Sediment Retention on a Deltaic Floodplain in Response to Climate and Land-Use Changes

Steven Matthew Winter
University of California, Davis,
USA

Eric W. Larsen
Department of Environmental Design,
University of California, Davis,
USA

Report to the California Tahoe Conservancy

June 2006

Keywords: floodplain, land-use change, Lake Tahoe, marsh, suspended sediment, climate change, water quality, wetland, nutrient transport, watershed disturbance.

Abstract

The Lake Tahoe basin on the borders of California and Nevada, USA, has been subjected to two major phases of anthropogenic disturbances to sediment and nutrient transport processes: the construction of roads and timber harvesting in the 1860's and urbanization in the 1950's and 1960's. The Upper Truckee Marsh is located on a delta formed where the basin's two largest drainages (the Upper Truckee River and Trout Creek) flow into the southern end of Lake Tahoe. The marsh system – through its sedimentation record - provides an integrated record of the geomorphic effects of watershed disturbances. This study determined that sedimentation on the Upper Truckee Marsh is primarily a function of climate and land-use changes, and only secondarily of lacustrine processes. ^{14}C and ^{137}Cs dating procedures were used to investigate sedimentation rates on the marsh in the pre-disturbance era (10^3 yr scale), and in the post-urbanization era (the past 50 yrs). Mass sedimentation rates range from 0.025 to 0.075 g cm^{-2} yr^{-1}, and from 0.14 to 1.12 g cm^{-2} yr^{-1} for long term and short term (i.e. post-urbanization) periods, respectively. While the mid- to late-Holocene sedimentation record incorporates significant shifts in climate, the increase in sedimentation rate from 1950 to the present indicates that land-use changes have had an impact on the geomorphology of the Upper Truckee Marsh with increased overbank sedimentation rates. These results suggest that the Upper Truckee Marsh has the potential for future sediment and nutrient retention, which makes the site a good candidate for restoration efforts to reconnect a degraded (incised) channel, the Upper Truckee River, and floodplain systems to reduce impacts to Lake Tahoe's water quality.

Introduction

River-floodplain interactions are key ecosystem processes that process floodwaters and cycle sediments and nutrients into and out of the river system (Wolman 1957, Leopold et al. 1964, Knighton 1984, Peterjohn and Correll 1984, Johnston 1991, Mount 1995, Walling and He 1998b, Walling 1999, Craft and Casey 2000, Johnston et al. 2001, Walling et al. 2003). Anthropogenic changes in watersheds often have the effect of disconnecting the river from its floodplain via channel incision, damming for flood retention, and/or construction of levees (Dunne and Leopold 1978, Mount 1995). The disconnection of a river from its floodplain results in drainage systems that act as conduits for sediment and nutrients (Schumm 1973, Schumm et al. 1984, Craft and Richardson 1993). In recent years, the re-connection of rivers with their floodplains has become a primary goal of river restorations (Huggenberger et al. 1998, Wissmar and Beschta 1998).

The hydrologic connections between a river and its floodplain are controlled by several factors, including climate, geology, meander rates, and land-uses in the upper watershed (Wolman 1957, Walling 1983, Harvey and Watson 1986, Huggenberger et al. 1998, Steiger et al. 2001, Whipple and Tucker 2002). However, the relative influence of the controlling variables is unclear, and resists attempts at generalization.

Lake Tahoe is the second deepest lake in the United States. A documented decline in lake water quality since the 1960's has increased awareness in the Tahoe basin regarding the effects of land-use and higher population densities on the lake (Goldman 1988, Jassby et al. 1994, Hatch 1997, Heyvaert 1998, Forney et al. 2001, Stubblefield 2002). The Upper Truckee Marsh is the largest remaining lacustrine fringe marsh ecosystem in the Lake Tahoe basin (Murphy and Knopp 2000). The Upper Truckee

Marsh has been modified from the pre-disturbance condition by a combination of indirect impacts (e.g., land-use change, dam construction and associated rise in average lake level), and direct impacts (e.g., channelization, grazing, development) (Green 1998, Murphy and Knopp 2000, Kim and Rejmankova 2001, EDAW and ENTRIX 2003). The Upper Truckee Marsh provides an opportunity to study the relative importance of geomorphic factors in floodplain development, and in considering different models for marsh floodplain development. The Upper Truckee Marsh responds to changes in the sediment and water transport characteristics of the two streams running through it, and the marsh is also sensitive to lake level fluctuations (EDAW and ENTRIX 2003).

Theories of floodplain construction generally focus on: (1) channel meander rates, (2) overbank sedimentation, (3) baselevel change, (4) hydrologic changes, and (5) sediment supply (Wolman 1957, Schumm 1973, Walling and He 1998b, Blum and Tornqvist 2000). The goal of this study was to use sequence stratigraphy to quantify sedimentation rates on the marsh, and to investigate changes in sedimentation rates and patterns on the marsh. Established dating procedures were used to develop age-depth relations in different areas of the marsh, and provide a temporal context to consider changes in the physical characteristics of sediments being deposited on the marsh. The results of the stratigraphy are considered in the context of climate and land-use changes to attempt to determine the primary geomorphological factors that shape the Upper Truckee Marsh (UTM).

Two models of the effects of climate and sea-level change have been offered (Blum and Tornqvist 2000). The conveyor-belt model attempts to explain deltaic sedimentation by sediment supply/stream power provided by the upper portions of the watershed, while the vacuum cleaner model focuses on changes in base level resulting in the cut and fill of the lower alluvial valleys. Watershed scale processes are hypothesized to have significant impacts on the UTM because changes in land use have directly affected the sediment supply, stream power, and morphology of the streams flowing through the UTM. If watershed scale disturbances have a distinct signal on the UTM, this result will support the conveyor belt theory. Using the measured sedimentation rates from this study, the key geomorphic processes are discussed and are used to give a first-order comparison between the conveyor belt and vacuum cleaner models of sedimentation.

Methods and site description

Site Description

Lake Tahoe has an average depth of 313 m and has an approximate surface area of 500 km^2 (Gardner *et al.* 2000). The retention time of the lake is approximately 600 years (Goldman 1988). The Upper Truckee Marsh, located on the southern end of Lake Tahoe, exists on a delta that has formed as the Upper Truckee River and Trout Creek flow into the south side of the lake (Figure 1). These two streams are the largest single contributors of water, sediment, and nutrients to the lake (CDSC 1969, Hatch 1997, Rowe and Allander 2000, Rowe et al. 2002, USGS 2002) and account for 31% of Lake Tahoe's watershed (Rowe and Allander 2000). The Upper Truckee Marsh has been fragmented by development, and was once contiguous with Pope Marsh, further to the west (Green 1998, Kim 1999) (Figure 1). Recently Stubblefield et al (ref) described the sediment transport of these two streams and concluded that there is currently deposition on the marsh surface due to the two streams.

The Upper Truckee River and Trout Creek watersheds begin high along the rim of the Tahoe basin in intrusive granodioritic Sierra Nevada batholiths (Burnett 1971, Gardner *et al* 2000). Glaciations of the high Sierra in the last 5-10 million years have eroded significant amounts of sediment from the upper watershed, depositing a significant glacial outwash plain in the lower alluvial valley (Birkeland 1963, Curry 1966, Blum 1979, Phillips et al. 1996, Rowe and Allander 2000, Bischoff and Cummins 2001). Gravimetric measurements indicate that the wedge of glacial outwash materials is on the order of 1,600 feet thick at the edge of the lake (Blum 1979).

The Lake Tahoe basin and the UTM have been significantly modified by human activity over the past 150 years. In the mid 1800's, the discovery of silver in Nevada resulted in immediate demand for the timber of the Lake Tahoe Basin (Heyvaert 1998; Murphy and Knopp 2000), resulting in widespread deforestation, and direct manipulation of the Upper Truckee and Trout channels to facilitate the moving of logs into the lake. In addition, altering the marsh and drainage patterns for cattle grazing operations appears to have taken place. In the 1960's vacation homes and resorts along the lake began to draw significant numbers of people to the area on a permanent or temporary basis (Murphy and Knopp 2000). Greater population density resulted in development of a portion of the UTM and significant development in the upper watershed (CDSC 1969, Murphy and Knopp 2000). Urbanization and continued logging of the watershed is assumed to have decreased the time to peak and increased the magnitude of storm runoff peaks in the stream channels, as less forest cover and greater areas of impervious surfaces direct stormwater directly into the river systems (Dunne and Leopold 1978).

