UNIVERSITY OF CALIFORNIA
Santa Barbara

The influence of valley morphology and coarse sediment distribution on rainbow trout populations in Sespe Creek, California at the landscape scale

A Thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Science

in

Geography

by

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December 2000

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December 2000

ABSTRACT

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In an eroding, mountainous landscape, the supply, sorting and storage of sediment have a profound effect on the distribution of plant and animal life within any particular watershed. This research focuses on the variables that dictate the geomorphic conditions of a channel and its valley, their effect on the sorting and storage of the supplied sediment, and whether or not this in turn affects the distribution and/or density of rainbow trout (*Onchorynchus mykiss*) populations that rely on the supplied sediment to provide spawning gravel. Combinations of field and computer-derived data are used to describe the geomorphic conditions present in the river valleys of Sespe Creek, California. With these data, patterns of sediment storage and sorting are described. The data suggest a landscape where patterns of valley width and gradient are controlled by a combination of lithologic, tectonic, and hydrologic variables. Multiple controlling variables result in a valley pattern where narrow, high-gradient bedrock reaches are interspersed with wide, low-gradient alluvial reaches. Howard Creek, a subwatershed located in the middle reaches of the Sespe, has high rainbow trout densities in all size classes as well as the most potential sediment storage per unit stream length. On the other hand, Alder Creek, a subwatershed located in the lower reaches of the Sespe, has low rainbow trout densities and low potential sediment storage per unit stream length. These results suggest that valley configuration influences rainbow trout densities by affecting the location and amount of valley sediment storage.

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1.0 - Introduction

In an eroding, mountainous landscape, the supply, sorting, and storage of sediment have a profound effect on the distribution of plant and animal life within any particular watershed. Animal populations that rely on the landscape to provide sediment of a certain size in order to breed will be especially affected, such as rainbow trout (*Oncorhynchus mykiss*) that require pea-sized gravel to build their nests and spawn. The natural supply of sediment to the channel can result from mass wasting events caused by high intensity rainfall, tree throw, fire, or the slow process of dry raveling. The supply of sediment to stream channels can also be affected by logging, road building, or grazing.

Once the sediment reaches the channel, sorting and storage of the supplied sediment occurs. Sediment sorting depends on the hydrologic conditions of a stream and its watershed as well as the geomorphic configuration of the channel and its valley.

This research will focus on the variables that dictate the geomorphic conditions of channels and their valleys in a steep, mountainous watershed. The goal of this research is to determine the relationships among channel and valley configurations, the sorting and storage of supplied sediment, and the distributions and/or densities of rainbow trout populations in the Sespe Creek watershed of California (**Figure 1**). The approach will be to measure landscape characteristics and trout populations and assess their relationships at a watershed scale.

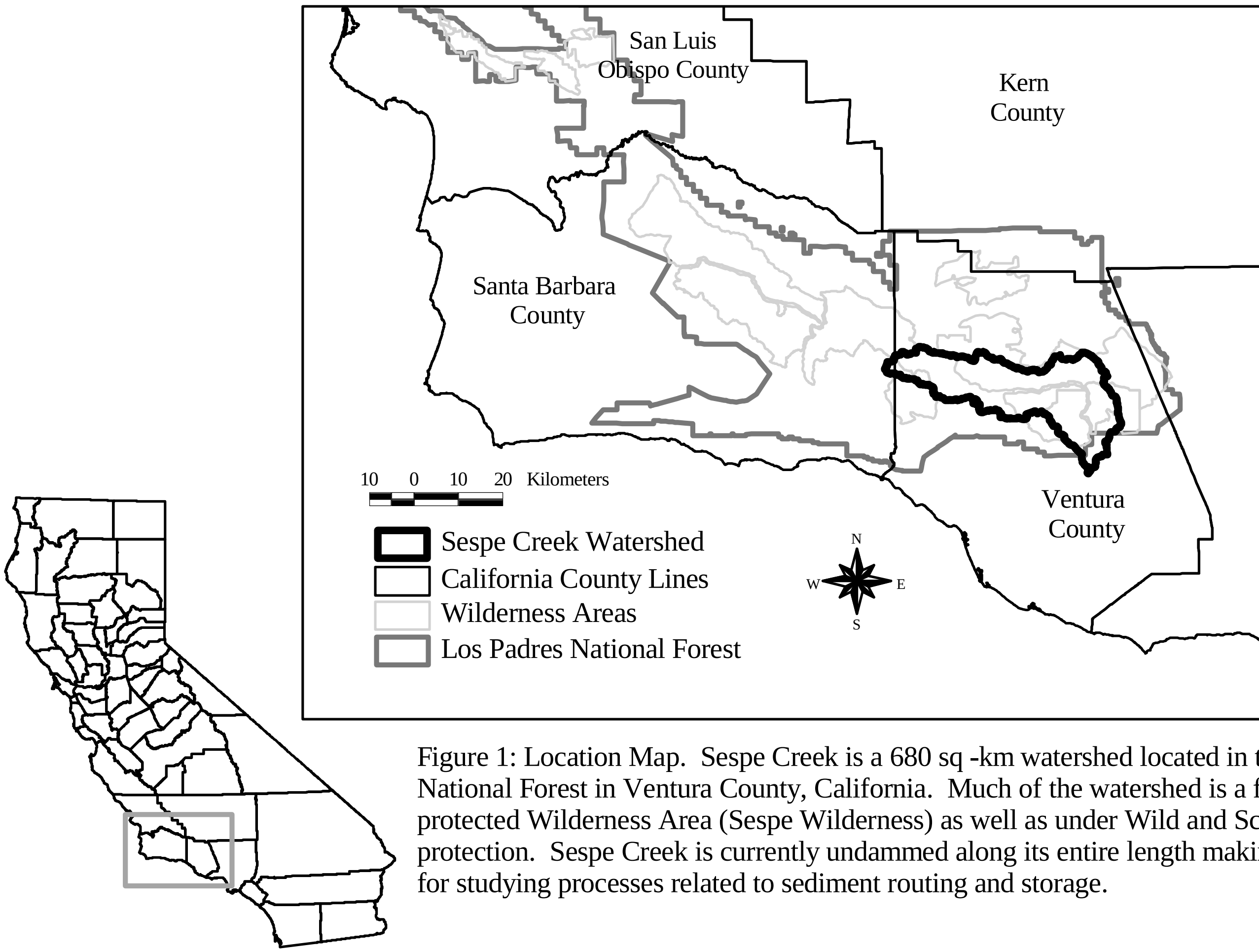


Figure 1: Location Map. Sespe Creek is a 680 sq -km watershed located in the Los Padres National Forest in Ventura County, California. Much of the watershed is a federally protected Wilderness Area (Sespe Wilderness) as well as under Wild and Scenic River protection. Sespe Creek is currently undammed along its entire length making it ideal for studying processes related to sediment routing and storage.

1.1 - Background

The small-scale habitat characteristics of streams and their influences on the densities and distributions of rainbow trout populations have been extensively studied, particularly in the Pacific Northwest (Chapman and Bjornn, 1969; Reiser and Bjornn, 1979; Sedell et al., 1984; Moore and Gregory, 1988). An important component of good quality trout habitat is appropriate sediment characteristics such as grain size and gravel availability. Clean gravel of the correct size (5-30mm) and relatively free of finer grained sediments must be available for rainbow trout to spawn. Without clean gravel, trout can persist but must migrate to locations where spawning gravels are available in order to reproduce.

The availability of sufficient gravel for spawning is a function of the hydrology and the landscape. The grain size supplied to the channel, flood frequency, and stream and sediment storage in the watershed may be important in determining where rainbow trout can maintain viable populations (Pitlick and Van Stetter, 1998; Van Steeter and Pitlick, 1998; Lanka and Hubert, 1987; Bellamy et al., 1992; Harris, 1988; Poff and Allan, 1995). The processes that provide sediment to the channel include debris flows, landslides, and dry raveling (Florsheim et. al., 1991; Spittler, 1995). These stochastic processes, collectively described as mass wasting, are driven by events that vary in space and time such as rainstorms and other perturbations (Benda and Dunne, 1997a, b).

Once sediment is supplied to the channel network, the stream system redistributes the supplied sediment along the downstream channel network. Sediment redistribution and sorting depends on stream flow characteristics such as the timing, magnitude, and intensity of flow, as well as channel characteristics such as valley width, configuration, and gradient. Stream flow and channel characteristics will interact to route, sort, and store the sediment that was supplied.

Because the available grain sizes and amount of sediment varies spatially throughout the watershed, and the goal of my research was to determine how sediment conditions were related to rainbow trout distributions, I chose to study the entire Sespe watershed. A variety of scientific fields have focussed on watershed-scale studies; the earliest were the Hubbard Brook Ecosystem Studies of the 1970's. Regional-scale studies have focused mostly on aquatic ecosystem dynamics and the longitudinal flow of energy, materials, and organisms within a watershed (Likens and Bormann, 1974; Montgomery et al., 1995; Ryan and Grant, 1991; Wiley et al., 1997; Sedell et al., 1990; Johnson and Gage, 1997; Allan and Johnson, 1997). Advances in computer technology and the increased availability of digital terrain models have also increased scientific capabilities for doing research at the watershed scale and led to the formalization of watershed analysis methods within government agencies (Berg at al., 1995; Sespe Watershed Analysis, 1997).

A watershed-scale study can quantify the type and amount of sediment that could potentially be supplied to the channel network based on information on soil properties, slope, lithology, vegetative cover, and land use (Allan, 1997; Ryan and Grant, 1991; Mertes et al., 1998). Once sediment is supplied to the stream, large woody debris (Keller and MacDonald, 1995) and valley morphology (Benda, 1990; Grant and Swanson, 1995) have strong influences on the storage and sorting of sediment within channels.

A study conducted in the Western Cascades of Oregon by Grant and Swanson (1995) found that valley morphology and channel landforms were strongly influenced by processes external to the channel. Reach-scale variations in valley width were found to correspond with bedrock outcrops and hillslope features such as landslides and alluvial fans. Another study in the Grand Canyon by Miller (1994) showed a correspondence between tributary debris fans and active channel features such as rapids and pools and out-of-channel features such as bars. A two-dimensional flow model was used to show the effect of tributary debris fans on channel geometry and local stream gradient.

Wohl and colleagues have looked at the role of unit stream power and extreme flows on valley morphology and channel gradient (Wohl, 1992; Wohl and Baker, 1994). Their research suggests that channel morphology is more a function of extreme flows rather than such innate basin characteristics as lithology or tectonics.

1.2 - Site Description

Sespe Creek (680-km^2; Figure 1) is a tributary of the Santa Clara River (4000-km^2), which drains the largest coastal watershed in Southern California. The Sespe Creek watershed is located completely within Ventura County and drains high peaks in the Western Transverse Ranges (Pine Mountain and Topatopa Ranges; 2290m and 2040m respectively). Sespe Creek was chosen because it supports a healthy resident rainbow trout population as well as a remnant run of steelhead trout (*Oncorhynchus mykiss mykiss*). It is one of the last undammed rivers in Southern California and is relatively free of water diversions, making it ideal for studying sediment storage and sorting under natural conditions. It is similar to many other coastal watersheds in Southern California. Fifty percent of the watershed is also located in a federally designated wilderness (Sespe Wilderness Area) and most of the mainstem has Wild and Scenic River status, making it less likely to be affected by intensive human activity.

Sespe Creek drains mountainous terrain throughout its entire length, flanked by 2290-meter Reyes Peak on the north and Topatopa Ridge on the south. The Sespe basin's geology consists of highly folded, fractured, and faulted rock units of primarily Miocene, Oligocene, and Eocene marine and non-marine sandstones and shales, including the Juncal, Cozy Dell, Coldwater, Matilija, Rincon, Sespe, Monterey, Santa Margarita and Caliente Formations and unnamed

Cretaceous strata (Dibblee, 1985-1996). The northeastern portion of the basin also includes gneiss and granitic rock units comprising approximately 15% of the drainage basin area (Sespe Watershed Analysis, 1997).

The region is seismically active and dominated by a series of thrust faults such as the San Cayetano thrust, Oak Ridge thrust, Pine Mountain Fault, and Santa Ynez Fault. Other faults in the area include the Agua Blanca Fault, Munson Creek Fault, and Tule Creek Fault. Although uplift rates for specific areas are not known, watersheds in Ventura County have been estimated to be uplifting locally at a rate of 7.5 meters per 1,000 years with the rate of denudation estimated to be 2.3 meters per 1,000 years (Scott and Williams, 1978).

Mixed chaparral and sage scrub dominate the vegetation of the watershed (82 percent of the cover) with species such as chamise, scrub oak, ceanothus, and manzanita. The north facing slopes, however, are dominated by canyon live oak, california bay, and big-cone douglas fir due to less solar insolation and evapotranspiration. The higher peaks (above 1700 meters) in the watershed have coniferous forests of considerable size (8 percent of the cover) containing such species as sugar pine, ponderosa pine, and Jeffrey pine. The riparian zone accounts for approximately 10 percent of the vegetative cover and is dominated by three classes of species. White alder and big leaf maple dominate wetter areas and act as good indicators of permanently flowing water and persistent rainbow trout populations. A mix of willow (various species), sycamore and cottonwood trees dominate drier reaches (Sespe Watershed Analysis, 1997).

The climate of the region is Mediterranean with cool, wet winters and warm, dry summers. Annual mean precipitation ranges from 450 mm in the valleys to over 800 mm along the ridges. Rainfall can exceed 1800 mm/year during the wettest years on the windward side of the higher peaks. Snow falls at the higher elevations in winter; however, melting occurs fairly quickly. Approximately 75% of the total average annual rainfall occurs between the months of December and March, producing a flashy hydrologic regime. For example, at the Fillmore gauging station, near the mouth of the Sespe, the peak average daily discharge is approximately 34 m^3s^{-1}, occurring in late January. In the winter of 1983, the peak flow in mid-February reached 740 m^3s^{-1} (**Figure 2**). Such flashy flows are the result of meso-scale midlatitude cyclones, often invigorated by subtropical moisture during El Nino years. These storms produce heavy rains resulting in flows 4 orders of magnitude greater than average winter base flows (Elford and Stilz, 1969; Hydrosphere Data Products Inc, 1997).

Sediment is supplies to the channel from such hillslope processes as rockslides, debris slides, soil slippage, and dry raveling, measurement of which is beyond the scope of my research. The amount of sediment supplied to the channel depends on rock type, vegetation type, fire history, rainfall history, and the amount of time that has passed since the last major erosion event (Scott and Williams,

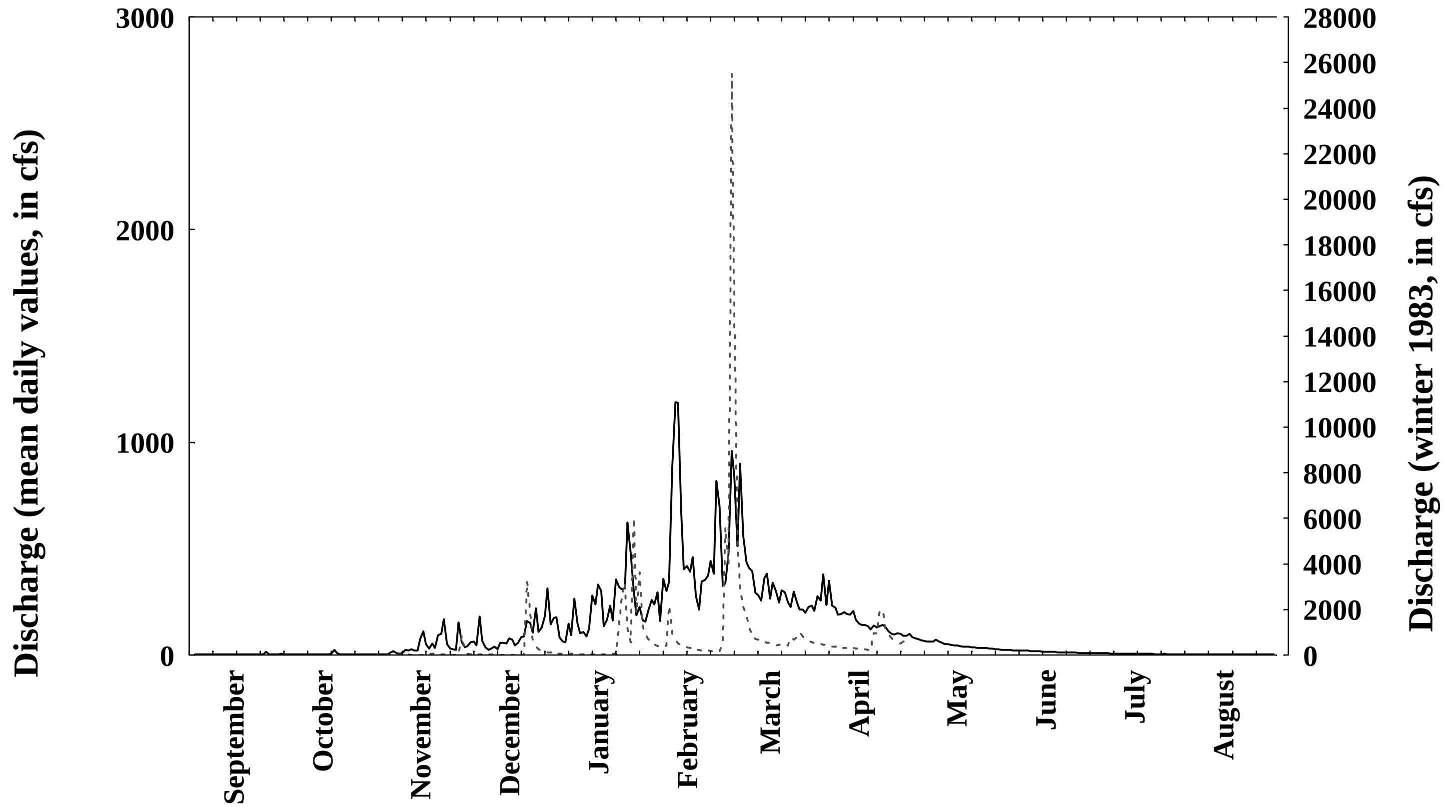


Figure 2: Hydrograph. The average hydrograph for Sespe Creek at the Fillmore gauging station. The solid line represents averaged daily values from 1930-94. The dotted line represents daily discharge for the winter of 1983. The climate of Sespe Creek is characterized as semi-arid with hot, dry summers, and cool, wet winters. The hydrologic setting is therefore flashy with flood peaks 5 orders of magnitude greater than summer base flows (Hydrosphere Data Products Inc, 1997).

1978). Using a model developed for watersheds of the Western Transverse Ranges based on past fire frequency, storm recurrence intervals, and previous debris flow events, Keller et al (1997) estimated that debris flow events occurred once every 1000 years.

A U.S. Forest Service study conducted in the Eastern Transverse Ranges (Rice and Foggin, 1971) estimated that soil slippage from a single storm in 1965 was 153 m^3/km^2 in converted grass areas and 21 m^3/km^2 in brush areas. In 1969, renewed slippage was estimated to have produced 5.4 times as much erosion in converted grass areas and 14 times as much slippage in brush areas compared to the same location in 1965.

In watersheds where the major bedrock type is shale, dry raveling is estimated to be the dominant sediment supply process, providing pebble-size sediment (4-64mm) to near-channel areas (Scott and Williams, 1978). Sediment supplied to the channel via dry raveling is associated with talus cones along the base of steep slopes and along upslope sides of vegetation. Dry ravel stored on hillslopes by vegetation will be more readily transported to channels after fires have removed this impediment to downslope movement (Florsheim, et. al., 1991; Krammes, 1960). Dry ravel stored at channel edges will be activated by flood events (Anderson et al., 1959).

After sediment reaches the channel it could be moved by suspension, bedload or debris flows. In steep terrain, a significant amount of sediment is moved through the channels. During floods, most of the silt and clay (<0.0625mm) and a significant portion of the sand (0.0625-2mm) will be transported as suspended sediment. The rest of the sediment would be transported as bedload or debris flows which may account for the bulk of coarse (> 2mm) sediment movement (Scott and Williams, 1978). Evidence of debris was commonly observed in the Transverse Ranges following the floods of 1969. In the lower reaches of Sespe Creek, coarse fill was continuous across the channel to a point 1.3-km downstream from the mountain front near the confluence with the Santa Clara River. The fill was estimated to be 1.2 to 1.5 meters deep (Scott and Williams, 1978).

The USGS, Ventura County Department of Public Works, and the Ojai Resource Conservation District (Scott and Williams, 1978) estimated total sediment yield for 32 watersheds in the Eastern Transverse Ranges in Los Angeles County, by measuring debris basin sediment volumes for multiple storms between 1938 and 1970, including the record floods of 1969. These results were then regressed against measured physiographic and hydrologic variables (e.g.; peak discharge, mean slope, mean stream length) from the Eastern Transverse Range watersheds to provide total sediment yield estimates for 27 watersheds in the Western Transverse Ranges in Ventura County.

Total sediment yields from 7 Los Angeles County watersheds ranged from 4,550 m^3/km^2 to 39,300 m^3/km^2 in 1938, 810 m^3/km^2 to 16,900 m^3/km^2 in 1943, and 1,620 m^3/km^2 to 9,980 m^3/km^2 in 1952. Estimated sediment yields for 27 watersheds in Ventura County for a 50-year storm, based on the regressions from 32 watershed in Los Angeles County ranged from 2,420 m^3/km^2 to 16,100 m^3/km^2. For a January, 1969 storm, estimates ranged from 9,120 m^3/km^2 to 24,900 m^3/km^2 for the Ojai area and 1,330 m^3/km^2 to 8,240 m^3/km^2 for the Santa Clara River watersheds. The long-term average rate of denudation for small watersheds in the Transverse Ranges was estimated to be 2.3 meters per 1000 years (Scott and Williams, 1978).

Total sediment yields, however, do not provide information on the patterns of sediment storage and sorting that occur in individual streams. The characteristic geomorphic pattern of the valleys and channels of Sespe Creek, and many other watersheds in the Transverse Ranges, is alternations between steep channel reaches in narrow valleys and low-gradient channel reaches in wider valleys. The wide, low-gradient reaches upstream of constrictions in the valley are potential sites of sediment storage (**Figure 3a and b**). The location of constrictions is related to bedrock outcrops, meanders in the stream channel, woody debris, and landslides.

