(a) Potential of Engineered Floodplains and Wetlands as Fine Particle BMPs: Case Study of Trout Creek and the Upper Truckee River

(b) Theme 3: Water Quality
Subtheme: Best Management Practices

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(e) Total Funding Requested
$286,614

(f) Total value of in-kind and financial contributions
$66,295

a. JUSTIFICATION STATEMENT

The long-term decline of Lake Tahoe's clarity is the focus of a recently developed Total Maximum Daily Load (TMDL) program. Though not yet fully implemented, research in support of the TMDL program has shown that fine, inorganic soil particles (< 20 microns diameter) are the primary cause of this decline (Jassby et al., 1999; Swift et al., 2006). There are several sources of these fine particles, including urban uplands, non-urban uplands, stream channel erosion, atmospheric deposition, and shoreline erosion (Fig. 1). Of these, the largest contribution is from urban uplands (70-75%), referring to those areas directly affected by urbanization including residential and commercial areas, roadways etc. (Roberts and Reuter, 2007).

As part of the TMDL program a range of pollutant reduction options has been explored, including increased application of current best management practices (BMPs), higher and more aggressive use of advanced, gravity-driven treatment technologies, and collection, pumping and centralized treatment facilities. Estimates of 20 year costs for such approaches are $1.5-3.2 billion (Lahontan, 2007).

A BMP that was not considered as part of the TMDL analysis was the role of engineered/restored floodplains and wetlands in reducing fine sediment loads during overbank events, despite the fact that such projects have long been planned and promoted for reasons related to habitat restoration and other ecologic benefits. For the TMDL, the pollutant reduction opportunities streams related to stream channel reconstruction/restoration were evaluated solely from the point of view of minimizing in-stream channel erosion. As evident in Fig.1, in-stream channel erosion represents only a small fraction (4%) of the sediment load and associated BMPs (such as armoring stream banks) would have a correspondingly small impact on overall load reduction. It was acknowledged that there was insufficient data to quantify the load reduction potential of riverine floodplains and wetlands (Lahontan, 2007)

Because of the diversion of storm flows from urban areas into streams, the lower reaches of the basin's streams carry most of the urban particle load (Roberts and Reuter, 2007). Thus the actual stream-borne load is far higher than the material attributable to stream erosion processes in Fig. 1 suggests. Since floodplains are known to be highly effective in the removal of fine sediments in flood waters (for example, the Tahoe City wetland has demonstrated 80% removal efficiency for fine particles from urban storm water (Heyvaert et al., 2006)), the construction of engineered floodplains and wetlands along streams adjacent to urban areas has a large potential to remove the primary load of clarity-reducing particles to Lake Tahoe at relatively low annual cost.

A simple calculation bears this out. The present Upper Truckee River (UTR), in its present entrenched form, overtops its banks at a flow of 1350 cfs (EDAW & ENTRIX, 2003) in the Upper Truckee marsh area. Using the regressions between flow and fine particle load developed by Rabidoux (2005), flow records from the USGS from 1981-2007, and assuming that during overtopping 90% of sediment is removed (Stubblefield et al., 2006), it can be shown that the UTR floodplain removed only 2.5% of the load during that 27 year period. Overtopping occurred in only 5 of the 27 years, resulting in 97.5% of the fine sediment flowing directly into the lake (see Fig. 2). If the UTR was restored such that the overtopping flow was reduced to 450 cfs (the recommendation of the EDAW and ENTRIX report), the removal rate of fine sediment from this major tributary could increase by an order of magnitude to ~30%. With an overtopping flow of 350 cfs this could increase to ~40% removal of fine sediment. This calculated reduction from the UTR alone accounts for 3-5% of the total annual fine sediment loading from all sources combined and therefore represents one of the largest, single-project pollutant reduction opportunities in the Basin.

Additionally, the use of engineered floodplains as BMPs has the potential to create multiple local and regional environmental benefits. These may include: downstream flood control, groundwater recharge, nutrient removal and general water quality improvement, fisheries production, habitat creation, and recreational opportunities (Tockner & Stanford 2002).