Construction of a dam at the outlet at the Truckee River (note that this is at the other end of the lake and is not the Upper Truckee River) has influenced lacustrine processes on the Upper Truckee Marsh. The dam on the Truckee River at Tahoe City has the capacity to increase lake level up to 2.3 meters above the natural rim, raising the average lake level to 6225 ft above sea level NGVD, 0.6 meters higher than the natural rim. This process is likely an important element in the geomorphology of the UTM during wet years, when the additional storage can be used, thereby raising lake level into the site, and increasing the groundwater elevation. In dry years, however, the additional storage likely is not a large factor after the lake drops below the outlet, and no longer naturally flows into the Truckee River (Berris *et al.* 2001).

Geomorphology & Sedimentation

All sediments on the UTM have been deposited and/or reworked by flowing water. The interaction between the Upper Truckee River, Trout Creek, and Lake Tahoe results in spatially and vertically heterogeneous sedimentation patterns typical of floodplain sediments (Wolman 1957, Huggenberger et al. 1998). Sedimentation patterns on the UTM reflect river meandering in the construction of bars on the inside of meander bends, with associated erosion of the outer channel banks; overbank flooding as the sediment load of the river is deposited on the floodplain during high flow events; and lake level fluctuations as the level of the receiving basin varies in time. The patterns on the Upper Truckee Marsh appear to be typical of patterns in deltaic environments (Wolman 1957, Gallaway 1975, Colman 1976, Elliot 1986, Easterbrook 1993, Walling and He 1998b, Boggs 2001).

The UTM site is largely cut off from direct wave action of the lake by a barrier beach, which is currently only open at the mouth of the UTR. Historical air photos and anecdotal evidence indicate that at least one branch of Trout Creek flowed out of a second opening in the barrier beach, further east from the current opening. Analysis of air photos indicate that the mouth of the UTR has been relatively stable, ranging over a 300 meter distance until the mouth was hard-engineered into its current location in the late 1960's (EDAW and ENTRIX 2003).

Vertical sediment accretion can occur via overbank deposition during flood events, or during the process of river meander migration as the channel bank on the inside of the curve is deposited. Inspection of air photos of the UTM spanning the last 65 years indicate that meander migration is not a dominant fluvial process, nor is channel avulsion where an entirely new channel is formed. Changes in channel plan form do occur, but in general, these changes are limited to switching between already established channels.

Lacustrine processes have helped to shape the UTM site over the Holocene (Murphy and Knopp 2000). Climatic changes have resulted in high lake stands as glacial ice blocked the one outlet of the lake (Birkeland 1963, Burnett 1971). Droughts have caused lake level to drop well below the "natural rim" at 6223 feet above MSL-NGVD datum (Lindstrom 1990). Shifting lake levels should have significant impacts on sedimentation patterns. Low lake stands have lower groundwater levels on the site, and lower baselevel of streams (Green 1998, Rowe and Allander 2000). As groundwater levels drop, the extent of soil saturation is limited, allowing decomposition rates of organic materials increase. Lower baselevels effectively increase the longitudinal slope of the streams, increasing the erosion potential, which could result in channel incision.

Climate and Watershed Changes

The climate of the Tahoe basin features cool dry summers and cold snowy winters. Precipitation patterns tend to include rain storms in the fall and late spring, with snow falling in late fall through early spring. Average snow accumulations in the upper part of the watershed are around 1.1 m, with the average dropping to 40 cm in the middle of the watershed (ref?). The melting of the snowpack has a significant influence on the rate and magnitude of stream discharges through the UTM site. Rain on snow events have resulted in the significant runoff peaks in the Upper Truckee River and in Trout Creek.

Significant changes in climate have occurred in the past several thousand years (Barlein 1997). Changes in climate have the potential to change the types of geomorphic processes that occur on the UTM and the surface elevation of Lake Tahoe. Fluctuations in lake level have the potential to cause significant deposition and scour as the baselevel to which the stream channels can erode fluctuates (Florsheim *et al.* 2001). There is physical evidence in the basin of much higher and much lower lake stands than are indicated in the historic record (Lindstrom 1990, Murphy 2000). Studies of climate change over the Holocene offer some general patterns of oscillations between warm and dry, cool and dry, and cool and wet conditions in the Sierran landscape (Murphy and Knopp 2000).

Changes in the watershed are primarily a result of changes in land use. It is widely accepted that forest harvest, road construction, and urbanization change the sediment transport characteristics of watersheds (Reid and Dunne 1984, Bilby et al. 1989, Foltz and Jr 1990, Megahan and Ketcheson 1996, Luce and Black 1999). Using generally accepted geomorphic relationships as a guide for the conceptual model, it is assumed that both the sediment supply and stream power of the UTR and TC have increased since the

1860's (Goldman 1988, Hatch 1997, Green 1998, Heyvaert 1998, Kim 1999, Kim and Rejmankova 2001, Kim et al. 2001, Stubblefield 2002). Sediment cores from the lake bottom dated with ^{210}Pb and other geochemical proxies for time indicate that the first round of logging resulted in a significant increase in sediment delivery to the lake. As shown in Table 1, it appears that sediment delivery dropped during the re-growth of the forest (circa 1900-1950), and has increased again with the current trend of urbanization (Heyvaert 1998). Heyvaert (1998) used 210Pb, along with other geochemical proxies to investigate lake-bottom sediment accretion rates through the Comstock and urbanization periods in the Tahoe basin.

Table 1 Lake bottom sediment accretion rates (Heyvaert 1998)

Time Period	Sediment Accretion Rate ($g\ cm^{-2}\ yr$)	Interpretation
before 1850	0.006 (+/- 0.003)	Pre-disturbance condition
1860-1890	0.043 (+/- 0.011)	Increased sediment load due to forest harvesting
1900 - 1970	0.009 (+/- 0.004)	Forest re-growth, Low population densities
1970 - 1990	0.027 (+/- 0.006)	Modern land use patterns, High population densities

Evidence for increased sediment loads from the watershed has also been determined in investigations in what is now Pope Marsh, the western portion of the historic marsh system, now separated from the UTM by the Tahoe Keys development. Kim (1999) reported increased levels of mineral deposition in the marsh in the late 1800's, concurrent with widespread timber harvesting activities in the basin. The timing of sediment deposition was determined with the use of ^{210}Pb and elemental Pb, along with pollen indicators. The Pope Marsh investigations do not show significant changes over the urbanization period. This may be due to the lack of surface water inputs to the west side of the marsh once the Tahoe Keys broke the connection between Pope and UT Marshes.

In order to document the processes of sediment retention on the freshwater delta of the UTM, Stubblefield et al (ref) collected suspended sediment (SS) and total phosphorus (TP) load data from the delta formed by the Upper Truckee River and Trout Creek. During the spring snowmelt flow events of 2003 sediment budgets were constructed from the turbidity record, SS correlation, and discharge data. During the spring snowmelt flow events monitored, 13-41% of the SS load was retained in the Upper Truckee River system and 68-90% retained in the Trout Creek system. Similar retentions of TP load were observed: 13-32% for the Upper Truckee River and 61-84% for Trout Creek. Monitoring of Trout Creek indicated retention in load per unit volume of 20-34% in a moderately incised reach versus retention of 51-77% in a non-incised marsh reach containing lagoons, braided channels and backwater areas created by a beaver dam. Smaller particle sizes, <10 um, were retained in the lower marsh reach with similar efficiencies as larger particle sizes. If retention rates from the Trout Creek portion of the marsh were applied to the Upper Truckee River, sediment deposition in the marsh for 2003 would have been 917 tons of SS.

