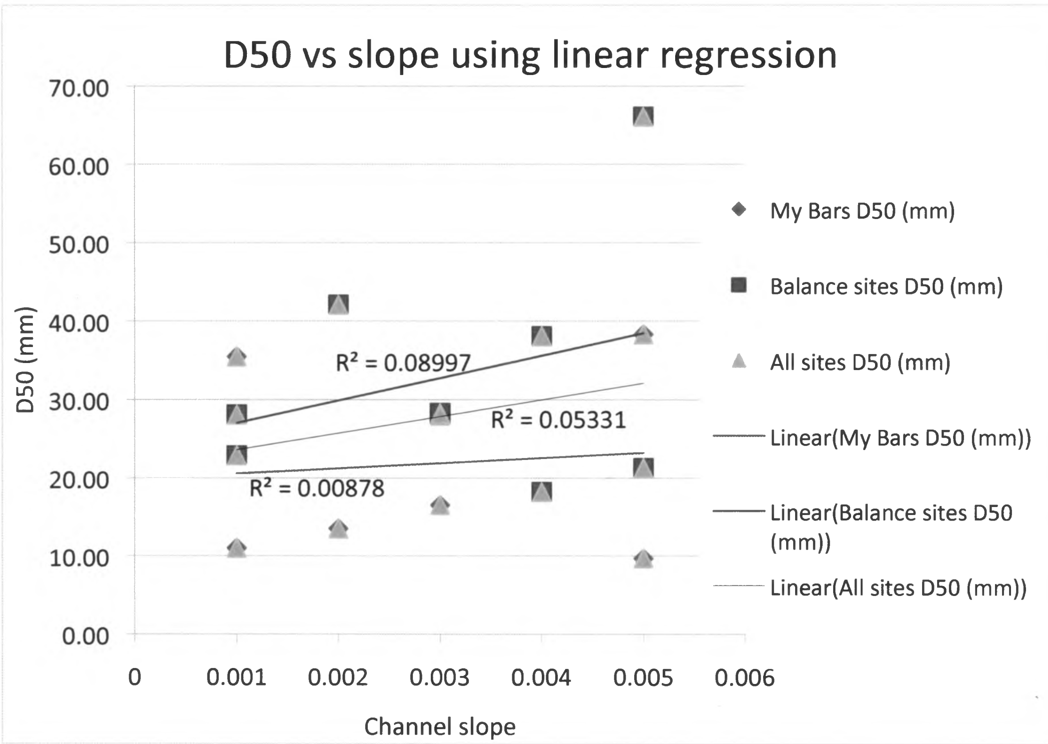


Figure 18. D50 vs. channel slope using linear regression.
This figure shows a plot of channel slope versus median grain size (D50) for my gravel bars and for the Balance sites. When analyzing only my gravel bars (blue diamonds) there is quite a bit of scatter and a resulting R^2 value (blue line) of only 0.008, suggesting an extremely weak correlation between these two variables. I found similar results when examining only the Balance sites (red squares), with an R^2 value (red line) of only 0.09. The grouped data (green triangles) also showed a weak correlation, with an R^2 value (black line) of 0.053.

