Fine Sediment Deposition and Invertebrate Communities in the middle Truckee River, California: Development of Criteria for Establishing TMDLs

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Executive Summary

The middle Truckee River, from the outlet of Lake Tahoe to the Nevada state line, was designated as impaired due to sediment pursuant to Clean Water Act regulations in 1992, necessitating the preparation of a Total Maximum Daily Load (TMDL). The objective of this study was to assess the responses of benthic (i.e., bottom-dwelling) macroinvertebrate communities to sediment deposition in the middle Truckee River. This study was motivated by the need to determine whether impairment of the biotic community from increased sediment supply is evident in the middle Truckee River, and to provide information that may assist in the development of a TMDL. The effects of sediment on water quality and biota are often difficult to assess because transport and deposition of sediment is a natural process of streams, conditions today may reflect a legacy of historical practices along with contemporary practices, and attributing sediment supplies to particular non-point sources and land uses is challenging. In addition, the construction of reservoirs on many of the middle Truckee River tributaries, increases in impervious surfaces from urbanization, and decreases in vegetative cover have affected the magnitude, timing, and frequency of the hydrological features of the river, which are strongly coupled with sediment transport and deposition dynamics.

A review of documentation related to historical impacts to macroinvertebrate communities on the middle Truckee River revealed an extreme sedimentation event and biological impacts downstream of Donner Creek in 1958 as a result of a gravel mining operation. The decimation of a large freshwater mussel population during the 20th century may also be attributable to such events, as well as increased sediment supply in general. Large increases in the population in the middle Truckee River basin and the surrounding area in recent decades, including a four-fold increase in the Town of Truckee since 1990, has also likely affected sediment supply dynamics for the river. Additional review of historical records and documentation, and trends in settlement and land use is needed to characterize historical and existing sediment supply dynamics.

Previous research into sediment dynamics in the middle Truckee basin included a study of benthic macroinvertebrate communities and modeled sediment loads in several middle Truckee River tributaries for the development of a sediment TMDL for Squaw Creek. That study concluded that sediment loads in Squaw Creek would need to be reduced by at least half to meet biological and habitat target conditions. In addition, two studies on sediment transport in the middle Truckee River have been completed. The first modeled sediment production in middle Truckee River sub-basins and tributaries, concluding that sediment loads to the Truckee River would need to be reduced by about half to approach an "undisturbed" target condition. The second evaluated the nature and extent of sediment transport in the middle Truckee River itself, characterizing the range of sediment loads and variability of sediment transport events during 2002 and 2003. Although methodological issues were identified for both of these studies, modeled sediment loads for individual tributaries from the former study were compared with data measured in this study.

The effects of increased sediment supply and altered hydrology on stream channel morphology and channel habitat are often complex. Wash material, functionally defined as fine sediment particles that are transported in suspension, comprises the major portion of total sediment load in most river systems, is the main component of sediment supply resulting from anthropogenic activities, and strongly influences the physical and biological structure of streams. During transport events, wash material scours stream channels and can lead to temporarily turbid, inhospitable conditions for many organisms (i.e., acute effects). At lower flows, wash material will be deposited within the interstices of coarser bed material, and, when in sufficient supply, even cover or bury coarser bed material under surface patches of fine sediment. Thus, for a given hydrologic regime, as sediment supply increases fine particles will become more abundant on the bed surface and fill the open space around larger particles, decreasing the overall substrate particle size distribution and reducing the availability and heterogeneity of benthic habitat.

In this study benthic macroinvertebrate community surveys are used as a direct measure of aquatic life beneficial use attainment. Benthic macroinvertebrate community composition is sensitive to the effects of sediment transport and deposition, and to physical and chemical disturbance in general. Because benthic macroinvertebrates often have life cycles of one year or more, they reflect long-term water quality conditions, integrating the influence of changes in hydrological and water quality conditions over all seasons. Their populations will also reflect synergistic and antagonistic effects of a mixture of disturbances and pollutants. In the case of increased sediment transport and deposition in a stream, reduced substrate particle size and loss of interstitial habitat are likely to cause a shift in macroinvertebrate community composition favoring organisms that can exploit those conditions and tolerate recurring disturbance from sediment transport events.

Generally, wash material will be transported directly through a reach without being deposited in the main channel. However, such fine sediment may be deposited along channel margins, where it is expected that the effects of deposition from increased sediment supply will most influence long-term benthic habitat. We hypothesize that as sediment supplies increase, the substrate quality in channel margins is likely to shift from a heterogeneous mixture of largely coarse bed materials, to a more homogenous matrix dominated by deposited wash material, with a corresponding shift in benthic biological communities. Thus, while physical disturbance of benthic organisms may occur during both sediment transport and deposition processes, we expect that long-term effects from increased sediment supply will be most evident in channel margin deposition zones.

In this study, we developed a sampling method to simultaneously collect samples of fine sediment volume and macroinvertebrates from locations on channel margins. These "pump-core" samples were collected from the middle Truckee River upstream and downstream of each of seven tributaries selected *a priori* to represent a range of sediment loading. A standard, targeted riffle, reach-scale bioassessment sample was also collected downstream of each tributary. This design permitted the comparison of samples between tributary locations to elucidate a tributary-dependent sediment dose-response relationship in the middle Truckee River, if any. The pump-core samples also allowed for a finer-scale comparison of local sediment deposition conditions and the biological response.

Sediment volumes measured in the pump-core samples spanned two orders of magnitude, but most were in the lower range of the distribution. Differences in mean sediment volume downstream of the tributaries were not statistically significant, and did not reveal patterns that might be expected based on modeled sediment loads.

Sediment volumes measured in the pump-core samples often exhibited expected relationships with macroinvertebrate community metrics. Substantial scatter, commonly found when comparing environmental gradients to biological responses, was apparent in these relationships, however a metric response consistently in the direction predicted with increased sediment volume was apparent, indicating that sediment deposition was a driving factor in community composition, along with other, unmeasured explanatory variables. Transition in the types of invertebrates present as sediment deposition volumes increased above about 100 ml per sample was exhibited in several metrics, suggesting this may be near the limit of biological capacity to assimilate sedimentation stress.

Multivariate, statistical ordinations of the macroinvertebrate taxa in the pump-core samples were performed to examine similarities in the communities in each sample, and elucidate patterns between samples based on sediment volume or tributary location. These analyses indicated that samples grouped by site were more similar than samples grouped by sediment volume, but that the lowest and highest sediment volume classes were distinct. As distance between sites increased, community dissimilarity increased. These dynamics may be explained by variability in environmental factors between sites, including sediment loading, or differences along the natural continuum of the river independent of differences in sediment loading, or a combination of these factors.

For the targeted riffle samples, total taxa richness generally increased with distance downstream. A region-specific, multi-metric index of biological integrity (IBI) calculated for each of these samples indicated that three sites scored just below an impairment threshold, and five sites (including one in Nevada) scored in ranges designated as fair or good. No trends were apparent between the IBI scores and the modeled sediment loads for each tributary. These modeled loads also were not correlated with individual macroinvertebrate community metric values, nor mean sediment volumes measured in the pump-core samples.

This study produced mixed results, with samples from channel margins showing degraded conditions under exposure to increased deposition of fines, and bioassessment samples showing marginal degradation at some sites relative to a regional reference condition. No correlations, however, existed between modeled tributary loads and associated downstream bioassessment scores, or above and below tributaries.

Sampling for this study was limited to a single event at each site. Although samples were collected during base-flow conditions during late summer and the study was designed to examine long-term, chronic effects from sediment, without multiple sampling events over time we cannot be certain the degree to which these samples were representative of the conditions of these sites over time. This study was also limited in the spatial representation it afforded, given that it was intended to characterize such a long segment (i.e., 63 km) of a relatively large, non-wadeable stream.

Other environmental factors, besides sediment supply, may have influenced macroinvertebrate community composition. These factors may result from human activities or natural gradients in habitat conditions or food resources. It was assumed in this study that for the stretch of the middle Truckee River studied, the characteristic gradient, discharge, and food resources would be sufficiently similar that natural variability in community composition would be equalized. However, some of the variability in pump-core samples could be explained by the location of each site along the Truckee River. While this may indicate a natural gradient in community composition, these between-site differences may have been correlated with other environmental factors or cumulative anthropogenic influences, including sediment. Additional correlated measurements of environmental factors and macroinvertebrate community data could further elucidate these dynamics, and characterize the system under different hydrological conditions.

It was expected that the influence of sediment discharged from the various tributaries would be sufficient, and of enough variability between tributaries, that a sediment dose gradient could be detected in the macroinvertebrate communities. The lack of such a correlation found in this study indicates that individual tributaries may not have a strong influence on local downstream macroinvertebrate communities. It is also possible that the limited temporal and spatial scales investigated in this study failed to reveal it. The morphologic responses of the stream channel occur across a range of spatial scales, and often at a large spatial scale (macro-scale) that varies with distance downstream of a sediment source. However, individual samples of the macroinvertebrate community necessarily represent a small spatial scale (micro-scale). Reconciling these scale differences in how sediment is transported and deposited, and the response of biological indicators of habitat quality will require study designs that match these scales.

This study reveals the need for measurement and characterization of the geomorphic features of the middle Truckee River, including morphologic channel features and substrate particle-size distributions. This would be the most direct means to assess the physical channel response to sediment supply dynamics, and a necessary step for interpreting responses in the biotic community of the river.

Introduction

In 1992, the Lahontan Regional Water Quality Control Board (LRWQCB) listed 63 km of the Truckee River from Lake Tahoe to the Nevada state line (hereafter, middle Truckee River) on the Clean Water Act Section 303(d) list as having impaired beneficial uses due to sediment. This listing was based largely on professional judgment due to discharges of sediment, complaints from municipal water treatment plants, and elevated turbidity levels. As part of developing a Total Maximum Daily Load (TMDL) for sediment for the middle Truckee River, the LRWQCB commissioned studies completed in 2001 and 2004 to evaluate sediment production in middle Truckee sub-basins and tributaries, as well as the nature and extent of sediment transport in the river (McGraw *et al.* 2001; Dana *et al.* 2004). However, to date the LRWQCB has little quantitative evidence of direct impairment of beneficial uses caused by increased supplies of sediment. The objective of the study was to assess whether impairment to beneficial uses is indicated in the middle Truckee River based on channel margin sediment deposition and the relationship of sediment volume per area to the composition of associated benthic macroinvertebrate assemblages.

The effects of sediment on water quality and biota are often difficult to assess because transport and deposition of sediment is a natural process of streams. Sediment derived from the landscape contributes to the dynamic processes of building, shaping, and renewing stream channels. Forming the principal substrate of stream bed habitat for periphyton, invertebrates, and fish, sediment is also essential to the ecological function of streams. However, increased sediment supply to a stream (*i.e.*, at levels exceeding natural background due to anthropogenic activities) can impair indigenous stream communities and their ecological function. Thus, the challenge for researchers and managers seeking to understand the effects of watershed disturbance and increased sediment loading on a stream is to determine: (1) whether impairment to aquatic life is occurring; (2) what portion of observed impairment can be attributed to watershed disturbance; and, (3) the degree to which sediment loads must be reduced to facilitate historical habitat quality and beneficial uses.

Previous Evidence of Sediment Impairment on the middle Truckee River

<u>Sediment Releases in 1958</u>

At least one available historical account documents anthropogenic activities causing sediment deposition and impacts to biological communities in the middle Truckee River. Researchers for the California Department of Fish and Game described sedimentation events on the middle Truckee River and its tributaries during the Summer and Fall of 1958 (Cordone & Pennoyer 1960). Two main sources were identified in these events: (1) highway construction activities that included rechannelization of sections for Donner Creek and Squaw Creek and bridge construction and other activities along the middle Truckee River itself; and (2) a large gravel washing plant on Cold Creek one-half mile upstream of its confluence with Donner Creek, near the town of Truckee. Both sources were described as follows:

> Rechannelization of sections of Donner Creek and Squaw Creek, construction at several bridge crossings on the main Truckee River, and activity alongside the

> Truckee River all contributed silt. However, these sources were intermittent and relatively short-lived, compared to an almost continuous discharge of silt from [the] large gravel washing plant
>
> . . . The half-mile section of Cold Creek, one and a half miles of Donner Creek, and the Truckee River from the mouth of Donner Creek downstream to an undetermined point in the State of Nevada were turbid throughout most of the summer recreation period. . . .
>
> The muddy appearance of the water was not attractive to fishermen. . . . The turbidity virtually eliminated angler activity except for some minor use on Sunday and Monday mornings, when the river was slightly clearer following plant shutdown for the week end [sic]. . . .
>
> The Truckee River above the mouth of Donner Creek was clear at the time of the survey. There was some evidence of siltation in the shallows along the margins and in the pools. This material was probably derived from rechanneling of sections of Squaw Creek during construction of the Winter Olympics site. . . .
>
> Effects of the silt load on the substrate of Cold Creek and the Truckee River were striking. The greater portion was covered with silt. Most of the rubble and gravel in the riffle areas was cemented together to form a hard bedrock-like substrate. . . . The margins of both streams were coated with silt, in some places to depths of a foot or more. Eddy areas behind boulder also contained thick mud deposits. . . .

Based on a single sample of the gravel washing plant effluent, it was estimated that the facility released 20 to 25 tons of fine sediment per-day of operation that summer. The authors completed a biological survey in September 1958 to determine the extent of silt impacts to aquatic life, including the collection of samples of benthic macroinvertebrates from riffle habitat and of resident fishes. Samples were collected above and below the gravel washing operation as well as the confluence of Donner Creek with the Truckee River. The abundance, diversity, and mass (wet-weight) of benthic macroinvertebrates and the condition of fishes all declined significantly below the discharge from the gravel plant, and the degraded conditions persisted at least 10.5 miles downstream of the Donner Creek confluence. This was the only year that that operation existed (A. Cordone, personal communication). But the extreme amount of sediment transport and deposition that summer likely affected biological communities for a long period after, especially in combination with other subsequent and ongoing disturbance that would have increased watershed sediment loads, including road construction and development as a function of population growth (Table 1).

Table 1: Summary of available decennial US census population data for Truckee, California (California DOF-DRU 2006; note that data are not available for many decades) and data for the same decades for Reno, Nevada (Nevada State Library 2006). These data indicate that the population of Truckee, the largest urban area within the middle Truckee River basin (excluding the Lake Tahoe basin), has grown more than 13-fold since 1950, and 4-fold since 1990. The magnitude of growth has been even greater in Reno, a relatively large urban region downstream of the middle Truckee River. These data are one indication of increased watershed disturbance in the project area during this period. Historical aerial photographs, maps, and land use records could provide additional data to characterize historical trends that may have affected sediment loads and hydrology in the middle Truckee River basin.