Conceptual Model of Marsh Development

In considering generalized deposition and aggradation of river systems, Blum and Tornqvist (2000) identify climate (which drives stream power, vegetation cover, and soil type) and base (sea)-level change as primary forces that control sedimentation patterns in watersheds. These two drivers have resulted in two conceptual models of channel and floodplain development: the conveyor belt model and the vacuum cleaner model (Blum and Tornqvist 2000). In this study, stratigraphic analyses are used to investigate the relative importance of these geomorphic processes.

The geomorphology of the Upper Truckee Marsh is a result of the deposition of sediment from the watershed at the fluvial/lacustrine boundary. Given the landscape position of the site, the geomorphology of the UTM is assumed to be primarily depositional in nature. Therefore, the Upper Truckee Marsh provides a good field site to test for the relative importance of watershed sediment delivery processes versus base level changes in the construction of the modern-day delta floodplain.

A significant trait of the Tahoe basin is that lake level is controlled by local climate conditions. The same local climate conditions control the amount of streamflow in the Upper Truckee and Trout Creek watersheds. Therefore, when the lake is low, stream power will also be low, limiting the ability of a change in baselevel to scour the lower alluvial valley. Further, when the lake is high, the climate will be colder and wetter, favoring increased sediment production and transport from the upper watershed. Therefore, the conveyor belt model appears to be the likely primary sedimentation process in our conceptual model of sedimentation within the Upper Truckee Marsh.

Soil Coring and Processing

It was anticipated that both climate change and watershed land-use changes would be reflected in the stratigraphy and sediment retention characteristics of the UTM. Stratigraphy were used to test conceptual models of site-specific changes due to watershed modifications (Pasternack *et al.* 2001). Stratigraphic interpretations of soil cores collected at the Upper Truckee Marsh were used to investigate what types of processes have been the most effective at shaping the marsh system.

To investigate the patterns of sedimentation on the UTM site, soil cores were collected from the major geomorphic zones on the site (Figure 2). Cores were located generally along the course of the river channels to attempt to resolve longitudinal variations through the site. Core locations were chosen in both the UTR and TC floodplains, attempting to sample in areas of more and less entrenchment on the UTR side of the marsh.

Soil cores were collected using either a 7.62 cm diameter aluminum irrigation pipe with a vibracorer, or a 3.1 cm plastic tube with an ESP+ corer. The vibracorer consisted of a Honda 5hp motor that vibrated the aluminum tube into the ground in wet locations. In dry locations the ESP+ slide hammer design was used to drive a plastic sampling tube in 0.8 meter segments.

Compaction was measured for all cores before removing the core from the ground by measuring from a datum (e.g., the top of the sampling tube) to both the top of the sample within the tube, and to the ground surface. The difference between the measurements was used to determine the amount of sample compaction. The compaction was then assumed to be uniform through the core, and used as a correction factor when plotting core data with a depth axis. In general, compaction was less than 5% for the ESP+ cores, however, compaction could reach 20% for the vibracores. The greater amount of disturbance for the vibracores is attributed to the shaking of the sediment in the sampling tube.

The sampling interval was set depending on the approximate bulk density of the soil, tube diameter, and the amount of soil required for various analyses. While very narrow sampling intervals would allow for greater vertical resolution of the analyses, the narrow intervals would limit the amount of soil material available for analysis. Therefore, where possible, the sampling interval was set at a resolution that would yield between 75-200 grams of material.

The subsamples collected from the cores were analyzed for grain size distribution and bulk density. The amount of organic matter was also investigated using the loss-on-ignition technique (ref). These parameters were selected to investigate the amount and types of sediments being deposited on the Upper Truckee Marsh, and to quantify differences between strata within a single soil profile.

Cesium-137 (^{137}Cs) and Carbon-14 (^{14}C) techniques were used to derive an age-depth relationship in order to determine the rate at which sediment has accumulated on the site, the goal being to determine dates for, at best, four locations in the profile, to allow for comparisons of sedimentation during different time periods. The ^{137}Cs method was used for 10 cores, and the ^{14}C method was used for 4 of the deeper vibracores.

Cesium-137, a radioactive element that has a half-life of 30.2 years (Robbins and Edgington 1975), was anthropogenically introduced into the environment as a by product of above-ground nuclear weapons testing (Ritchie and McHenry 1990). The dispersion of ^{137}Cs residue reached the stratosphere and entered the global atmospheric circulation cycles. The deposition of ^{137}Cs provides a mark of the recent period, as the radioactive element strongly sorbs to clay and organic materials in the topsoil (He and Walling 1996). Therefore, the ^{137}Cs technique is assumed to provide a reasonable estimate of the soil surface at both 1954, the first year of measureable ^{137}Cs deposition, and 1963, the peak of deposition. The ^{137}Cs dating technique has been widely applied, and often provides collaborative confirmation of recent chronologies when compared with ^{210}Pb or other dating proxies (Robbins et al. 1978, Oldfield 1979, McCall et al. 1984, Walling and He 1998b, a, Craft and Casey 2000, Collins et al. 2001, Walling et al. 2003).

The 1963 date is typically taken to be the more reliable of the two dates, due to a stronger signal, and more potential post-deposition bioturbation in the lower 1954 surface (Ritchie and McHenry 1990). However, the 1954 date is used in this study, as it is a priority to capture the full extent of the recent urbanization period in the Tahoe Basin. Two steps were taken to minimize the potential error in using the initiation of ^{137}Cs in the profile to indicate the soil surface in 1954. Signal processing software was used to differentiate excess ^{137}Cs gamma emissions from the measured background. The processing software algorithms were set to discourage the identification of false positives for ^{137}Cs. Second, the intervals tested are generally coarse, in the 2.5 to 5 cm range. Therefore, the error introduced by testing relatively thick intervals of the core will likely subsume the possible error introduced by downward migration of ^{137}Cs in the profile.

Two of the four cores were analyzed for ^{14}C by normal radiometric counting of the bulk carbon from a 5 cm section of core. The remaining two were analyzed by AMS counting on individual pieces of wood or charcoal.

Results

Soil Coring Physical Characteristics - Stratigraphy, LOI, and Bulk Density

Two distinct patterns were observed in the stratigraphy of the cores taken in the UTM. One stratigraphic pattern displayed a fining upward sequence from deeper sand and gravel C horizons to silt and clay dominated A horizon at the surface. This pattern was generally observed closer to the lake, in the area with long durations of ponded water. The second pattern was a bimodal deposition pattern where multiple upward fining sequences are interspersed with 5 to 60 cm thick sand and gravel lenses.

Patterns in LOI generally display a significant decrease with depth (Richardson and Vesparakas 2001). LOI trends deviated from the smooth decrease in areas with buried marsh layers, where the buried horizons could have LOI values that surpassed the surface values. LOI for the silt dominated A horizons ranged from 5 to 25%. Sand and gravel layers generally had very low LOI values, usually less than 1%. In the area closest to the lake, organics are a portion of the upper marsh surface, but the overall amount is too small to be considered an O horizon. The highest organic contents occur in the region in the region above average lake level. For all samples collected on the Upper Truckee Marsh site, the LOI % scaled with the percent fines (particles less than 62.5 µm) in the soil (Figure 3).

Bulk density variations generally showed increasing densities with depth. Variations in bulk density within a single core reflect the differences between organic-rich A horizons and the sand and gravel C horizons. The bulk densities ranged from 0.5 g cm^{-3} in the marsh horizons to 1.8 g cm^{-3} in the sand and gravel layers. Bulk densities were comparable between all cores throughout the Upper Truckee Marsh.

Age-Depth Relations

The ^{137}Cs dating technique provides a profile of deposition of ^{137}Cs from the atmosphere. Most cores had measurable amounts of ^{137}Cs starting between 25 and 50 cm from the soil surface, with a peak occurring between 10 and 40 cm below the soil surface. The relatively deep ^{137}Cs profiles indicate that net deposition since 1954 has occurred in all of the analyzed cores. The ^{137}Cs profile data were used to determine sedimentation rates by assuming that the midpoint of the last interval with measurable ^{137}Cs represented the soil surface in 1954. Error estimations were determined using the minimum (top of the core interval), and maximum (bottom of the core interval) sedimentation rates. The results of the dating analysis were used in combination with the bulk density data to determine depth and mass sedimentation rates.