Figure 3a and 3b illustrate the geomorphic setting of a typical stream channel within the Sespe Creek Watershed. The alluvial sediment component of the landscape is characterized by three storage elements: long-term or inactive storage characterized by abandoned terraces; semi-active storage characterized by

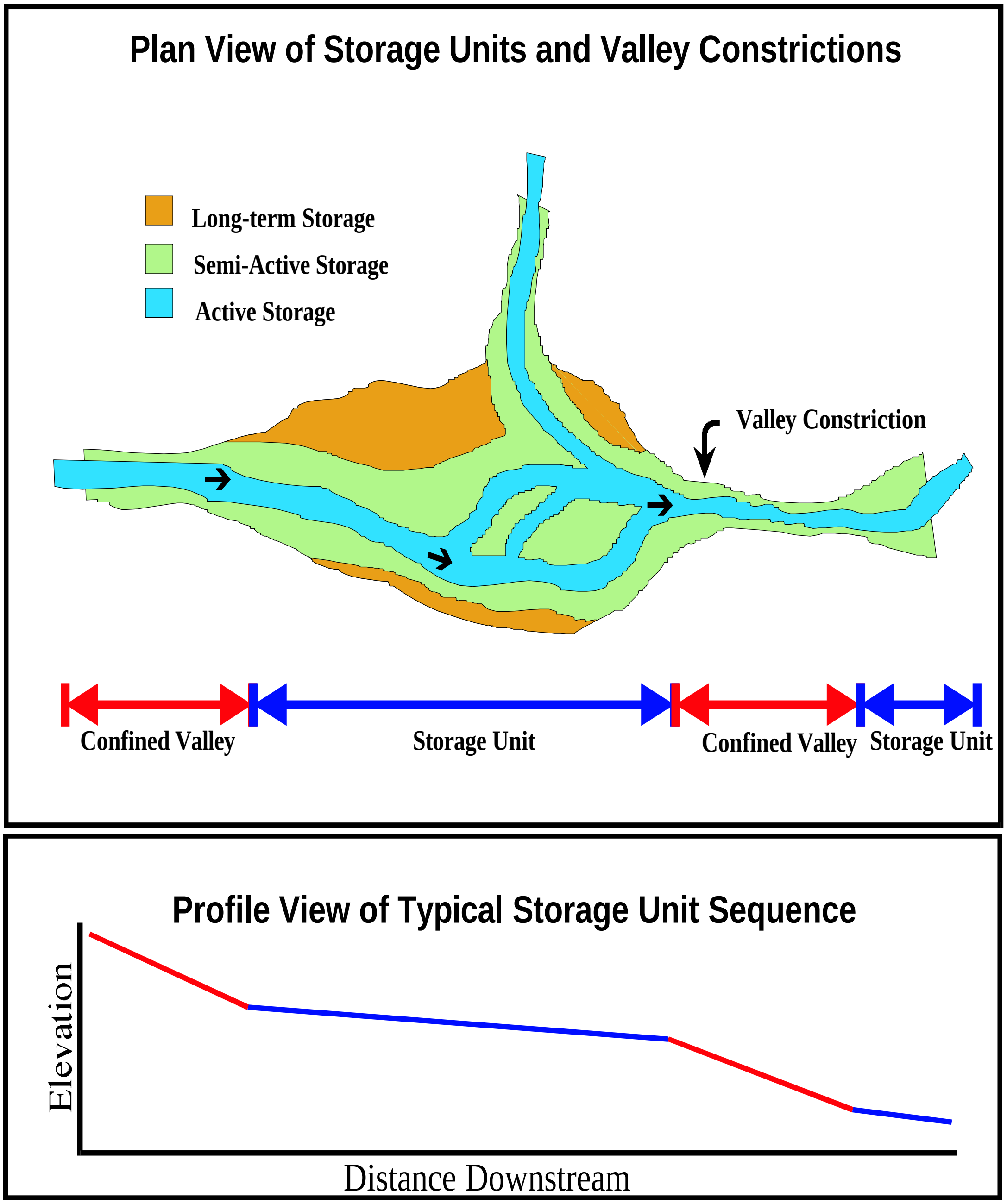
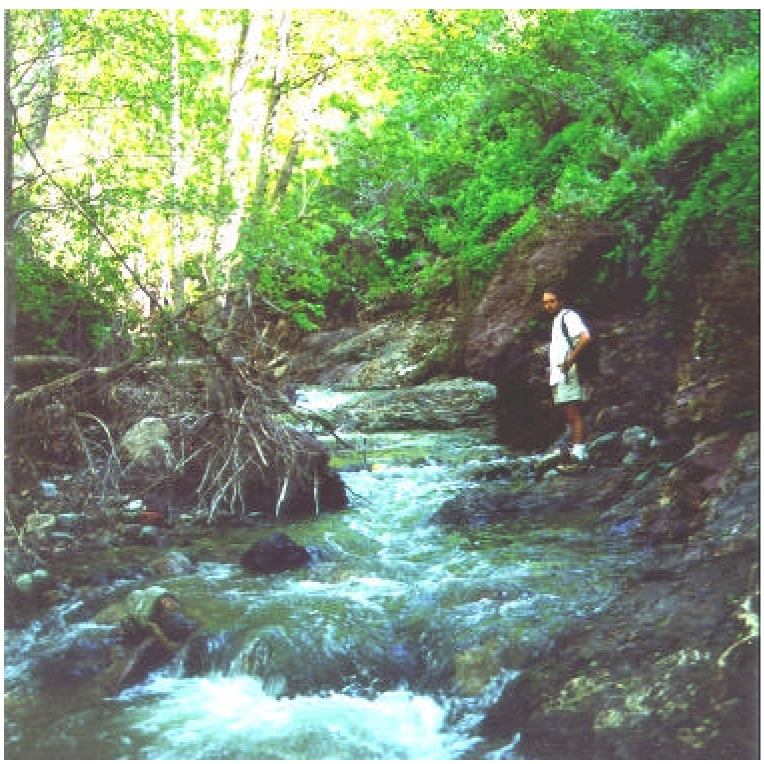


Figure 3a: Illustration of the geomorphology of a typical mountainous stream in the Western Transverse Ranges of Southern California. Brown areas represent locations of long-term sediment storage, green areas semi-active storage, and blue areas represent active storage. The lower graph represents parts of four reaches, the scale depending on factors such as drainage area. Red areas represent narrow, steep valleys. Blue areas represent wide, flat valleys. A constriction often occurs at the boundary between wide valleys and narrow valleys.

A



B

Figure 3b – Photos A and B were taken approximately 3 years after a major fire in the Western Transverse Ranges of Santa Barbara County (Marre Fire). Birabent Creek was intensely burned which resulted in heavy sediment loads for several years after the fire. Photo A shows a wide valley section just upstream of Photo B where sediment was deposited. Subsequent storms have reformed the channel, although it represents poor rainbow trout habitat. Photo B depicts a narrow reach where bedrock and cobble are the dominant sediment size classes. The habitat quality is good for rainbow trout due to available hiding spots, canopy shading, and deep pools.

floodplain features; and active channel storage (Best and Keller, 1986). The inactive storage is represented by abandoned terraces resulting from either stream downcutting or tectonic uplift. Sediment in inactive storage only is mobilized during rare situations of channel aggradation and subsequent migration. Sediment in semi-active storage can be deposited or mobilized during periods of flooding when the main channel's capacity is exceeded and water overtops the natural stream levees or starts flowing into floodplain channels. Bank erosion also can result in mobilization of the semi-active storage component. Active storage landforms include bars and the active channel bed. The sediment stored in these landforms is mobilized and reworked frequently, even during moderate flows. This is especially true for smaller sediment sizes such as fine and coarse gravel.

Flood conditions produce shear stresses on the channel bed that are high enough within confined channels to move a considerable amount of bedload (mean of 642 N/m^2 at peak flows of 520 m^3s^{-1} for a depth of 1.6 m, mean of 167 N/m^2 at bankfull flows of 15 m^3s^{-1} for a depth of 0.4 m computed for all transects surveyed in this study. *See Figure 5*). For example, 12 mm gravel is easily moved as bedload when bed shear stresses exceed 120 Newtons/m^2. Steep, confined, tributary reaches are often scoured to bedrock or cobble/boulder beds when bankfull is exceeded, with gravel being deposited in wide, shallow reaches. In addition, wide, shallow reaches can be a source of gravel when the sediment in their floodplains are reworked and transported, which may result in the deposition of gravel in narrow, steep reaches further downstream.

The narrow valley reaches are prime rainbow trout habitat because water is available year-round due to the intersection of the water table with the bedrock surface. However, gravel may not be available in these reaches without a steady supply from upstream reaches. Conversely, in low gradient reaches where gravel is readily available, water is not available year-round which reduces riparian canopy cover, resulting in increased water temperatures. Downstream barriers to fish migration often prevent access to these reaches as well. Therefore, tributaries with gravel storage upstream of narrow valley reaches may produce higher densities of rainbow trout because gravel is stored in the wide valley reaches and is slowly provided to locations where rainbow trout can persist.

2.0 - Methods

2.1 - Subwatershed Delineation

To examine relationships between landscape characteristics and rainbow trout densities I first determined the distribution of rainbow trout in Sespe Creek and its tributaries. Subwatersheds where rainbow trout were present were then chosen for further study based on representative landscape characteristics and ease of access.

The subwatersheds chosen for detailed study were Alder, Trout, Bear, Lion, Howard, Tule, Portrero John, Ladybug, and Cherry Creeks based on historic accounts of trout populations in those creeks and evidence of perennial surface water along certain reaches. **Figure 4** shows a map of the chosen subwatersheds.

To characterize the geomorphology of each subwatershed I divided the channel network into reaches with similar geomorphic character, according to criteria developed by Rosgen (1994). The method considers valley confinement, gradient, and bed material to classify a river into self-similar stream segments. The Rosgen method assigns a code to each stream reach. A simple form of the Rosgen classification uses letters A through D to define the confinement and gradient of the channel and valley, with A representing narrow, incised, steep channels and D representing wide, meandering, low-gradient channels. A number

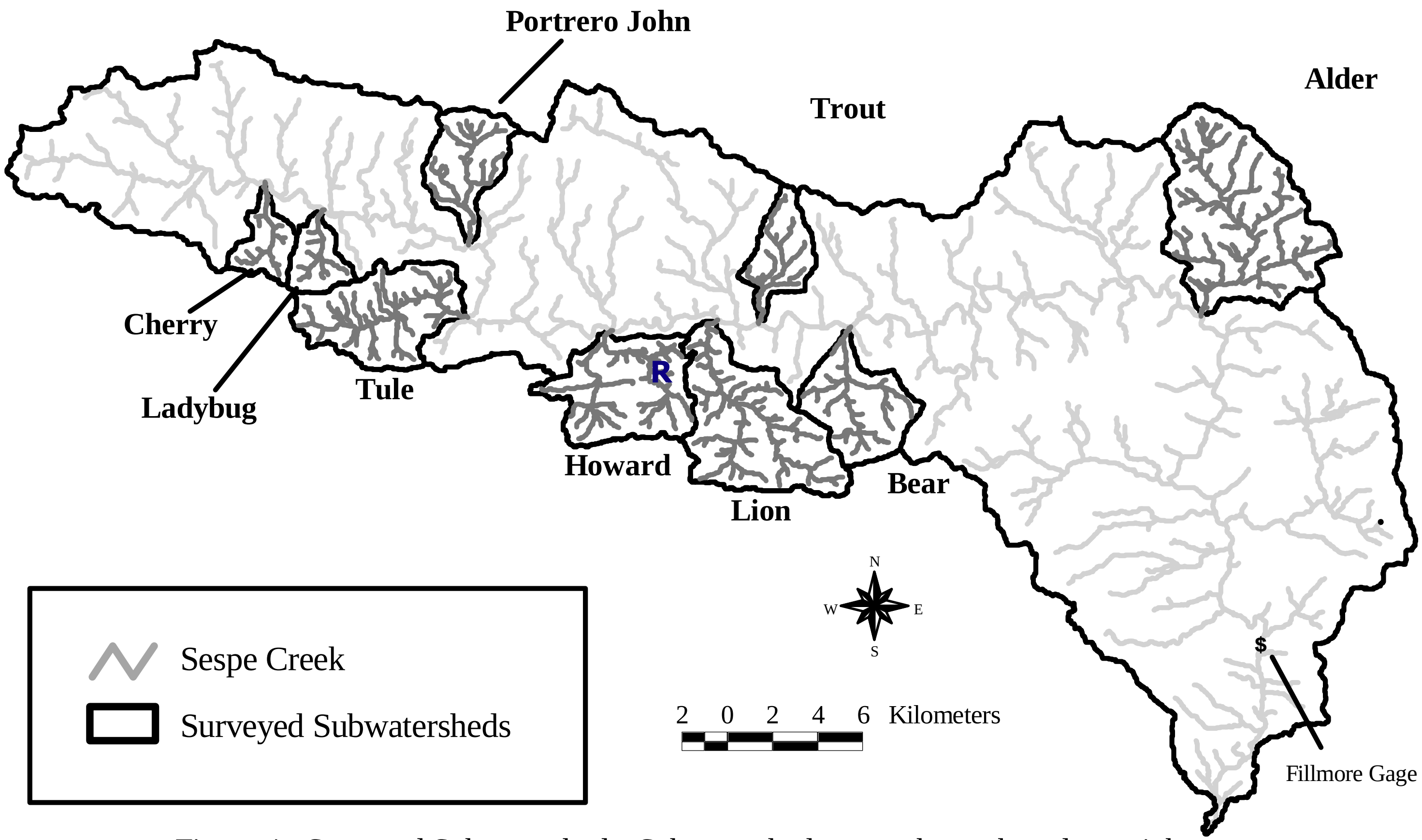


Figure 4 - Surveyed Subwatersheds: Subwatersheds were chosen based on rainbow trout presence, ease of access, and their locations throughout the Sespe Creek Watershed. The 'R' on Howard Creek denotes the location of Rose Valley.

from 1 through 5 is then used after the confinement letter to describe the dominant bed material, ranging from 1 for bedrock channels to 5 for sand and silt channels.

2.2 - Geomorphic Characteristics

Typically 2 or 3 cross-sections were measured within each study reach, described in Section 2.1. **Figure 5** shows a map of transect locations in the Sespe Watershed. Transect locations on the mainstem of Sespe Creek and other tributaries not surveyed for rainbow trout are coded differently because they were only used in the analyses of the geomorphic characteristics of the watershed and not in relation to rainbow trout densities.

A hand level was used to measure cross-sectional elevations at each transect and the locations of fluvial features such as bankfull height and floodplain channels were determined. Total valley width also was measured. In some circumstances the total valley width was difficult to measure accurately due to the influences of tributary canyons and channel meandering within the valley. As a consequence, confluences of channels were avoided when possible.

Either pebble counts or sediment samples were taken at each geomorphic feature (e.g.; bars, floodplain channels, main channel) along the length of the transect to determine the grain size. Sampled geomorphic features included bankfull channel, active channel bars, floodplain channels, floodplain channel bars, floodplain terraces, abandoned terraces, and valley margins. Pebble count

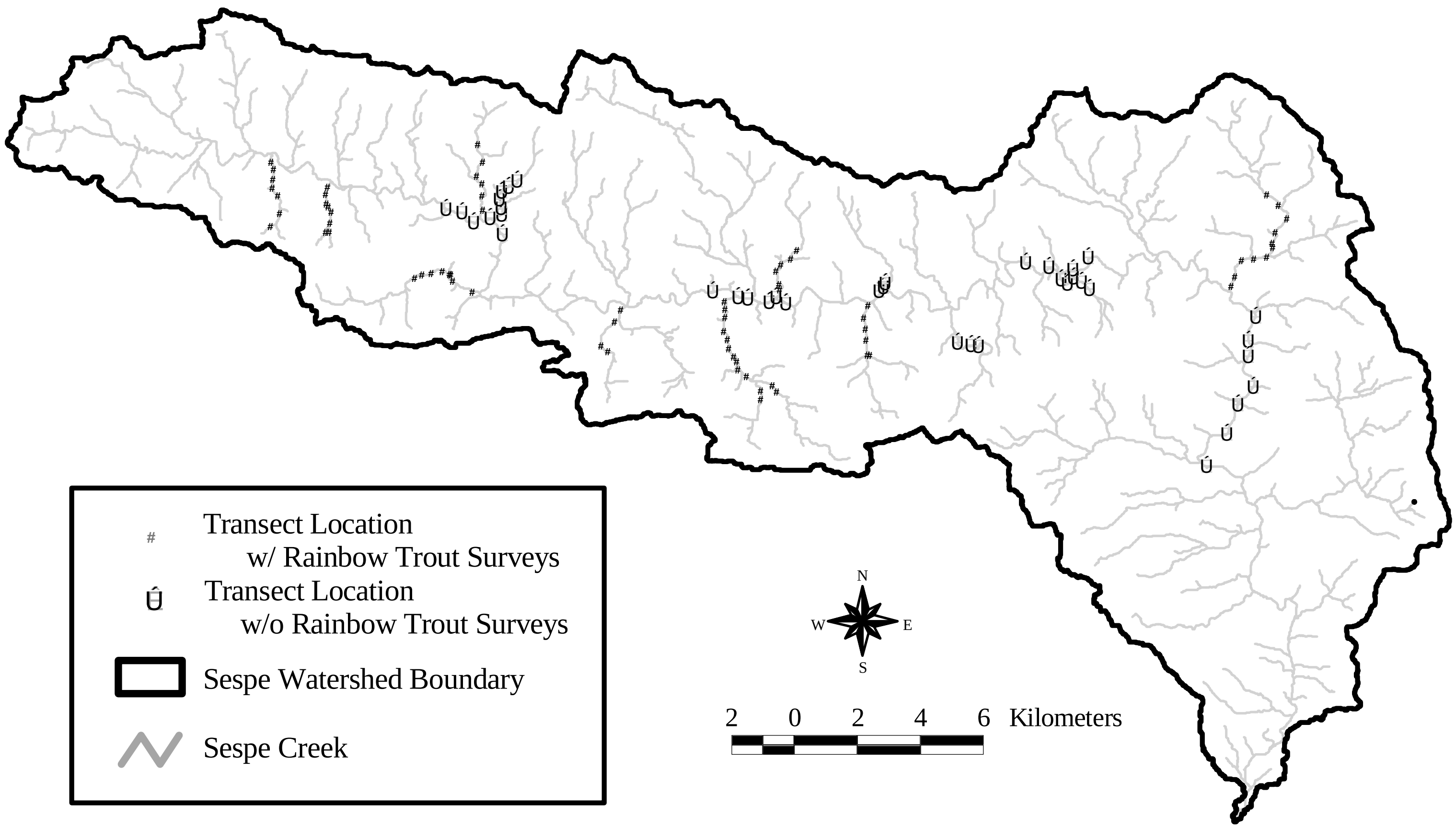


Figure 5 - Transect Locations on Sespe Creek. Dark circles represent transect locations on subwatersheds surveyed for fish populations and sediment characteristics. Stars represent subwatersheds with only cross-section and sediment information.

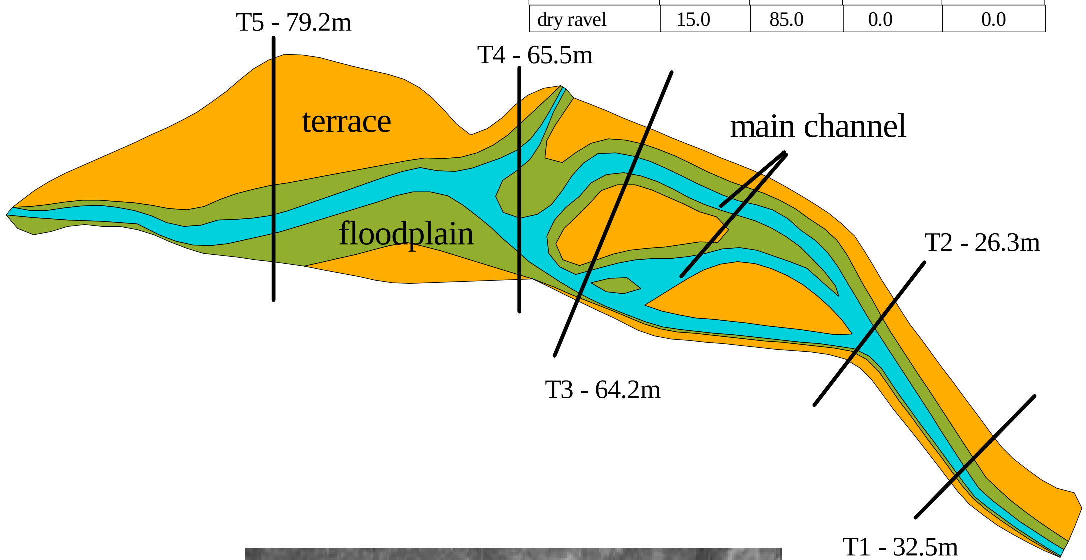
surveys covered the entire feature that fell within the vicinity of each transect location. Sediment samples were taken at a representative location on the feature in order to describe the entire feature. A 200-point random sampling method was used for the pebble counts, consistent with Wolman (1954), Church et al., (1987), and Wohl (1996). Sediment sizes were divided into ϕ sizes from –1 to –11 (0-2 to 2048-4096 mm). Grab samples were taken back to the lab and sieved through a sieve series corresponding to integer ϕ categories in an automatic shaker (Guy, 1969).

In addition to the reach-scale surveys, a detailed survey was conducted on a representative storage unit on Lion Creek (**Figure 6**). The site was mapped using a compass and tape, cross-sectional transects were placed at five locations along the length of the storage unit, and either pebble counts or grab samples were taken for landforms including the active channel, channel bar, terrace, floodplain channel, floodplain bar, abandoned channel, and abandoned bar. Grab samples were also taken from three dry ravel cones to determine grain-size distributions in these depositional features. Pebble count and grab sample analyses were conducted in the same manner as for the reach-scale cross sections. Results from the analyses of pebble counts and sediment samples were combined and summarized into main channel, floodplain, or terrace features.

a

Mean Percent Grain Size
(from pebble count data)

Feature	% Fines	% Gravel	% Cobble	% Boulder
floodplain	9.1	71.0	19.0	0.9
main channel	8.8	41.4	35.4	10.9
terrace	11.5	70.1	18.5	0.0
dry ravel	15.0	85.0	0.0	0.0



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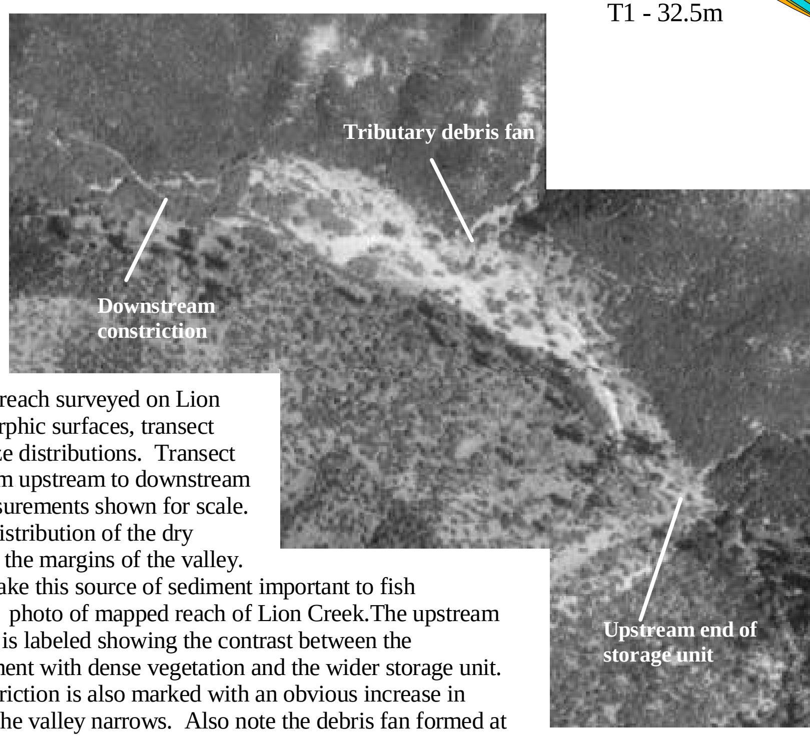


Figure 6 - a) Map of a reach surveyed on Lion Creek showing geomorphic surfaces, transect locations, and grain size distributions. Transect sites are numbered from upstream to downstream with valley width measurements shown for scale. Notice the grain-size distribution of the dry ravel cones sampled at the margins of the valley. High gravel content make this source of sediment important to fish populations. b) Aerial photo of mapped reach of Lion Creek.The upstream end of the storage unit is labeled showing the contrast between the narrow, upstream segment with dense vegetation and the wider storage unit. The downstream constriction is also marked with an obvious increase in riparian vegetation as the valley narrows. Also note the debris fan formed at the outlet of a tributary canyon.