Year	Truckee	Reno
1880	1,147	1,302
1890	1,350	3,563
1950	1,025	32,497
1970	1,392	72,863
1980	2,389	100,756
1990	3,484	133,850
2000	13,864	180,480

Margaritifera falcata

The decimation of the freshwater mussel *Margaritifera falcata* population in the middle Truckee River likely provides further evidence of historical and ongoing impacts from increased sediment supply. This mussel was reported at high densities in two reaches of the river in 1941 (Murphy 1942):

> The Truckee River with its large, stable, gravelly and sandy stretches is apparently an ideal habitat for *Margaritifera*. The mussel population in a half-mile of stream above the club house was estimated at 20,000 individuals over 40 mm. in length. In this stretch one bed was found containing 10,000 mussels.

Some time after these observations, *M. falcata* was reported to have disappeared from the middle Truckee River (Hovingh 2004). A recent snorkel survey (Summer 2006), however, reported about 150 individuals found in the same area where the 1941 observations were made (J.Howard, pers. com.). These long-lived mussels, which Murphy (1942) found at lengths up to 9.2 cm in length, are unique in having a parasitic, developmental life-stage, termed a glochidia, in which they attach to the gills of some trout species. Although native cutthroat trout spawning migrations, the presumed native hosts, had ceased in the early 20th century, *M. falcata* were apparently able to reproduce using introduced rainbow and brown trout.

Surveys of other populations of *M. falcata* and its physiological and life history characteristics indicate that its near disappearance may be due to a combination of changes in the hydrology and sediment loads of the middle Truckee River. Vannote & Minshall (1982) showed that high-density, stable populations of *M. falcata* occurred primarily in large, block-boulder-controlled reaches of the Salmon River, and secondarily in cobble/boulder-shielded runs. They suggested that habitat protected from large flood events by the presence of large boulders allowed stable, modal populations of old-age organisms to persist, but that in less well-protected habitats, scour from large flood events yielded a younger population with greater turnover. They also demonstrated in experiments that mature *M. falcata*, in response to burial by sediment, migrated either slowly or not at all vertically, and generally appeared poorly adapted to aggrading substrate conditions compared to a competing mussel. Another study in two southeastern New York rivers demonstrated that the locations of mussels in the same superfamily as *M. falcata* were spatially coincident with flood flow refuges, but not with other habitat features that were measured, including water depth, velocity, and sediment grain size (Strayer 1999). This implies that *M. falcata* populations can only persist in streams with boulders that can anchor substrate and provide refuge during large flood events. Pollution associated with eutrophication of European streams has also been implicated in declines of a similar species, *M. margaritifera* (Bauer 1988).

This research indicates that *M. falcata* was susceptible to both changes in hydrologic conditions that might result in extreme flood conditions, as well as increased sediment supply leading to smaller characteristic substrate sizes, aggradation of fine material that buries preferred substrates and flow refuges, or the reduction of streambed armoring that increases bed load mobility and reduces the occurrence of flow refuges. Therefore, it is likely that chronic and/or extreme increases in sediment supply and/or alterations to the hydrology of the middle Truckee River were the primary cause of the great losses to the *M. falcata* population. The construction of reservoirs on many of the middle Truckee River tributaries, increases in impervious surfaces from urbanization, and decreases in vegetative cover have affected the magnitude, timing, and frequency of the hydrological features of the river (Figure 1). Extreme releases of fine sediment historically likely caused accumulation of fine sediments and the burial or loss of flood refuges and habitat required by *M. falcata*. Other impacts to water quality may also have played a role in its decimation.

Previous Research on Sediment Loads in the Middle Truckee River and Tributaries

Squaw Creek TMDL

Herbst (2002) completed a study comparing benthic macroinvertebrate communities and modeled sediment loads in several middle Truckee River tributaries for the development of a sediment TMDL for Squaw Creek. In that study design, conditions at reference sites on minimally-disturbed streams within the middle Truckee River watershed were used to characterize the natural spatial and temporal variability of streams similar to Squaw Creek. This allowed for the assessment of conditions in the Squaw Creek watershed, and the development of target conditions as part of the TMDL. The study found that modeled sediment loads in these streams were correlated with their median particle size and proportion of fine and sand particles, and that these streambed characteristics were correlated with diminished integrity of several macroinvertebrate metrics, especially those related to richness and community tolerance. The study concluded that sediment loads in Squaw Creek would need to be reduced 50 to 75% to meet biological and habitat target conditions

Sediment Load Dynamics in the Middle Truckee River and its Tributaries

Two studies on sediment transport in the middle Truckee River have been completed as part of developing the sediment TMDL for the middle Truckee River. McGraw *et al.* (2001) evaluated and modeled sediment production in middle Truckee River sub-basins and tributaries.

Their model indicated that overall sediment loads to the Truckee River would need to be reduced 47% to approach an "undisturbed" target condition. They also evaluated sub-basins to prioritize targeted reductions in sediment loads. Dana *et al.* (2004) evaluated the nature and extent of sediment transport at four sites in the middle Truckee River itself. Their objective was to characterize the range of sediment loads and variability according to total amount, maximum, duration, timing and frequency of sediment transport events during 2002 and 2003.

Of particular interest for our study, McGraw *et al.* (2001) also estimated sediment loads in tributaries for calendar-years 1996 and 1997 using rating curves derived from measurements and/or predictions of discharge, turbidity, and suspended sediment concentration data. Part of our study design examined the association between benthic macroinvertebrate communities and sediment deposition downstream of selected tributaries of the middle Truckee River, so these estimates provided for a comparison of tributary sediment loads with our measurements, given that no other sediment load predictions were available for Truckee River tributaries.[1] However, a review of the McGraw *et al*. predictions yielded some concerns regarding their use and interpretation. Dana *et al.* (2004) found that the load estimates for 1996 and 1997 at the Farad site, the only site for which load estimates were calculated in both studies, were consistently 2 to 6 orders of magnitude lower than those calculated by the methods of their study.[2] This indicates that the magnitudes of the tributary sediment load predictions for 1996 and 1997 may have been substantially underestimated compared to the presumed best sediment load measurement and analysis data now available. An additional factor is that 1996 and 1997 were anomalous years for precipitation and flooding, both of which may have had a profound affect on sediment transport.[3]

McGraw *et al.* did not discuss the overall validity of the tributary load estimates, nor did they compare estimated values to sediment loads reported in other studies for other watersheds. Their report did rely on the predicted sediment loads to calibrate and validate the AnnAgNPS watershed sediment production model, so presumably, by some unspecified criteria, they were deemed sufficiently accurate or representative for that purpose. We presume that the McGraw *et al.* predictions should reflect relative sediment loads between tributaries, and therefore should be useful to compare with macroinvertebrate community data, even from a different year, to examine whether the macroinvertebrate communities at each site associated with a tributary exhibited a signal proportionate to the estimated sediment load for that tributary (*i.e.*, higher sediment load tributaries had lower biotic integrity in associated sites).

[1] Dana *et al.* (2004) estimated sediment loads at four sites on the middle Truckee River, but they were not coupled with specific tributaries

[2] Dana *et al.* (2004) relied on measurements of a greater number input variables and more sophisticated statistical techniques, so their estimate would be expected to have greater accuracy.

[3] Calendar-year 1996 had the highest total precipitation on record (*i.e.*, since 1914) and the third highest recorded for the month of December; calendar-year 1997 included the third highest recorded precipitation for the month of January (WRCC 2006). Therefore, it is not clear that either of these years was particularly representative of "wet" or "average" years for precipitation or sediment transport, as indicated by McGraw *et al.* (2001). The report does acknowledge that 1996 was "extreme," and that 1997 included an "extreme" event (*i.e.*, the New Years 1997 flood, which resulted from a rain on snow event), but these years were reportedly chosen primarily because each had the best overall, most continuous dataset available. The report does not specify the reason for quantifying sediment load in terms of calendar-year, instead of by water-year, which would make characterizing years as "wet" or "average" more tenable.

The Effects of Increased Sediment Supplies on Stream Morphology and Benthic Macroinvertebrates

Stream sediment is supplied from sources both external and internal to the stream channel. External sources include mass movement, roads and trails, and surface erosion on slopes, while internal sources include material stored within the channel bed, in banks, and on adjacent floodplains. Anthropogenic activities in the watershed can influence both rates of erosion and hydrologic conditions, affecting the quantity and quality of sediment sources, as well as the transport and storage capacity of a stream. The net affect of increased erosion and altered hydrology in a watershed will likely include increased delivery of sediment to a stream, increased transport of sediment by the stream, and increased storage of sediment in the stream channel, resulting in modification of the channel's morphology (*e.g.*, extent of bars, channel width and sinuosity, *etc*.) and bed composition (*e.g.*, substrate particle size distribution, armoring, flow-resistant structures, *etc.*). Thus, not only does landscape disturbance result in increased erosion and delivery of sediment to a stream, but the stream's within-channel storage and transport capacity are also likely to be influenced by activities in the watershed, including the construction of impervious surfaces, the removal of vegetative cover, and the construction of dams, all of which alter the timing, duration, and magnitude of flow events. Given this large number of interconnected variables that influence stream channel dynamics and habitat, interpreting the response to changes in sediment supply from watershed disturbance is complex. For example, changes in the sediment storage capacity of a stream from modified hydrologic conditions can cause major changes in sediment transport rates, even if external sediment sources are unaltered. On the other hand, within channel sediment storage may delay and attenuate sediment waves introduced from external sources (Hassan *et al.* 2005). Thus, the effects of increased sediment delivery to a stream cannot necessarily be decoupled from alterations to its hydrology, and sediment transport rates may not respond linearly to increases in sediment supply.

Sediment in streams is functionally classified as wash load and bed material load. Wash load is relatively fine material that moves rapidly in suspension through a reach without being deposited in the main channel, while bed material load is larger material that occasionally settles out and is stored on the bed (Hassan *et al*. 2005). Wash material comprises the major portion of total sediment load in most river systems, and strongly influences the physical and biological structure of streams (Gomi *et al*. 2005). During transport events, both wash material and bed material load will scour stream channels, and can lead to temporarily turbid, inhospitable conditions for many organisms. At lower flows, some of the transported material will be deposited within the interstices of coarser bed material, and, when in sufficient supply, even cover or bury bed material under surficial patches of fine sediment (Lisle & Hilton 1999). Thus, for a given hydrologic regime, as sediment supply increases fine particles will become more abundant on the bed surface (Dietrich *et al*. 1989). Increases in sediment supply (Dietrich *et al.* 1989; Church *et al*. 1998) and alterations to a stream's hydrology (Hassan *et al*. *in press*) can also reduce the extent and effect of bed surface armoring, which may result in an overall increase in sediment transport rates, and a smaller characteristic surface substrate particle size.

Generally, wash material will be transported directly through a reach without being deposited in the main channel (Hassan *et al.* 2005). However, suspended bed material and some of the wash material may be deposited in portions of a stream where channel velocities are low, such as pools, channel margins, and upstream of flow obstructions such as boulders or large woody debris (Figure 2). In these locations, it is expected that the effects of deposition from increased sediment supply will most influence benthic habitat. In particular, we hypothesize that as sediment supplies increase, the substrate quality in channel margins is likely to shift from a heterogeneous mixture of largely coarse bed materials, to a more homogenous matrix dominated by deposited wash and fine bed material, with a corresponding shift in benthic biological communities. Thus, while physical disturbance of benthic organisms may occur during both sediment transport and deposition processes, we expect that long-term effects from increased sediment supply will be most evident in channel margins.

The effects of sediment supply may also vary longitudinally along a stream, both from variability in the locations and magnitudes of sediment sources and from fluvial processes such as sorting and abrasion that influence the deposition of sediment spatially. While locations with substantial bank erosion and other direct contributions of sediment to a stream may be important, it is expected that watershed disturbance will particularly influence sediment delivery from tributaries. Tributary confluences can result in abrupt changes in bed sediment character and water quality in a main channel, depending on the volume and character of the water and sediment a tributary delivers (Rice *et al.* 2001). These changes also have implications for a number of important habitat characteristics. Abrupt changes in sediment supply and discharge may cause adjustments in channel form (slope, width, depth), bed sediment character (size, sorting, shape), and channel hydraulics (near-bed velocity and shear stress fields). Such effects will also vary downstream from a confluence due to sorting and abrasion processes that cause a downstream "fining" of channel substrates as finer sediment particles are preferentially transported and eventually deposited (Rice & Church 1998). Thus, this longitudinal variability presents an additional challenge to measuring biological impairment from sediment, one that requires appropriate sampling frequency and site selection to account for downstream changes in sediment composition and channel morphology. But it also presents the potential opportunity to detect variable effects from each tributary, such that a range of sediment "doses" may be detected.

In this study, benthic macroinvertebrate community surveys were used as a direct measure of aquatic life beneficial use attainment. Benthic macroinvertebrate community composition is sensitive to the effects of sediment transport and deposition, and to physical and chemical disturbance in general. Because benthic macroinvertebrates often have life cycles of one year or more, they reflect long-term water quality conditions, integrating the influence of changes in hydrological and water quality conditions over all seasons. Their populations will also reflect synergistic and antagonistic effects of a mixture of disturbances and pollutants. These features of benthic macroinvertebrates yield great value in their use as indicators of ecological integrity and water quality for streams (*e.g.*, Rosenberg & Resh 1993).

A number of studies have examined the effects of sediment transport and deposition processes on benthic macroinvertebrates. During sediment transport, both the duration and magnitude of an event will determine its effects. Macroinvertebrates may be impacted by abrasion, reduced visual efficiency in feeding, and interference with food gathering, which has been shown to induce many animals to drift downstream (Waters 1995). These effects may be temporary, as macroinvertebrate communities can be expected recover rapidly if habitat and substrate characteristics are restored to pre-event conditions and intact colonization sources persist upstream.

The effects of sediment deposition on benthic macroinvertebrate communities are often more substantial, and presumably detectable long after an event. As described above, increased sediment deposition can alter the particle-size distribution of streambed substrate through the addition of fine particles. Macroinvertebrate abundance and community composition are often dependent on substrate particle size, such that a gradient of abundance of particular taxa is observed across the series of particle sizes (Waters 1995). Especially sensitive to substrate particle size are mayfly (Ephemeroptera), stonefly (Plecoptera), and caddisfly (Trichoptera) taxa, collectively referred to as EPT, that often inhabit interstitial spaces of coarse substrate. Several studies have demonstrated that EPT abundance is best correlated to a mixture of heterogeneous gravel, pebbles, and cobbles (Bjornn *et al.* 1974 and 1977; Rutherford & Mackay 1986; Ciborowski *et al.* 1977). Taxa that inhabit the hyporheic zone and depend on the flow of oxygen-containing water through interstitial spaces also show this relationship to substrate particle size (Waters 1995). A study of coastal water bodies in the southeastern United States found that the amount of oxygen decreased as particle size decreased (Burbanck & Burbanck 1967), and Eriksen (1966) demonstrated that the presence of more than 10 to 20 percent fine sand and silt (*i.e.*, <0.25 mm) can cause a significant reduction in the oxygen content within the substratum.