Some cores had horizons that prevented the determination of the entire ^{137}Cs profile. The ^{137}Cs technique is not appropriate for sand and gravel, due to the low sorption potential (He and Walling 1996). Therefore, locations with sand and gravel lenses near the surface may reflect scour that has disrupted the ^{137}Cs profile. The results from these locations would only provide a minimum sedimentation rate that may not reflect the full depositional history of that location.

The ^{137}Cs dating results were used to determine the mass sedimentation rate at each location. The mass sedimentation rates (MSR) were determined using the date 1954 for the lowest core interval with ^{137}Cs and the bulk densities of the overlying sediments to determine the mass deposited per area per year over the past 49 years. The MSR were calculated with and without the organic matter by removing the portion lost in the LOI analysis from consideration. The MSR without organic material for the UTM ranged from 0.10 to 1.13 g cm^{-2} yr^{-1}. The overall average recent MSR without organics for all of the datable cores was 0.55 g cm^{-2} yr^{-1}. The average MSR for sites along the UTR is 0.63, and for sites subject to flooding from Trout Creek is 0.46 g cm^{-2} yr^{-1}. The results for all cores are shown in Table 1.

Table 2 Short-Term Sediment Accretion Rates

Core	**MSR + organic** **g cm-^{2} yr^{-1}**	**MSR w/o organics** **g cm^{-2} yr^{-1}**	**Vertical Accumulation** **cm yr^{-1}**
VC1	1.13 +/- 0.01	1.12 +/- 0.01	1.16 +/- 0.03
TC2	0.99 +/- 0.05	0.89 +/- 005	1.19 +/-0.05
FPB	0.42 +/- 0.07	0.41 +/- 0.07	0.52 +/- 0.05
KB	0.17 +/- 0.05	0.17 +/- 0.05	0.52 +/- 0.05
BT	1.10 +/- 0.05	1.09 +/- 0.05	0.87 +/- 0.05
VC2	0.15 +/- 0.01	0.14 +/- 0.01	0.66+/- .05
2040	0.17 +/- 0.01	0.15 +/- 0.01	0.69 +/- 0.03
EOSF*	0.83*	0.81*	0.71*
VC4	0.55 +/- 0.04	0.51 +/1 0.04	0.66 +/- 0.007
EOW	0.32 +/- 0.03	0.31+/- 0.03	0.60 +/- 0.05

*Minimum Value

Vertical sedimentation trends are similar to the mass sedimentation rates. The average depth accretion rate from the ^{137}Cs profiles is 0.76 cm yr^{-1}. The average accretion rates are 0.89 and 0.64 cm yr^{-1} for sites influenced by the Upper Truckee River or Trout Creek, respectively.

Longer term mineral MSR's were determined using the bulk density of the overlying sediment and dates provided by the ^{14}C technique (Table 2). Four samples were analyzed for ^{14}C, all from between 1.35 and 2.0 meters depth in VC1, VC3, VC4, and VC5. VC2 did not contain any datable material below the 1954 date provided by ^{137}Cs.

Table 3 ^{14}C Dating Results from Four Cores

Core	**Sample Type**	**Depth (cm)**	**Age (BP)**

VC1	Bulk Carbon	132-137	1650 +/- 50
VC3	Bulk Carbon	134-139	4190 +/- 60
VC4	AMS charred material	144	4620 +/- 40
VC5	AMS wood	158	2100 +/- 40

Using the ^{14}C dates, and the bulk densities of the VC cores, it was determined that the average long term mineral MSR is 0.050 g cm^{-2} yr^{-1}. The average depth accumulation rate was 0.064 cm yr^{-1}. The values for each core are shown in Table 3. The error margins were determined by combining the known sources of error: the 5 cm depth interval of the sample, and the range of ages predicted by the ^{14}C date. Therefore, maximum and minimum rates of accumulation were determined, differenced from the mid-point value, and averaged to provide the +/- value shown in the table.

Table 4 Long Term Sediment Accumulation Rates

Core	**MSR + organic g cm^{-2} yr^{-1}**	**MSR w/o organics g cm^{-2} yr^{-1}**	**Vertical Accumulation cm yr^{-1}**
VC1	0.079 ± 0.0035	0.075 ± 0.0022	0.082 ± 0.0050
VC3	0.031 ± 0.0006	0.030 ± 0.0003	0.032 ± 0.0001
VC4	0.027 ± 0.0004	0.025 ± 0.0005	0.070 ± 0.0002
VC5	0.070 ± 0.0002	0.031 ± 0.0003	0.074 ± 0.0002

An example of core results is shown in figure 4. VC2 was collected from the lagoon area behind the barrier beach, at 6224 ft (Figure 2). This area is generally saturated to the surface from Trout Creek stream flow and the groundwater gradient to the lake. Saturation appears to exist in this area throughout the summer as perched shallow groundwater from the distributary portion of Trout Creek flows into the lagoonal area as the lake level drops, sustaining the saturated soil conditions. This core is typical of the bimodal nature of the site, with finer grained marsh sediments overlaying 2 m of sands and gravels. The vertical sedimentation patterns in VC2 are the most straightforward on the site, with 35 cm of marsh sediments overlaying at least 200 cm of sands and gravels (Figure 4).

Discussion

The Upper Truckee Marsh has retained sediments transported by the Upper Truckee River and Trout Creek. During recent times sediment retention rates appear to have increased significantly when compared to longer term retention rates. Caution must be used when comparing the calculated rates because of the different methods, and significantly different time periods.

While the methods for determining sedimentation rates varied, the higher sedimentation rate during the urbanization period of the Tahoe Basin argues for the importance of the condition of the upper watershed on sedimentation rates on the lower alluvial floodplain. As urbanization disturbed soils and concentrated flow within stormwater systems, it is reasonable that higher sediment loads in each creek translated into larger amounts of sediment being deposited on the floodplain during high flows.

To investigate how the rate of sediment retention at the Upper Truckee Marsh compares to other systems, Table 4 provides a partial summary of previously published sedimentation rates.

Table 5 Sedimentation Rates from freshwater marshes, wetlands, and floodplains

Location	Geomorphic Setting	Sedimentation Rate (cm/yr)	Mass Sedimentation Rate (g/m^2 yr)	Method	Source
Upper Truckee Marsh	Floodplain/Delta	0.52 to 1.19	1,500 to 11,400	^{137}Cs	This study
Pope Marsh Lake Tahoe, CA	Lacustrine fringe	0.09 to 0.38	81 to 1,347	^{210}Pb	Kim et al (2001)
Jug Bay		0.35 to 0.89	1,100 to 5,600		Khan and Brush (1994)

Louisiana Deltaic Plain		0.65 to 1.06			Hatton et al (1983)
Everglades, FL	Freshwater marsh	0.48 to 1.13			Reddy et al (1993)
Everglades, FL	Freshwater marsh	0.16 to 0.40	144 to 360		Craft and Richardson (1993)
Everglades, FL	Freshwater marsh	0.14 to 0.67			Craft and Richardson (1998)
Upper St. John River Basin		0.24 to 0.40	250 to 530		Brenner et al. (2001)
Belize	Coastal fringe wetland	0.09 to 0.12	254 to 329	^{210}Pb	Kim and Rejmankova (2002)
River Culm, UK	Floodplain	0.16	400 to 9,000	^{137}Cs	Walling and He (1998)
River Severn UK	Floodplain	0.10	200 to 10,000	^{137}Cs	Walling and He (1998)
River Rother, UK	Floodplain	0.07	100 to 5,700	^{137}Cs	Walling and He (1998)
River Avon, UK	Floodplain	0.11	100 to 6,000	^{137}Cs	Walling and He (1998)
River Stour, UK	Floodplain	0.07	200 to 3,000	^{137}Cs	Walling and He (1998)
Clear Lake, CA	Freshwater marsh	0.41 to 0.52	1,070 to 1,380	^{210}Pb	Kim (2003)
Otter Point Creek, MD	Tidal Delta	0.5 to 3.46	664 to 40,800	Pollen, ^{14}C, stratigraphy	(Pasternack *et al.* 2001)
River Garonne, France	Riparian wetlands	0.5 to 2.5		^{137}Cs	(Steiger *et al.* 2001)
North Inlet, South Carolina	Salt marsh	0.14 to 0.45		^{210}Pb, ^{137}Cs, ^{7}Be	(Sharma *et al.* 1987)
Navarro River CA	Riverine wetland	0.074 to 0.734	969 to 13,400	Pollen, ^{14}C	Constantine pers. com.
Sacramento River, CA	Delta marsh		400 to 14,300	^{14}C	Brown and Pasternack pers. com.
Flint River, SE US	Floodplain and depressional wetlands		1,036	^{137}Cs, ^{210}Pb	(Craft and Casey 2000)

The sedimentation rates at the Upper Truckee Marsh are on the higher end of the ranges found in other studies. Fluvial energy and sediment supply are both high within the two streams and watersheds, which could result in the higher sedimentation ranges.