2.3 - Rainbow Trout Surveys

Rainbow trout population surveys were conducted in the spring and summer of 1997 along Alder, Trout, Bear, Lion, Howard, Tule, Portrero John, Ladybug, and Cherry Creeks (**Figure 4**). Fish sampling methods were based on U.S. Forest Service techniques, which combine habitat surveys and fish population estimates. These techniques produce estimates of fish densities along an entire reach of stream by weighting the densities at surveyed habitat units by that habitat types distribution throughout the reach. For the fish density surveys, a snorkeling method was used to count fish (Thuron, 1994).

Fish population density estimates were obtained using a two-step process. The first step was to determine the percent of habitat types (run, riffle, or pool) within a particular reach of creek. The second step was to determine the fish densities present within each habitat type. Each reach of stream is first divided into run, riffle, or pool habitats. Mean length, width, and depth are measured to determine the volume of water present in each habitat unit. Because no measurable rainfall fell after the end of January in 1997, base flow conditions were reached early in the dry season. As a consequence, there were only small changes in hydrologic conditions through the duration of sampling.

Once the distribution of habitat types was known, 20% of the surveyed habitat units of each type were sampled to obtain fish population estimates. Areas of run, riffle, and pool habitats were determined so that each habitat type was represented in the fish populations in proportion to their areal extents in each reach. Estimates of fish densities could then be extrapolated to the entire surveyed reach based on this method.

Fish were surveyed by snorkeling, which consisted of a snorkeler swimming along each habitat unit from downstream to upstream (Thuron, 1994). The swimmer took care to look in all potential hiding places and to minimize recounts. Often two swimmers would survey the unit independently and counts were examined for consistency. Potential error in counting fish varies based on the type of habitat unit being surveyed (run, riffle, or pool) and the complexity of cover (white water, woody debris, emergent vegetation) within the habitat unit. Previous work by the Los Padres National Forest Fisheries Crew shows good agreement between electrofishing and snorkeling results. In some cases, such as deep pools and swiftly flowing water, snorkeling produces higher counts than electroshocking (Sara Chubb, USFS, unpublished data).

Rainbow trout counted along snorkeling transects were placed into four separate size classes including 0-75mm, 75-150mm, 150-250mm, and > 250mm. Based on electrofishing results for the Sespe Watershed Analysis conducted by the Los Padres National Forest, these size classes correspond well with age classes of 0, 1, 2, and 3+ years, respectively (Sespe Watershed Analysis, 1997).

Fish densities were then computed based on the volume of water present in each habitat unit. Because the volume of water and size of the watershed varies considerably from tributary to tributary, dividing the fish population estimate by the volume of water to obtain a volumetric density normalizes the data. Fish densities were determined for the habitat-unit scale then extrapolated to the entire surveyed stream. Fish migration within a tributary stream, therefore, does not become a factor and migration is unlikely to occur between subwatersheds.

2.4 - GIS Methods

Thirty meter resolution Digital Elevation Models were available for the Sespe Creek watershed via the USGS (United States Geologic Survey, 1990). The 7.5-minute quadrangles for Sespe Creek were assembled in ArcInfo and streamlines and watershed boundaries were delineated using hydrologic tools available in ArcInfo (Jensen and Dominque, 1988; Burroughs, 1986; Tarboton et al, 1991). The techniques work well in landscapes with a considerable amount of relief and lacking natural sinks such as lakes and ponds (Garbrecht and Starks, 1995; Bolstad and Stowe, 1994; Carter, 1992; Lopez, 1997; Florinsky, 1998; Chang and Tsai, 1991). The Sespe fits these criteria well.

In addition to deriving the basic streamlines and boundaries for the subwatersheds, scripts were developed using ArcInfo's programming language (Arc Macro Language, AML). The AML's that were developed are described in **Table 1** and were used to derive landscape information, such as stream gradient and valley width, using a digital elevation model.

Function	Description
Separate Stream Orders	Separates an entire watershed into separate stream orders.
Create Stream "Reaches"	In order to provide statistically significant results for computer-derived landscape attributes, it was necessary to divide the streams into equally spaced segments ("reaches").
Longitudinal Profiles	Longitudinal profiles were derived using the DEM by determining the elevation at each "reach" along the length of a stream.
Derive Reach Gradient	Reach gradient was derived by dividing the difference in elevation at the beginning and end of a stream reach by the length of that reach.
Derived Reach Valley Width	Valley cross-sectional width was determined at the center of each reach segment using the DEM. This variable was used as a proxy for determining sediment storage in each reach.

Table 1: The derivation of basin attributes from a digital elevation model (DEM) of the Sespe Creek watershed were conducted using a set of programming scripts in the ArcInfo Macro Language (AML). This table describes the function of each of the AML scripts.

Derivation of valley width is complicated by the hydrologic methods used in ArcInfo, including problems associated with the quality of the DEM and the automated selection of valley width cross-sections. In order to determine a line perpendicular to the flow of the stream the program first must determine the direction of flow. The ArcInfo algorithm allows flow from one cell to the next in only eight directions: N, S, E, W, NW, NE, SW, and SE (Burroughs, 1986). Because actual stream flow directions are continuous and do not always conform to one of these eight directions, the actual flow direction will have an error of up to (+ or -) 22.5^0 compared to the DEM derived flow direction. To account for these errors at the location along the reach where valley width is being determined from the DEM, several cells both up and downstream from the cross-section location are queried for flow direction values. An average of the queried cells is then assumed to represent the "correct" flow direction.

Errors in computing valley width are often associated with the increased inaccuracies of the DEM in valley bottoms and ridgelines. DEM's tend to smooth these topographic features, particularly valley bottoms where riparian vegetation often biases the photogrammetric techniques used to create the DEM (Lopez, 1997; United States Geological Survey, 1990). The method used to minimize this systematic error was to compute valley width at a specified vertical distance above the channel (5 m in this case), therefore avoiding the channel bottom altogether.

The final class of errors associated with the use of DEM's for the computation of valley width lies with the automated selection of cross-section locations. After the stream network is broken up into reach segments, a point halfway along the reach is selected as the cross-section location to determine valley width. Due to the necessity of using an automated method of choosing the cross-section location along a reach segment, the site location may not be ideal. If the cross-section location is chosen at a tributary confluence, the valley width measurement may not be representative of the reach as a whole. No attempt was made to exclude such errors because they are not considered to be systematic.

Derived values of valley width were then grouped into valley width classes to reduce the number of possible values and to reduce the influence of extremely high valley width values, which may be in error. **Figure 7** shows the method used to group the valley width values into classes. Raw values, in meters, were converted to Very Narrow (VN: 0 – 30m), Narrow (N: 60 – 90m), Average (A: 120 – 150m), Wide (W: 180 – 270m), and Very Wide (VW: > 300m). For statistical reasons, these named classes were then converted to numbered classes from 1 to 5 with Very Narrow having a value of 1 and Very Wide having a value of 5.

In order to measure differences in potential sediment storage among the nine surveyed subwatersheds, three dimensionless storage indices were developed. The first index is the areal extent of storage (m^2) in a particular subwatershed divided by the drainage basin area (m^2) and is named the Normalized Basin

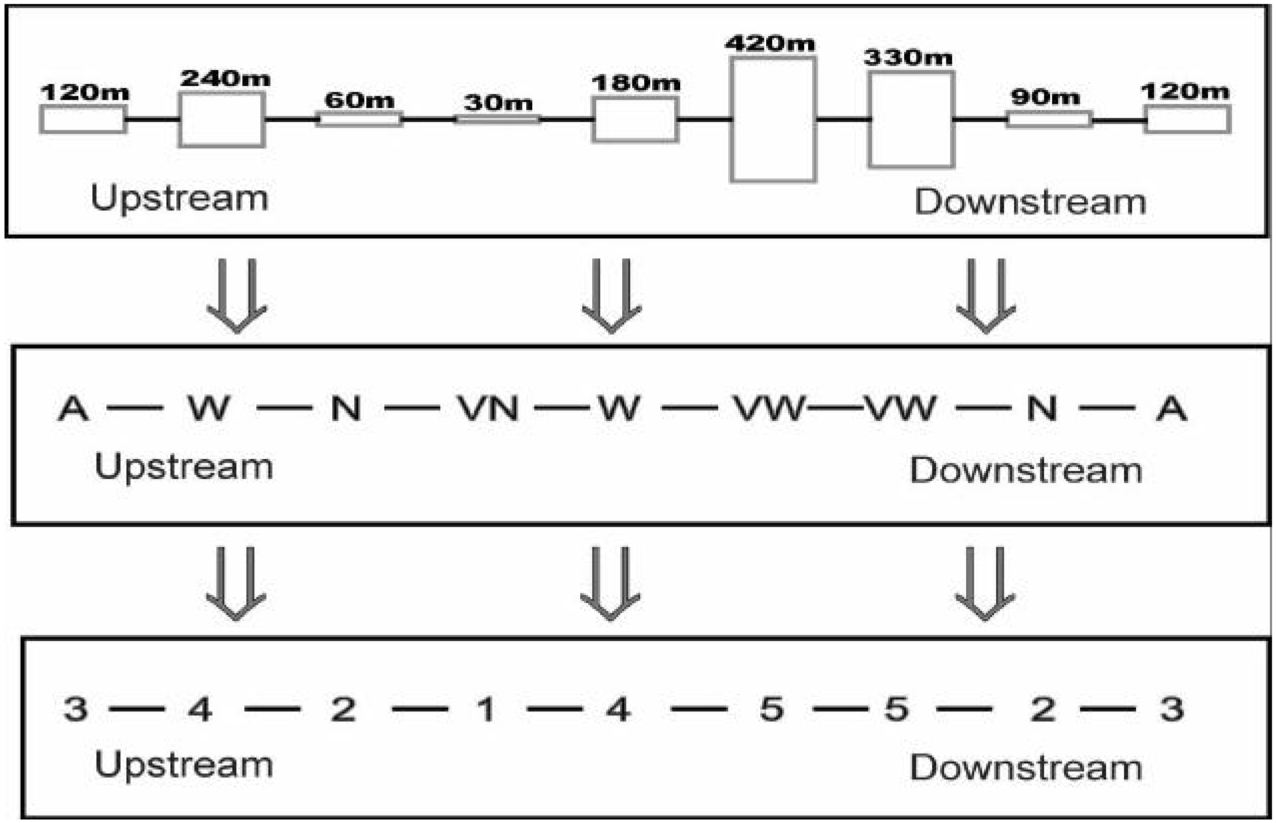


Figure 7 - The system used to generalize the results from the DEM derived analysis of valley width is shown. Classes were chosen based on the distribution of valley types in the Sespe Creek Watershed Raw values, in meters, were converted to Very Narrow (VN: 0 – 30m), Narrow (N: 60 – 90m), Average (A: 120 – 150m), Wide (W: 180 – 270m), and Very Wide (VW: > 300m)

Storage (NBS). The second index was developed to measure the relative amount of stream length characterized by wide, low-gradient reaches as opposed to narrow, high-gradient reaches and is termed the Storage Length Index (SLI). The SLI is computed by summing the lengths of all of the reaches (m) in a particular stream that are characterized by wide (>90m), low gradient (<4%) reaches then dividing by the total stream length (m). The third storage index was developed to measure the relative amount of areal storage in wide, low-gradient reaches compared to the total amount of storage in the subwatershed and is termed the Areal Storage Index (ASI). The ASI is computed by summing the areal storage (m^2) in the wide, low-gradient reaches and dividing by the total areal storage (m^2) for the subwatershed.

In order to determine relationships between geomorphology and geology, geologic maps were digitized using ArcInfo and 1:24000 Dibblee maps of the area (Dibblee, 1985-1996). Geologic features were only digitized for the region adjacent to the valley bottom, delineating both right and left rock types (looking downstream) for each reach. The geologic layers allow comparisons between geologic rock types and landscape characteristics derived from the DEM, such as valley width or valley gradient.

2.5 - Statistical Methods

Standard statistical techniques were used to assess relationships between landscape, habitat, and fish density variables. A correlation matrix was developed for the fish population and stream habitat data to determine if any of the measured habitat or storage variables were related to rainbow trout densities. Relationships that resulted in a p-value less than or equal to 0.05 were considered to be significant. Statistically significant variables were then used in a linear regression model to quantitatively examine their relationship to rainbow trout densities.

To assess whether patterns were present in the valley width and valley gradient data for each surveyed subwatershed, an autocorrelation analysis was used. Input into the autocorrelation analysis was longitudinal valley width and gradient data generated from a DEM. Each stream was divided into approximately equally spaced segments. The highest stream segment in each subwatershed was given a value of 1 and each subsequent stream segment in the downstream direction was given a value of n + 1. Valley width and valley gradient values were then assigned to each stream segment and the correlations (termed the autocorrelation function or ACF) were determined between reaches of increasing lag. The actual length of each stream segment varied by subwatershed with a range from 158 to 207 meters. The lag is defined as all combinations of reaches that are separated by the same distance. For example, the ACF value at a lag of ten is defined as the correlation between all stream reaches and corresponding reaches ten stream-segments away. If the correlation value is 1 then the stream reaches separated by the defined lag have exactly the same valley width or gradient.

3 – Analysis of Results

3.1 - Geomorphic Patterns and Storage Model

At the reach scale, field surveys were used to determine valley width, grain size distributions, and fish densities. At the watershed scale, valley width, gradient, and other landscape characteristics were derived using a DEM. No direct comparisons between field-derived reach characteristics and DEM-derived watershed characteristics were made. The DEM derived data are consistent with the trends observed in the field measurements, although no formal statistical analysis was conducted.

A summary of the important landscape characteristics of the surveyed subwatersheds, derived from the DEM, are presented in **Table 2** including drainage area, maximum stream order, minimum and maximum elevations, elevation range, mean slope of the subwatershed, mean stream gradient, mean valley width, total sediment storage, stream length, dominant rock type, NBS, SLI, ASI, and drainage density (DD). The subwatersheds are ordered by their proximity to the mouth of Sespe Creek. Alder Creek has the largest drainage area (36 km^2), highest elevation range (1465 m), steepest average slope (28^0), and lowest mean valley width (78 m). It is also the only surveyed subwatershed with non-sedimentary rock, composed mostly of granites (**Table 2**). Howard Creek has

Name	Area (km^2)	Order	Minimum Elevation (m)	Maximum Elevation (m)	Elevation Range (m)	Average Slope (degrees)	Standard Deviation	Average Valley Gradient (%)	Standard Deviation	Average Valley Width (m)	Standard Deviation
Alder	36	4	640	2100	1460	28	9.1	11.5	7.1	80	140
Bear	14	4	860	1950	1090	27	8.5	12.3	7.3	160	290
Trout	8	4	910	2110	1200	22	8.9	15.9	14.0	270	390
Lion	26	4	920	1960	1040	23	8.2	7.5	6.5	100	140
Howard	20	4	970	1620	650	20	10.1	3.4	5.4	210	230
Tule	19	3	1040	1770	730	22	8.0	6.6	6.3	130	150
Portrero John	11	3	1110	2280	1170	26	9.9	11.8	7.6	100	170
Ladybug	5	3	1220	1770	550	25	7.5	8.2	5.5	150	210
Cherry	5	3	1250	1740	490	23	7.8	0.1	4.6	90	110

Name	Total Storage (km^2)	Stream Length (km)	Dominant Rock Type	NBS	SLI	ASI	Drainage Density
Alder	2.6	33.1	granitic	0.07	0.19	0.26	0.9
Bear	1.8	11.6	shale	0.13	0.30	0.79	0.8
Trout	2.3	8.5	sandstone	0.29	0.31	0.68	1.0
Lion	2.3	21.5	shale	0.09	0.32	0.72	0.8
Howard	6.2	32.1	shale/sandstone	0.18	0.56	0.91	1.6
Tule	1.7	12.9	shale	0.09	0.45	0.83	0.7
Portrero John	0.9	10.5	sandstone	0.08	0.19	0.61	0.9
Ladybug	0.6	3.7	shale	0.11	0.30	0.70	0.7
Cherry	0.4	4.9	shale	0.08	0.23	0.71	0.9

Table 2: Surveyed Subbasin Characteristics. All attributes were derived using 30-meter resolution digital elevation model data and ArcInfo's hydrologic modelling functions. (NBS = Normalized Basin Storage, SLI = Storage Length Index, ASI = Areal Storage Index). Creek data are sorted by their distance from the mouth of the mainstem Sespe.

the gentlest average slope (20^0), lowest mean valley gradient (3 %), highest mean valley width (213 m), and is composed of equal amounts of sandstone and shale.

Based on the basin characteristics shown in **Table 2**, there does not seem to be any clear groupings that would distinguish subwatersheds located in one part of the Sespe watershed from others. Although some distinctions could be made when looking at one basin characteristic such as mean stream gradient, in general the basin characteristics show a continuous variation across the subwatersheds.

Figure 8 shows locations in the entire Sespe watershed and, in detail, on Lion Creek where the criteria of wide valleys (> 90m) and low gradients (< 4%) are met, based on the DEM. These areas of wide valleys and low gradients are hypothesized to be areas of sediment accumulation and storage. Many second and third order reaches show wide valleys and low gradients resulting in a high potential for sediment storage. Conversely, the model shows less storage occurs in the downstream reaches of the mainstem of Sespe Creek where it flows south.

Figure 9 depicts the storage and gradient conditions that exist along the mainstem of Sespe Creek, from its headwaters to its mouth. The results show a higher proportion of storage occurring in stream orders 2, 4 and 5 (SLI of 0.44 to 0.63), with less storage occurring in stream orders 3 and 6 (SLI of 0.13 and 0.31, respectively). Gradient shows a general decrease from orders 2 through 5 (3% to 1.1%) with a slight increase at order 6 (1.5%).

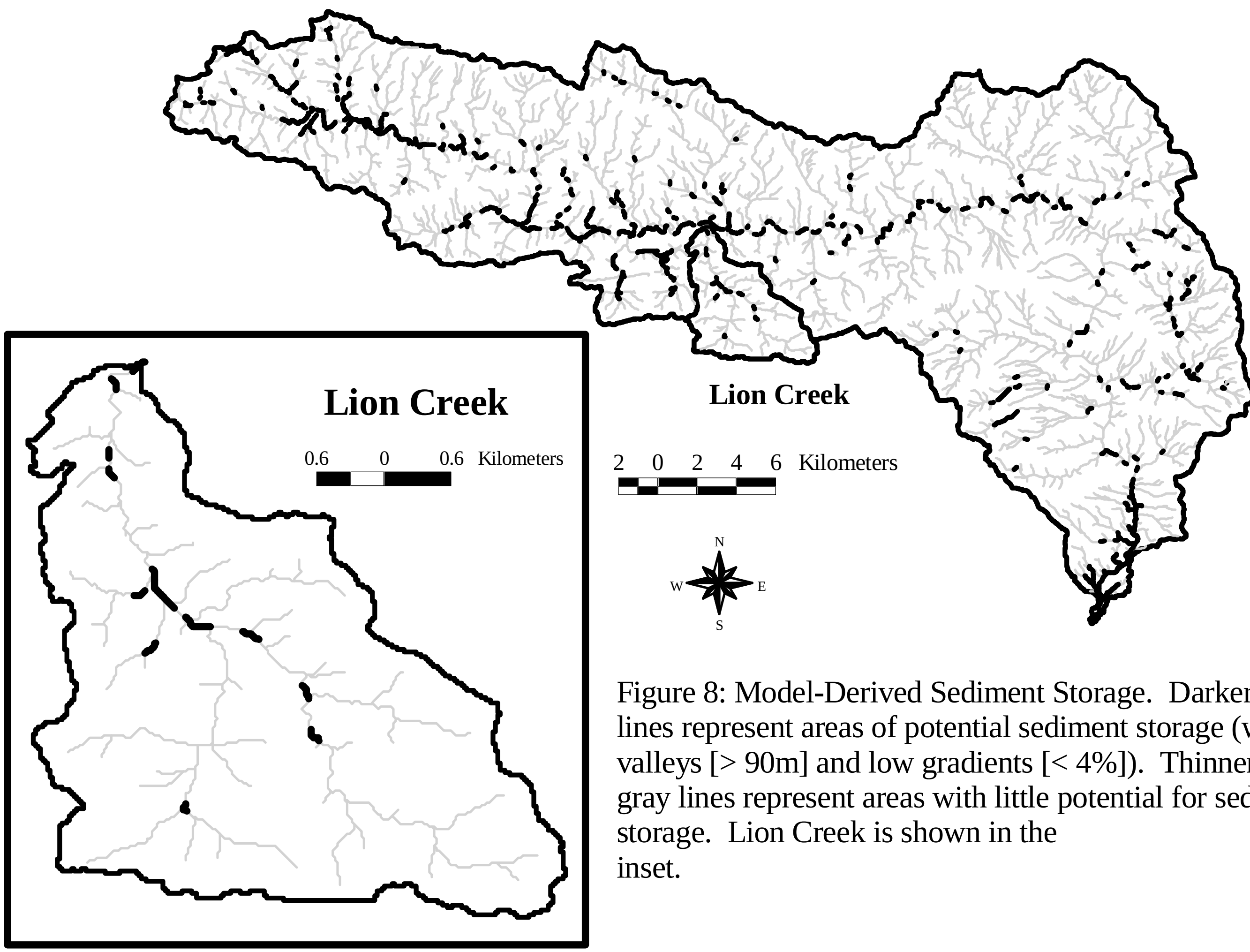


Figure 8: Model-Derived Sediment Storage. Darker, thick lines represent areas of potential sediment storage (wide valleys [> 90m] and low gradients [< 4%]). Thinner, gray lines represent areas with little potential for sediment storage. Lion Creek is shown in the inset.