Although individual taxa may be particularly sensitive to increased sediment inputs, the effect of increased sediment may be best characterized in terms of a shift in overall community composition (Waters 1995). Dominant species types and diversity may change as increased sediment inputs convert the dominant substrate from coarse to fine particles. A response often observed is a change from a community dominated by larger EPT taxa to one dominated by small and sometimes burrowing macroinvertebrates such as Oligochaeta (*i.e.*, segmented worms) and Chironomidae (*i.e.*, midges). These changes do not necessarily follow linear trends. For example, with additions of small amounts of sediment, overall abundance may decrease, while the community structure and species richness remain unaltered. However, greater amounts of sediment, sufficient to change the dominant substrate type to sand-silt, may change the number and type of taxa, altering community composition and structure, with variable effects on overall density (Lenat *et al.* 1981).

Standard bioassessment techniques that measure macroinvertebrate community abundance and composition, such as the targeted riffle method, are intended for use in assessing biological integrity, providing a standardized indication of overall physical and chemical disturbance levels at a reach-scale (*e.g.*, 150 m). Additional measurements or techniques are required to evaluate the cause of any observed disturbance or impairment. In the case of sediment effects, and at the scale of the middle Truckee River, sediment deposition and its long-term effects are likely to be patchy, ranging widely along the river and even within a reach. Thus, reach-wide average measurements of macroinvertebrate communities and sediment are not ideal for sampling in such a patchy environment, nor for isolating the dose-response dynamics of increased sediment supplies. The challenge is to measure representative sediment deposition quantity and quality and associated benthic macroinvertebrate communities at particular locations within zones of potential deposition, and to also characterize several representative reaches along the river that are exposed to variable sediment loads from particular tributary sources.

The "pump-core sample" approach developed for this study incorporates an innovative benthic sampling technique for simultaneously collecting samples of fine sediment and macroinvertebrates from the same microhabitat patch. This technique utilizes a section of ABS pipe placed over shallow stream margin substrates, such that it isolates a sample of fixed area from which sediments and associated invertebrates are collected using a hand-operated bilge pump and an aquarium net for removal. Following collection, fine sediment volume is measured in the field and macroinvertebrates are preserved for identification in the laboratory. These pump-core samples are most suitable for collections from shallow channel margin habitat. As described above, channel margins have lower flow velocities than the main channel, and so are depositional zones for fine sediment (Figure 2).

Methods

Study Design

In this study we characterized benthic macroinvertebrate communities in the middle Truckee River at seven tributary confluences (Figure 3). These tributaries, Bear Creek, Squaw Creek, Trout Creek, Martis Creek, Juniper Creek, Gray Creek, and Bronco Creek, were selected *a priori* to represent a range of sediment loading, while eliminating tributaries likely influenced by other sources of disturbance to the extent feasible (*i.e.*, discharge manipulation, urban development, etc.). Except for Martis Creek, these tributaries also lacked dams, which would have affected sediment transport dynamics.[4] This design permitted the comparison of samples between tributary locations to elucidate a tributary-dependent sediment dose-response relationship in the middle Truckee River, if any.

At each site, one targeted riffle sample and six pump-core samples from channel margins were collected. One pump-core sample was collected upstream of each tributary, and five samples in an array up to 250 m downstream, such that conditions upstream and downstream of each tributary could be characterized. This array of downstream samples was intended to characterize spatial variability downstream of tributaries and to detect the local influence of downstream fining, if any. One additional tributary site was selected downstream of the others, at Canyon 24, for collection of a targeted riffle sample. This was intended for comparison with a larger dataset of macroinvertebrate samples collected on the Truckee River downstream in Nevada, which had been used to develop an IBI for that portion of the river. All samples were collected between 6 and 9 September, 2004.

Pump-Core Samples

Six pump-core samples of sediment and associated invertebrates were taken at each site, one 50 m upstream of the confluence, one each 50, 100, and 250 m downstream of the confluence, and one each from downstream locations judged to have low and high levels of sediment deposition. The rationale for these locations was to represent the gradient downstream from tributaries, if any, as well as a wide range of sediment deposition conditions across sites. Samples were collected from channel margins at locations where coarse substrates were dominated by gravel and pebble (*i.e.*, up to 64 mm sieve axis length), having sufficient flow to prevent surface deposition of organic matter (*i.e.*, pools were avoided), along the same side of the river that the tributary entered, and at depths ranging from 6 to 29 cm.

The pump-core samples were collected using a custom-built stovepipe sampler (Figure 4). A 16 cm inner diameter (200 cm^2 area), 30 cm length piece of ABS pipe was fit with a

[4] The dam on Martis Creek is operated to provide temporary storage for flood control purposes, and typically stores a minimum pool of only 800 acre-feet (California DWR 1991). We presume that it has a bottom-release outlet, such that the dam may block sediment passage temporarily, but does not manipulate sediment transport dynamics or discharge to the extent of other reservoirs on Truckee River tributaries.

polyurethane foam collar that extended 2 cm beyond an inner-beveled edge at one end. The collar formed a seal around the sampler as it was pushed into the substrate to be sampled. Once seated, the substrate inside the sampler was disturbed by hand to entrain sediment and organisms and to remove any large pebble- and cobble-size substrate particles present. Three liters of water and sediment inside the sampler were then pumped into a bucket using a 4.5 cm diameter hand bilge pump (Figure 5). Following pumping, the sediment was disturbed once more by hand to entrain sediment and organisms, and five sweeps of the sediment surface were made with a 10 cm wide, 100 µm aquarium net, followed by one sweep of the water column.

After collection, each sample was processed on the stream bank to quantify the settled volume of fine (i.e. <1 mm) granular and non-granular material, and to separate invertebrates for preservation and identification (Figure 6). Each sample was first passed through a 1 mm mesh, stainless steel sieve into a bucket and washed using a plastic wash bottle filled with stream water. The coarse fraction remaining in the sieve was set aside for processing (*i.e.*, removal of leaf and wood debris and sediment). The fine fraction was allowed to settle for three minutes, and then the supernatant was slowly poured through a 100 µm aquarium net so that less than one liter of settled particles and water remained in the bucket. Invertebrates and sediment in the net were saved as part of the macroinvertebrate sample. The remaining sediment and water were poured into a one-liter capacity Imhoff cone, filled to capacity with supernatant, and allowed to settle for ten minutes. Imhoff cones were held in a metal frame mounted to a wood base with a bubble-type level (Figure 7). After settling, the volume of granular (*i.e.*, faster settling and coarser-appearing particles) and non-granular sediment in the cone was recorded. The interface between these two fractions was generally obvious (*see* inset Figure 7). The material in the cone was then processed. Following processing, invertebrates from all of the sample fractions were combined and preserved in ethanol and rose bengal (a stain to aid in laboratory processing) for transport to the laboratory.

Targeted Riffle Sampling

At each site a single targeted riffle sample, consisting of eight composited kick samples, was collected from riffles located in the main channel from 25 to 125 m downstream of the confluence with each tributary. Kick samples were collected with a 500 µm mesh D-frame net by disturbing a 30-by-30 cm (1 ft^2) area upstream of the net for a constant effort of approximately 30 seconds by hand. At sites with a sufficient number of riffle series available, two kick samples each were collected from each of the four longest riffle series, taken at mixed positions within each riffle series. If fewer riffle series were available, the samples were assigned by proportion to the size of each riffle. The kick samples were combined in a bucket, and processed to clean and remove most leaf and wood debris and sediment. The remaining sample was strained through a 100 µm aquarium net and preserved in ethanol and rose bengal for transport to the laboratory.

Macroinvertebrate Identification and Analysis

Following transport to the laboratory, macroinvertebrate field samples were subsampled using a rotating drum splitter, if necessary, and organisms were removed and sorted from subsamples under a 10X stereomicroscope and identified to the lowest practical taxonomic level (usually genus; species when possible based on the availability of taxonomic keys; except for Oligochaeta and Ostracoda which were not identified further). For the targeted riffle samples, a minimum count of 550 organisms was identified, with each subsample sorted and identified entirely to exceed this count. For the pump-core samples, all organisms were sorted and identified from each sample, except for one sample (Martis B250), which had an anomalously high density of organisms and was split once. All stages of sample processing and identification were checked using quality control procedures to assure uniformity, standardization, and validation (Herbst 2001).

For both the targeted riffle and pump-core samples, a suite of density and relative abundance metrics representing taxonomic composition and community structure and tolerance were calculated. In addition, a provisional 10-metric Index of Biological Integrity (IBI) score was calculated for each targeted riffle sample (Herbst & Silldorff 2006). Targeted riffle samples were statistically subsampled using a randomization technique to a fixed count of 500 organisms for calculation of community metrics and the IBI. These metrics and scores were compared among sites, to the sediment deposition volume measurements taken with the pump-core samples, and to estimated tributary sediment loads reported by McGraw *et al.* (2001).

For the pump-core sample data, we applied an ordination technique that compares all of the organisms in a sample with those in all others and plots the samples on axes such that the most similar sites are closest together. This technique, called nonmetric multidimensional scaling (NMS), can also used be used to examine whether the locations of plotted samples are correlated with environmental variables, in this case, sediment volume. It effectively reduces correlated or redundant information in the taxa data such that as much unique information as possible is represented in as simple a fashion as possible. Importantly, the correlation of each axis with individual taxa or environmental variables can be calculated, enabling an analyst to determine which taxa are driving the differences between samples, as well as to explore explanatory variables that influenced the patterns observed in the ordination.

All ordination calculations were completed using PC-ORD software (McCune & Mefford 1999). Each NMS ordination was derived from the calculation of a dissimilarity matrix using the Sorensen distance measure, an index of how close ("distant") or similar communities are in the make-up of their constituent species (McCune & Grace 2002). In order to determine whether certain taxa or certain samples might influence the ordination unacceptably, Sorensen distance matrices were calculated for raw abundance, abundance relativized by sample (*i.e.*, relative abundance for all taxa at each site summed to 1), and abundance relativized by taxa (*i.e.*, relative abundance for each taxon at all sites summed to 1). The variance of samples for each input matrix was then calculated to identify potential outliers. Ordinations were calculated using taxa ranging from all of the taxa collected (n = 144) to those occurring at 10 or more sites (n = 49; *i.e.*, so that the effect of rare taxa could be examined, if any). All ordinations were evaluated based on separation of samples in space, correlation with sediment volume, and biological relevance, with the most representative selected for presentation and further analysis. For the selected ordination, the correlation coefficients between each taxon and the ordination axes were examined to determine which taxa were influential in the ordination. The correlation of each axis with sediment volume was also calculated to determine the degree to which sediment volume corresponded with community composition.

Sediment pump-core samples were categorized into four groups based on the quartile values of sediment volume (*i.e.*, lowest 25% of samples, etc). Within-group agreement and between-group distinctness were tested using Multi-Response Permutation Procedure (MRPP) with Sorensen distances (McCune & Grace 2002). This procedure yielded two statistics: an *A*-statistic ($-1 \leq A \leq 1$), describing the effect-size of the grouping, and a *p*-value indicating the likelihood that the calculated differences were due to chance. Samples grouped by site (*i.e.*, adjacent tributary) were also tested.

Finally, a Mantel test was used to evaluate the correlation between the macroinvertebrate community composition Sorensen dissimilarity matrix and a matrix of the longitudinal distance of each site along the Truckee River. The longitudinal distances were estimated to the nearest kilometer manually using a map, and the same distance was used for each sample collected from the site. Similar to MRPP, this procedure yields two statistics: the standardized Mantel statistic ($-1 \leq r \leq 1$), describing the effect-size of the correlation between the two matrices, and a *p*-value estimated from a Monte Carlo randomization test to evaluate the likelihood that the calculated effect-size was due to chance.

Sediment Dry-Weight Density

To characterize the dry-weight density and organic content of the granular and non-granular sediment fractions measured in the Imhoff cones, two additional pump-core samples were collected at the Juniper Creek site. Two replicate aliquots each of the granular and non-granular fractions from each sample were collected and sealed in vials for transport back to the laboratory. At the laboratory, the volume of sediment in each sample was measured, each sample was dried in an oven at 60^{o}C, weighed, ashed in a furnace at 500 ^{o}C, and weighed again to determine both ash-free dry mass and the mass of inorganic matter in each sample. The mean of the four replicates of both granular and non-granular fractions were used to calculate the dry-weight densities of each fraction. This density then allowed for the calculation of the approximate mass of sediment deposited per-area of each sample (*i.e.*, kg m^{-2}), for potential comparison with other studies.

Results

Pump-Core Samples

Sediment Dry-Weight Density

The mean sediment dry-weight densities of organic and inorganic matter in the granular and non-granular Imhoff cone fractions in the Juniper Creek samples are summarized in Table 2. With one exception, the densities of each of the replicates were in good relative agreement, as indicated by the relatively low standard deviations. One of the inorganic fraction replicates was the exception; its value was an order of magnitude different from the others, and therefore was excluded from the calculation of the mean and standard deviation. The lighter, slower-settling fraction, termed “non-granular,” contained 11.5% organic content by weight (dry), while the “granular” fraction contained 3.5% organic matter.

Table 2: Summary of mean ± standard deviation dry-weight density of organic and inorganic matter for granular and non-granular sediment fractions measured in pump-core samples settled for 10 minutes in Imhoff cones.

	Dry-Weight Density (g ml^{-1})	
Sediment Fraction	**Organic Matter**	**Inorganic Matter**
Non-granular (~silt-clay) (n = 4)	0.026 ± 0.001	0.20 ± 0.03
Granular (~fine sand) (n = 3)	0.040 ± 0.002	1.10 ± 0.09

These mean values are assumed indicative of the dry-weight density and organic content of all of the samples, however there may have been some site-to-site or sample-to-sample variability, which was not quantified. For this reason, all pump-core sample sediment measurements are presented as sediment volumes. Using the mean values to calculate dry-weight densities for all pump-core samples, the quantity of total fine sediment (<1 mm) mass-per-area ranged from approximately 118 to 28,200 g m^{-2} in the 42 samples collected on the middle Truckee River.

<u>Sediment Volume</u>

Total settled volumes of sediment in the 42 samples ranged from 4.5 to 570 ml. Sample sediment volumes were biased to the lower third of this range (*i.e.*, 39 of 42 samples had sediment volumes of 210 ml or less). Volumes of the granular and non-granular fractions ranged from 1.5 to 480 ml and 3 to 110 ml, respectively. The ratio of granular to non-granular sediment fraction volumes ranged from 0.3 to 55, and the granular and non-granular fractions were not well correlated (Figure 8). The volume of the granular fraction exceeded that of the non-granular fraction in 30 of the 42 samples. Because the granular and non-granular fractions were not well correlated, and subsequent analyses did not reveal any useful correlations between either of these fractions and the macroinvertebrate community, all analyses that follow are reported using only the total sediment volume.