The significant sediment retention rates on the floodplain found in this and other studies indicates that sediment retention is a reasonable project target for stream and wetland restoration projects, keeping in mind that sediment retention could be balanced by sediment export, and will vary by geomorphic position.

CONCLUSIONS

This study determined that sedimentation on the Upper Truckee Marsh is primarily a function of climate and land-use changes, and only secondarily of lacustrine processes. Stratigraphic investigations on the site reveal bimodal depositional patterns of fine-grained organic rich marsh layers, and coarser sand and gravel layers throughout the site. Buried marsh soils dated to 1650 and approximately 4300 y.a. were formed under climate conditions similar to the current period. Significant sand and gravel layers overlaying dated marsh layers are correlated with the sediment generation and transport functions associated with colder neo-glacial or neo-pluvial periods. These sequences of marsh and alluvium that correlate with climatic fluctuations in the Sierra suggest that climate controls sedimentation and marsh processes on the 10^3 yr time scale.

Land-use changes in the Lake Tahoe basin have had a significant impact on the geomorphology of the Upper Truckee Marsh over the past 150 years. The Comstock period of the late 1800's resulted in an incised Upper Truckee River channel that was less likely to overtop its banks than in the pre-disturbance condition. Average mass sedimentation rates during the last 50 years (0.6 g cm^{-2} yr^{-1}) are an order of magnitude higher than long-term (10^3 yr) average mass sedimentation rates (0.05 g cm^{-2} yr^{-1}). The high sedimentation rates in the recent period correspond with rapid urbanization of the Tahoe basin, higher sediment loads, and documented impacts to lake water quality and clarity. Though sedimentation rates are high, the retention of sediment on the site is estimated to be less than 5% of the yearly sediment load being supplied to the Upper Truckee Marsh (ref Stubblefield).

The 10^3 year sedimentation rates are comparable with contemporary freshwater marshes and smaller river floodplains. The sedimentation rates of the past 50 years are high compared to other freshwater marshes, and are comparable with other deltas and floodplains of larger rivers. Vertical accretion has been significant enough to reduce the frequency of overbank flooding on portions of the site. Sedimentation on the marsh shows a decreasing trend since 1963 in most areas of the marsh. The reduction is likely due to a combination of the river building its floodplain out of reach of overbank flooding, and a re-equilibration of the site to a higher average lake level. Also, changes in policy have led to the implementation of watershed scale sediment and erosion control projects that have resulted in a reduction in sediment loading to the UTR and TC.

This work indicates that watershed forces (the conveyor belt theory of sedimentation) has been the primary driver of sedimentation processes in the short and long time scales investigated for the Upper Truckee Marsh. While changes in lake (base) level have unquestionably played a role in the dynamic equilibrium of the ecology of the marsh, changes in climate and land-use in the watershed have provided the driving forces for sediment mobilization, transport, and deposition. The vacuum cleaner model of sedimentation is not as effective at the Upper Truckee Marsh as decreases in lake (base) level are caused by droughts which, in turn, decrease the stream flow in the UTR and TC, thereby reducing the potential for geomorphic change on the site.

One result of land-use changes in the watersheds of the UTR and TC is a stream channel that does not interact with its floodplain in a manner consistent with the pre-disturbance condition. The stream channel is currently in the process of widening and rebuilding an inset floodplain in the incised reaches. However, the cohesive soil materials will result in a re-adjustment process that will likely be beyond the human time scale (>100 years). Therefore, restoration techniques could be applied to the Upper Truckee River channel that will jump-start the adjustment process. This research indicates that the restoration approach should take into account the sediment being supplied to the site, along with the long-standing interplay between the UTR and TC channels and their floodplain that has shaped the Upper Truckee Marsh.

ACKNOWLEDEMENTS

The authors gratefully acknowledge funding and support from the California Tahoe Conservancy and the unfailing support for this work from Rick Robinson and Steve Goldman of the Conservancy.

REFERENCES

Barlein, P. J., 1997. Past Environmental Changes: Characteristic Features of Quaternary Climate Variations. Past and Future Rapid Environmental Changes: The Spatial and Evolutionary Reponses of Terrestrial Biota **147**:11-29.

Berris, S. N., G. W. Hess, and L. R. Bohman, 2001. River and Reservoir Operations Model, Truckee River Basin, California and Nevada, 1998. 01-4017, USGS, Carson City, Nevada.

Bilby, R. E., K. Sullivan, and S. H. Duncan, 1989. The Generation and Fate of Road-Surface Sediment in Forested Watersheds in Southwestern Washington. Forest Science **35**:453-468.

Birkeland, P. W., 1963. Pleistocene Volcanism and Deformation of the Truckee Area, North of Lake Tahoe, California. Geological Society of America Bulletin **74**:1453-1464.

Bischoff, J. L., and K. Cummins, 2001. Wisconsin Glaciation of the Sierra Nevada (79,000-15,000 Yr B.P.) as Recorded by Rock Flour in Sediments of Owens Lake, California. Quaternary Research **55**:14-24.

Blum, J. L., 1979. Geologic and Gravimetric Investigation of the South Lake Tahoe Groundwater Basin, California. Master's Thesis. UCD, Davis, CA.

Blum, M. D., and T. E. Tornqvist, 2000. Fluvial Responses to Climate and Sea-Level Change: A Review and Look Forward. Sedimentology **47**:2-48.

Boggs, S. J., 2001. Principles of Sedimentology and Stratigraphy, Third edition. Prentice Hall, Upper Saddle River, New Jersey.

Burnett, J. L., 1971. Geology of the Lake Tahoe Basin. California Geology:119 - 130.

CDSC, 1969. Sedimentation and Erosion in the Upper Truckee River and Trout Creek Watersheds, Lake Tahoe, California. State of CA Resources Agency Department of Conservation, Division of Soil Conservation.

Collins, A. L., D. E. Walling, H. M. Sichingabula, and G. J. L. Leeks, 2001. Using ^{137}cs Measurements to Quantify Soil Erosion and Redistribution Rates for Areas under Differenct Land Use in the Upper Kaleya River Basin, Southern Zambia. Geoderma **104**:299-323.

Colman, J. M., 1976. Deltas: Processes of Deposition and Models for Exploration. Continuing Education Publication Company, Inc., Champagne, IL.

Craft, C. B., and W. P. Casey, 2000. Sediment and Nutrient Accumulation in Floodplains and Depressional Freshwater Wetlands of Georgia, USA. Wetlands **20**:323-332.

Craft, C. B., and C. J. Richardson, 1993. Peat Accretion and N, P, and Organic C Accumulation in Nutrient Enriched and Unenriched Everglades Peatlands. Ecological Applications **3**:446-458.

Curry, R. R., 1966. Glaciation About 3,000,000 Years Ago in the Sierra Nevda. Science **154**:770-771.

Dunne, T., and L. Leopold, 1978. Water in Environmental Planning. W.H. Freeman and Company, New York.

Easterbrook, D. J., 1993. Surface Processes and Landforms. Macmillan Publishing Company, New York.