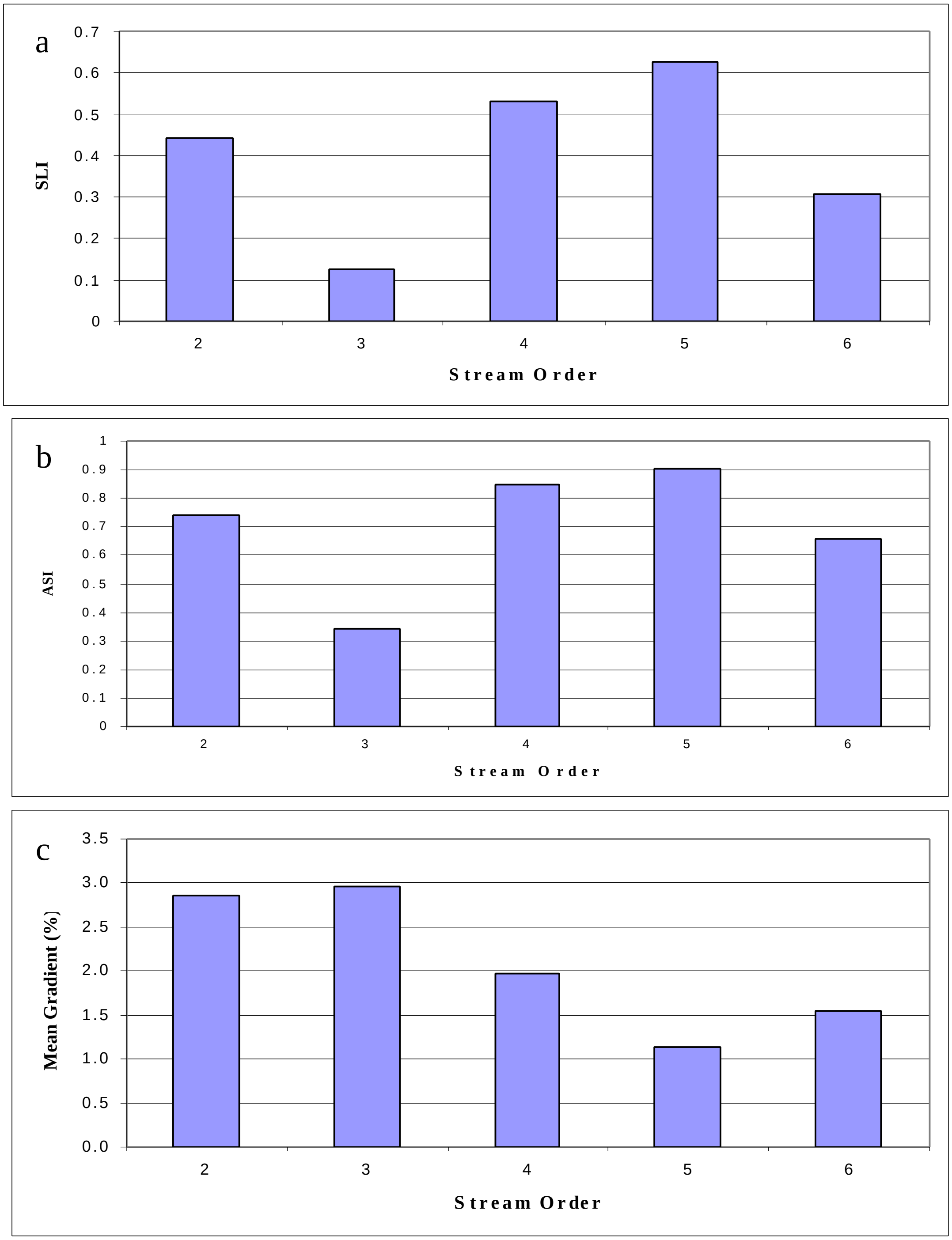


Figure 9 – Mainstem of Sespe Creek, Storage Characteristics. a) Depicts the SLI (Storage Length Index) as it relates to stream order. The SLI is a ratio between the length of predicted sediment storage reaches and total stream length. b) Depicts the ASI as it relates to stream order. The ASI (Areal Storage Index) is a ratio between predicted total areal storage in the stream segment and total storage. c) Depicts derived valley gradient as it relates to stream order.

Table 2 presents results from the analysis of storage in Howard Creek, with total sediment storage of 6.2 km^2 (Figure 10a). Howard Creek is the basin with the most potential total storage followed by Alder (2.6 km^2), Trout (2.3 km^2), Lion (2.3 km^2), Bear (1.8 km^2), Tule (1.8 km^2), Portrero John (0.9 km^2), Ladybug (0.6 km^2), and Cherry (0.4 km^2) (Table 2). Howard Creek is also the only subwatershed within the Sespe where an extensive alluvial basin is present (known as Rose Valley) which has characteristics different from typical valleys in the watershed. Although most valleys in the Sespe Creek watershed have valley widths ranging from 15 to 200 meters, Rose Valley can reach 1 kilometer at its widest section and is approximately 2 kilometers long (*see Figure 4*). Areas downstream of Rose Valley are the most productive sections for rainbow trout in the Sespe watershed (discussed later).

When the total potential storage is divided by subwatershed area to obtain a basin normalized storage value (NBS – Figure 10a), Trout Creek (0.29) becomes the subwatershed with the most storage, followed by Howard Creek (0.18), Bear (0.13), Ladybug (0.11), Tule (0.09), Lion (0.09), Portrero John (0.09), Cherry (0.08), and Alder (0.07). The results for ASI have a similar pattern (Figure 10b). Howard Creek has the highest value (0.91) followed by Tule (0.83), Bear (0.79), Lion (0.72), Cherry (0.71), Ladybug (0.7), Trout Creek (0.68), Portrero John (0.61), and Alder (0.26). Howard Creek again has the highest value for the SLI (0.56), followed by Tule (0.45), Lion (0.32), Trout (0.31), Bear (0.3), Ladybug

(0.3), Cherry (0.23), Portrero John (0.19), and Alder (0.19). The results for ASI and SLI are depicted graphically in **Figure 10b and 10c**. Also shown in Figure 10d is how total storage, NBS, ASI, and SLI relate to drainage basin area. Considering all sediment storage values, the subwatersheds with the highest storage potential are Howard, Tule, and Trout Creeks, the subwatersheds with mixed results are Lion, Bear, and Ladybug Creeks, and the subwatersheds with low storage potential are Cherry, Alder, and Portrero John Creeks (**Table 2, Figure 10**).

The results depicted in **Figure 10** suggest that the three storage indices (NBS, ASI, and SLI) may covary due to the common elements of length and width used to compute the indices. Table 6 shows the correlation r-values and P-values for total storage, NBS, ASI, and SLI for all surveyed subwatersheds, with and without Howard Creek. The correlation was assumed to be significant at a P-value < 0.05. The only two significant results are the correlations between Total Storage and SLI, and ASI and SLI. Excluding Howard Creek in the analysis, the only significant correlation is between ASI and SLI. **Figure 11** shows the graphical relationships for the correlations that are significant.

Sespe Creek and its major subwatersheds show a general trend of increasing valley width and decreasing gradient with distance downstream, but this pattern is interrupted by irregular variations in both of these valley characteristics. **Figure 12** shows the elevation change, valley width, and valley gradient profiles

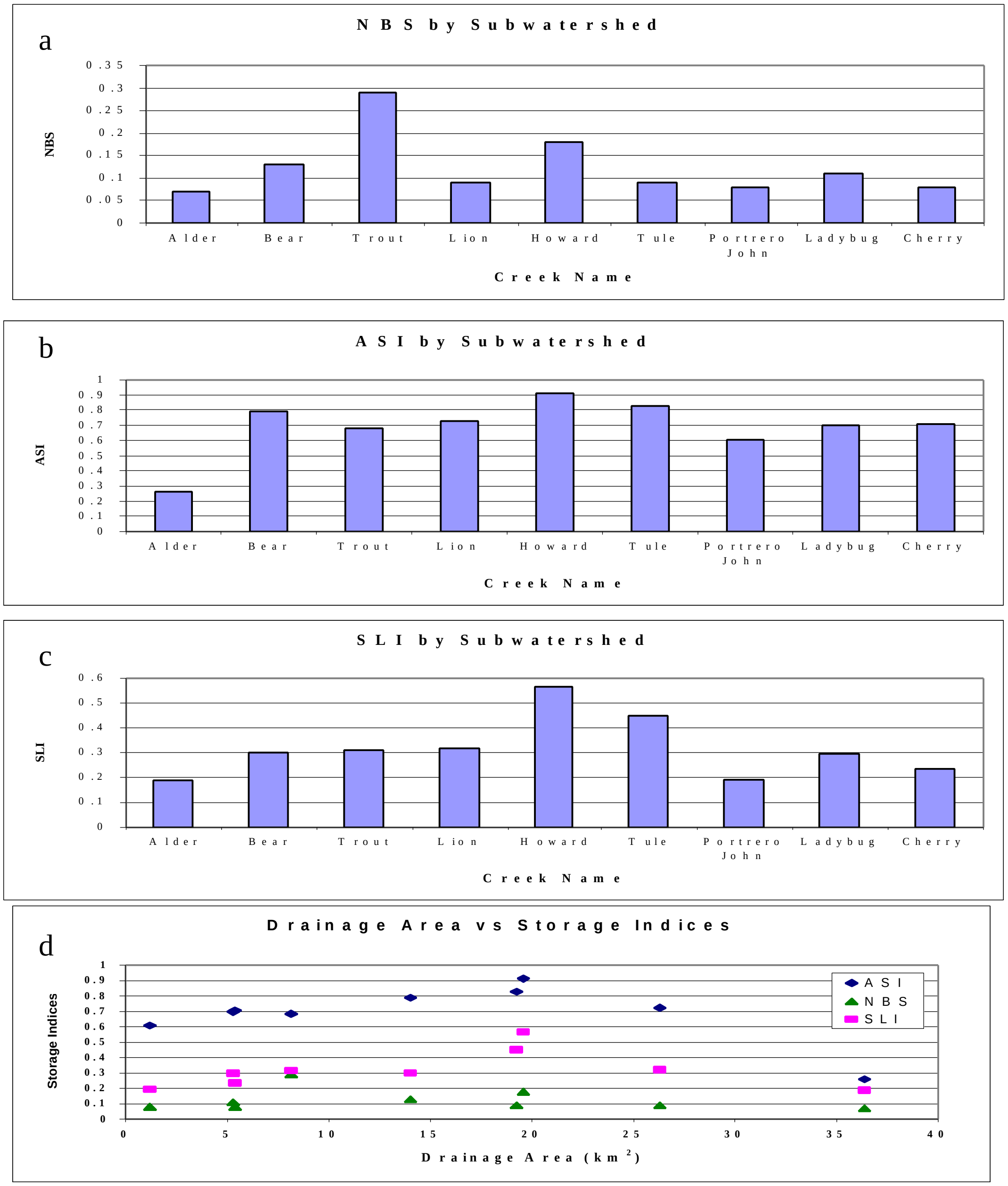


Figure 10: Subwatershed Storage Characteristics. a) NBS (Normalized Basin Storage as it relates to each surveyed subwatershed. b) ASI (Areal Storage Index) as it relates to each surveyed subwatershed. c) SLI (Storage Length Index) as it relates to each surveyed subwatershed. d) Drainage Area versus Storage Indices. The plot suggests that a peak in relative storage potential occurs in medium sized basins.

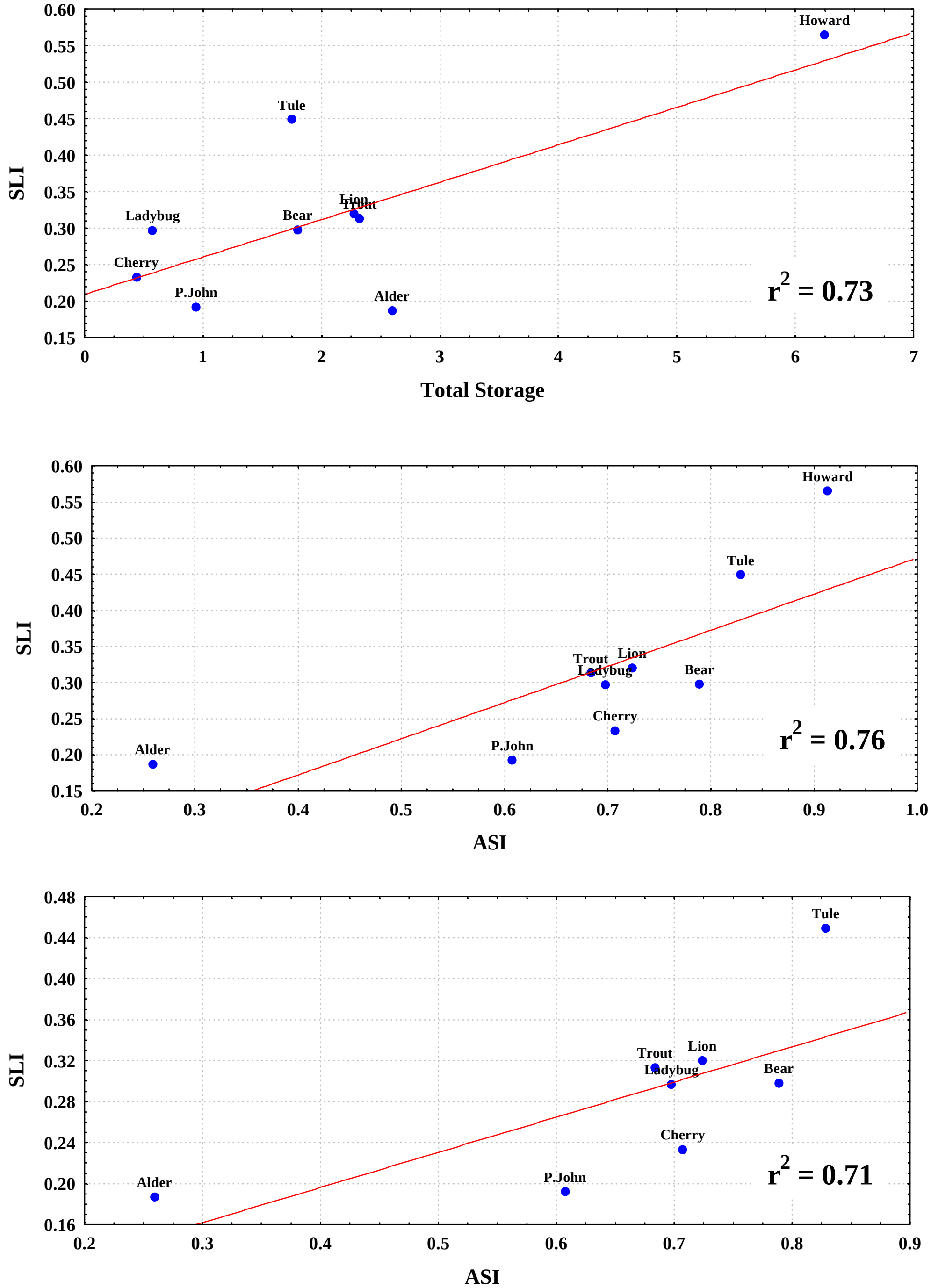


Figure 11. Scatterplots of Storage Indices. Shown are the statistically significant storage relationships at $P < 0.05$ from Table 6. a) Total Storage plotted against SLI for all subwatersheds. b) ASI plotted against SLI for all subwatersheds. c) ASI plotted against SLI with Howard Creek exlcuded.

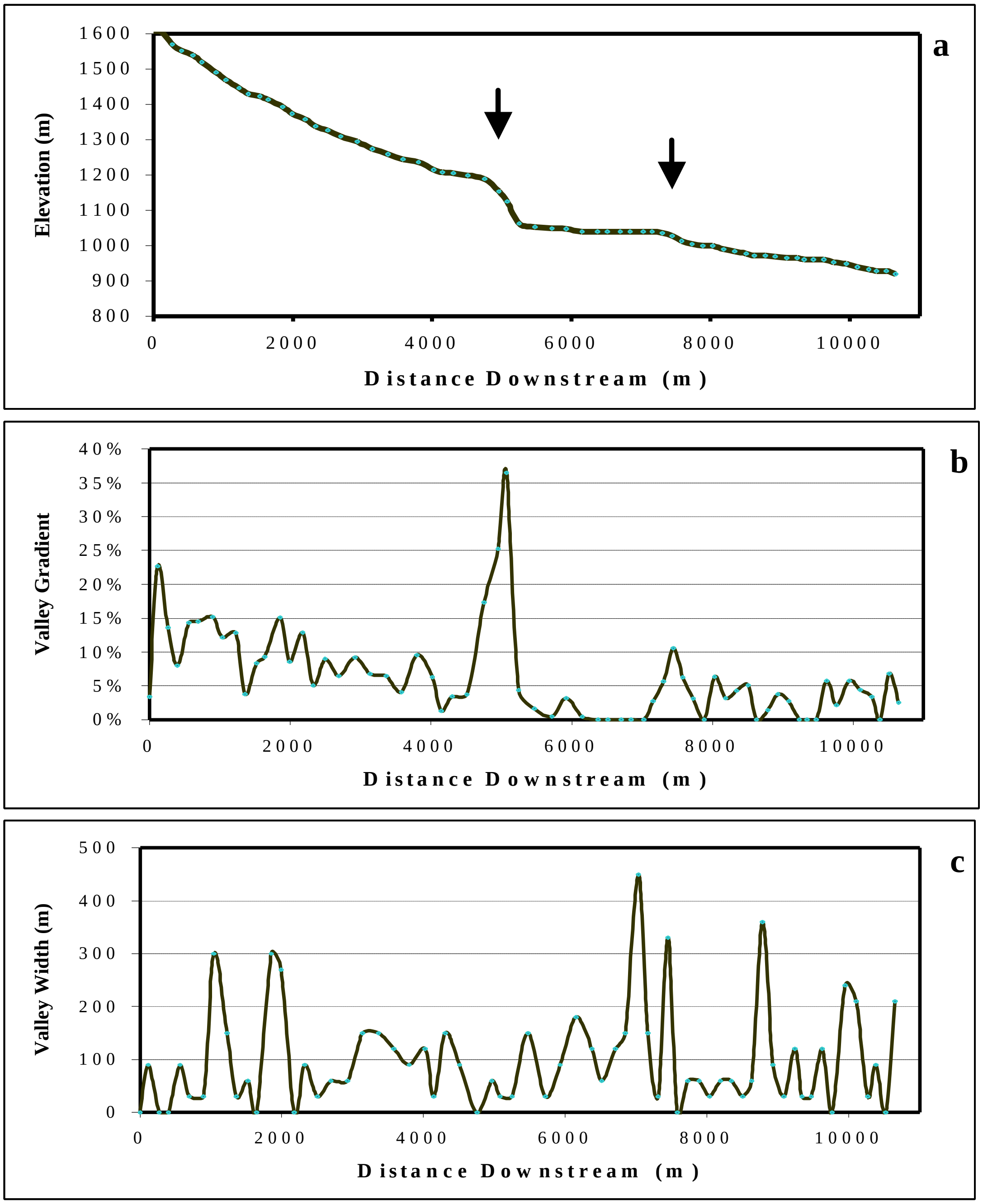


Figure 12. Lion Creek Valley Characteristics a) Longitudinal Profile along the mainstem. Arrows point to reaches described in the text. b) Valley Gradient along the mainstem (derived from the DEM). Valley gradient is described rather than stream gradient due to the resolution of the DEM. c) Valley width along the mainstem (DEM derived).

for the Lion Creek subwatershed from its headwaters to mouth. The results for Lion Creek show a high-gradient reach (**Figure 12b**) in the 4500-5500 meter section (*first arrow on Figure 12a*) followed by a low-gradient reach extending to approximately 7000 meters, followed by another increase in gradient in the next 1-kilometer section (*second arrow on Figure 12a*). The high gradient reach in the 4500-5500 meter section corresponds to a narrow valley area with valley width ranging from 0 to 150 meters (**Figure 12c**). A general widening of the valley occurs downstream in the 5500-7000 meter section with valley width ranging from 30 to 450 meters. The valley then constricts again in the next downstream reach. Repeated variation in valley width and gradient are characteristic of the other eight subwatersheds as well as the mainstem of Sespe Creek.

In order to determine if the relationships seen in **Figure 12** between valley width and gradient have a regular, predictable pattern, spatial autocorrelation analysis was conducted on the surveyed subwatersheds and the mainstem of Sespe Creek. **Figure 13** shows the results of the signal analysis for both valley width and gradient. The results seem to suggest some periodicity on a few subwatersheds. For example, the results for Bear Creek (**Figure 13c**) show alternating positive and negative autocorrelations for successive lags suggesting that wide valley reaches are interspersed with narrow reaches. The valley widths are negatively correlated at a lag of one stream segment (-0.4 ACF). Other subwatersheds such as Alder, Lion, Trout, and Portrero John show similar patterns,

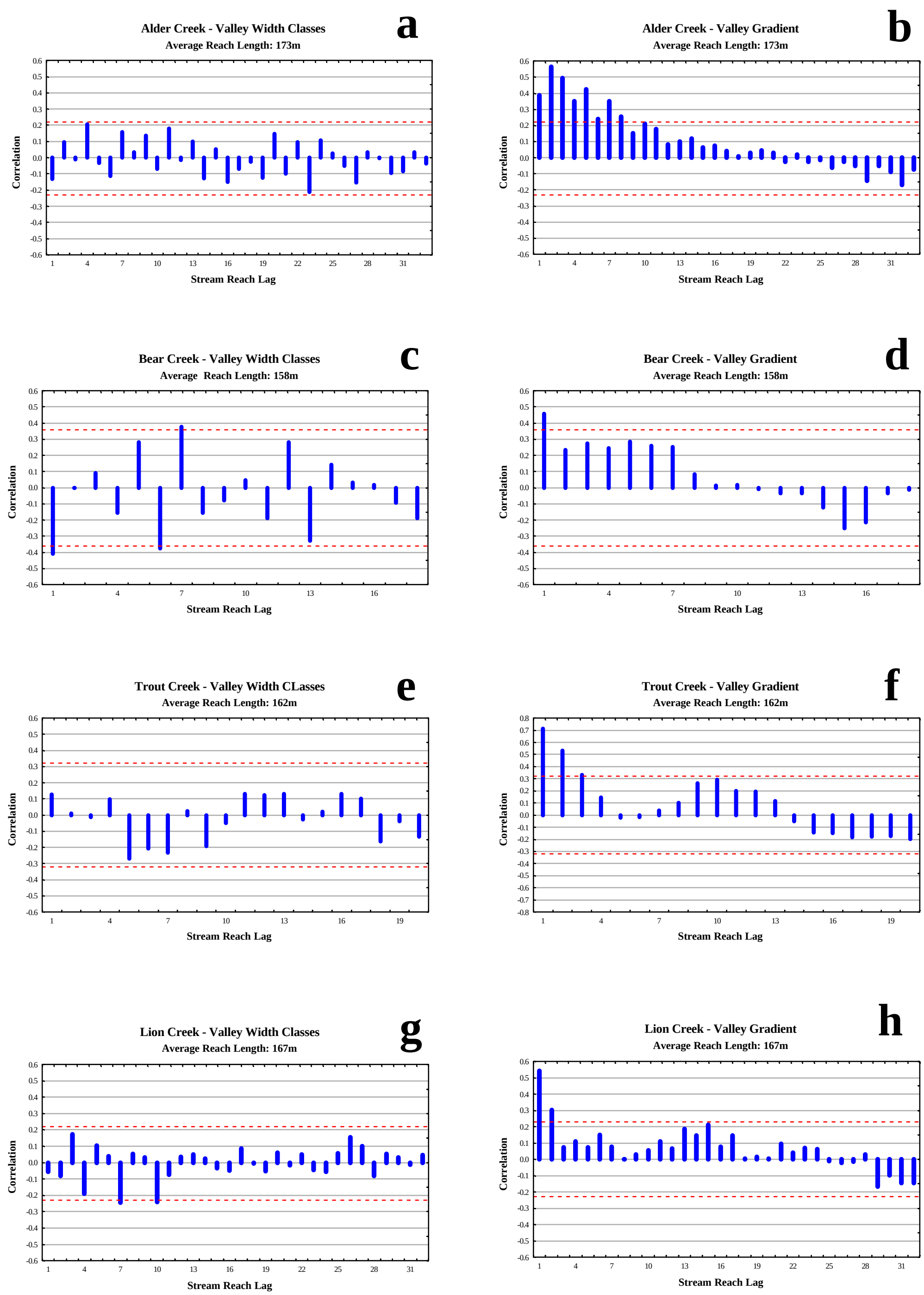


Figure 13 - Spatial Autocorrelation Analysis. The autocorrelations for valley width and gradient for stream reaches of a specified lag are shown. Positive values suggest that stream reaches separated by such a distance (# of lags) are similar in valley width or gradient. The average length of each stream reach is shown for each stream. Horizontal lines represent bounds of statistical significance.