Some differences in total sediment volume were apparent upstream and downstream of each tributary within and between sites (Figure 9). However, given limitations in the number of samples collected and the amount of variability within samples from each site, statistically significant (*i.e.*, p>0.05) inference from these differences was not possible. Only one sample was taken upstream at each site, such that statistical significance could not be calculated upstream versus downstream of tributaries within sites. Standard deviations of mean values for downstream samples at each site overlapped, indicating that differences in mean sediment volume between sites were not statistically significant. The mean value for the downstream Martis Creek samples was particularly influenced by one sample (B250) that had a sediment volume of 570 ml; the mean and standard deviation of the other four samples was 148 ± 95 ml, similar to values at the other sites.

<u>Macroinvertebrate Community</u>

Review of the macroinvertebrate community data prior to analysis indicated a departure in the Trout Creek pump-core samples. The density and composition of the macroinvertebrate community in these samples uniformly deviated from that at the other six sites. Mean and standard deviation of density and total taxa richness in the Trout Creek samples (n = 6) was 4,750 ± 2,400 organisms m^{-2} and 15 ± 8 taxa, respectively, compared to 35,550 ± 24,860 organisms m^{-2} and 35 ± 8 taxa in all other samples (n = 36). Furthermore, as presented in the next section, the macroinvertebrate community measured in the targeted riffle sample at Trout Creek did not deviate substantially from that at the other sites, indicating that the community measured in the channel margin at Trout Creek was depauperate relative to the other sites, but that in the main channel it was not. Based on these factors, we concluded that the margin habitat at the Trout Creek site was substantially affected by factors other than sediment alone, and therefore pump-core samples from the Trout Creek site were excluded from the analysis of the macroinvertebrate pump-core sample data. Most pump-core samples were taken very close to the bank margins at the Trout Creek site because the habitat was otherwise too deep to sample using the pump-core. These edge areas may be regularly exposed due to fluctuating flows from dam releases upstream. Other factors that potentially affected macroinvertebrates in the pump-core samples at Trout Creek include proximity to the large concrete pylons of the highway 267 bridge overpass and nearby railroad bed and tracks, accessibility by trails and paths, and stormwater run-off from the City of Truckee.

Sediment volume of pump-core samples showed a relationship to selected macroinvertebrate community metrics in the pump-core samples from all tributary locations, excluding Trout Creek (Figure 10).[5] The metrics selected for presentation generally exhibited the strongest relationships between sediment volume and macroinvertebrate community response, and represent various aspects of the community that would be expected to respond to sediment deposition. Scatter is apparent in each of these plots, indicating that sediment volume is not the only explanatory variable for the community metrics, but a metric response consistently in the direction predicted as sediment volume increased is apparent for each. Excluding the proportion of filterers (*i.e.*, filter-feeders on fine organic particles; discussed below), regression coefficients for linear and logarithmic curve fits for each of these metrics ranged from 0.17 to 0.38 and 0.08 to 0.58, respectively, and all but one had associated *p*-values of less than 0.05, indicating that the slope of the curve fit was statistically significant (Table 3). The directions of each of these relationships were consistent with those expected based on knowledge of how macroinvertebrates respond to environmental stress and pollution in general.

The regression data in Table 3 are not presented to suggest that sediment volume quantitatively predicted community responses according to these values, but rather to describe the directions and nature of these responses, and their significance. Indeed, these data must be interpreted with the knowledge that the range of sediment volumes represented in the samples are biased toward sediment volumes of less than or equal to 150 ml (*i.e.*, 30 of 36 samples). Thus, only six samples were available to describe the community response for sediment volumes between 150 and 570 ml. This small number of samples may have had a strong effect on regression slopes for some metrics, and cannot be considered sufficient to describe the variability in community response at higher sediment volumes. However, these six samples were consistent with the direction and nature of metric responses at lower sediment volumes, and therefore give an indication of the overall response over a much wider range of sediment volumes than if they were excluded.

The proportion of filterers (organisms that feed on suspended organic particles) present in samples exemplified a possible subsidy-stress-gradient response (*aka* hormetic response) that may also exist with other metrics, including total density, tolerant taxa richness, Chironomidae richness, and proportion of Oligochaeta. For these metrics, a small increase in sediment may provide a food or habitat subsidy permitting enhanced growth and abundance (because of the organic content of a portion of the sediment), but greater volumes of sediment become inhibitory to survival as the substrata become choked and buried.

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[5] In all plots and relationships with community metrics in this report the total sediment volume was used. Plots with either the granular or non-granular fractions did not yield additional information or relationships sufficient to warrant presentation individually.

Table 3: Select macroinvertebrate community metric responses versus total sediment volume in pump-core samples, excluding samples from Trout Creek site. A provisional limit value of 100 ml was selected to illustrate differences in these metric values above and below this level (approximating an effect that may be moderated by other environmental factors). The values reported are the median and range for the samples below and above 100 ml (n = 18 for both). The first eight metric listed are plotted in Figure 10.

	Response to Increased Sediment Volume		Regression Coefficient (r^2)		Potential Sediment Volume Limit	
Metric	Expected	Observed	Linear	Logarithmic	<100 ml	≥ 100 ml
Total Taxa Richness	Decrease	Yes	0.17 (*p*=0.01)	0.08 (*p*=0.1)	37 (28 - 49)	34 (18 - 44)
EPT Taxa Richness	Decrease	Yes	0.26 (*p*=0.001)	0.34 (*p*<0.001)	11 (9 - 20)	8 (3 - 20)
Biotic Index	Increase	Yes	0.22 (*p*=0.004)	0.46 (*p*<0.001)	4.6 (2.3 - 6.4)	5.8 (2.8 - 6.2)
Sensitive Taxa Richness	Decrease	Yes	0.29 (*p*<0.001)	0.24 (*p*=0.002)	9 (7 - 15)	8 (0 - 18)
% Tolerant Taxa Richness	Increase	Yes	0.22 (*p*=0.004)	0.24 (*p*=0.003)	21 (11 - 30)	27 (16 - 38)
% Chironomidae + Oligochaeta	Increase	Yes	0.38 (*p*<0.001)	0.58 (*p*<0.001)	49 (10 - 72)	70 (26 - 94)
Filterer Density	Subsidy-Stress	Not Definitive	<0.01 (*p*=0.57)	0.02 (*p*=0.39)	2,300 (300 - 30,600)	4,425 (250 - 39,100)
Dominance (3 taxa)	Increase	Yes	0.17 (*p*=0.01)	0.12 (*p*=0.04)	58 (34 - 68)	63 (43 - 86)
% EPT	Decrease	Yes	0.29 (*p*<0.001)	0.55 (*p*<0.001)	35 (4 – 84)	6 (1 – 67)
% Chironomidae	Increase	Yes	0.19 (*p*=0.008)	0.36 (*p*<0.001)	33 (5 – 57)	50 (1 – 82)
% Oligochaeta	Increase	Yes	0.17 (*p*=0.01)	0.17 (*p*=0.01)	13 (1 – 33)	17 (1 – 73)
Shredder Density	Decrease	Not Definitive	0.04 (*p*=0.23)	0.03 (*p*=0.35)	100 (0 – 2,200)	25 (0 – 950)
Acari Richness	Decrease	Yes	0.25 (*p*=0.002)	0.12 (*p*=0.04)	4 (2 – 7)	4 (0 – 7)

The capacity for tolerance to sediment deposition for the invertebrate community appears to become most consistently evident above 100 ml sediment volume per sample (Table 3). The biotic index metric and metrics that included Chironomidae and/or Oligochaeta taxa, all indicators of a tolerant community, increased to consistent high levels above 100 ml, while diversity measures (*i.e.*, total and EPT richness), which are correlated with communities of high integrity, were generally best below 100 ml. This cutoff was also consistent with the ordination results, presented below.

<u>Community Ordination</u>

The NMS ordinations were performed using all pump-core samples except those from the Trout Creek site, for the reasons discussed in the previous section. The dissimilarity matrices calculated for both absolute abundance and relative abundance (by sample and by taxon) yielded similar coefficients of variation between samples and nearly identical ordination results. Relative abundance relativized by sample was selected for use in further analyses because density differences, which were removed by this relativization, showed little correlation with sediment volume (*see* Table 3). In addition, when not relativized, one sample (Bronco Creek - Blow) was an outlier (*i.e.*, its Sorenson distance was greater than two standard deviations from the grand mean). Ordinations that included a range of all taxa collected to those that occurred at ten or more sites all yielded nearly identical stress, instability, ordination results, and explanatory power with each axis. The selected ordination included all taxa that occurred at five or more (14%) of the sites, which included 75 of the 144 total taxa collected. Thus the data used in the ordination did not include the rarest taxa, which would have added little discriminatory information to the ordination and potentially complicated its interpretation.

The NMS ordination converged on a stable, 2-dimensional solution (stress = 16.8, final instability = 0.00005, $p = 0.0196$). A 2-dimension solution was selected over higher-dimensional solutions because it represented a substantial portion of the information in the dataset (78%) and was simpler to interpret; higher-dimension solutions did not yield additional interpretable pattern separation given the available environmental variable measurements. The coefficients of determination (r^2) for the first and second axes were 55 and 23%, respectively.

For presentation and interpretation, the ordination space was rotated by sample sediment volumes, such that the correlation of sediment volume with axis 1 was maximized (Figure 11). This yielded a correlation coefficient of $r = 0.50$ with axis 1 and 0.02 with axis 2 (Figure 11c). Sample depth had a higher degree of correlation with both of these axes, with correlation values of 0.53 and 0.29, respectively. However, examination of an overlay of depth values indicated that this degree of correlation was an artifact of lower sample depths in the Bear and Squaw creek site samples, most of which plotted in the lower left quadrant of the ordination. Poor correlation of depth with sediment volume and with individual macroinvertebrate community metrics also indicated that the depth was not a relevant explanatory variable.

Despite the correlation between sediment volumes with axis 1 in the ordination, there was substantial overlap between sediment volume classes (Figure 11b). Furthermore, this level of overlap was similar to that found between sites in the ordination (Figure 11a). MRPP analysis using each of the quartile sediment classes as groups (*i.e.*, the total of 36 samples were placed in 4 equal groups of 12 based on the *lowest to 25th percentile, 26th to 50th, 51st to 75th, and 76th to highest*) indicated statistically significant within-group agreement, but a moderate effect size ($A = 0.08$; $p < 0.001$).[6] MRPP analysis of groups determined by sample site indicated a larger effect size ($A = 0.19$; $p < 0.001$). A Mantel test indicated that longitudinal distance along the river was correlated with community composition ($r = 0.60$; $p = 0.001$). Together, these analyses provide evidence that groups formed by site were more cohesive than groups formed by each of the sediment volume quartiles. Also, as distance between sites increased, community dissimilarity increased. These dynamics may be explained by variability in environmental factors between sites, including sediment loading, or differences along the natural continuum of the river independent of differences in sediment loading.

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[6] Values for A are commonly below 0.1 in community ecology, with $A > 0.3$ considered fairly high (McCune & Grace 2002).

The individual taxa that correlated best with axis 1 tended to be those expected to be most affected by sediment (Table 4). Overlays of the abundance of a selection of these taxa that are both negatively and positively correlated with axis 1 illustrate this correlation (Figure 12). These overlays also reveal that even the strongest indicator taxa are not found in high abundance at every site at the end of the axis with which it is most associated.

Table 4: Twenty taxa with highest correlations with Axis 1 of the NMS ordination for pump-core sample community composition. The correlation coefficient of sediment volume with Axis 1 was 0.50 and with axis 2 it was 0.02. The four taxa with relatively high positive correlations with Axis 1 included 3 midge taxa and worm taxa, while 10 of the 16 taxa negatively correlated with Axis 1 were EPT taxa. NMS ordination overlays for eight of these taxa are included in Figure 12.

Taxa	Axis 1	Axis 2
Tanytarsus sp.	0.64	0.14
Paracladopelma sp.	0.49	-0.01
Oligochaeta	0.49	-0.53
Cladotanytarsus vanderwulpi grp.	0.41	0.25
Torrenticola sp.	-0.44	-0.38
Antocha monticola	-0.45	-0.04
Protoptila sp.	-0.46	-0.26
Dugesia tigrina	-0.46	-0.38
Polypedilum aviceps	-0.48	-0.19
Skwala parallela	-0.49	-0.14
Ceratopsyche sp.	-0.50	-0.15
Corynoneura sp.	-0.53	-0.20
Calineuria californica	-0.55	-0.30
Rhithrogena sp.	-0.57	-0.37
Diphetor hageni	-0.59	-0.26
Hydropsyche sp.	-0.59	-0.21
Atractides sp.	-0.62	-0.23
Glossosoma sp.	-0.63	-0.43
Epeorus sp.	-0.65	-0.32
Micrasema sp.	-0.82	-0.29

Targeted Riffle Samples

Community Metrics

Total taxa richness generally increased upstream to downstream, ranging from 36 at Bear Creek to 50 at Bronco Creek (Figure 13a). However, the biotic index was best (*i.e.*, lowest, indicating greater community sensitivity) upstream at Bear and Squaw creeks (Figure 13b). These two sites also had the highest proportion of EPT and sensitive taxa, and the lowest proportion of Chironomidae and tolerant taxa (Figure 14). The proportion of taxa richness for each of these groups was relatively similar between sites, indicating that the communities at all sites were composed of similar taxa, but that they occurred in substantially different proportions. For example, the proportion of Chironomidae organisms was higher at the five downstream sites, but Chironomidae richness as a percent of total richness was similar.

Metric and IBI Scores

The IBI metric scores indicate that most or all of the sites scored high for Trichoptera richness and tolerant taxa richness metrics (Table 5). Many of the sites scored low for Ephemeroptera richness, Plecoptera richness, Acari richness, and shredder abundance. The total IBI scores ranged from 55 to 80. Comparison of reference and test sites used in the development of the IBI indicated that scores of 62 and below were indicative of impaired water quality (Herbst & Silldorff 2006). Three sites, Bear Creek, Martis Creek, and Juniper Creek, scored 62 or below. These sites tended to score low for richness metrics, and in the case of Bear Creek, for dominance. The remaining 5 sites would be rated in the fair to good range.

Table 5: Individual metric and IBI scores for each of the targeted riffle samples based on the provisional 10-metric IBI for the Lahontan region (Herbst & Silldorff 2006). Metric scores range from 0 to 10, with 10 indicating the upper end, in terms of biotic integrity, of the reference site distribution. IBI scores are the sum of the individual metric scores.