EDAW, and ENTRIX, 2003. Processes and Functions of the Upper Truckee Marsh. Sacramento, CA.

Elliot, T., 1986. Deltas. Pages 113-154 ***In*** H. G. Reading, editor. Sedimentary Environment and Facies. Blackwell Scientific, Oxford.

Florsheim, J. L., J. F. Mount, and L. T. Rutten, 2001. Effect of Baselevel Change on Floodplain and Fan Sediment Storage and Ephemeral Tributary Channel Morphology, Navarro River, California. Earth Surface Processes and Landforms **26**:219-232.

Foltz, R. B., and E. R. B. Jr. 1990. Sediment Production from Forest Roads with Wheel Ruts. Pages 266-275 ***In*** R. E. R. e. al., editor. Watershed Planning and Analysis in Action. American Society of Civil Engineers, New York.

Forney, W., L. Richards, K. D. Adams, T. B. Minor, T. G. Rowe, J. R. Smith, and C. G. Raumann, 2001. Land Use Change and Effects on Water Quality and Ecosystem Health in the Lake Tahoe Basin, Nevada and California. Open-File Report 01-418, USGS.

Gallaway, W. E., 1975. Process Framework for Describing the Morphologic and Stratigraphic Evolution of Deltaic Depositional Systems. Pages 87-98 ***In*** M. L. Broussard, editor. Deltas: Models for Exploration. Houston Geological Society, Houston.

Gardner, J. V., L. A. Mayer, and J. E. H. Clarke, 2000. Morphology and Processes in Lake Tahoe (California-Nevada). GSA Bulletin **112**:736-746.

Goldman, C. R., 1988. Primary Productivity, Nutrients, and Transparency During the Early Onset of Eutrophication in Ulta-Oligotrophic Lake Tahoe, California-Nevada. Limnology and Oceanography **33**:1321-1333.

Green, C. T., 1998. Integrated Studies of Hydrogeology and Ecology of Pope Marsh, Lake Tahoe. Master's. UCD, Davis.

Harvey, M. D., and C. C. Watson, 1986. Fluvial Processes and Morphological Thresholds in Incised Channel Restoration. Water Resources Bulletin` **22**:359-368.

Hatch, L., 1997. The Generation, Transport, and Fate of Phosphorous in the Lake Tahoe Ecosystem. Ph.D. Thesis. UC Davis, Davis.

He, Q., and D. E. Walling, 1996. Interpreting Particle Size Effects in the Adsorption of 137cs and Unsupported 210pb by Mineral Soils and Sediments. Journal of Environmental Radioactivity **30**:117-137.

Heyvaert, A., 1998. The Biogeochemistry and Paleolimnology of Sediments from Lake Tahoe, California-Nevada. Ph.D. Thesis. UC Davis, Davis.

Huggenberger, P., E. Hoehn, R. Beschta, and W. Woessner, 1998. Abiotic Aspects of Channels and Floodplains in Riparian Ecology. Freshwater Biology **40**:407-425.

Jassby, A. D., J. E. Reuter, R. P. Axler, C. R. Goldman, and S. H. Hackley, 1994. Atmospheric Deposition of Nitrogen and Phosphorus in the Annual Nutrient Load of Lake Tahoe (California-Nevada). Water Resources Research **30**:2207-2216.

Johnston, C. A., 1991. Sediment and Nutrient Retention by Freshwater Wetlands: Effects on Surface Water Quality. Critical Review of Environmental Control **21**:491-565.

Johnston, C. A., S. D. Bridgham, and J. P. Schubauer-Erigan, 2001. Nutrient Dynamics in Relation to Geomorphology of Riverine Wetlands. Soil Science Society of America Journal **65**:557-577.

Kim, J. G., 1999. Paleoecological Studies for Assessment of Anthropogenic Impacts in Montane, Mediterranean, and Tropical Marshes. Ph.D. Thesis. UCD, Davis, CA.

Kim, J. G., and E. Rejmankova, 2001. The Paleoecological Record of Human Disturbance in Wetlands of the Lake Tahoe Basin. Journal of Paleolimnology **25**:437-454.

Kim, J. G., E. Rejmankova, and H. J. Spanglet, 2001. Implications of a Sediment-Chemistry Study on Subalpine Marsh Conservation in the Lake Tahoe Basin, USA. Wetlands **21**:379-394.

Knighton, D., 1984. Fluvial Forms and Processes. Halsted Press, New York.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964. Fluvial Processes in Geomorphology. Dover Publications, Inc., New York.

Luce, C. H., and T. A. Black, 1999. Sediment Production from Forest Roads in Western Oregon. Water Resources Research **35**:2561-2570.

McCall, P., J. A. Robbins, and G. Matisoff, 1984. ^{137}cs and ^{210}pb Transport and Geochronologies in Urbanized Reservoirs with Rapidly Increasing Sedimentation Rates. Chemical Geology **44**:33-65.

Megahan, W. F., and G. L. Ketcheson, 1996. Predicting Downslope Travel of Granitic Sediments for Forest Roads in Idaho. Water Resources Bulletin **32**:371-382.

Mount, J. F., 1995. California Rivers and Streams. University of California Press, Berkeley.

Murphy, D. D., and C. M. Knopp, (Editors). 2000. Lake Tahoe Watershed Assessment. Pacific Southwest Research Station, Forest Service, USDA, Albany, CA.

Oldfield, F., 1979. ^{210}pb, ^{137}cs, and ^{239}pu Profiles in Ombrotrophic Peat. Oikos **33**:40-45.

Pasternack, G. B., G. S. Brush, and W. B. Hilgartner, 2001. Impact of Historic Land-Use Change on Sediment Delivery to a Chesapeake Bay Subestuarine Delta. Earth Surface Processes and Landforms **26**:409-427.

Peterjohn, W. T., and D. T. Correll, 1984. Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest. Ecology **65**:1466-1475.

Phillips, F. M., M. G. Zreda, L. V. Benson, M. A. Plummer, D. Elmore, and P. Sharma, 1996. Chronology for Fluctuations in Late Pleistocene Sierra Nevada Glaciers and Lakes. Science **274**:749-751.

Reid, L. M., and T. Dunne, 1984. Sediment Production from Forest Road Surfaces. Water Resources Research **20**:1753-1761.

Ritchie, J. C., and J. R. McHenry, 1990. Application of Radioactive Cesium-137 for Measuring Soil Erosion and Sediment Accumulation Rates and Patterns - a Review. Journal of Environmental Quality **19**:215-233.

Robbins, J. A., and D. N. Edgington, 1975. Determination of Recent Sedimentation Rates in Lake Michigan Using ^{210}pb and ^{137}cs. Geochimica et Cosmochimica Acta **39**:285-304.

Robbins, J. A., D. N. Edgington, and A. L. W. Kemp, 1978. Comparative ^{210}pb, ^{137}cs and Pollen Geochronologies of Sediments from Lakes Ontario and Erie. Quaternary Research **10**:256-278.

Rowe, T. G., and K. K. Allander, 2000. Surface- and Ground-Water Characteristics in the Upper Truckee River and Trout Creek Watersheds, South Lake Tahoe, California and Nevada. 00-4001, USGS, Carson City, Nevada.

Rowe, T. G., D. K. Saleh, S. A. Watkins, and C. R. Kratzer, 2002. Streamflow and Water-Quality Data for Selected Watersheds in the Lake Tahoe Basin, California and Nevada, through September 1998. Water-Resources Investigations Report 02-4030, USGS, Carson City.

Schumm, S. A., 1973. Geomorphic Thresholds and Complex Response of Drainage Systems. Pages 2990309 ***In*** M. Morisawa, editor. Fluvial Geomorphology. New York state University, Binghampton.

Schumm, S. A., M. D. Harvey, and C. C. Watson, 1984. Incised Channels: Morphology, Dynamics, and Control. Water Resources Publications, Littleton, Colorado.

Sharma, P., L. R. Gardner, W. S. Moore, and M. S. Bollinger, 1987. Sedimentation and Bioturbation in a Salt Marsh as Revealed by ^{210}pb, ^{137}cs, and ^{7}be Studies. Limnology and Oceanography **32**:313-326.