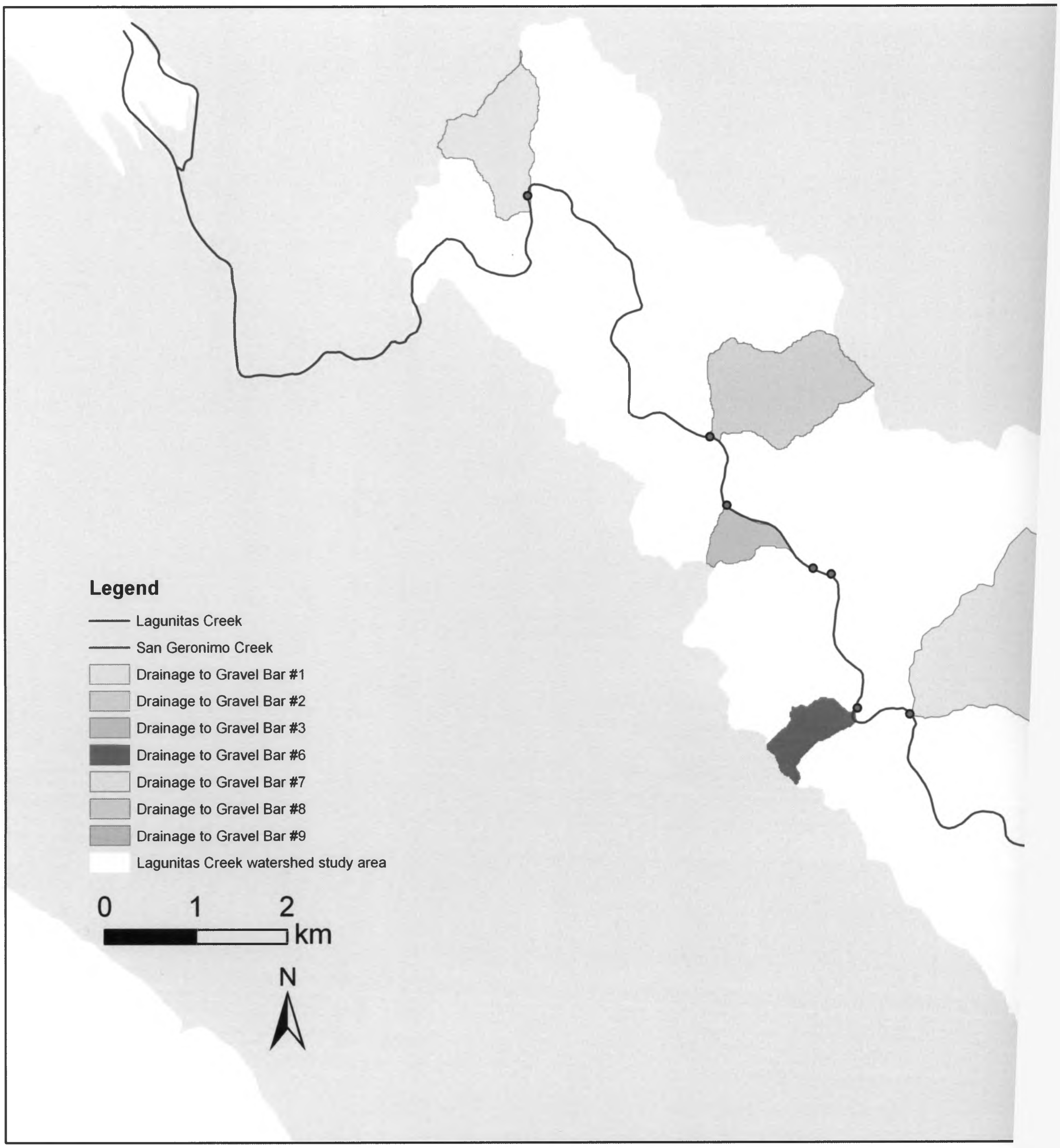
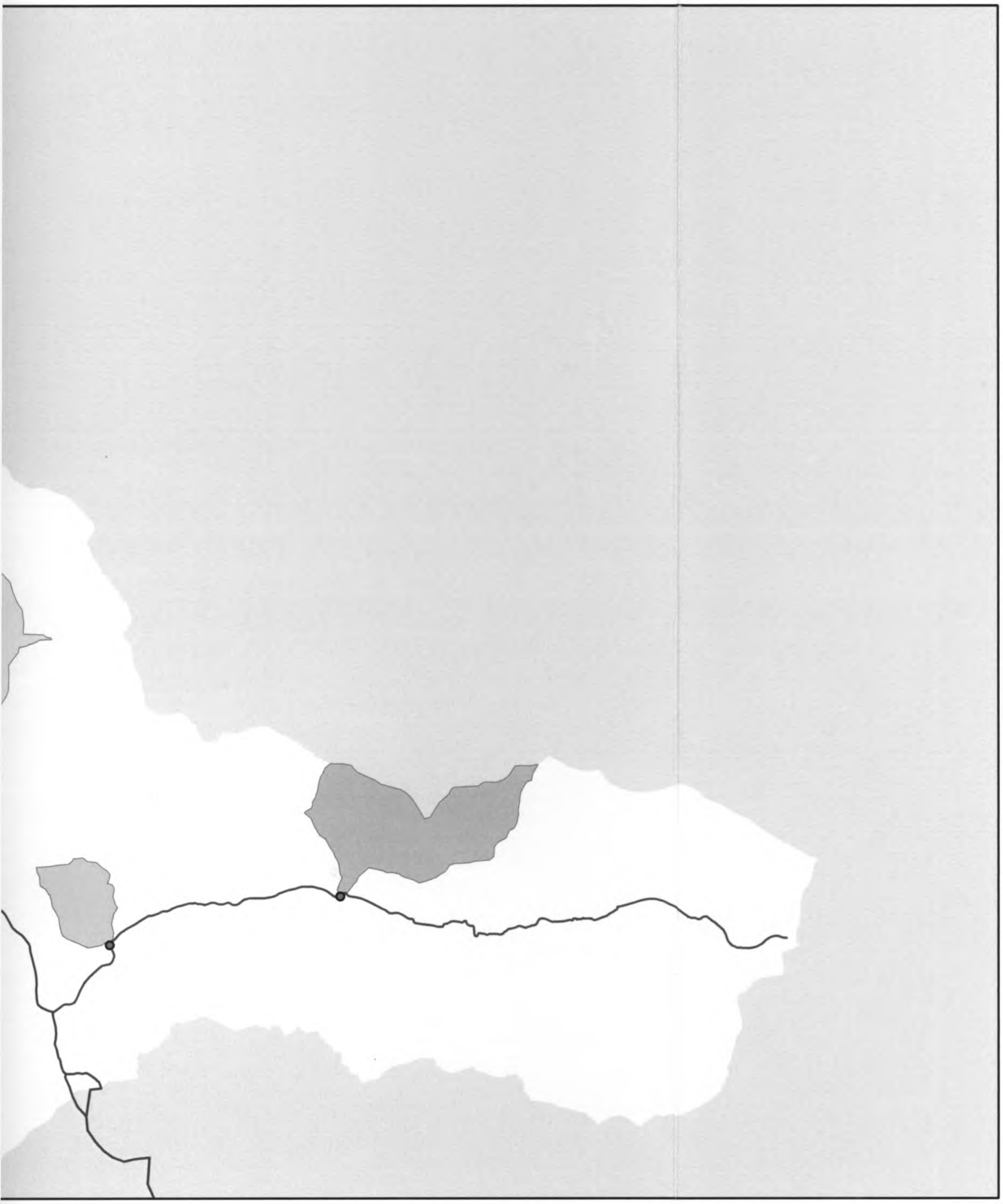