	Tributary Confluence Site							
Normalized Metric Scores	Bear Cr	Squaw Cr	Trout Cr	Martis Cr	Juniper Cr	Gray Cr	Bronco Cr	Canyon 24
Total taxa richness	3.0	4.0	7.0	5.5	6.5	8.0	10.0	7.5
Ephemeroptera richness	5.0	5.0	8.3	0.0	5.0	6.7	10.0	8.3
Plecoptera richness	4.0	6.0	2.0	2.0	4.0	8.0	8.0	6.0
Trichoptera richness	8.3	10.0	10.0	10.0	6.7	10.0	10.0	10.0
Acari richness	2.0	6.0	6.0	6.0	0.0	6.0	2.0	4.0
Chironomidae richness as % of total richness	7.6	10.0	10.0	6.9	5.0	7.6	10.0	9.8
Tolerant taxa richness (7-8-9-10) % of total richness	9.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Shredder abundance as % of total abundance	5.2	3.0	4.4	5.9	9.6	3.0	5.2	0.0
Abundance of 3 dominant taxa as % of total abundance	0.0	3.3	9.1	5.0	9.1	7.6	9.3	4.0
Biotic Index	10.0	10.0	10.0	8.7	6.2	9.2	5.4	7.8
IBI Score	**55**	**67**	**77**	**60**	**62**	**76**	**80**	**67**

Comparison with lower Truckee River IBI

We attempted to calculate IBI scores for the targeted riffle samples using the 6-metric IBI developed for the Nevada portion of the Truckee River (Tetra Tech 2004).[7] Except for total

[7] Tetra Tech (2004) did not provide sufficient information to reliably calculate IBI scores. A standard taxonomic effort list was not provided, nor a list of "clinger" taxa or the criteria for their selection. In addition, values given in Table 3 of that report, which provided an example IBI score calculation, could not be reproduced, indicating either error in our interpretation of calculating the IBI score, or error in the calculations by the report's authors.

richness, the suite of metrics in that IBI were distinct from those in the Lahontan IBI, including % Ephemeroptera, % Chironomidae, % dominant taxon, % filterers, and % clingers. In the development of the lower Truckee River IBI, data from only two sites upstream of Reno totaling five samples was used, such that the vast majority of data used in its development came from lower-gradient sites within or downstream of Reno.

For the targeted riffle samples, all sites scored relatively low for % Ephemeroptera. Conversely, all samples scored the maximum possible for total richness.[8] Average scores for the five metrics that could be calculated (*i.e.*, excluding % clingers) ranged from 73 to 84. The ranks of the average scores for each site did not agree with those of the Lahontan IBI scores. For instance, the Bronco Creek site scored the highest using the Lahontan IBI, but lowest using the lower Truckee River IBI. Given that the dataset used to develop both IBIs included sites that were generally different in gradient and surrounding land use, these results indicate that the lower Truckee River IBI is not appropriate for use in the middle Truckee River. As further evidence, the farthest downstream site, Canyon 24, scored 84 using the lower Truckee River IBI, the highest score among the sites we sampled, but ranked fourth using the Lahontan IBI.

<u>Comparison with Predicted Sediment Loads</u>

No trends were apparent between predicted sediment loads for 1996 and 1997 and the IBI scores for the middle Truckee River associated with each tributary (Table 6). In addition, individual macroinvertebrate community metric values were not correlated with sediment load prediction values in either year, nor were predicted sediment loads correlated with mean sediment volumes measured in the pump-core samples. The lower and upper limits of predicted sediment load ranged 2 to 3 orders of magnitude, which were determined from the 95% confidence intervals for a regression of turbidity and suspended sediment concentration measurements (McGraw *et al.* 2001).

Table 6: Estimates of annual sediment loads for each tributary reported to two significant figures (McGraw *et al.* 2001), and the provisional Lahontan 10-metric IBI scores in the middle Truckee River immediately downstream of each tributary in 2004. The tributary load estimates were based on sediment rating curves derived from historic and recent discharge, turbidity, and suspended solids measurements, but were found to greatly underestimate sediment loads compared to the methods in a subsequent study (Dana *et al.* 2004; *see* discussion in the introduction). Values reported are the predicted sediment load, with the range of lower and upper prediction limits in parentheses.

	Tributary						
Sediment Load Estimate (tons yr^{-1})	Trout Cr	Juniper Cr	Bronco Cr	Martis Cr	Bear Cr	Squaw Cr	Gray Cr
1996	120 (6-2,600)	200 (44-890)	210 (59-830)	510 (180-1,500)	510 (35-7,800)	1,400 (270-7,200)	1,400 (550-3,800)
1997	150 (7-3,100)	360 (82-1,600)	450 (130-1,600)	500 (170-1,400)	880 (61-13,000)	3,600 (680-19,000)	6,600 (1,700-27,000)
IBI Score	77	62	80	60	55	67	76

[8] This was the case even excluding all Chironomidae and Acari taxa. Tetra Tech (2004) indicates that Chironomidae were identified to sub-family only, and there was no discussion of taxonomy for Acari.

Discussion

To assess sediment effects over such a large spatial scale, even on a single river, presents a difficult challenge. However, this study does provide evidence that sediment deposition may be impairing macroinvertebrate communities in the middle Truckee River. Most macroinvertebrate community metrics in pump-core samples taken from channel margins were correlated with the quantity of deposited fine sediment. Of the 36 pump-core samples (excluding samples at Trout Cr that were considered unreliable), about half of exhibited loss of integrity evident in a variety of indicators, which corresponded to a sediment volume of about 100 ml/sample area. We do not know if these sediment volumes represent an excess relative to natural background sedimentation, but they do suggest that perhaps only half of marginal deposition zones on the middle Truckee River support the invertebrate biota that signal unimpaired habitat conditions, assuming they represented both a random sample and the range of best and worst conditions at that time, Analysis of overall community composition in pump-core samples also corresponded with fine sediment deposition volume, with most of the indicator taxa found to be consistent with expected sediment deposition sensitivity. Finally, community metrics and IBI scores for targeted riffle samples indicated that biological integrity at 3 of 8 sites on the Truckee River was somewhat impaired relative to reference conditions for the Lahontan Region.

The nature of the responses between sediment volumes and macroinvertebrate community metrics in the pump-core samples was variable, in some cases linear or logarithmic, and in some case indicative of a subsidy-stress gradient response. The percent of filter-feeding organisms suggested a possible subsidy-stress gradient response, where a mid-range sediment volume stimulated the greatest maximum values, but with greater volumes filterers were diminished. Increased sediment availability may provide a subsidy of particulate organic matter, which is the food source for this guild of invertebrates. But as sediment volumes increase, the benefit of this food subsidy for some filterers may be overcome by the deleterious effects of excess suspended or deposited sediments (Strand and Merritt 1997).

Regardless of the shape of the response, most of the macroinvertebrate community responses exemplified capacity responses, a dynamic in ecology that has also referred to as a "solid curve" response (McCune & Grace 2002). These capacities likely represent a ceiling or limit on the response that is attainable for a given level of sedimentation exposure. These levels provide a provisional estimate of sediment volumes at which metric responses showed impairment. For most metrics, the values indicating highest biotic integrity had sediment volumes of 100 ml or less, and impaired responses above this level. Additional sampling may further refine these relationships.

Some additional factors must be considered in interpreting these results. First, the design used in this study attempted to characterize sediment effects over much of the length of the middle Truckee River. In so doing, each site was sampled only once. Thus, any interpretation of these data must rely on the extent to which it can be assumed the sampling methodology represented long-term effects of sediment deposition. Given that the pump-core samples collected from the channel margins were expected to reflect habitat where chronic impacts of deposition exist, this seems a reasonable assumption. However, without multiple sampling events over time, we cannot be certain the degree to which these samples were representative of the conditions of these sites over time.

Second, other environmental factors, besides sediment loads, may have influenced macroinvertebrate community composition. These factors may result from human activities or natural gradients in habitat conditions or food resources. It was assumed in this study that for the stretch of the middle Truckee River studied, the characteristic gradient, discharge, and food resources would be sufficiently similar that natural variability in community composition would be equalized. However, some of the variability in pump-core samples could be explained by the location of each site along the Truckee River. While this may indicate a natural gradient in community composition, these distances may have been correlated with other environmental factors or cumulative anthropogenic influences, including sediment. In particular, the hydrograph of the middle Truckee River is altered by the presence of dams, including at its source Lake Tahoe (storage capacity 744,600 ac-ft), on Donner Creek (9,500 ac-ft), and on Prosser Creek and the Little Truckee River (*i.e.*, Prosser, Independence, Stampede, and Boca reservoirs; *see* California DWR 1991). The Prosser Creek and Little Truckee River reservoirs, which are primarily operated to provide water for municipal and irrigation purposes in the Summer and Fall, have a combined storage capacity of 314,900 ac-ft, and are located upstream of Juniper, Gray, and Bronco creeks (Figure 1a). In contrast, the river's hydrology at Bear and Squaw creeks is influenced primarily by releases from Lake Tahoe (Figure 1b). Thus, not only does discharge increase downstream, but the shape of the daily and seasonal hydrograph is increasingly altered downstream. In some years, there is no discharge from Lake Tahoe. Water year 2004, during which the samples in this study were collected, was a relatively dry year, with the daily measurements at the Tahoe City gage all below 100 cfs in the month preceding sample collection, and declining to zero later in September. In this study design, we could not control for these effects. We also could not control for effects from varied levels and locations of urbanization and reduction in vegetative cover, which, along with hydrology, may be intimately coupled with sediment supply dynamics and the resulting biological effects. Additional correlated measurements of environmental factors and macroinvertebrate community data could further elucidate these dynamics, and characterize the system under different hydrological conditions.

It was expected that the influence of sediment discharged from the various tributaries would be sufficient, and of enough variability between tributaries, that a sediment dose gradient could be detected using the pump-core sampling technique of this study. However, there were no clear patterns in fine sediment deposition volumes between up- and downstream samples within tributary sites, nor in mean values compared between sites (Figure 9). It is possible that such patterns could have been detected with a greater number of samples and/or different sample location selection criteria, but the data gathered were inadequate to draw sound statistical conclusions and were not scaled to reflect broad geomorphic patterns in channel deposition. The locations of downstream deposition of fine particles carried by tributary inflows results from a dynamic process influenced by a combination of sediment supply and of a stream's competence and capacity (of flows to carry some grain size and volume of sediment). It is the macro-scale geomorphic features that these processes yield that must be characterized, yet most sampling methods measure micro-scale features, requiring a high sampling frequency to characterize these processes. Another method that could be used to characterize downstream deposition patterns between tributaries would be pebble counts at numerous locations along the middle Truckee River. By targeting specific geomorphic features, this approach has proven effective in detecting variable tributary sediment load effects along gravel-bed streams (Rice & Church 1998; Rice *et al*. 2001). Such data, coupled with additional macroinvertebrate sampling, could further define the sediment dose and biological response associated with particular tributaries, and provide additional evidence to evaluate whether increased sediment supply is impairing aquatic life beneficial uses.

The IBI scores from the targeted riffle samples taken from the river suggest mixed and marginal quality of 8 sites along the river. With three sites showing impaired scores, and others in a fair-to-good range, these results leave open the question of how consistent and uniform the benthic invertebrate communities would be in repeated assessments at these and other locations. The pump-core samples did show that increased sediment volume reduced macroinvertebrate diversity and altered the structure and function of benthic communities. While the data collected did not evenly cover the range of sediment deposition observed, or clearly indicate a threshold for all indicators, many measures showed declining integrity above 100 ml settled sediment volume in a pump-core sample, equivalent to approximately 3.4 kg m^{-2} of dry sediment, assuming equal parts granular and non-granular composition (Figure 10). If the frequency distribution of such marginal deposition zones exceeds natural background, then sediment accumulation in the river from human sources may be at the point of producing impaired ecological condition.

Defining the extent of impaired biological integrity resulting from increased sedimentation will ultimately depend on determination of the proportion of transported and deposited sediment that is attributable to human-caused landscape disturbance in the watershed. Complicating such a determination are factors such as that dams on many of the tributaries trap sediment to varying degrees, that some amount of increased sediment supply may not impair ecological function, and that there are only limited historical data available for establishing the reference or natural biological conditions on the middle Truckee River. Geomorphic assessments (as used by Simon *et al*. 2004) may also help in characterizing how different channel reaches have responded to watershed disturbance that alters channel stability and exposes streams to an overload of surplus sedimentation.

We reviewed historical documentation related to impacts to macroinvertebrate communities on the middle Truckee River, however there are many other potential sources of historical information on watershed development and land use that have not been systematically reviewed and synthesized in available reports. In particular, historical maps and aerial photos may allow for an evaluation of the increases in road density and development and changes in land use over the past century, as well as changes in the morphology of the river itself that may be attributable to altered sediment loading. Public agency files may also include documentation of events that could have affected sediment loads. A review of all such available information would assist in establishing background conditions and the nature of changes over time that may have led to increased sediment supplies to the middle Truckee River, both essential for beginning to discern the relative impact of human activities on sediment dynamics and to completing a source assessment for the sediment TMDL. Finally, it is also possible that historical collections of benthic macroinvertabrates are available, which may allow for investigating contrasting biological conditions over time.

Historical documentation and literature reviewed in this study indicates that the native mussel *M. falcata*, nearly eliminated from the middle Truckee River some time after 1941, may only thrive under relatively natural hydrologic conditions and sediment supply regimes. Thus, while the losses of this native species are likely indicative of historical or ongoing hydrologic and sediment impacts, this organism has the potential to serve as an effective indicator for the success of any future restoration efforts for the river. Thus, the recovery of *M. fulcata* populations in the middle Truckee River may serve as one suitable biological endpoint for a sediment TMDL. In addition, further targeted riffle samples and pump-core collections would aid in gauging improvements over time and along the river, under different hydrologic states, and in defining where sediment exceeds limits on biological health.