Steiger, J., A. M. Gurnell, P. Ergenzinger, and D. Snelder, 2001. Sedimentation in the Riparian Zone of an Incising River. Earth Surface Processes and Landforms **26**:91-108.

Stubblefield, A. P., 2002. Spatial and Temporal Dynamics of Watershed Sediment Delivery, Lake Tahoe, Ca. Ph.D. UC Davis, Davis, CA.

USGS, 2002. Estimated Flood Flows in the Lake Tahoe Basin, California and Nevada. Fact Sheet FS-035-02, US Department of the Interior.

Walling, D. E., 1983. The Sediment Delivery Problem. Journal of Hydrology **65**:209-237.

Walling, D. E., 1999. Linking Land Use, Erosion and Sediment Yields in River Basins. Hydrobiologia **410**:223-240.

Walling, D. E., and Q. He, 1998a. The Spatial Variability of Overbank Sedimentation on River Floodplains. Geomorphology **24**:209-223.

Walling, D. E., and Q. He, 1998b. The Spatial Variability of Overland Sedimentation on River Floodplains. Geomorphology **24**:209-223.

Walling, D. E., P. N. Owens, J. Carter, G. J. L. Leeks, S. Lewis, A. A. Meharg, and J. Wright, 2003. Storage of Sediment Associated Nutrients and Contaminants in River Channel and Floodplain Systems. Applied Geochemistry **18**:195-220.

Whipple, K. X., and G. E. Tucker, 2002. Implications of Sediment-Flux-Dependent River Incision Models for Landscape Evolution. Journal of Geophysical Research-Solid Earth **107**.

Wissmar, R. C., and R. L. Beschta, 1998. Restoration and Management of Riparian Ecosystems: A Catchment Perspective. Freshwater Biology **40**:571-585.

Wolman, M. G., and LB Leopold, 1957. River Floodplains: Some Observations on Their Formation. USGS Professional Paper 282-C, US Geological Survey, Washington DC.

FIGURES

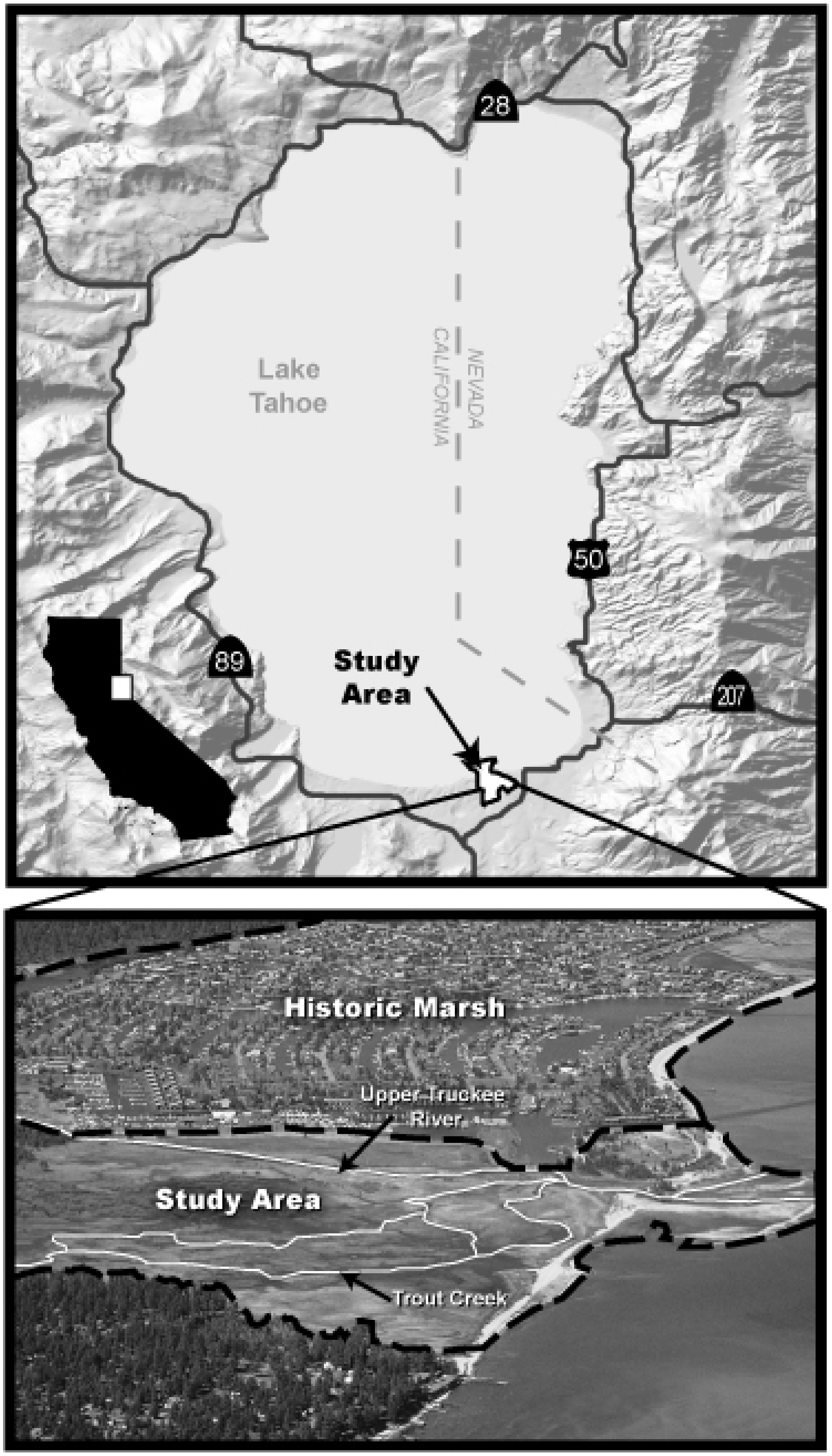
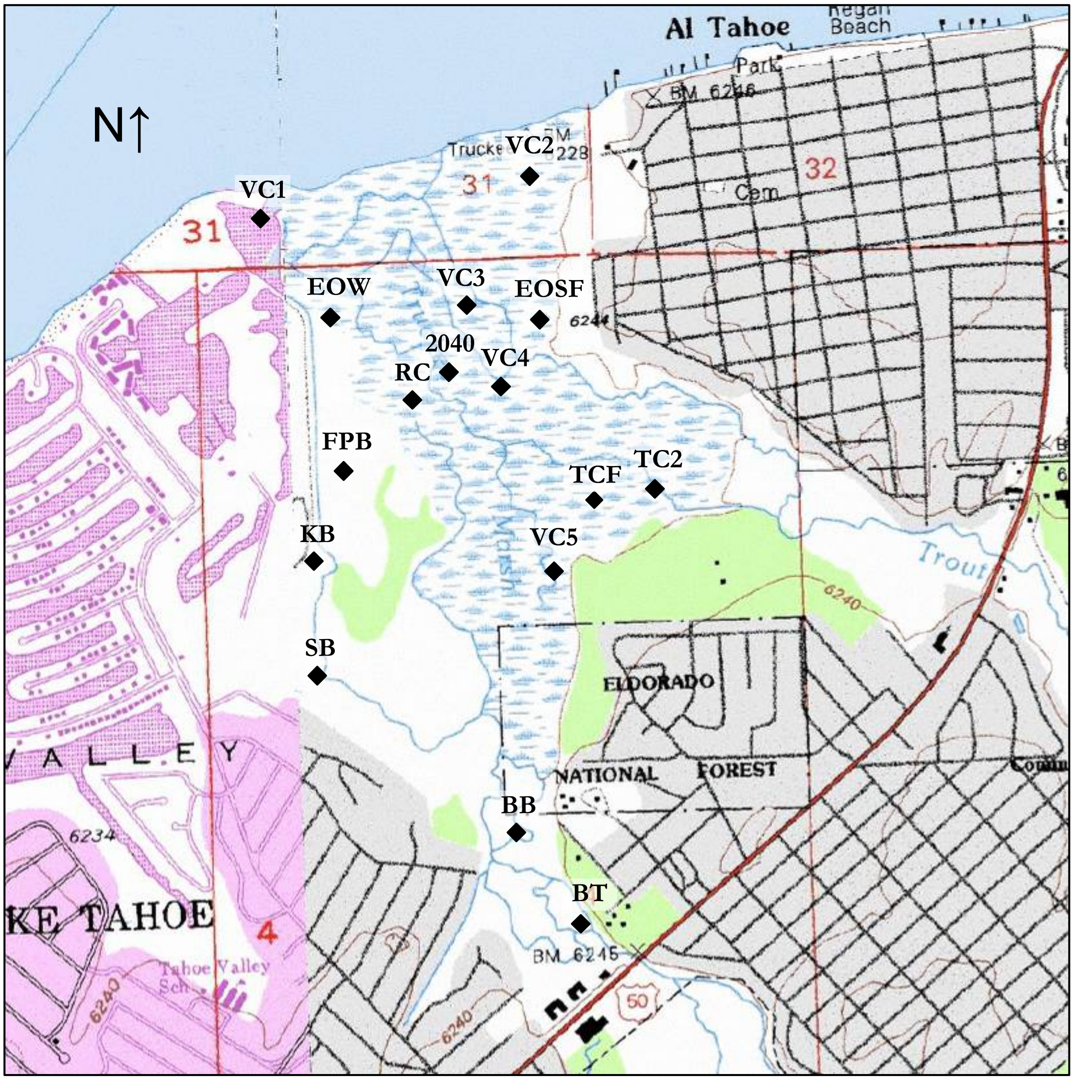