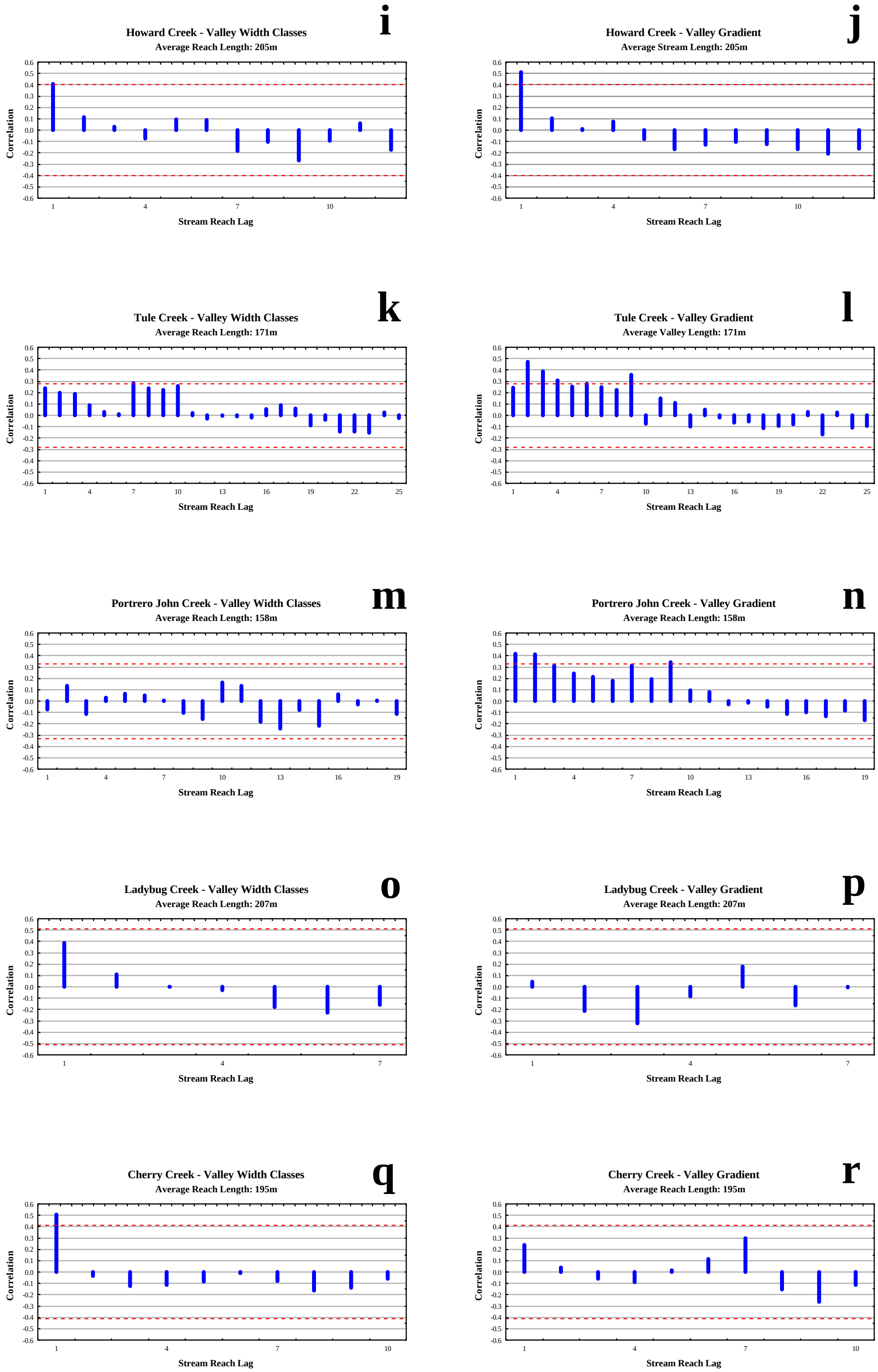


Figure 13 continued.

although in most cases the patterns are not consistent and are usually not significant. The results for the mainstem of Sespe Creek (**Figure 14**) are less variable. Stream segments near each other tend to be positively correlated and zero or negative at longer lags.

The autocorrelation results for valley do show some patterns. Stream reaches close to each other show similar gradient characteristics (positive autocorrelation) whereas stream reaches that are far apart have different gradient characteristics (negative autocorrelation). This is the expected result with decreasing gradient as you go from the headwaters of a given stream to the mouth. On Trout and Lion Creek there is a slight deviation from the expected valley gradient characteristics. Trout Creek (**Figure 13f**) shows positive autocorrelations for gradients at a lag of around 8 to 13 stream segments following no correlation for lags between 4 and 7 stream segments. This suggests a regular pattern on the order of 1.5 to 2 km based on the average length of each stream segment (162 m for Trout Creek).

Relationships between valley width class and valley gradient for the surveyed subwatersheds and the mainstem of Sespe Creek are presented in Figures **15a and 15b**, respectively. Although there is a lot of scatter in the data, the general trend is a decrease in gradient with an increase in valley width. In both figures the median gradient for width class 5 increases, especially in the case of the surveyed subwatersheds.

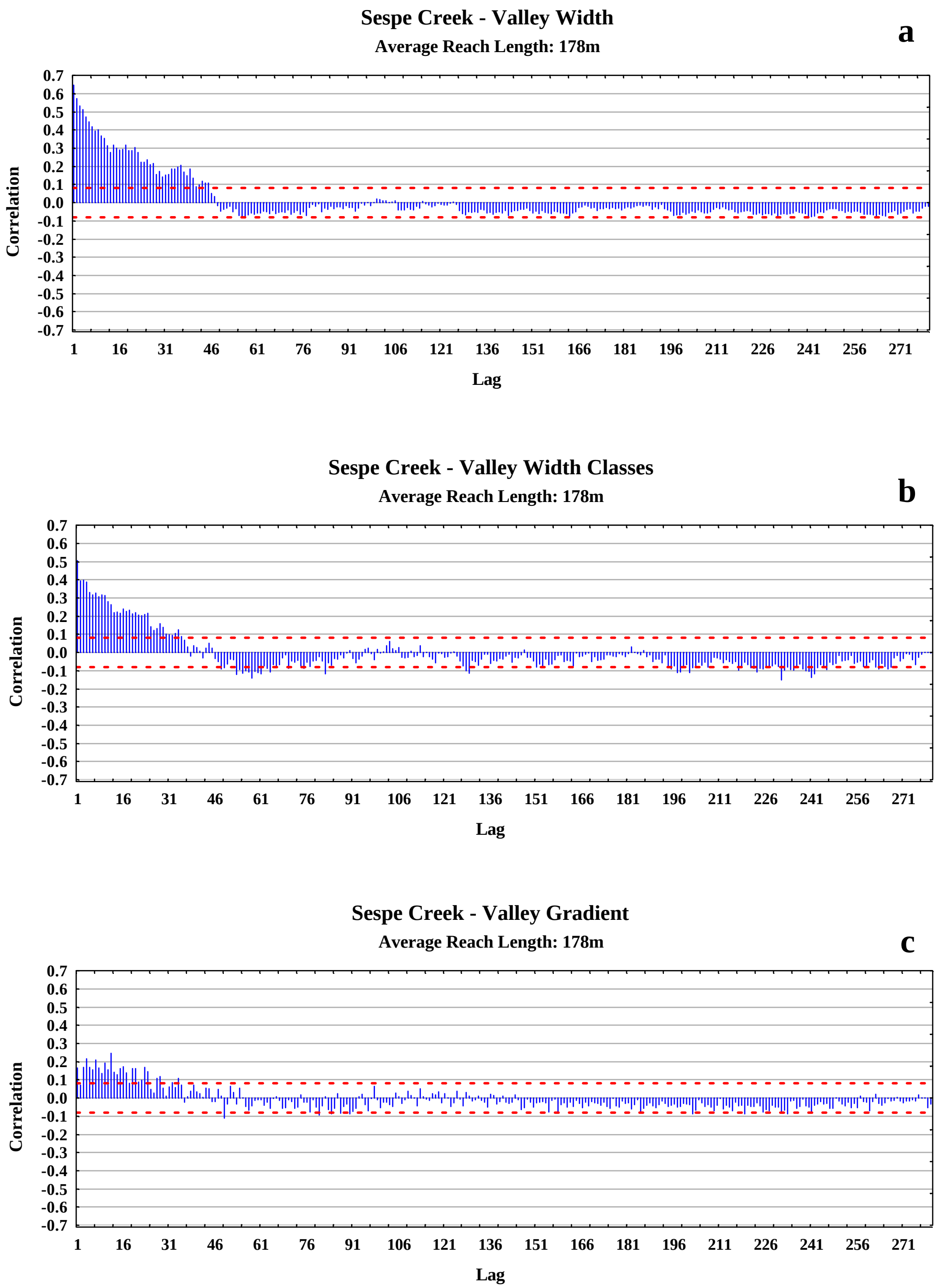


Figure 14. Spatial Autocorrelation Analysis. Autocorrelations for valley width, valley width class, and gradient for stream reaches of a specified lag is shown for the mainstem of Sespe Creek.

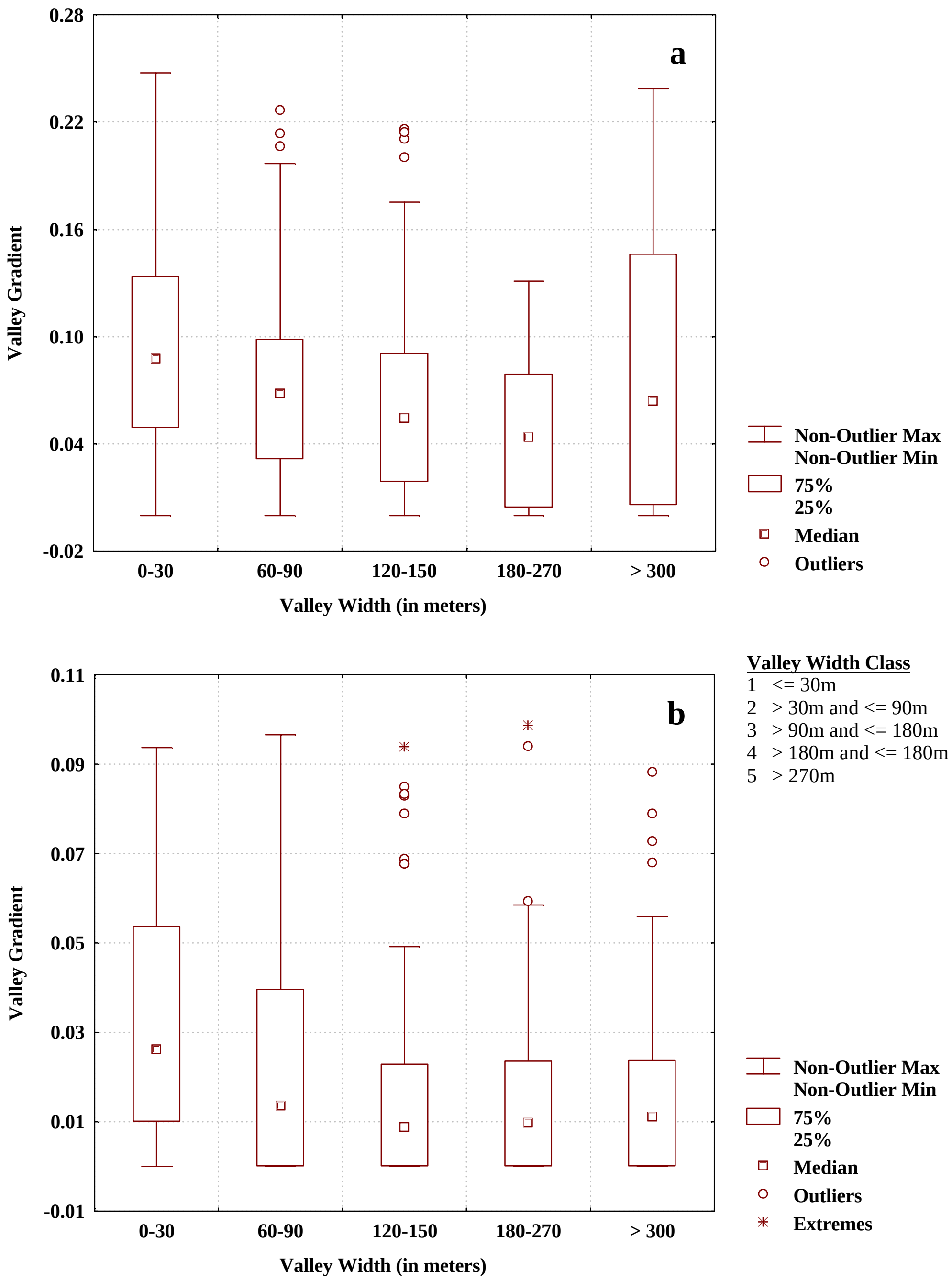


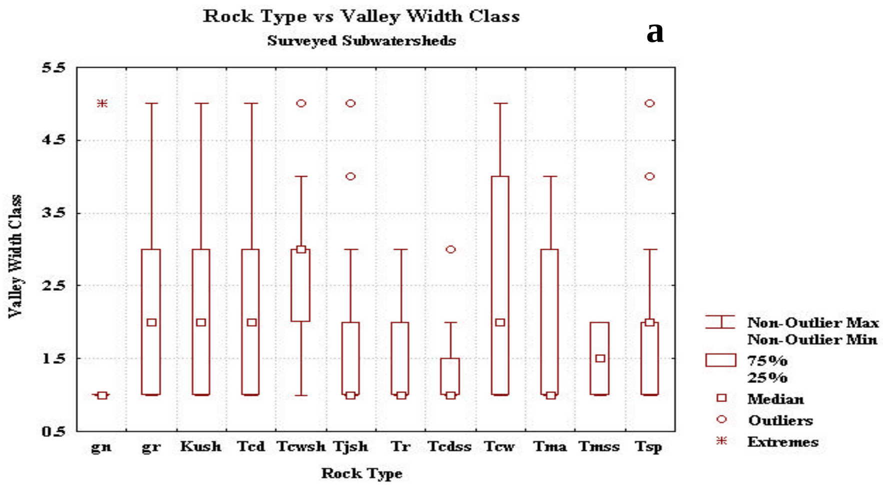
Figure 15: Valley Width versus Gradient. a) Valley width as it relates to gradient for all surveyed subwatersheds. b) Valley width as it relates to gradient for the mainstem of Sespe Creek. In both a and b, there is a general trend of decreasing gradient with an increase in valley width . The exception is class 5 (> 270m) which may be the class with the most inherent error for width from the derivation process.

Results on the relationship between landscape characteristics and geologic rock type are shown in **Figure 16**. Rock types are grouped based on their dominant characteristic such as shale (sh) or sandstone (ss). Because information about the hardness or erodibility of each of the specific rock types is not known, coarse comparisons will be made between rock types based on the assumption that igneous and metamorphic rocks are the hardest and least erodible followed by sandstone then shale.

Generally, **Figure 16a** shows no relationships between individual rock types and valley width class. The results for individual rock types result in a considerable amount of overlap. Considering major rock types, igneous and metamorphic rocks have an average median valley width value of 1.5, sandstone has an average median value of 1.4, and shale has an average median value of 1.8.

Because it cannot be assumed that sandstones from one formation are harder than shales from another formation, comparisons were made between shale and sandstone types within the same rock formation. In the case of the Cozy Dell and Coldwater formations, both shale and sandstone layers are present in the same rock formation. In both rock formations, the median value for valley width is higher for the shale layer (2 and 3 respectively) compared to the sandstone layer (1 and 1 respectively).

Relationships between valley gradient and rock type are shown in **Figure 16b**. For gneiss and granitic rocks, the average median valley gradient value is



Rock Types

gn – Gneiss
gr – Granite
K_{ush} – unnamed(Cretaceous)
T_{cd} – Cozy Dell Shale
T_{cwsh} – Coldwater Shale
T_{jsh} – Juncal Shale
T_r – Rincon Shale
T_{cdss} – Cozy Dell Sandstone
T_{cw} – Coldwater Sandstone
T_{ma} – Matilija Sandstone
T_{mss} – Monterey Sandstone
T_{sp} – Sespe Sandstone

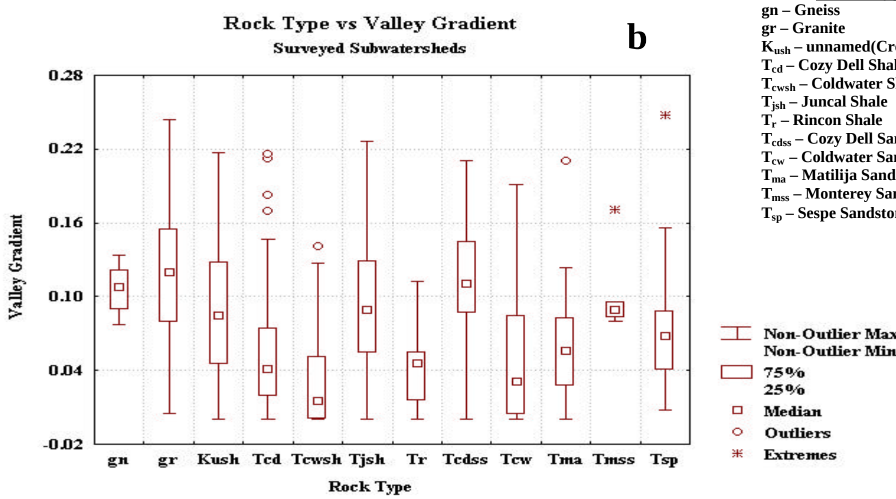


Figure 16 – a) The distribution of valley width classes are plotted for each dominant rock type found in the surveyed subwatersheds of Sespe Creek. Specific values for erodibility and rock hardness for each rock type are not known. b) Valley gradients are versus each dominant rock type found in the surveyed subwatersheds.

0.12, the average median value for sandstone is 0.08, and the average median value for shale is 0.04. Again, a comparison can be made between the different layers of the Cozy Dell and Coldwater Formations to determine if there are distinct differences between shale and sandstone rock types within the same rock formation. In both cases, the sandstone layer (0.12 and 0.03 respectively) has a higher median value for valley gradient than the shale layer (0.04 and 0.01 respectively).

3.2 - Grain-Size Analysis

Geomorphological patterns in the Sespe Creek Watershed are hypothesized to influence the distribution of rainbow trout through their effects on the supply, sorting, and storage of spawning gravels. Grain-size measurements were taken at different points in each subwatershed to examine relationships among spatial position, landform type, and grain size distributions in each subwatershed. **Tables 3 and 4** summarize the results from the grain-size analysis for the nine subwatersheds where fish surveys were conducted.

Coarser sediments dominate in lower subwatersheds (Alder, Bear, Trout, and Lion Creeks) as compared to upper subwatersheds (Portrero John, Ladybug, and Cherry Creeks) (**Figure 17**). The lower subwatersheds have a mean grain size (D50) that ranges from 144 mm to 190 mm, whereas the upper subwatersheds

Creek	D50 (mm)	D84 (mm)	D16 (mm)	% Fines (0-2mm)	% Fine Gravel (2-16mm)	%Coarse Gravel (16-64mm)	% Gravel (2-64mm)	%Cobble (64-256mm)	%Boulder (>256mm)
Alder	145.1	535.4	28.2	8.2	7.4	19.7	27.1	38.9	25.8
Bear	171.5	807.6	27.7	3.8	11.1	24.8	35.9	26.2	34.2
Trout	143.9	656.5	26.0	9.2	4.6	28.9	33.4	28.2	29.1
Lion	190.0	776.1	30.3	5.1	11.1	18.1	29.2	30.3	35.4
Howard	89.3	253.1	10.2	9.8	22.7	28.5	51.2	16.0	23.0
Tule	159.8	417.2	27.4	5.2	9.1	25.5	34.6	37.8	22.4
Portrero John	86.4	422.8	4.1	18.8	8.8	24.6	33.4	31.2	16.6
Ladybug	84.8	389.4	15.7	5.7	18.4	33.6	52.0	22.8	19.5
Cherry	64.6	295.4	9.0	9.6	20.4	28.4	48.8	30.7	11.0

Table 3: Sediment Size Data Averaged for Subwatersheds. Mean sediment size averaged over all transects within each subwatershed expressed as a distribution (D16, D50, D84) and as a percentage. Creek data are sorted by their distance from the mouth of the mainstem of Sespe.

Creek	Transect #	F18-#	D50 (mm)	D84 (mm)	D16 (mm)	% Fines (0-2mm)	% Fine Gravel (2-16mm)	%Coarse Gravel (16-64mm)	% Gravel (2-64mm)	%Cobble (64-256mm)	%Boulder (>256mm
Alder	1030	1	371	1407	56	6	6	7	14	31	49
	1060	2	158	543	26	7	8	17	25	43	25
	2025	3	8	196	1	48	14	10	24	23	5
	2050	4	134	317	32	8	6	24	30	54	8
	2075	5	138	384	19	4	14	22	36	44	16
	3050	6	142	439	57	2	5	27	32	47	20
	4025	7	179	814	45	2	2	28	30	37	31
	4050	8	295	1069	52	1	6	16	22	35	42
	4075	9	543	1231	81	1	4	14	18	23	58
	5015	10	192	505	41	2	6	20	25	48	25
	5040	11	93	239	16	9	10	32	42	44	5
Bear	1020	1	152	627	30	5	7	26	33	34	28
	1050	2	207	914	24	0	16	26	42	24	34
	2025	3	86	569	16	3	19	30	50	23	24
	2050	4	445	1415	83	1	4	13	17	28	54
	3025	5	91	787	24	4	12	35	48	22	27
	3070	6	231	765	19	10	8	19	27	26	38
Trout	1005	1	187	915	28	11	4	23	27	23	39
	1025	2	69	359	8	15	10	34	44	26	15
	1050	3	203	1269	34	4	4	29	33	19	45
	2030	4	142	736	28	10	3	29	31	30	28
	2060	5	222	973	37	7	5	23	28	24	41
	3030	6	196	800	51	5	3	23	26	34	35
	3060	7	79	220	20	13	4	41	45	41	2
Lion	1030	1	344	1107	72	2	4	13	17	34	47
	1060	2	22	497	3	15	37	22	59	8	18
	2010	3	178	493	15	10	12	12	24	41	25
	2040	4	808	2131	137	0	2	6	8	28	64
	2050	5	130	769	14	10	12	21	33	28	29
	2080	6	293	1248	26	2	13	13	26	29	43
	3025	7	361	1260	18	7	11	13	24	20	49
	3060	8	866	2088	227	4	3	2	5	17	74
	3080	9	728	1936	64	2	3	18	21	15	62
	4015	10	170	594	52	1	3	23	25	47	26
	4060	11	118	185	60	1	1	32	33	65	1
	5020	12	107	373	25	4	12	31	42	38	15
	5040	13	31	498	5	12	34	15	49	19	21
Howard	1035	1	226	881	4	15	8	16	24	25	35
	1060	2	529	1365	36	6	8	11	19	20	56
	2030	3	43	109	22	4	13	64	77	19	0
	2070	4	12	31	4	14	62	22	85	0	1
Tule	1010	1-T	56	117	14	6	19	54	73	21	1
	1010	1	101	263	37	3	5	40	45	48	4
	1050	2	192	544	12	11	7	18	25	42	22
	2020	3	125	287	50	3	4	29	33	56	8
	2040	4	194	451	26	7	8	20	28	45	21
	2060	5	445	968	42	2	10	10	20	21	57
	2070	6	326	848	76	4	6	7	13	38	45
	2080	7	112	516	13	6	15	26	41	32	21
Portrero John	1030	1	143	484	24	6	10	23	33	41	20
	1060	2	64	350	2	31	7	19	25	31	13
	2025	3	55	755	2	24	4	37	41	14	22
	2050	4	146	610	7	15	6	17	23	38	24
	2075	5	64	173	3	16	14	34	48	32	4
	3030	6	89	424	2	21	12	19	31	32	17
Ladybug	1030	1	93	346	31	6	5	40	45	35	14
	1060	2	111	905	28	6	7	34	41	25	29
	1095	3	669	2006	11	8	15	9	24	10	58
	2020	4	48	290	15	2	24	42	66	19	13
	2075	5	81	583	19	6	14	35	49	23	22
	3020	6	29	173	9	6	40	27	66	16	12
	3050	7	81	276	13	4	19	32	50	37	9
	3051	8	42	104	12	8	24	50	74	18	0
Cherry	1050	1	32	135	3	18	26	31	57	26	0
	1070	2	74	281	12	8	21	27	48	35	9
	2025	3	160	656	16	12	7	20	28	37	23
	2050	4	68	416	6	14	19	20	39	29	18
	2070	5	50	281	19	3	19	44	63	23	11
	2090	6	57	229	9	3	30	28	58	34	5

Table 4: Sediment Size Data for Individual Transects. Data are presented for all transects within their respective subwatersheds. The first digit in the transect number is the reach number followed by the percent distance along the reach that the transect is located, from downstream to upstream (e.g. 30% for 1030). The column labeled F18-# represents the corresponding numbers for the transects found on Figure 18.