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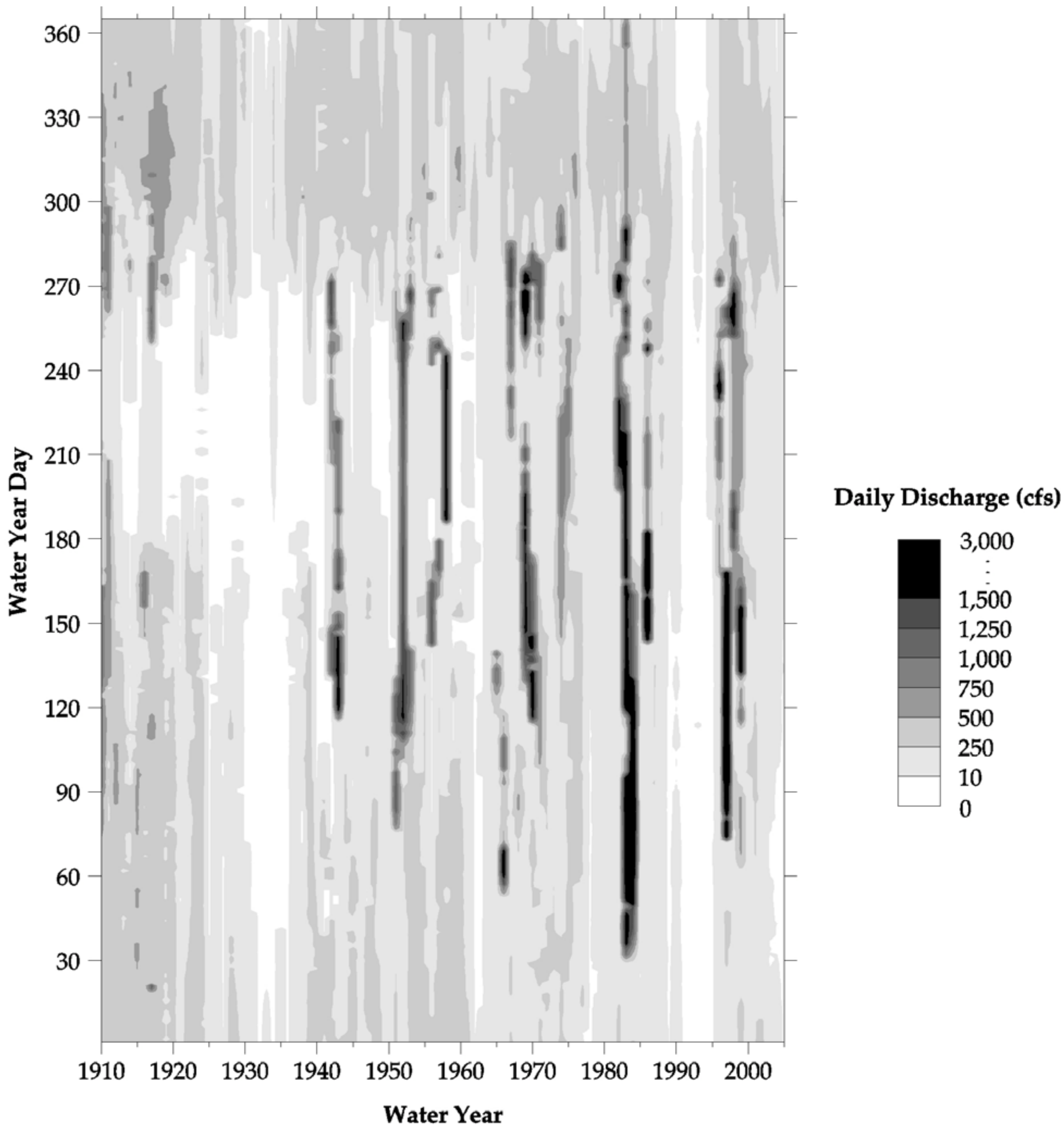
Figure 1: Mean daily discharge contour plots for water years (*i.e.*, 1 October to 30 September) 1910 to 2005 for the middle Truckee River at (a) Tahoe City (Gage No. 10337500), and (b) Farad (Gage No. 10346000).

(a) Discharge at the Tahoe City gage is quite variable year-to-year relative to the Farad gage. The Tahoe City gage is downstream of the outlet of Lake Tahoe, yielding discharge readings of 0 cfs during periods when the lake level is below its spill point. This is apparent during the "dust bowl" drought years in the 1920s and 1930s, as well as in the late 1980s and early 1990s. This plot, and the one that follows for the Farad gage indicate that discharge was also relatively low in the five years preceding this study.



(b) The hydrology at the Farad gage is more often characteristic of a snowmelt hydrograph, and exhibits high discharges with greater frequency than at the Tahoe City gage. It is difficult to interpret what effect human development and activities have had on the characteristics of these hydrographs, although it is possible that the greater frequency of high discharge events in the second half of the 20th Century was caused in part by increased development and extent of impervious cover in the middle Truckee River basin. Releases from dams at Lake Tahoe and on other tributaries would also be expected to significantly affect the hydrograph compared to natural conditions. Characterizing the nature of these hydrographs and any modifications to them from human activities will be essential in developing a TMDL for the middle Truckee River.

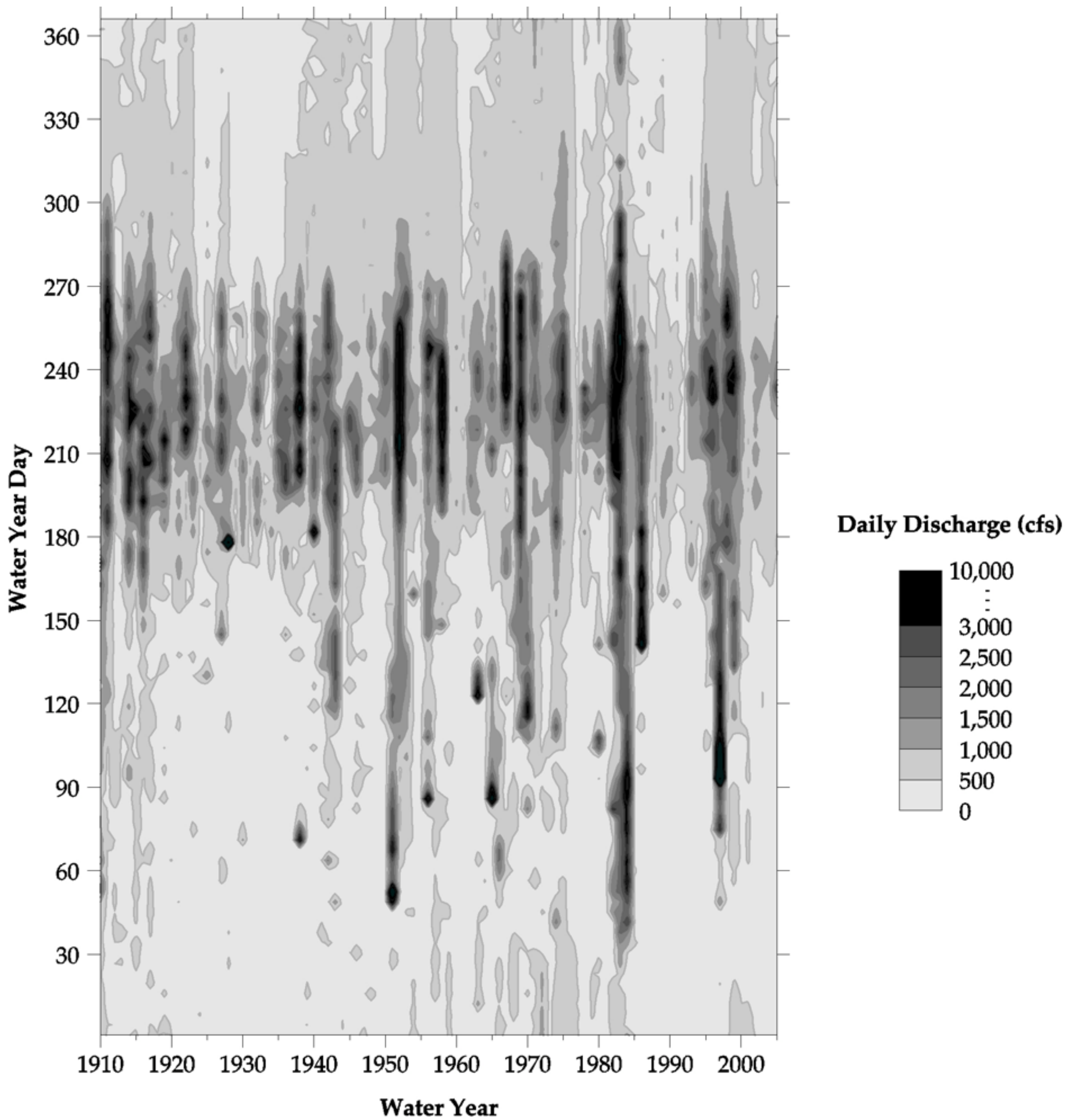


Figure 2: Schematic diagram of idealized wash material transport and deposition dynamics during peak and base flow conditions.

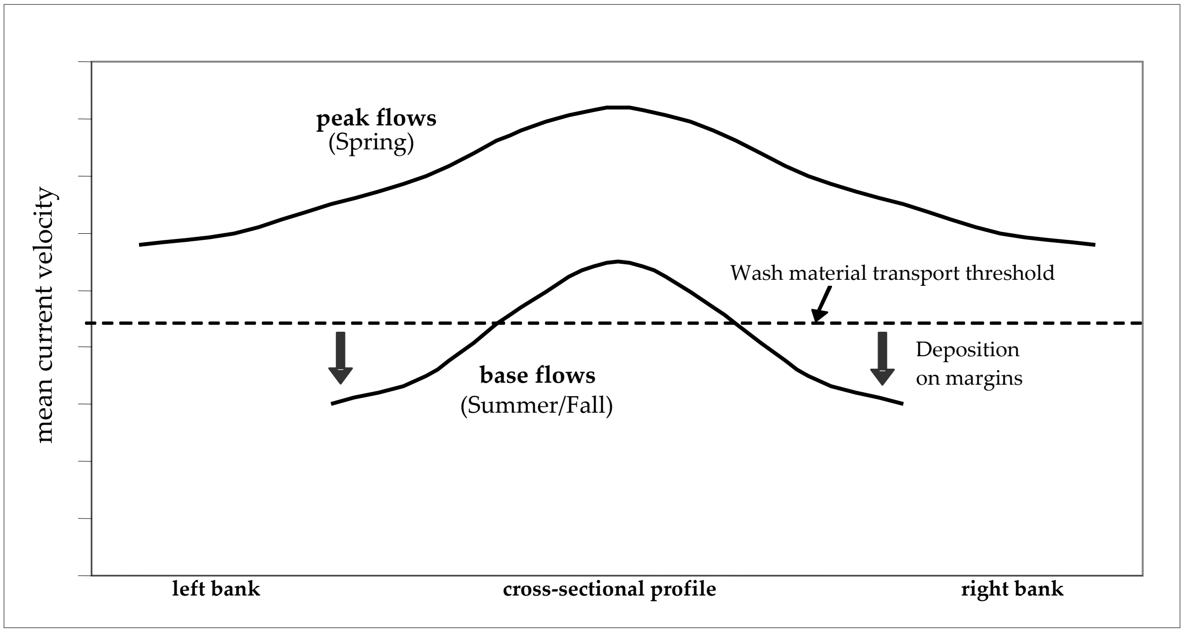


Figure 3: Map of the middle Truckee River tributary site locations.

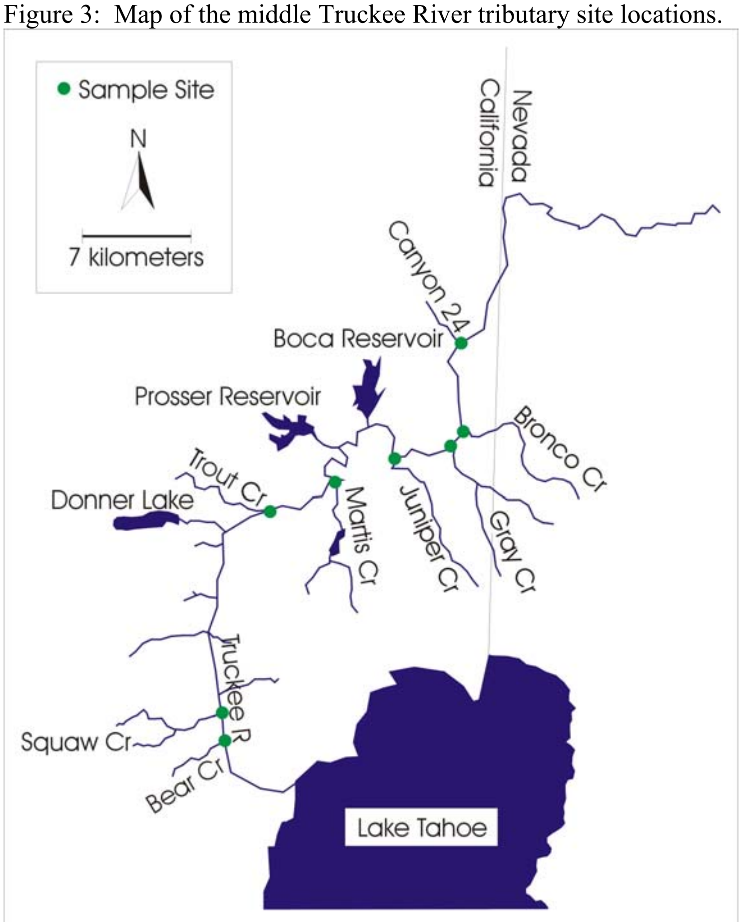


Figure 4: Pump-core sampling and processing equipment, including PVC-pipe sampler, hand bilge pump, sieve, buckets, wash bottle, and Imhoff cones and stand.

Figure 5: Collecting pump-core sample.

Figure 6: Flow chart describing the pump-core sample collection and processing method.

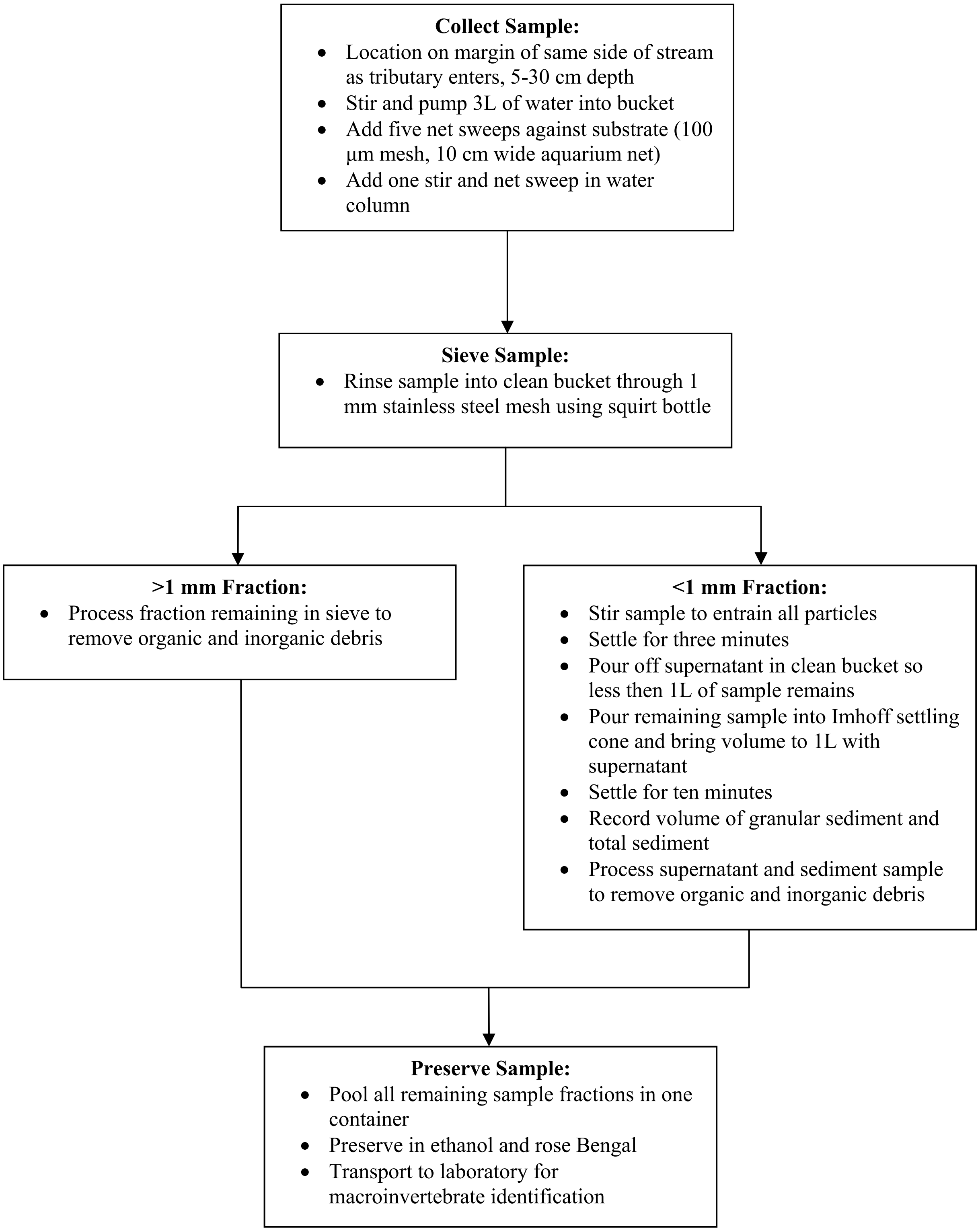


Figure 7: Photo of Imhoff cones with two pump-core samples settling. Inset photo is a close up of the right-hand sample showing the change in color in sediments that appeared granular (bottom) versus non-granular (top).