Figure 19. Selected subwatersheds within the Lagunitas Creek watershed.
This map shows the location of subwatersheds draining to my gravel bar sites. Each
Lagunitas Creek and a major tributary draining a subwatershed. Gravel Bar #4 and (
junction, so I did not analyze a corresponding drainage area for those two bars.



gravel bars (depicted as green circles) are located at the confluence of mainstem
Bar #5 (located in the middle of the map) were not located at a tributary

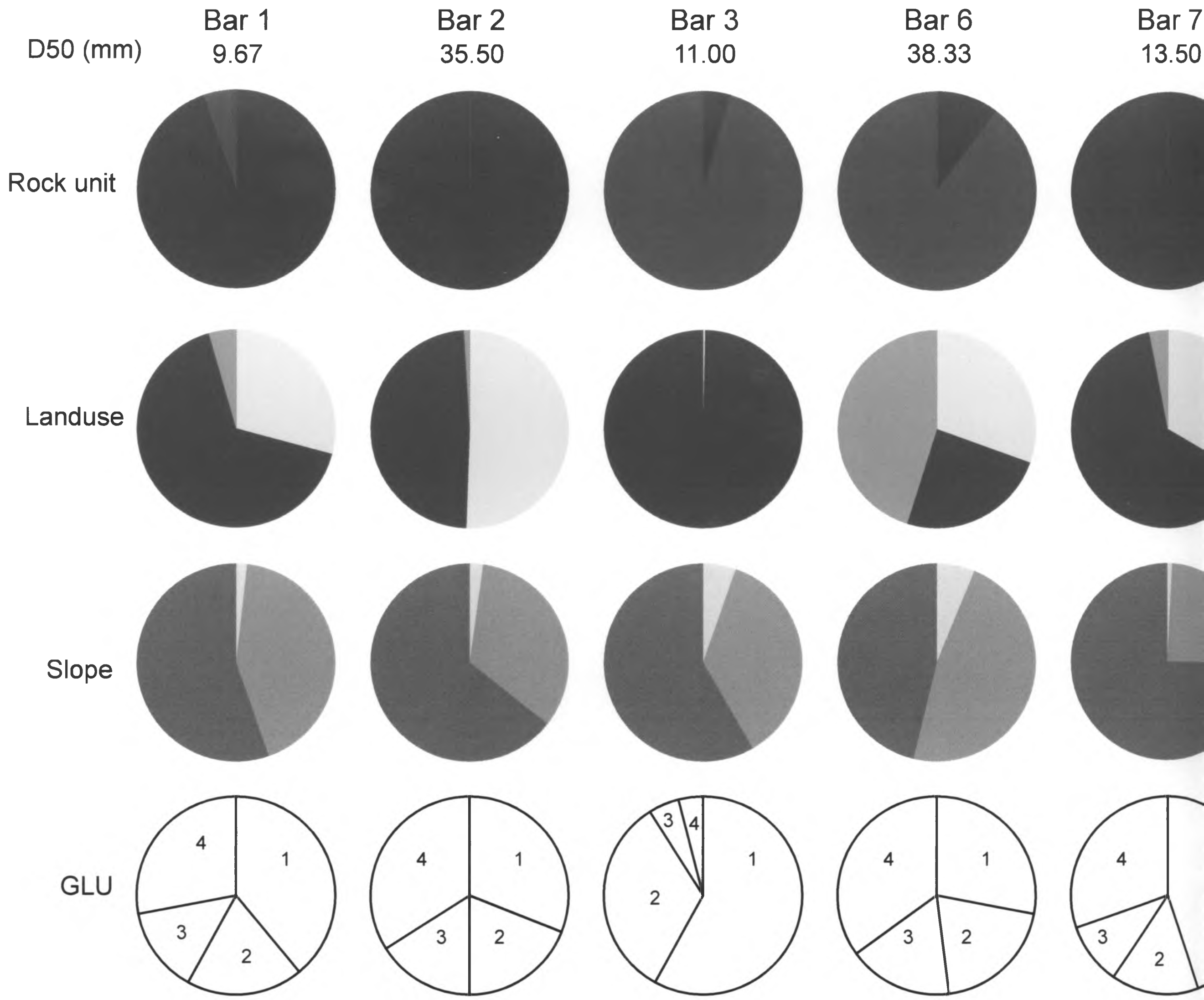
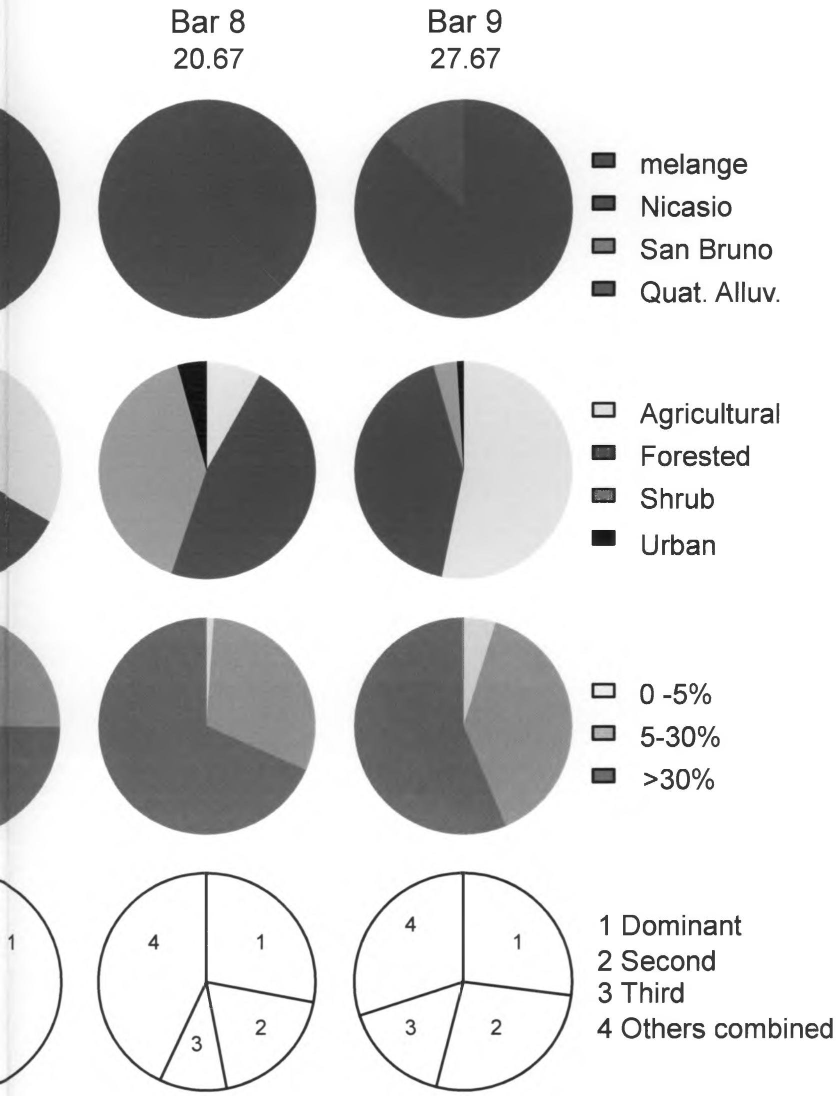


Figure 20. Distribution of watershed attributes for areas draining to my gravel bars.
Each column of pie charts indicates the distribution of rock unit, land cover, slope, an
across the top of the figure. For example, the left-most column of pie charts indicates
half of the area dominated by slopes greater than 30% (Slope- dark grey). The GLU d
top-ranked GLU, while roughly 25% of the area is comprised by GLUs not in the top 3



d GLUs for the area draining to a single gravel bar. Gravel bars, and their respective D50, are labeled
a subwatershed that is mostly Franciscan (Geology- blue), Forested (Landuse- green), with more than
listribution for this subwatershed indicates that approximately one-third of the area is represented by the
. See Table 7 for the exact percentages of each attribute for corresponding gravel bars.