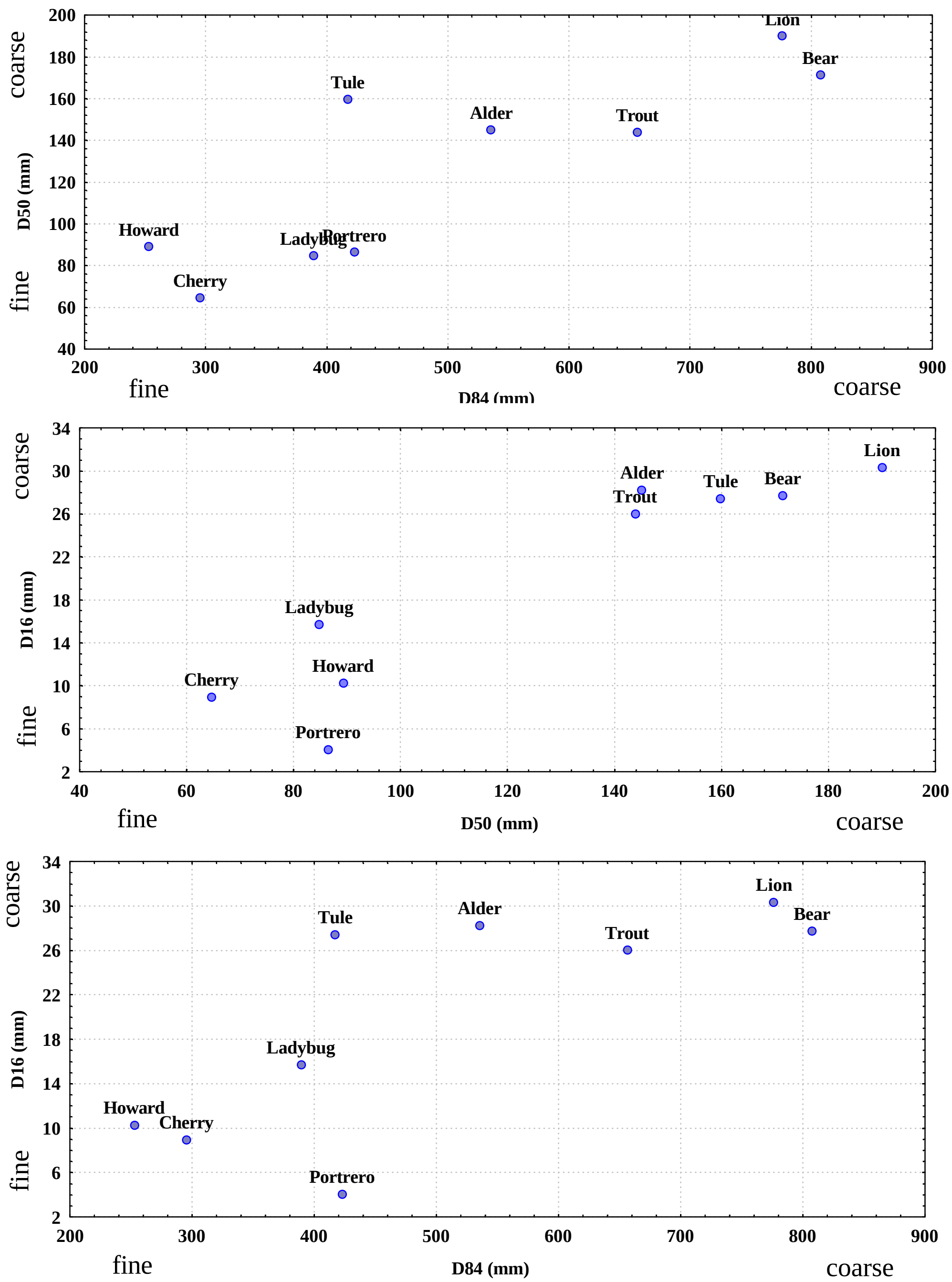


Figure 17 - Grain Size Distributions for Surveyed Subwatersheds. D50 versus D84, D16 versus D50, and D16 versus D84 are presented for each surveyed subwatersheds. D50 equals the mean grain size, whereas D84 (coarse fraction) and D16 (fine fraction) equal two standard deviations from the mean. Right to left on ordinate scale and bottom to top on abscissa scale go from fine to coarse sediments.

range from 65 mm to 86 mm. The values for percent of substrata composed of boulders showed a lower subwatershed range of 26-35 % compared to an upper subwatershed range of 11-20 %. For the percent of substrata composed of fine gravel, the lower subwatersheds ranged from 5-11% and the upper subwatersheds ranged from 9-20 %. Howard Creek had the highest value for fine gravel of 23 % (**Table 3**).

To examine trends within individual subwatersheds, **Table 4** and **Figures 18 and 19** show grain-size data for individual transects. In Howard Creek, large differences in grain-size were observed at sites in Reach 2 compared to sites in Reach 1. Percent gravel ranged from 24% to 18% in Reach 1 (1,2) and from 77% to 84% in Reach 2 (3,4,5). Reach 2 is a wide valley area with considerable storage potential; however, water does not flow year round. Some creeks, such as Alder Creek, showed an oscillation in percent boulder from the downstream to upstream reaches. In Alder Creek, there is a decrease in percent boulders from Reach 1 to 2, followed by an increase from Reach 2 to 4 (7,8,9), and finally a decrease again in Reach 5(10,11).

The variation in sediment characteristics from reach to reach becomes clearer when looking at a subwatershed where at least three reaches were surveyed (Alder and Lion Creeks), as graphically represented in **Figure 18 and 19** (percent of each grain size). An example of this is seen in Lion Creek, which has thirteen

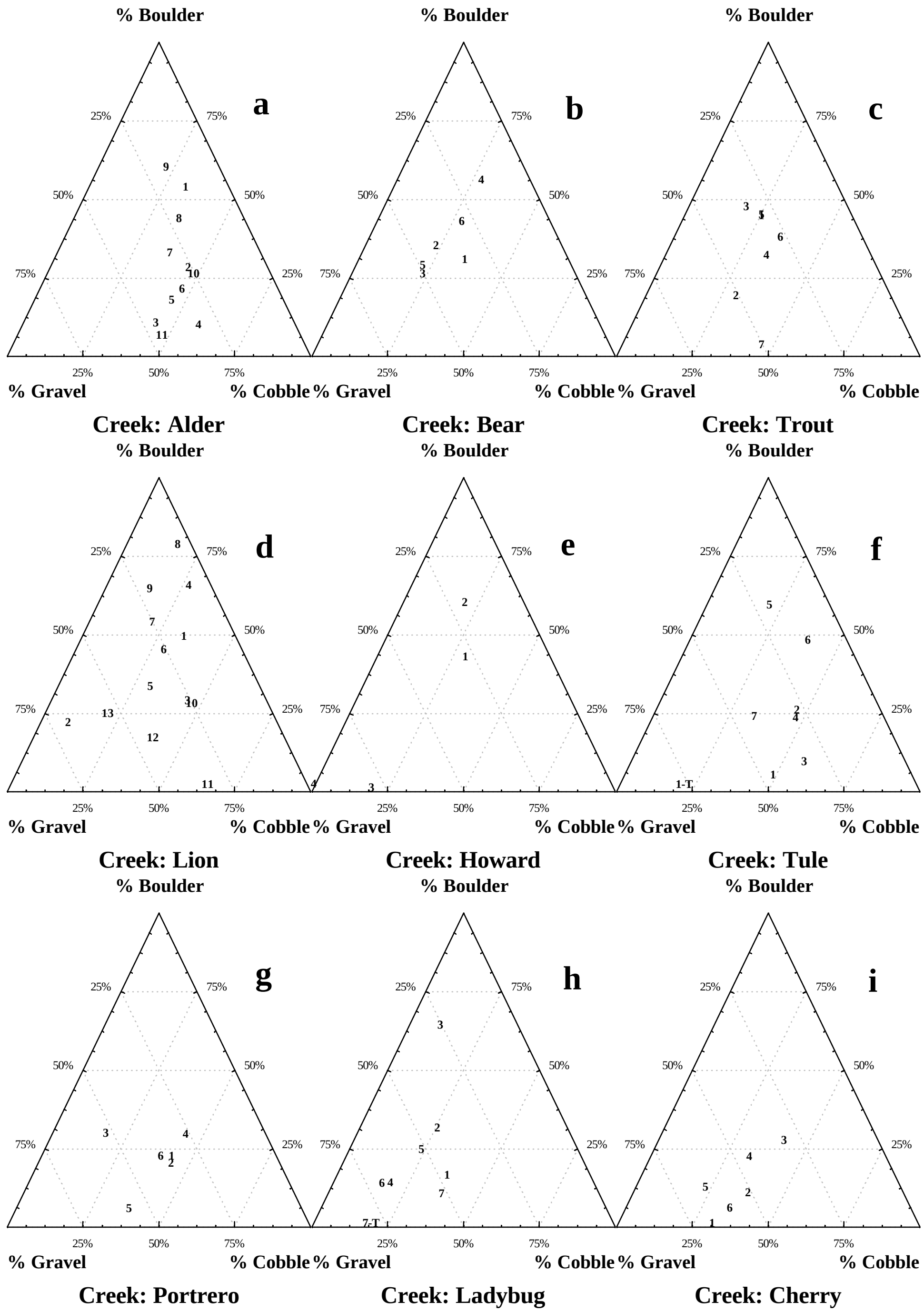


Figure 18 - Ternary Plots. Transects for each surveyed subwatershed are plotted based on their percentages of boulder, cobble, or gravel substrata. The transect numbers are ordered to represent downstream to upstream within the individual subwatersheds, and therefore can be used to trace the change in grain-size distribution along the valley (see Table 4). Transects labeled T represent sites on tributaries adjacent to the reach. The sediment data are standardized to exclude fines.

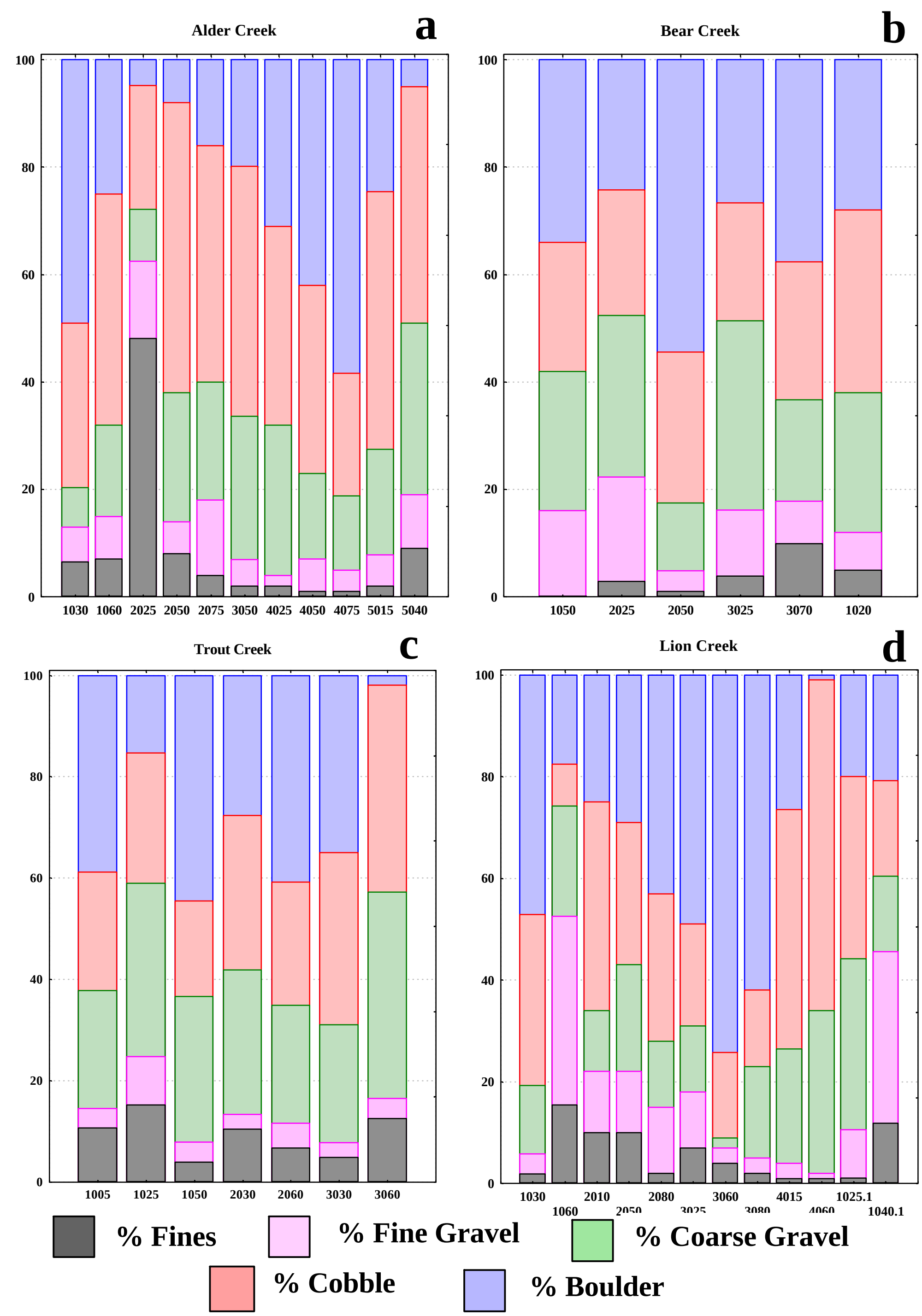


Figure 19 - Sediment Distribution for Surveyed Subwatersheds. Values for percent fines, fine gravel, coarse gravel, cobble, and boulder are presented at transect locations for each surveyed subwatershed. Transect locations are numbered from downstream to upstream, left to right but are not necessarily equally spaced. Creek data are sorted by their distance from the mouth of the mainstem Sespe.

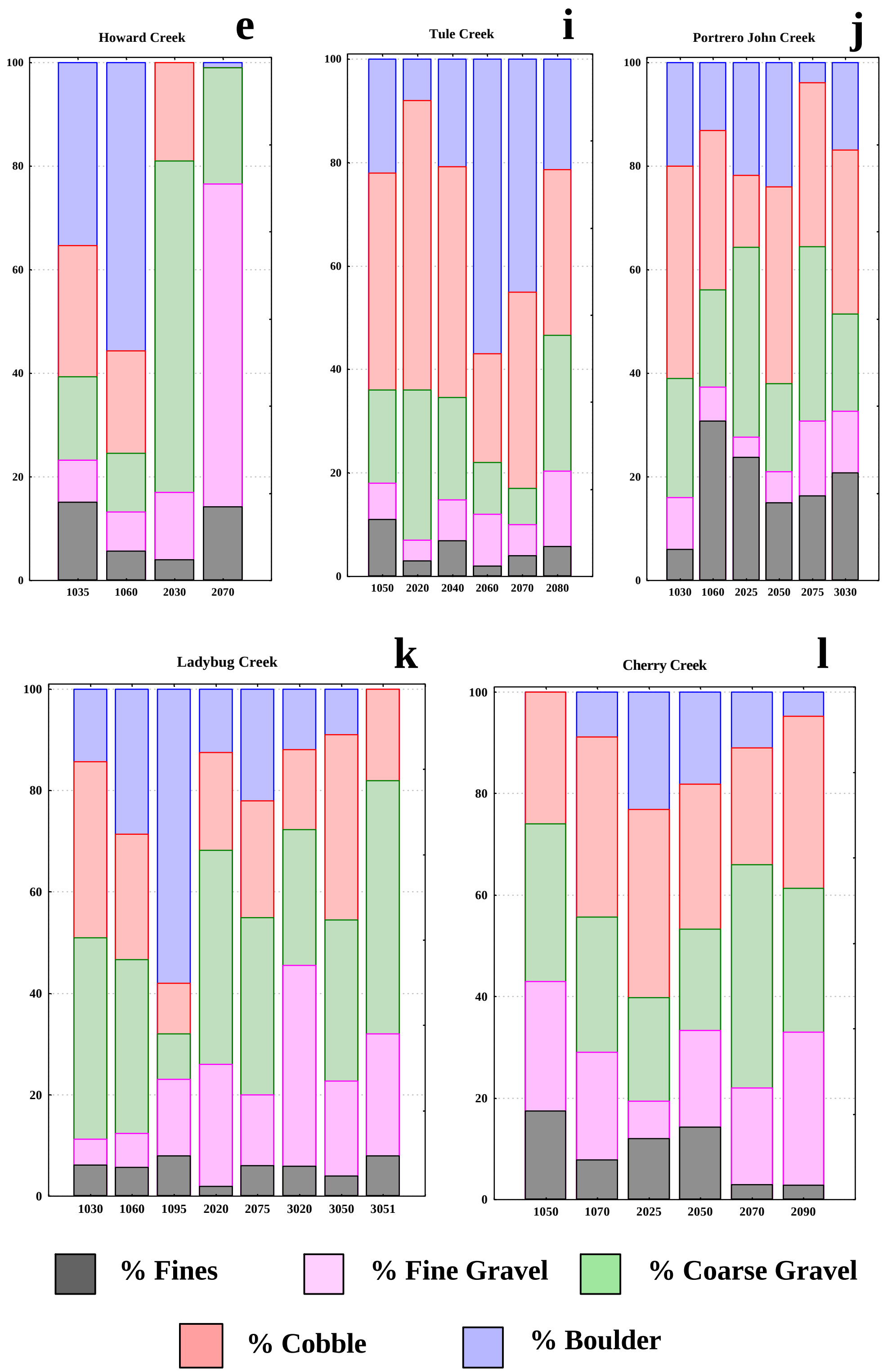


Figure 19 continued.

transects along the mainstem (**Figures 18d and 19d**). The most downstream transect has a percent boulder value of 47% (Transect 1030 – (1)). This value alternates in the upstream direction to 18% at Transect 1060 (2), 64% at Transect 2040 (4), 29% at Transect 2050 (5), 74% at Transect 3060 (8), and 1% at Transect 4060 (11).

There is some evidence for an upstream to downstream pattern of deposition for individual storage sites. Three transects were placed within Reach 2 (3,4,5) of Alder Creek at approximately equally spaced intervals (Figures 17a and 18a). Transect 2075 (5) captures sediment characteristics of the upstream end of the storage site, 2050 (4) the middle, and 2025 (3) the lower end. D50 decreases in size from 138 mm to 8 mm in the downstream direction. D16 decreases in size from 19 mm to 1 mm and D84 decreases in size from 384 mm to 196 mm. When looking at the percentage of sediment within each grain size the results support the same trend (**Figure 19a**). From Transect 2075 to 2025, percent fines increase from 4 to 48%. Percent fine gravel decreases from 14% to 6% then increases to 14%. Coarse gravel decreases from 22% to 10%, percent cobble decreases from 44% to 23%, and percent boulder decreases from 16% to 5%.

3.3 - Fish Population Surveys

Traditionally fish population sizes have been related to such habitat quality factors as pool/riffle ratios, food quantity, and water temperature. In contrast, landscape analyses consider the hydrologic and geomorphic condition of the watershed, the physical processes controlling the habitat conditions and the distribution of biological populations. This study has the advantage of looking at both scales of analyses because the field surveys of rainbow trout populations can be used for both landscape and habitat analyses.

Rainbow trout densities, overall and for different size classes, are presented in **Table 5**. Summaries of trout densities for each habitat type (run, riffle pool) are also shown. **Table 6** summarizes the statistical correlations between rainbow trout densities, habitat characteristics and sediment storage indices. Because Howard Creek was determined to be a significant factor in strengthening many of the statistically significant relationships, the analysis was repeated without Howard Creek with the results reported in **Table 6** in parentheses.

The only habitat characteristic that was found to have a positive correlation with trout densities was pool depth (**Figure 20**), except for density class 3. When Howard Creek is considered to be an outlier and is pulled out of the analysis the positive correlation breaks down. Pool depth also was positively correlated with total storage and SLI (**Figure 21**). The positive relationship still exists when Howard Creek is removed but is not considered to be statistically significant.