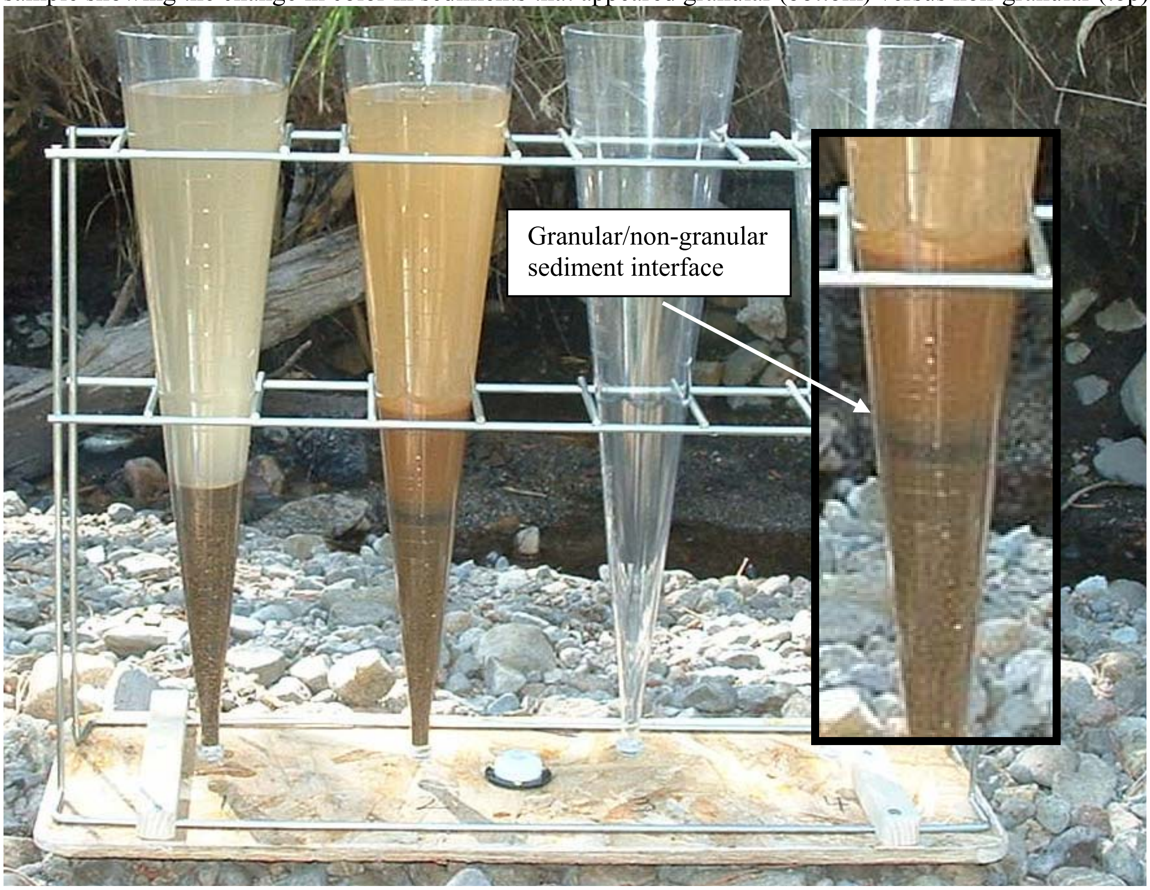


Figure 8: Granular versus non-granular settled sediment volume (200 cm^2 sample area) in each of the pump-core samples. Filled or enlarged symbols are the upstream sample at each tributary. Note the different scales of the axes.

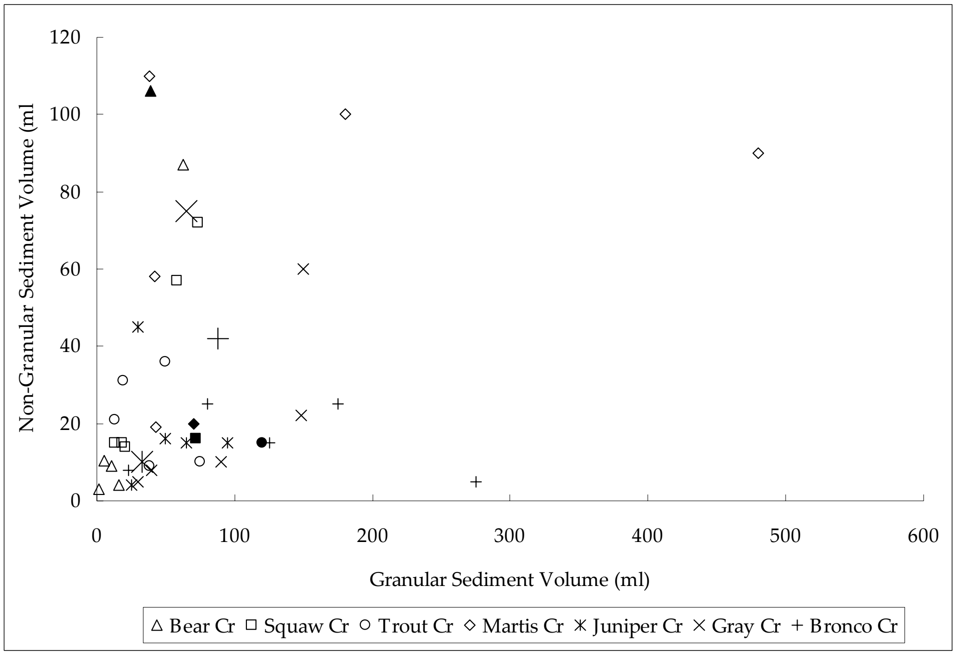


Figure 9: Total settled sediment volume for upstream (n = 1) and downstream (mean; n=5) pump-core samples at each middle Truckee River tributary confluence. Error bars are one standard deviation. Each sample was collected from a 200 cm^2 area and settled in an Imhoff cone for ten minutes. Including the targeted high and low sediment samples did not substantially affect the mean or variance for the downstream samples.

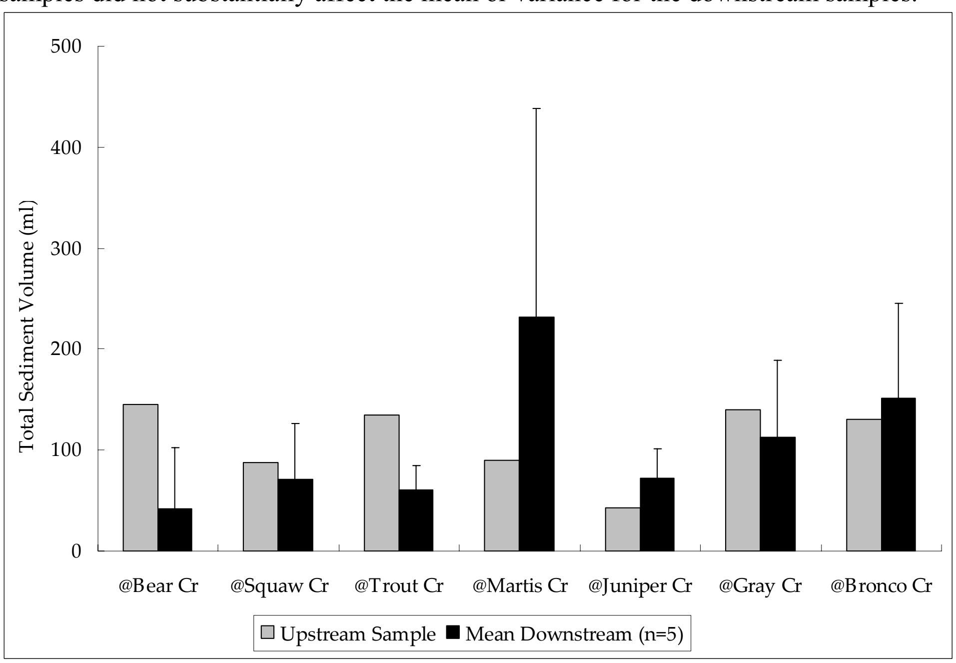


Figure 10: Plots of select macroinvertebrate community metrics versus total sediment volume in pump-core samples, excluding Trout Cr site samples.

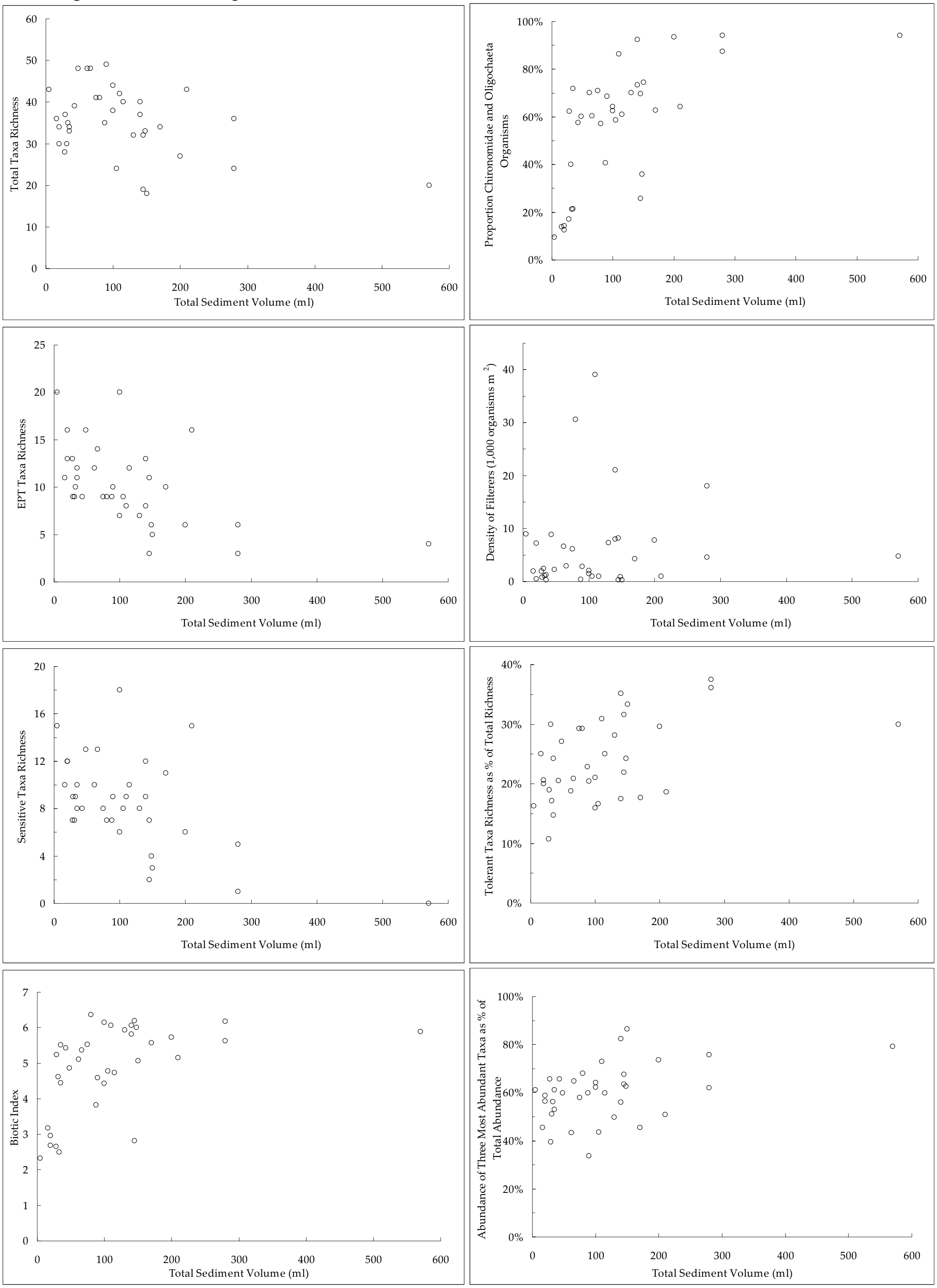
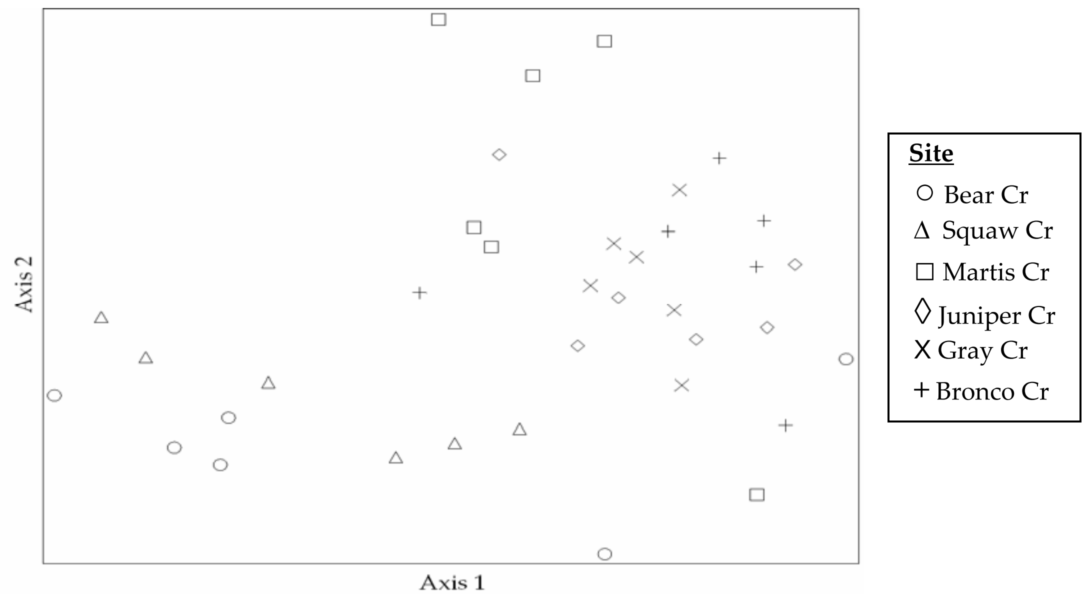


Figure 11: NMS ordination results plotted with Axis 1 rotated to best correlate with sediment volume. Distances between points reflect the calculated dissimilarity in community composition between samples. Samples are coded by (a) site (legend symbols listed upstream to downstream); (b) sediment volume quartiles (*i.e.*, lowest 25% of sites, etc.); and, (c) overlay plot with point-size proportional to sample sediment volume. Note that in each of these plots, and those that following in Figure 12, the location of each point does not change, but to convey the relationship between a point's location and potential explanatory variables, variables are proportionally overlayed as the size of each point. The correlation coefficient of sediment volume with Axis 1 was 0.50 and with Axis 2 it was 0.02. Ellipses of Fig. 11b show minimal overlap between 15 of 18 samples from lower quartiles, and 14 of 18 from the upper 2 quartiles (these groups separated above and below the median sediment volume of 100 ml/sample).