Figure 1 Upper Truckee River and Trout Creek Study Area Map (Stubblefield et al.)



Basemap: USGS Topographics

Figure 2 Locations of soil cores collected on the Upper Truckee Marsh

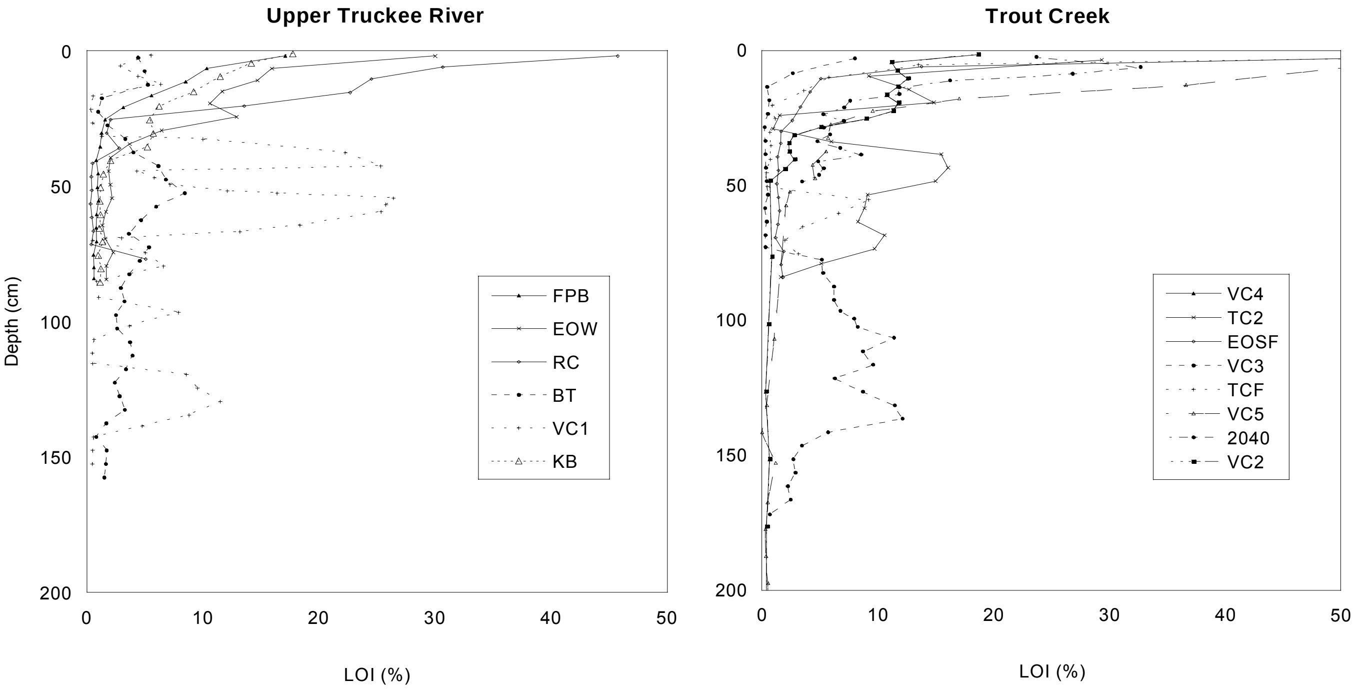


Figure 3 Loss-on-ignition summaries from UTR and TC cores

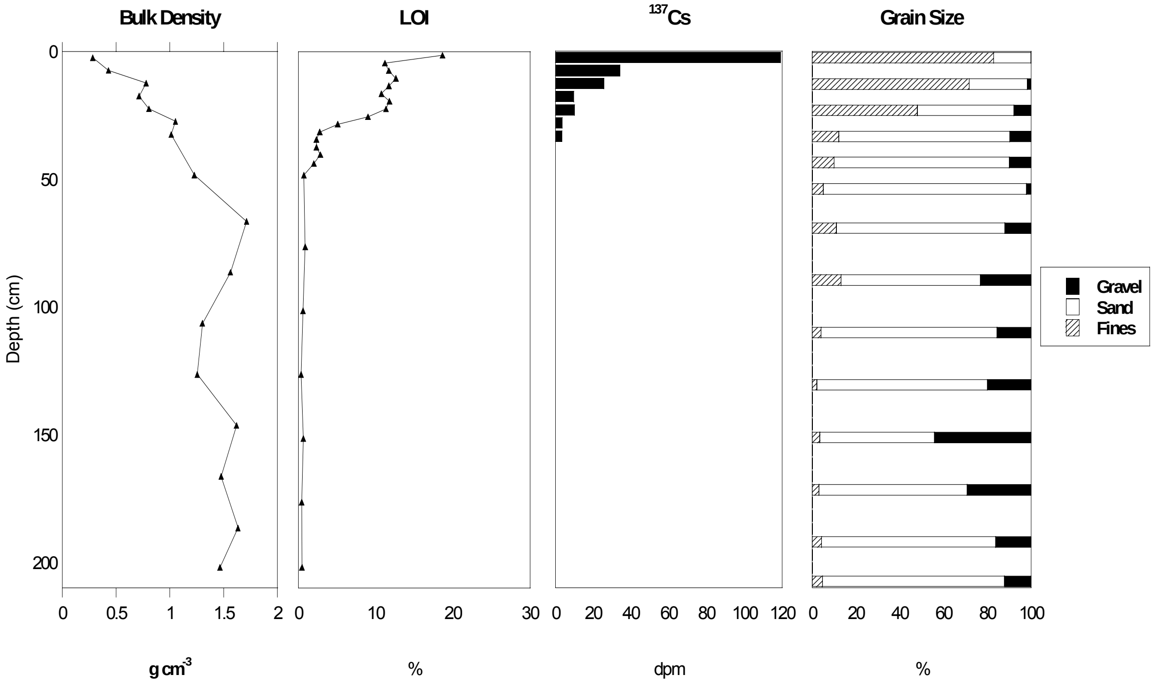


Figure 4 Core results from VC2 (Trout Creek).

Figure Captions

Figure 1. Lake Tahoe and Study Site location. The top map indicates the location of Lake Tahoe within California and Nevada and the location of the study site within the Lake Tahoe watershed. The bottom photograph indicates the location of the Upper Truckee River and Trout Creek within the remaining marsh, and the extent of development of the historic marsh. The perspective is from the east. Adapted from map created by EDAW, Inc.

Figure 2.

Figure 3.

Figure 4.