Creek	Habitat Type	% Habitat Type	Volumetric Density Class 1 ($fish/m^3$)	Areal Density Class 1 ($fish/m^2$)	Volumetric Density Class 2 ($fish/m^3$)	Areal Density Class 2 ($fish/m^2$)	Volumetric Density Class 3 ($fish/m^3$)	Areal Density Class 3 ($fish/m^2$)	Volumetric Density Class 4 ($fish/m^3$)	Areal Density Class 4 ($fish/m^2$)	Volumetric All Size Classes ($fish/m^3$)	Areal All Size Classes ($fish/m^2$)	Total Storage (km^2)	Mean Pool Width (m)	NBS	ASI	SLI	Mean Pool Depth (m)	Mean Pool Volume (m)
Alder	Run	49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.6	80	0.07	0.26	0.19	0.4	10.0
	Riffle	14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
	Pool	37	0.12	0.03	0.10	0.06	0.13	0.06	0.01	0.01	0.36	0.17							
	All	100	0.04	0.01	0.04	0.02	0.05	0.02	0.00	0.00	0.13	0.06							
Bear	Run	40	0.37	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.40	0.11	1.8	160	0.13	0.79	0.30	0.7	25.8
	Riffle	33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
	Pool	27	0.17	0.07	0.10	0.07	0.02	0.01	0.00	0.00	0.29	0.15							
	All	100	0.19	0.06	0.04	0.02	0.00	0.00	0.00	0.00	0.24	0.08							
Trout	Run	36	0.28	0.08	0.03	0.01	0.00	0.00	0.00	0.00	0.31	0.09	2.3	270	0.29	0.68	0.31	0.5	15.1
	Riffle	36	0.83	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.08							
	Pool	28	0.18	0.10	0.07	0.03	0.05	0.04	0.00	0.00	0.30	0.17							
	All	100	0.45	0.09	0.03	0.01	0.01	0.01	0.00	0.00	0.49	0.11							
Lion	Run	45	0.18	0.06	0.18	0.07	0.03	0.01	0.00	0.00	0.39	0.14	2.3	100	0.09	0.72	0.32	0.5	66.7
	Riffle	16	0.05	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.01							
	Pool	38	0.09	0.03	0.10	0.05	0.03	0.01	0.00	0.00	0.22	0.10							
	All	100	0.12	0.01	0.12	0.05	0.03	0.01	0.00	0.00	0.27	0.11							
Howard	Run	55	3.33	1.54	1.02	0.49	0.10	0.04	0.00	0.00	4.45	2.07	6.2	190	0.18	0.91	0.57	1.2	53.2
	Riffle	19	6.30	2.10	1.15	0.39	0.09	0.03	0.00	0.00	7.54	2.52							
	Pool	26	0.19	0.17	0.78	0.70	0.19	0.17	0.06	0.05	1.22	1.10							
	All	100	3.10	1.30	0.98	0.52	0.12	0.08	0.01	0.01	4.22	1.90							
Tule	Run	31	0.50	0.10	0.33	0.07	0.19	0.03	0.00	0.00	1.02	0.20	1.7	130	0.09	0.83	0.45	0.5	27.0
	Riffle	24	0.00	0.00	0.00	0.00	0.07	0.01	0.00	0.00	0.07	0.01							
	Pool	45	0.20	0.09	0.12	0.06	0.10	0.05	0.02	0.01	0.44	0.21							
	All	100	0.25	0.07	0.16	0.05	0.12	0.04	0.01	0.00	0.53	0.16							
P.John	Run	45	0.25	0.06	0.08	0.02	0.00	0.00	0.00	0.00	0.33	0.08	0.9	100	0.08	0.61	0.19	0.3	8.1
	Riffle	16	0.53	0.09	0.02	0.01	0.00	0.00	0.00	0.00	0.55	0.10							
	Pool	38	0.43	0.13	0.24	0.08	0.12	0.04	0.01	0.00	0.80	0.26							
	All	100	0.36	0.09	0.13	0.04	0.05	0.02	0.00	0.00	0.54	0.15							
Ladybug	Run	48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.6	150	0.11	0.70	0.30	0.4	10.6
	Riffle	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
	Pool	29	0.05	0.02	0.08	0.03	0.01	0.00	0.00	0.00	0.14	0.06							
	All	100	0.01	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.04	0.02							
Cherry	Run	50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.4	90	0.08	0.71	0.23	0.3	4.8
	Riffle	21	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00							
	Pool	29	0.02	0.01	0.06	0.02	0.01	0.00	0.00	0.00	0.10	0.04							
	All	100	0.01	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.01							

Table 5: Fish Densities and Habitat Information. Final results from habitat and snorkel surveys. NBS = Storage divided by total drainage area (km^2/km^2), ASI = Areal Storage Index; SLI = Storage Length Index (refer to methods for explanation). Both volumetric and areal densities are reported while only volumetric densities are presented in the results (though results using areal densities showed the same general trends).

Statistical Correlations

Bold correlations are significant at p < .05

	density - class1	density - class 2	density - class 3	density - class 4	density - all classes	Total Storage	NBS	ASI	SLI
Total Storage	**0.78** (0.50)	**0.79** (0.24)	0.63 (0.44)	**0.70** (0.20)	**0.81** (0.56)	NA	0.40 (0.30)	0.27 (-0.34)	**0.73** (0.17)
P-values	*.01 (.21)*	*.01 (.56)*	*.07 (.28)*	*.04 (.63)*	*.01 (.15)*		*0.29 (0.47)*	*0.48 (0.41)*	*0.03 (0.69)*
NBS	0.53 (0.47)	0.06 (-0.33)	-0.04 (-0.25)	-0.02 (-0.35)	0.44 (0.33)	--	NA	0.31 (0.20)	0.36 (0.21)
P-values	*.14 (.24)*	*.87 (.43)*	*.91 (.56)*	*.98 (.39)*	*.24 (.43)*			*0.42 (0.64)*	*0.34 (0.62)*
ASI	0.45 (0.22)	0.48 (0.21)	0.09 (-0.19)	0.22 (-0.16))	0.41 (0.15)	--	--	NA	**0.76 (0.71)**
P-values	*0.22 (.60)*	*0.19 (.61)*	*.83 (.61)*	*.56 (.71)*	*.27 (.73)*				*0.02 (0.05)*
SLI	**0.67** (0.31)	**0.76** (0.37)	0.55 (0.29)	**0.69** (0.32)	**0.70** (0.34)	--	--	--	NA
P-values	*.05 (.46)*	*.02 (.37)*	*.12 (.49)*	*.04 (.44)*	*.04 (.41)*				
Percent Run	-0.24 (-0.80)	-0.10 (-0.67)	-0.17 (-0.61)	--	-0.27 (-0.79)	0.34 (-0.36)	-0.24 (-0.50)	-0.17 (-0.54)	-0.04 (-0.81)
P-values	*.54 (.02)*	*.80 (.07)*	*.67 (.11)*	--	*.49 (.02)*	*.38 (.38)*	*.53 (.21)*	*.66 (.16)*	*.92 (.02)*
Percent Riffle	0.01 (0.16)	-0.23 (-0.35)	-0.06 (0.07)	--	0.03 (0.18)	-0.11 (0.05)	**0.70 (.79)**	0.43 (0.56)	0.17 (0.45)
P-values	*.99 (.71)*	*.56 (.40)*	*.88 (.88)*	--	*.95 (.66)*	*.77 (.91)*	*.04 (.02)*	*.35 (.15)*	*.66 (.27)*
Percent Pool	0.30 (0.42)	-0.11 (0.59)	0.38 **(0.74)**	0.16 **(0.83)**	0.15 (0.59)	-0.26 (0.27)	-0.55 (-0.49)	-0.28 (-0.11)	-0.15 (0.29)
P-values	*.44 (.30)*	*.78 (.12)*	*.32 (.04)*	*.69 (.01)*	*.70 (.13)*	*.49 (.52)*	*.12 (.22)*	*.47 (.80)*	*.70 (.49)*
Pool Depth	**0.74** (0.38)	**0.78** (0.14)	0.48 (-0.01)	**0.67** (0.02)	**0.75** (0.33)	**0.90** (0.44)	0.35 (.20)	0.56 (0.44)	**0.85** (0.58)
P-values	*.02 (.36)*	*.01 (.73)*	*.19 (.98)*	*.05 (.96)*	*.02 (.42)*	*.00 (.28)*	*.36 (.64)*	*.11 (.28)*	*.00 (.13)*
Pool Volume	0.50 (0.26)	**0.67** (0.54)	0.40 (0.20)	0.29 (-0.10)	0.55 (0.33)	0.63 (0.47)	0.07 (-0.09)	0.48 (0.33)	0.64 (.46)
P-values	*.17 (.53)*	*.05 (.17)*	*.28 (.64)*	*.44 (.82)*	*.12 (.43)*	*.07 (.24)*	*.85 (.83)*	*.19 (.42)*	*.07 (.25)*

Table 6: Statistical Relationships between Rainbow Trout Densities and Landscape/Habitat Characteristics. Correlations between rainbow trout density classes, sediment storage indices, and trout habitat characteristics along with the corresponding P-values (in italics) are shown. Relationships significant at P< 0.05 are shown in bold. The values in parenthese represent correlation values when Howard Creek was not included in the analyses.

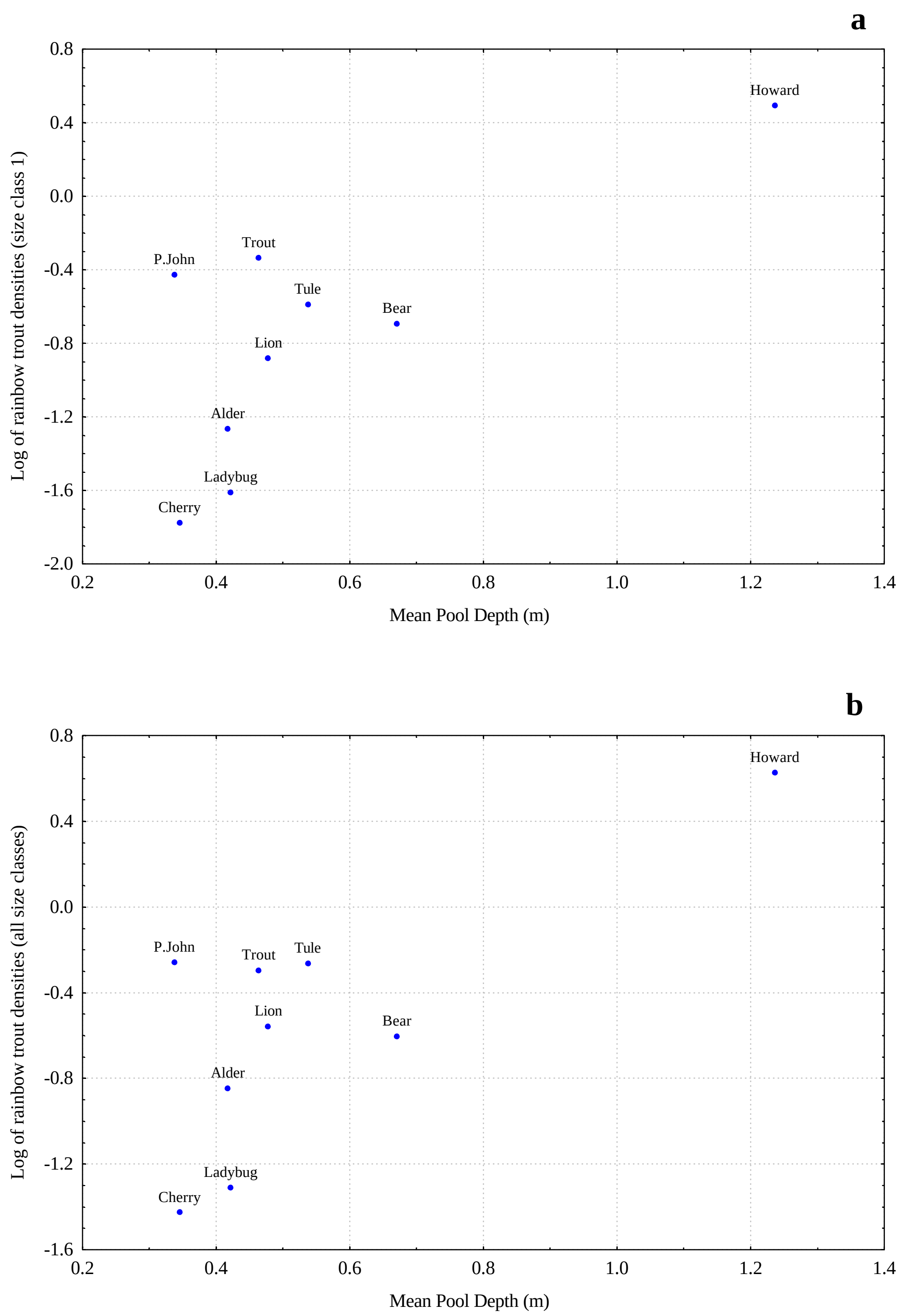


Figure 20 - a) Log of rainbow trout densties for size class 1 and b) all size classes versus mean pool depth (in meters). Refer to Table 6 for correlation values.

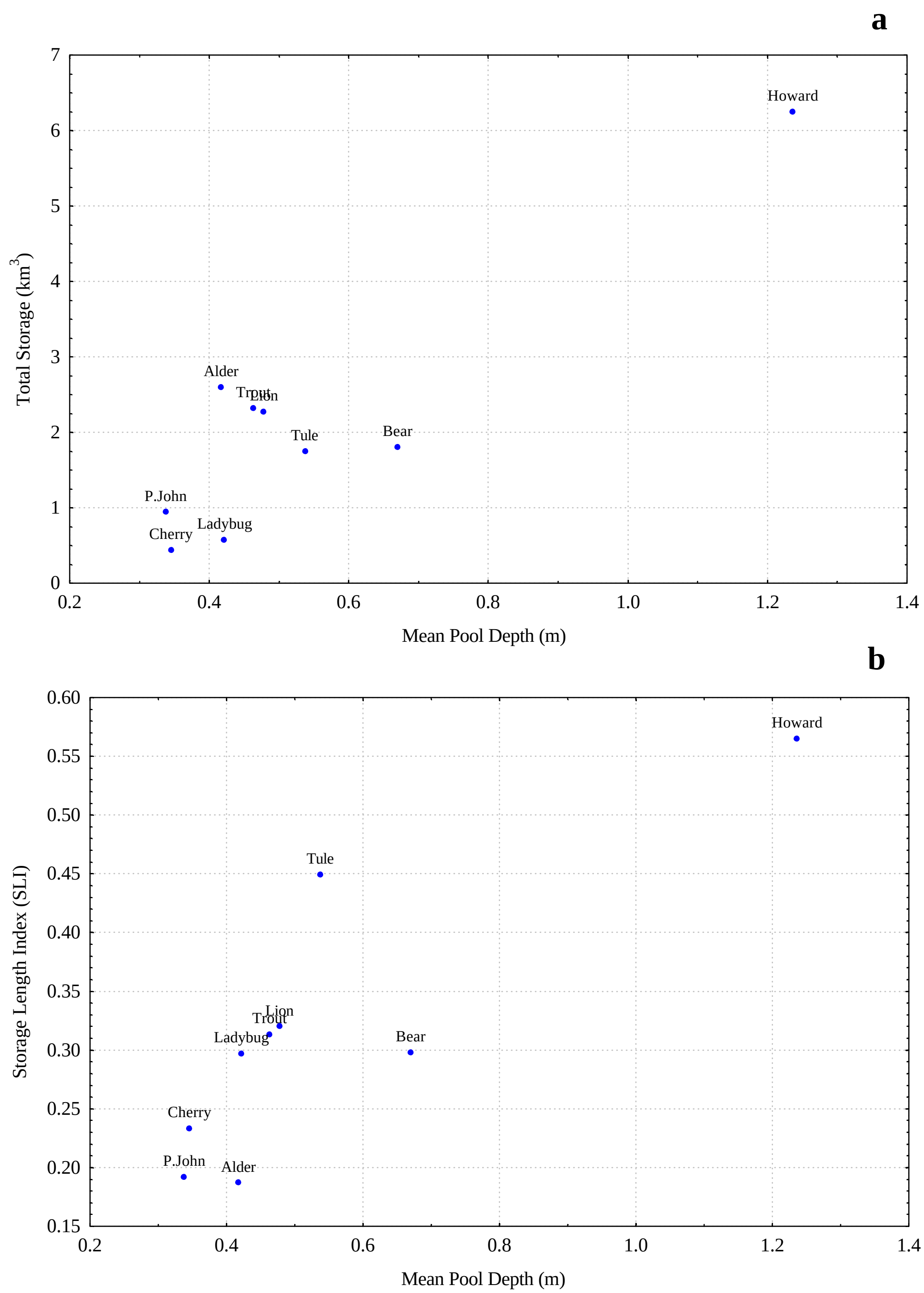
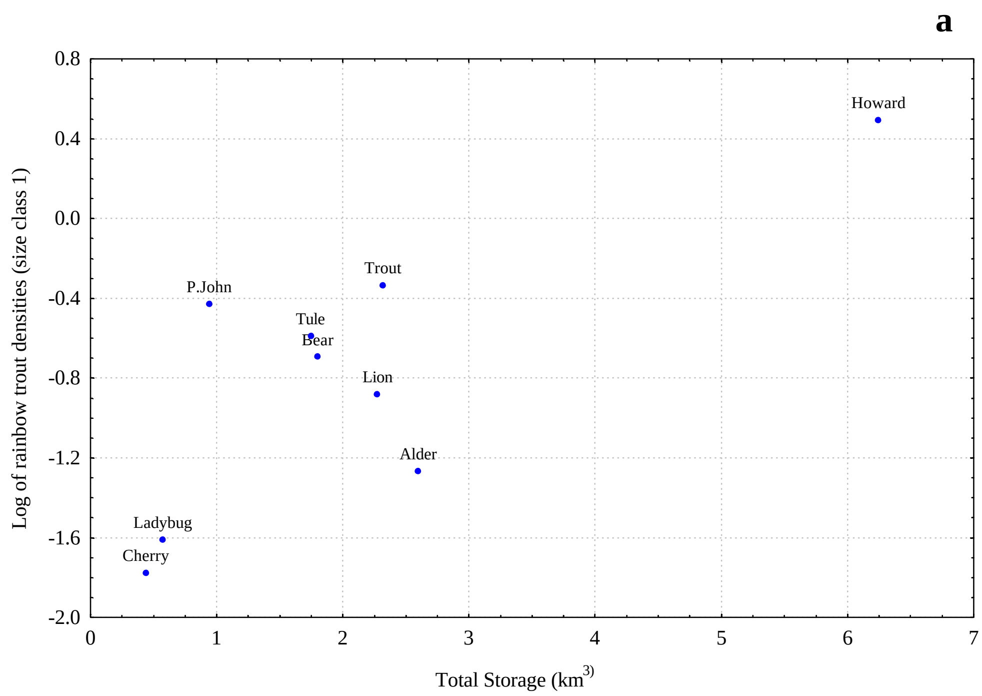


Figure 21 - a) Mean pool depth (in meters) versus total subwatershed storage (in km3) and b) the Storage Length Index (SLI). Refer to Table 6 for correlation values.

Total storage and SLI also have a high positive correlation to trout densities (**Figures 22 and 23**). Density class 3 does not show a statistically significant correlation although there is evidence a relationship does exist. When Howard Creek is removed from the analysis, the relationships weaken and are not statistically significant.

Assessing statistical relationships between habitat variables, landscape characteristics and trout densities provides important information about possible controlling variables on rainbow trout density but provide very little information about the spatial context of the information at the watershed scale. **Figure 24** expresses qualitatively the relationship between spatial position of the nine surveyed subwatersheds and important habitat characteristics such as pool depth and pool volume. In both cases, a general relationship can be seen where the subwatersheds that flow into the middle reaches of the mainstem of Sespe Creek generally have deeper pools of higher volume.

These results can be compared to **Figure 10**, which shows qualitative spatial relationships between creek position and potential sediment storage and **Figure 25**, which shows qualitative spatial relationships between creek position and rainbow trout densities. In all cases tributaries that flow into the middle reaches of Sespe Creek show a trend of high storage potential, good habitat indicators and high rainbow trout densities in all size classes. Conversely, the



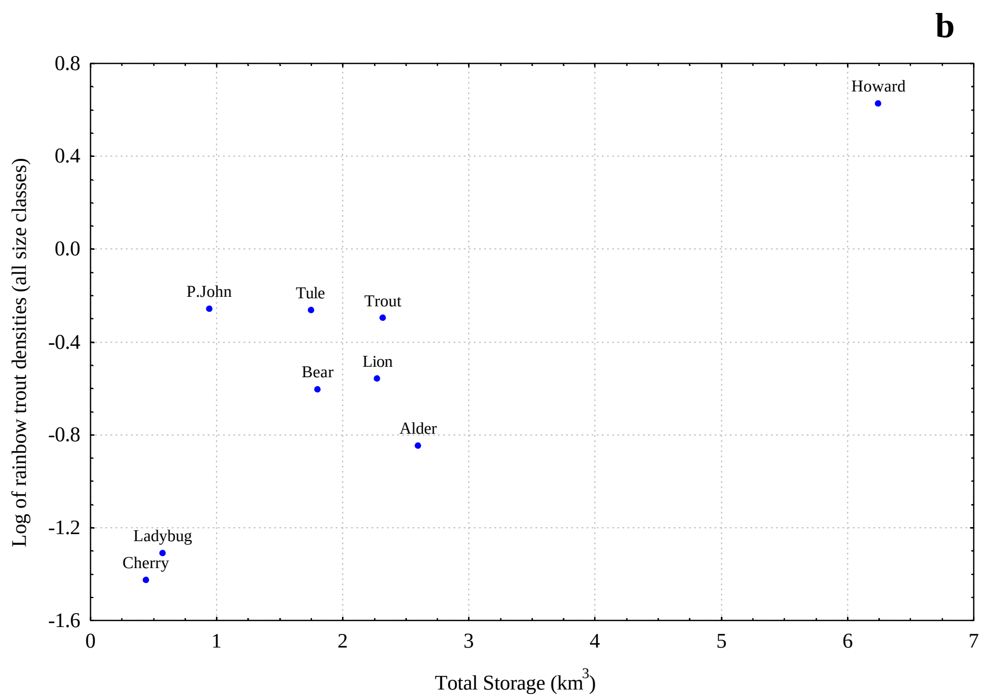


Figure 22 - a) Log of rainbow trout densities for size class 1 and b) for all size classes versus total subwatershed storage. Correlation values for each graph are presented in Table 6. In both cases, Howard Creek is supporting the high positive correlations.

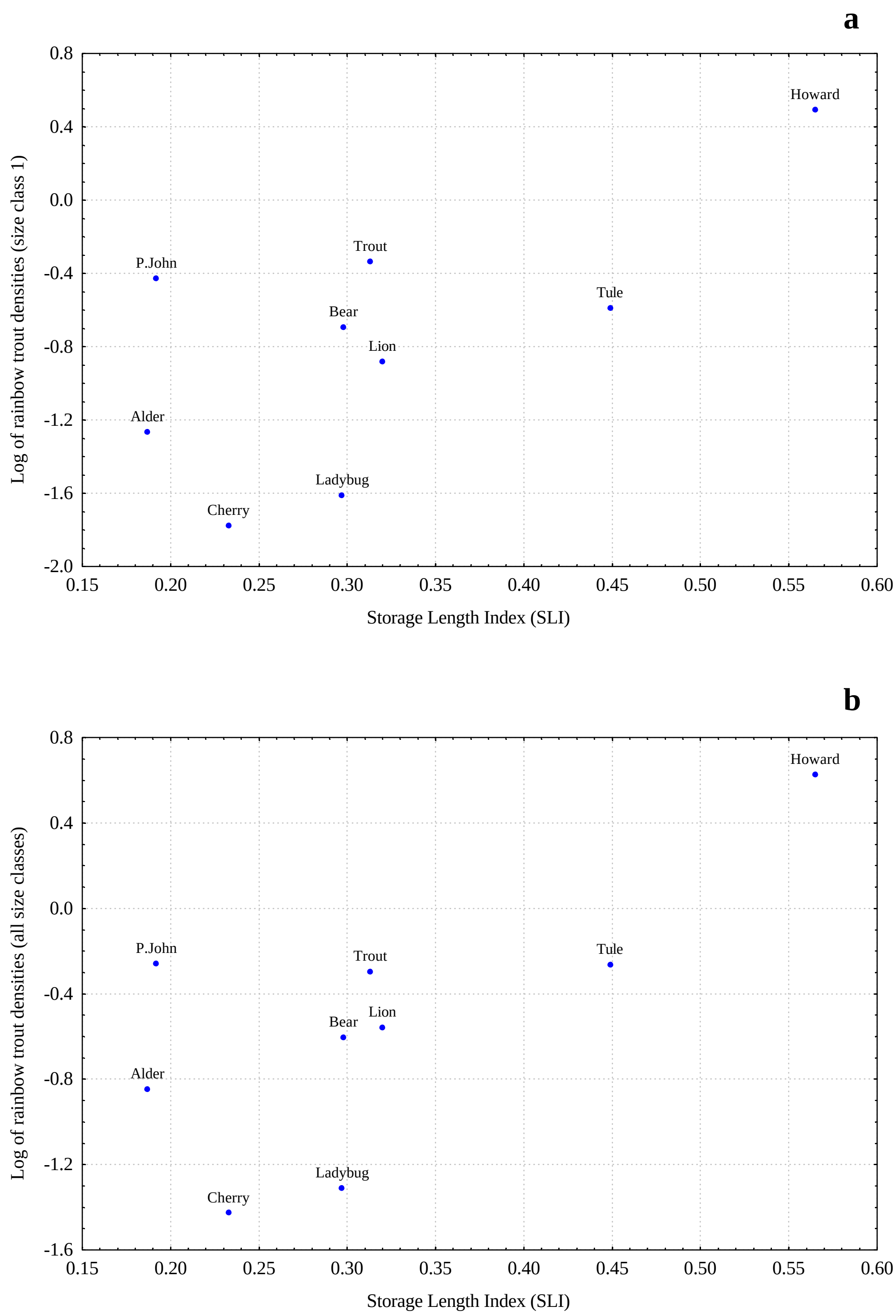


Figure 23 - a) Log of rainbow trout densities for size class 1 and b) all size classes versus the Storage Length Index (SLI). Refer to Table 6 for correlation values.