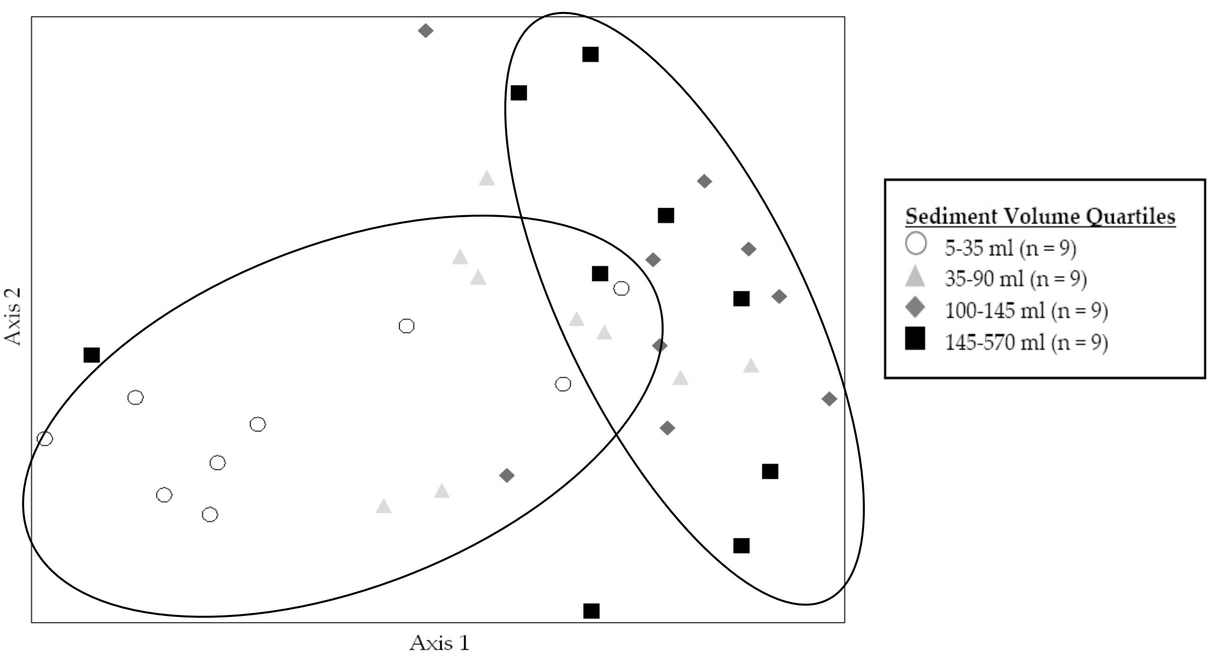


Figure 11c (continued): Sample points are labeled with a sample code that includes the first four letters of each site name and the sample location.

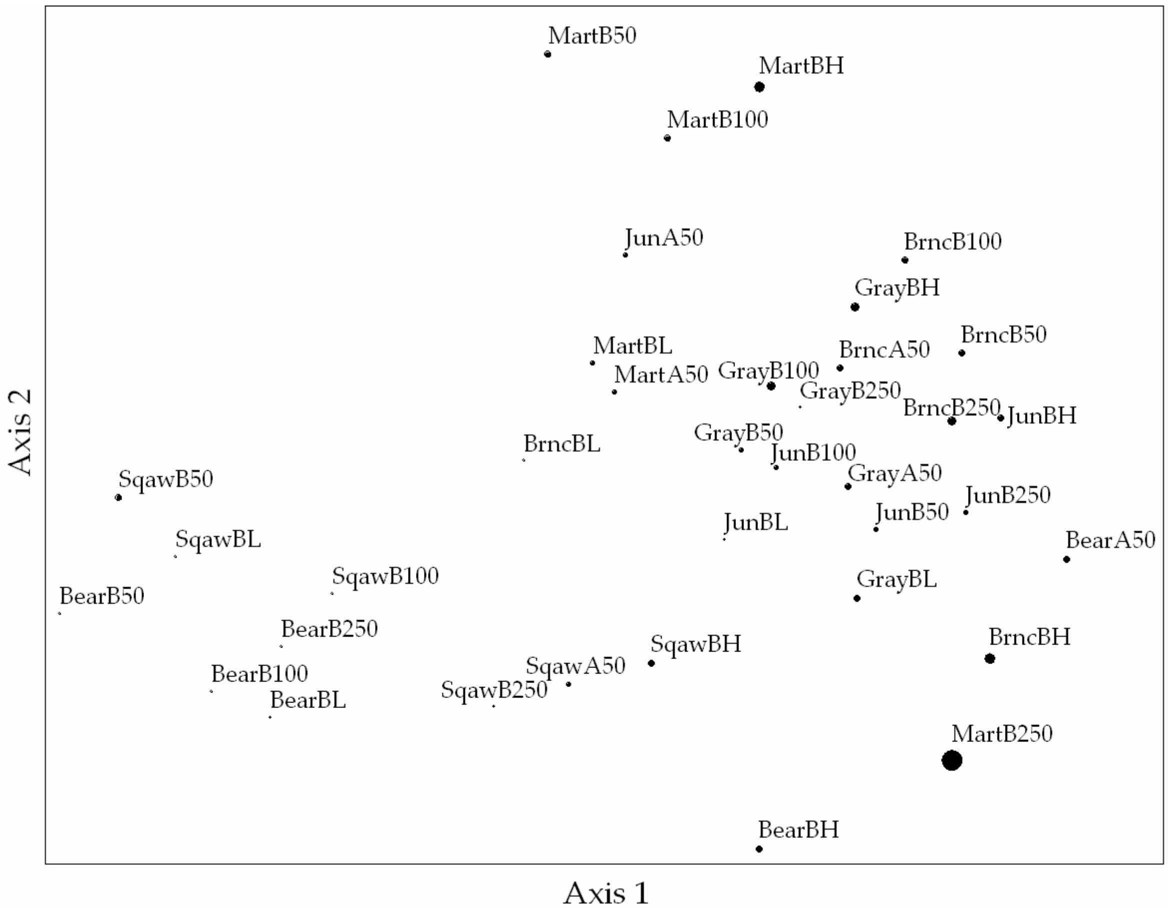


Figure 12: NMS ordination overlay plots of individual taxa having highest correlations with Axis 1. The size of the circle is proportional to the abundance of each taxon at each site.

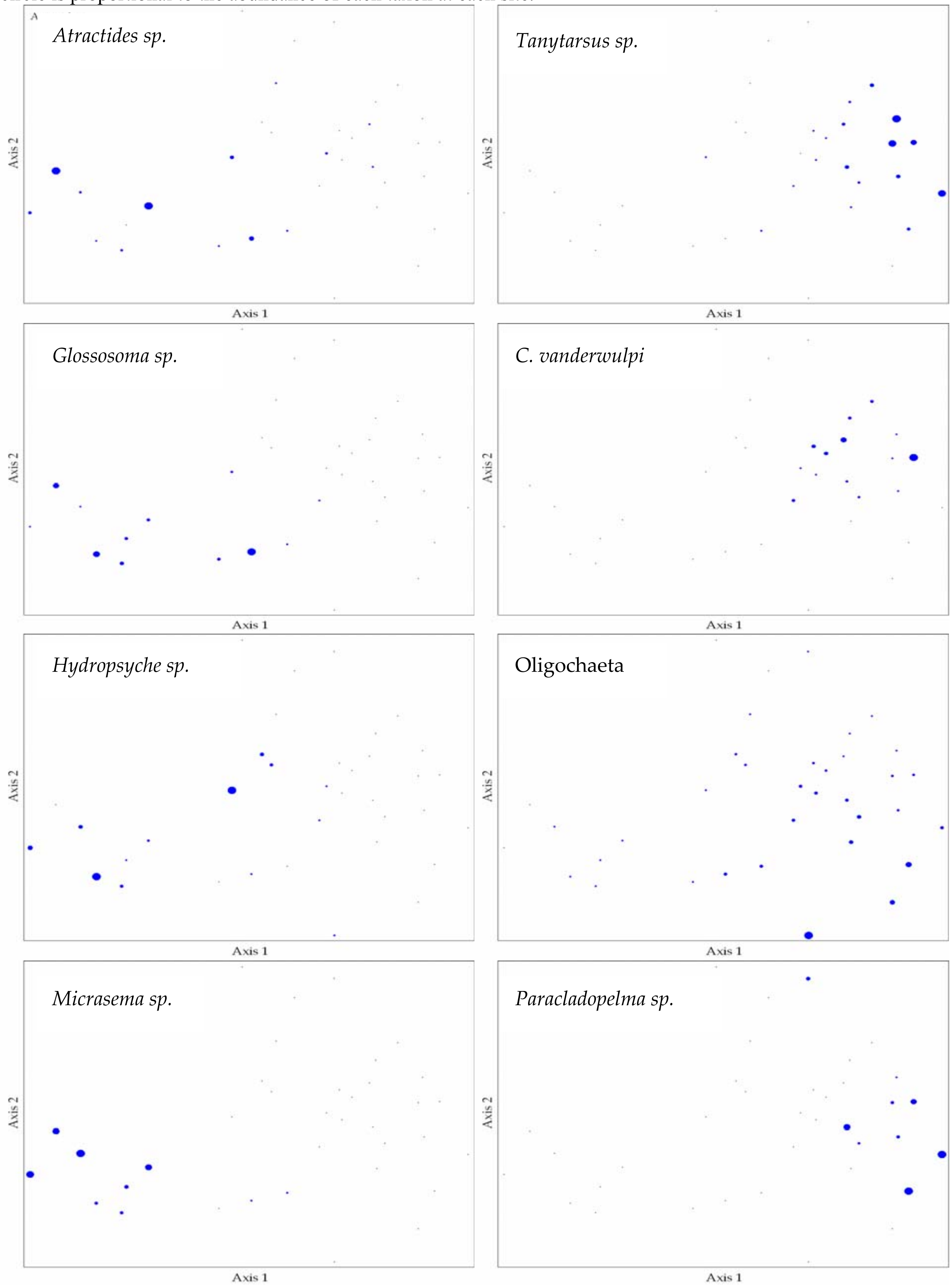


Figure 13 (a) Total taxa richness, (b) biotic index, and (c) provisional Lahontan IBI score for targeted riffle samples arranged left to right from up- to downstream.

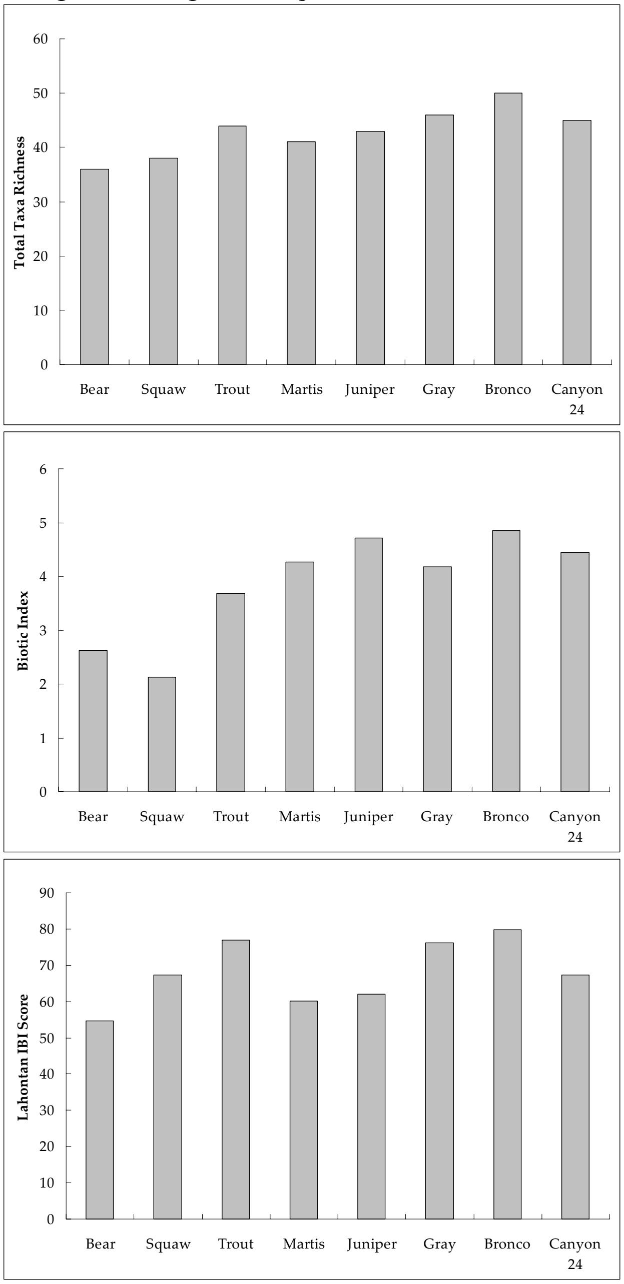


Figure 14 (a) Proportion EPT, (b) proportion sensitive organisms, (c) proportion Chironomidae, and (d) proportion tolerant taxa in the targeted riffle samples arranged left to right from up- to downstream. Measures of the total number of organisms and the total number of taxa in each category are displayed.