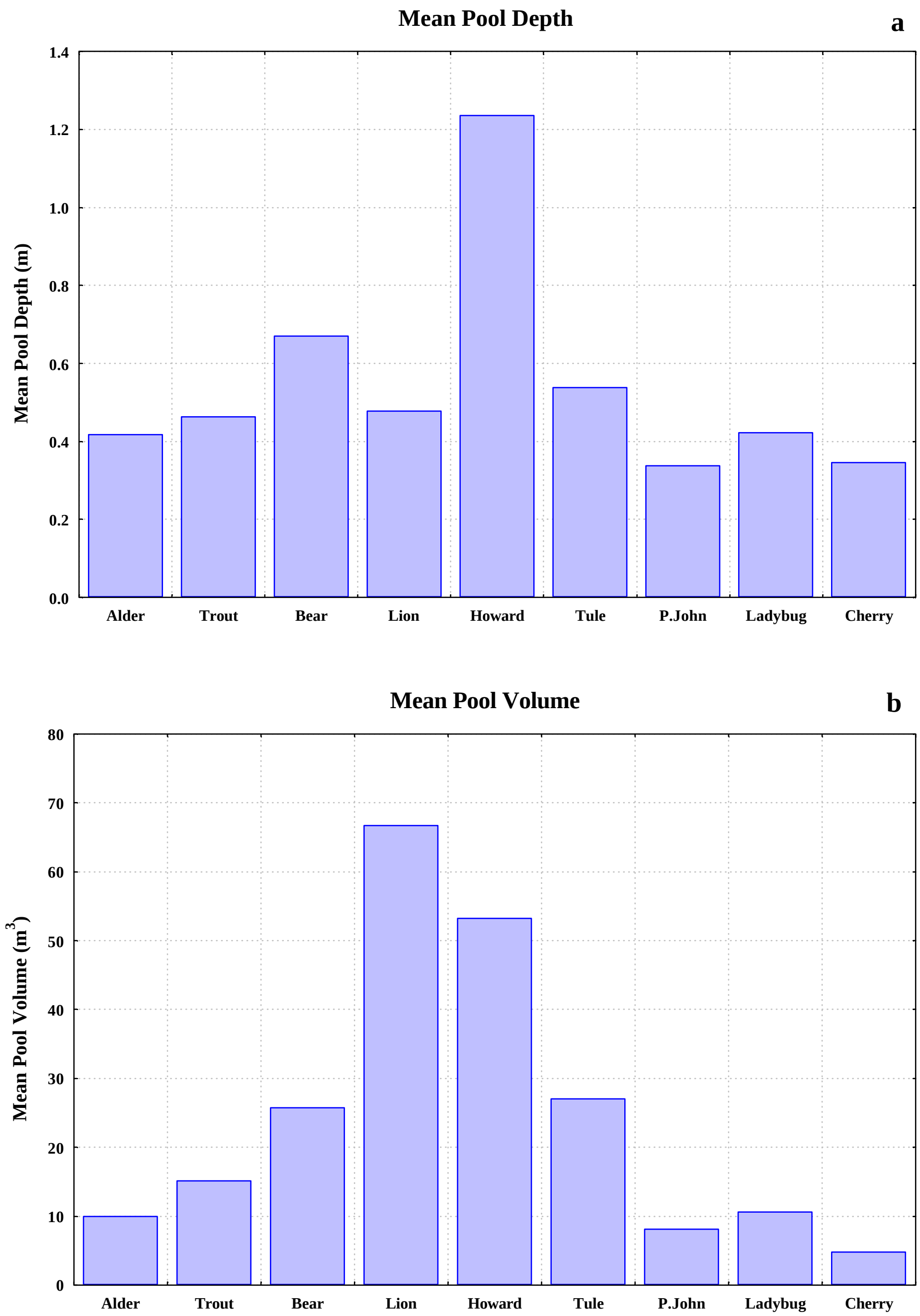


Figure 24 - a) Mean pool depth (m) and b) mean pool volume (m^3) for each surveyed subwatershed. Subwatershed data are sorted by their distance along the mainstem of Sespe Creek.

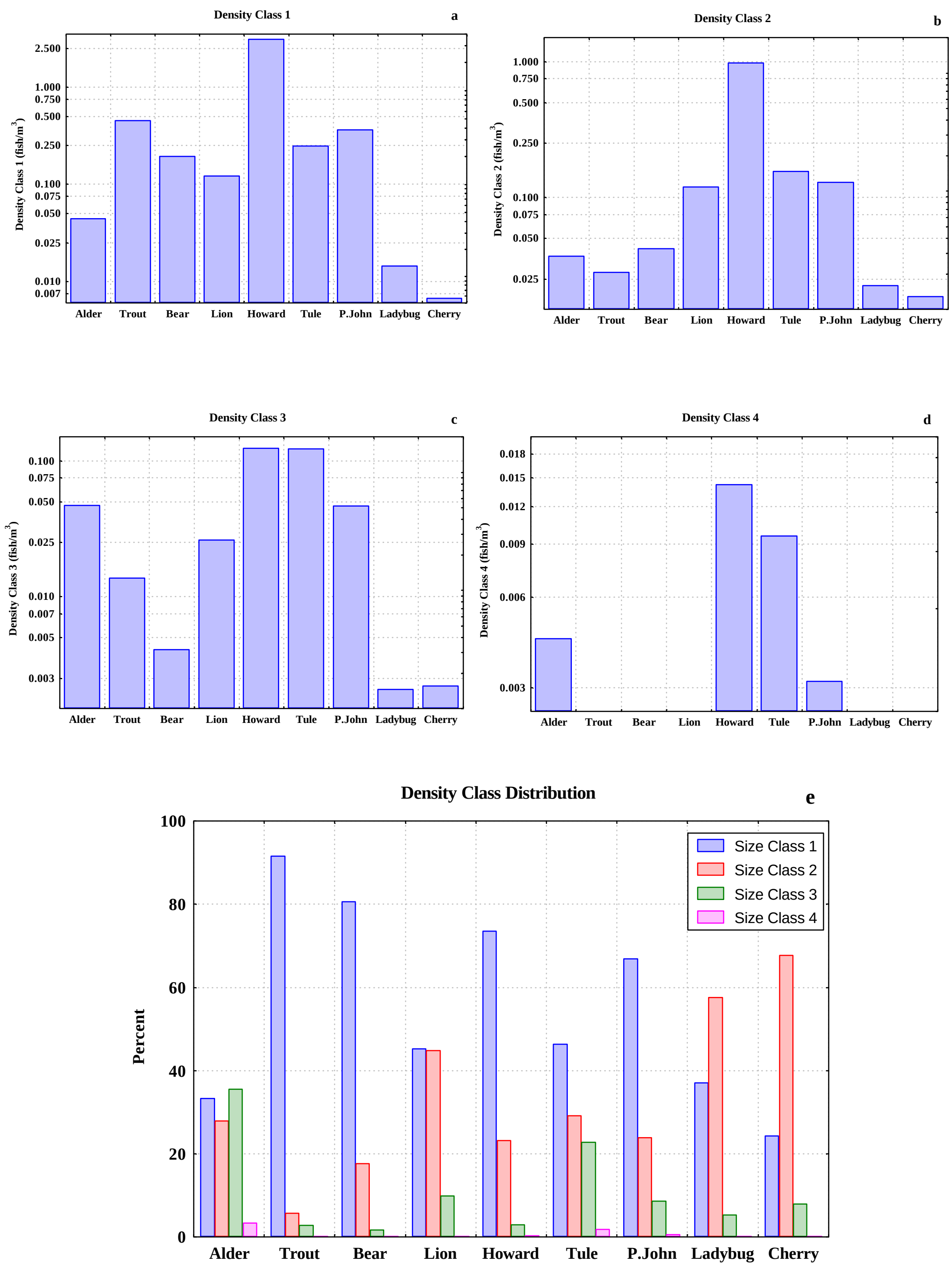


Figure 25 - a-d) average rainbow trout densities (log scale) for each size class for the nine surveyed subwatersheds. e) the percent of rainbow trout in each size class for each surveyed subwatershed.

lower and upper tributaries show low storage potential, poor habitat indicators and low rainbow trout densities.

4.0 - Discussion and Conclusion

4.1 - Geomorphic Control and Sediment Distribution

The dominant geomorphic pattern seen in Sespe Creek and its tributaries is periodic alternations in both valley width and gradient (**Figure 12**). This research used a variety of techniques to determine the variables that dictate these geomorphic patterns, how those patterns influence the sorting and storage of the supplied sediment, and whether or not the sediment patterns influence rainbow trout density by controlling the availability of gravel to the stream channel.

The results from the storage model (**Figure 8**) contrast considerably with the expectation that sediment storage would gradually increase downstream in a watershed with concurrent decreases in gradient (Schumm, 1977). Yet, the geomorphic pattern of alternations in both valley width and gradient found in mountainous stream systems within the Western Transverse Ranges (**Figure 12**), results in a stair-stepped pattern where sediment is stored in wide, low-gradient areas and bedrock dominates in narrow, high-gradient areas. The result is an irregular pattern of channel gradient and valley width along the network.

Many studies have investigated these types of patterns in bedrock rivers and rivers with thin alluvial layers which are controlled by bedrock near the surface (Wohl, 1992; Wohl and Baker, 1994; Grant and Swanson, 1995). There are three potential causes for the valley patterns seen in the Sespe study reaches: 1) Changes in rock hardness as the stream passes from one rock unit to the next can result in high erosion rates in the softer lithologic units and bedrock highs (or constrictions) in the harder lithologic units (**Figure 16**). This differential erosion would then result in low-gradient, wide valleys which store sediment; 2) Fault planes could be offsetting stream channels causing depositional basins to form as the stream flows parallel to the fault line; and 3) Alternating patterns of valley width and gradient are reach-scale examples of pool-riffle sequences seen in many streams and are caused by the conservation of energy and minimization of unit stream power along their entire lengths (Wohl, 1992).

Both qualitative and quantitaive methods were used in this research to assess the conditions resulting in the valley and channel patterns observed in streams of the Western Transverse Ranges. In general, my results indicate that it is unlikely that there is a single, overriding cause for the observed patterns. As suggested by Wohl (1992), multiple factors may converge to set the hydraulic conditions necessary for formation of valley patterns in high-gradient, bedrock-controlled, mountainous streams of the Western Transverse Ranges.

The transition from a steep, narrow reach, to a wide, shallow reach could be the result of a change in rock type or hardness. If the stream flows through alternating rock types (e.g. - sandstone and shale), the softer rock units would erode more easily resulting in a low gradient reach sandwiched between reaches of harder rock units. In the case of the Sespe River basin, exposure of alternating lithologic units occurs due to the tilting of the rocks, up to 90 degrees in some cases. This results in streams flowing across each rock unit except in the case where the stream is flowing parallel to the fault plane (e.g., in middle reaches of the mainstem Sespe).

For the nine surveyed subwatersheds, our results suggest that some relationship exists between valley characteristics and the type of rock unit underlying each reach (**Figure 16**). Because we had no information about the hardness or erodibility of each rock type, I assumed that shales were softer than sandstones which, in turn, were softer than igneous and metamorphic rocks. The results suggest that gradient increases as the rock type becomes harder. The analysis can be taken one step further by comparing rock formations that are represented by both shale and sandstone units. Although there are only two rock types that had this characteristic in the nine surveyed subwatersheds, the results are consistent. In both cases gradient were higher in the sandstone units and the median values for valley width were lower in the sandstone units. Although different sandstones and shales differ in hardness and erodibility, the cases described above suggest that rock type is an important variable when considering the geomorphic patterns observed on Sespe Creek.

Another technique used to explain the alternating valley width and gradient sequences seen along Sespe Creek and its tributaries was to determine if any regular or consistent patterns exist in the longitudinal valley width and gradient profiles for the nine surveyed subwatersheds. If a regular sequence of valley width and gradient does exist, it might suggest a pattern that is a function of the landscape rather than lithology or geologic structure. In other words, the patterns seen in the Sespe may represent the most stable geomorphic condition given the current hydrologic, tectonic, and geologic conditions of the landscape. These hypotheses were discussed by Wohl and others in relation to bedrock rivers or rivers with thin alluvial layers but controlled by bedrock, and were described in the context of stream power and extreme flows (Wohl, 1992; Wohl and Baker, 1994).

At the scale of individual Sespe subwatersheds, there is some evidence of a regular pattern in valley width and gradient (**Figure 13**). For example, the results for Bear Creek (**Figure 13c**) show alternating patterns of positive and negative correlations for successive lags suggesting that wide valley reaches are interspersed with narrow reaches. These patterns are only evident, however, in a few subwatersheds and are not consistent between subwatersheds, perhaps owing to the influence of other controlling variables on the pattern of valley width and gradient. In the subwatersheds where some pattern does emerge (Alder, Lion, Trout, and Portrero John), the results suggest that factors controlling valley morphology at the reach-scale may be similar to the factors controlling morphology at the habitat-scale reported by Keller (1993). Keller (1993) reported that pool-riffle sequences, velocity, stream power, and channel width were dictated by geomorphic conditions of the valley. At the scale of the reach, these same hydraulic variables may control the geomorphic configuration of the valley and may be defined by the hydraulic conditions present during extreme flow events.

The location of the dominant faults may influence the patterns seen in the mainstem of Sespe Creek (**Figures 8 and 9**). In sections of the mainstem of Sespe Creek that run east and west (upper and middle reaches) along the trend of the dominant fault line, valleys are wide and gradients are low resulting in high sediment storage potential. In the sections that flow southward (Sespe Gorge and Sespe Narrows), perpendicular to the fault lines, valleys are steep and narrow resulting in low sediment storage potential. Although this general pattern breaks down at the reach-scale (2000-3000 meters), the storage pattern depicted in **Figure 8** is clearly evident. The ultimate cause of the pattern seen in the Sespe is due to uplift along the San Cayetano-Oak Ridge thrust fault system, resulting in the recent formation of the Western Transverse Ranges (Sharp, 1954).

What is evident from the results is that multiple variables are interacting to define geomorphic conditions in the valley. Different controlling variables may be operating at different scales. Factors such as tectonic uplift, faulting, lithology, and hydrologic variables interact to produce the patterns in erosion and deposition seen in the current landscape. The next question to ask is how the geomorphic conditions of the valley influence the sorting and storage of sediment in the channel, floodplain and adjacent terraces.

The results from the grain-size analysis conducted on nine subwatersheds within Sespe Creek suggest that the sorting of the sediment in the channel is consistent with the geomorphic configuration of the valley. Finer sediments are being stored in wide, low gradient reaches and are being scoured from narrow, high gradient reaches (**Figures 18 and 19**), producing alternating bedrock and alluvial reaches ultimately confined by bedrock valleys.

Plots of the percent boulder-cobble-gravel characteristics of Alder Creek (**Figure 18a**) at each transect site provide insight into the sediment grain-sizes that are being stored in each reach. If a high percentage of boulders are present in a particular reach, it can be assumed that finer sediment sizes are being transported out of that reach. Conversely, if a high percentage of fine sediments are present in a particular reach, it can be assumed that finer sediments are being deposited, resulting in burial of the larger sediment classes. A longitudinal trace of the boulder percentage for Alder Creek can be traced in **Figure 18a** and **19a** by tracking the reach numbers from low (1) to high (11). The results suggest that deposition of finer sediment is occurring in Reaches 2 (3,4,5) and 5 (10,11) and bedrock/boulder reaches occur in Reaches 1 (1,2) and 4 (7,8,9). Reach 3 (6) constitutes a transitional reach between alluvial and bedrock/boulder.

The example of Alder Creek suggests that sediment storage is occurring within the wide valley reaches and becoming finer grained at the downstream end of the storage unit as the narrow valley (or constriction) approaches. The coarser sediment is deposited first as a river enters a wide valley and finer sediments settle progressively downstream.

It is often the case that riparian plant distributions and surface flow of water follow the same general pattern. In Alder Creek (also evident in *Figure 6* – Lion Creek), water is perennial as it enters the Reach 2 storage unit and white alders dominate the riparian vegetation. The flow then becomes intermittent further downstream with occasional pools, lined by willow and mulefat, during the summer months. In the middle of the reach, riparian vegetation becomes dominated mainly by mulefat and various chaparral species (e.g., sage scrub, yerba santa). Pools are often shallow and summer flows only occur during the wettest years. As the stream approaches the constricted part of the valley, surface flow again becomes perennial and white alders dominate the riparian vegetation. The sediment stored in the wide valley areas could be activated during high discharge events, providing a long-term gravel supply to downstream reaches.

4.2 - Storage / Rainbow Trout Relationships

Locations of potential storage were estimated using valley width and gradient (**Figure 8**). In my analyses I determined the length of stream available for sediment storage relative to the entire length of the stream (SLI) and the areal amount of storage (m^2) in the storage reaches relative to the total areal storage (ASI) were determined. After these indices were estimated, I related the sediment storage characteristics of the nine surveyed subwatersheds to their rainbow trout densities. Howard Creek has the highest values for both SLI and ASI, and also the lowest average basin slope (20 degrees), one of the lowest elevation ranges (650 m), despite it's large stream length (32.1 km), and the highest drainage density (1.6) (**Table 2**). These factors all contributed to Howard Creek's ability to store sediment by limiting the amount of stream power available for sediment transport during high flows. Conversely, the subwatershed with the lowest values for SLI and ASI was Alder Creek. Alder Creek had the highest average basin slope (28 degrees), the highest elevation range (1460 m), despite a total stream length of 33.1 km, comparable to Howard Creek, and was dominated by granitic rock (**Table 2**). Although the total sediment storage area in Alder Creek was high, values standardized by basin size and stream length were low.

In general, the drainage basins that enter the middle reaches of the Sespe (Trout, Lion, Howard, and Tule Creeks) appear to have the highest values of SLI (**Figure 10c**). The pattern for ASI (**Figure 10b**) is similar but not as conclusive. Plots of SLI and ASI against drainage area **(Figure 10d)** show that medium-sized subwatersheds have the highest per unit storage compared to smaller or larger subwatersheds. A possible explanation for these results is that large rivers are generating enough flow and stream power to move sediment and incise deeper canyons, preventing wide alluvial valleys from developing. In contrast, storage reaches exist in smaller subwatersheds but their extent is limited by the amount of stream power that can be generated by small drainage areas. Medium-sized subwatersheds can carve wide valleys, yet may lack the ability to transport the supplied sediment, resulting in extensive alluvial reaches.

The subwatersheds that are more varied in their valley width and gradient characteristics will have more extensive alluvial reaches interspersed with narrow bedrock/boulder reaches. The bedrock/boulder reaches provide year round flowing water, deep pools, and riparian vegetation to provide shading, allowing rainbow trout populations to persist through the summer months. Unless factors such as fire and landslide frequency vary among subwatersheds, the longitudinal configuration of the valley (e.g., valley width and gradient) will dictate total sediment storage and, ultimately, the amount of spawning gravel available to fish.

Which variables, then, are controlling rainbow trout densities in Sespe Creek? Are habitat characteristics such as pool depth, cover, food supply, and water temperature the dominant controlling variables? Do landscape properties and sediment supply and sorting characteristics of the subwatershed influence overall rainbow trout densities by affecting spawning success? The results of our analyses of both the habitat and landscape properties of nine subwatersheds on Sespe Creek suggest that each contributes to the control of rainbow trout densities and distributions in Sespe Creek.

Based on the results of the correlation analysis of the habitat characteristics of the nine surveyed subwatersheds (**Table 6**), the dominant habitat variable influencing fish densities was pool depth, and, to a certain degree, pool volume. For landscape variables the total storage and SLI were shown to influence fish densities. These relationships are much weaker when Howard Creek is removed from the analysis although the general trend still persists. Deep, large pools are well known indicators of good quality rainbow trout habitat. The fact that sediment storage characteristics of the landscape were also shown to be important controlling variables suggest that fish densities may be a function of both instream habitat characteristics as well as the physical conditions that define the habitat quality.

When assessing the results, there is also the issue of whether the quality of the habitat is related to spawning or rearing success. Some Sespe tributaries may produce a large number of fry but show very few large individuals suggesting the spawning quality of the creek is good but other habitat characteristics are poor such as food production or temperature. In other cases, very few fry are produced but there are a significant number of larger individuals suggesting that spawning habitat is limited but the habitat to support larger fish is good. For example, the sediment storage indices (ASI and SLI) for Alder Creek are the lowest of any of the surveyed subwatersheds (**Figure 10**). It has low densities for trout size classes 1 and 2 indicating that spawning success was relatively low compared to the other subwatersheds. Yet, rainbow trout densities for size class 3 were fairly high relative to the other subwatersheds (**Figure 25**). This suggests that adequate habitat is available to support adult rainbow trout populations in Alder Creek but that production of fry and juveniles is low. Alder Creek is characterized by a long stretch of channel lined by alder trees, which are often associated with year-round surface flow. Creeks such as Alder Creek may provide good quality rearing habitat and a perennial source of water to maintain adult rainbow trout populations, but sediment storage characteristics may limit the supply of gravel creating insufficient spawning habitat.

In contrast, rainbow trout densities for size class 1 are relatively high in Trout Creek compared to the other surveyed subwatersheds. Yet there is a large decline in the proportion of fish represented in each size class and no fish in size class 4 (**Figure 25**). These data suggest that Trout Creek provides adequate spawning habitat as indicated by its sediment storage characteristics (**Figure 10b and c**), but may provide poor rearing and adult habitat.

Overall, the results suggest that both the habitat and sediment characteristics of the watershed are influencing the densities of rainbow trout in the Sespe Creek watershed. The reaches where rainbow trout are found are characterized by perennial water and cool water temperatures, as well as access to these reaches. Densities of adult rainbow trout also may depend on habitat characteristics, such as pool depth, pool volume, adequate refuges from predators, and food supply although many of these habitat factors were not looked at in my research. Fry densities, on the other hand, may depend on the supply and sorting of sediment in the subwatershed.

The sediment and habitat characteristics of a particular subwatershed may interact to produce the observed distributions and densities of all rainbow trout size classes. In the case of Howard Creek, both habitat and sediment conditions converge to produce extremely high trout densities across all size classes. For Ladybug and Cherry Creek, poor habitat and sediment conditions result in low densities across all size classes.

Short-term research may only reflect the conditions present in a particular year or may be complicated by events occurring in previous years. Further work needs to assess the relationships that are suggested in this research to determine dominant influences of landscape and habitat conditions on rainbow trout populations.