This proposal seeks to explicitly quantify the potential for engineered floodplains and wetlands as fine sediment BMPs, and to explore methods whereby their efficiency can be maximized. The approach taken will be through the linkage of two types of models – (1) an urban hydrology model to represent particle loading from urban areas (SWMM) and (2) a floodplain/wetland model that incorporates both the hydrodynamics and water quality/sediment removal (SIFT2D-WQ). The models will be calibrated and validated using a previously restored floodplain in the Tahoe basin (on Trout Creek) and then the potential for sediment removal from the UTR will be quantified using the calibrated models.

b. BACKGROUND AND PROBLEM STATEMENT

Past studies suggest that floodplain remediation on the UTR will be an extremely effective BMP. First, the stormwater treatment wetland in Tahoe City, CA, operating since 1998, has been shown to effectively remove nutrients and suspended sediment in sub-alpine environments (Heyvaert et al., 2006). Despite initial questions on whether that system would function effectively in cold climates, because of decreases in microbially mediated processes at low temperatures, the wetlands retained 60% of total nitrogen, 80% of total phosphorus, and 90% of suspended sediments on an annual basis. These are greater percentages than lowland treatment areas (Heyvaert et al., 2006; Kadlec & Knight, 1996). Second, the question of whether natural riverine floodplains could similarly function to remove lake sediment and nutrient inputs was addressed by comparing the UTR and the adjacent Trout Creek. Because of recent restoration efforts, the frequency of overbank flooding events is much greater on Trout Creek than on the UTR. Trout was shown to retain 3-4 times the amount of total phosphorus and suspended sediment than the UTR, and fine particles (< 10 μm) were retained with similar efficiencies as larger particles (Stubblefield et al., 2006). What is not known is the extent to which these processes can be managed to control a known level of sediment and nutrient removal under a variety of flow conditions.

The physical and biogeochemical processes responsible for sediment and nutrient removal are well known for treatment wetlands. They include (1) particulate settling and trapping by vegetation, (2) uptake and translocation by macrophytes and phytoplankton, (3) ammonia volatilization and (4) denitrification for nitrogen, (5) sorption, and (6) precipitation for phosphorus (Kadlec & Knight, 1996). However, interactions between these processes, their spatial and temporal distributions, and the degree to which each process is responsible for removal are not well known. Floodplains are highly spatially heterogeneous, and their flow patterns, water depths, and hydrologic residence times reflect this with orders of magnitude differences between adjacent areas (Andrews, 2007). The few high resolution field studies that have been done, have linked this physical heterogeneity to water quality constituents, including temperature (Ascott et al., 2001), dissolved oxygen and chlorophyll (Ahearn et al., 2006), and suspended sediment (Mertes, 1997), and have emphasized the role of complex mixing patterns between channel derived waters and antecedent floodplain water.

No two-dimensional (2-D) mechanistic water quality modeling studies are described in the literature for riverine floodplains, freshwater marshes, treatment wetlands, or like environments. This is probably due to the lack of boundary condition data coupled with the difficulties inherent in the hydrodynamic modeling of floodplain environments. Modeling efforts have therefore been largely statistical and have related removal efficiencies with bulk variables such as average residence time, water depth, and constituent loadings (Kadlec & Knight, 1996). The mechanistic models that have been run are zero- or one-dimensional, and do not represent the lateral heterogeneity of wetlands (Arnold et al., 2001). Two- and three-dimensional water quality modeling efforts in other environments, such as rivers, lakes, and estuaries, have demonstrated the large effects that domain geometry and flow patterns can have on water quality processes and the local biota (Doyle & Stanley 2006; Na & Park 2006; Cerco & Cole 1993).

c. GOALS, OBJECTIVES, AND HYPOTHESES TO BE TESTED

Goals

1. Develop, calibrate, and validate a two-dimensional hydrodynamic/water quality model to quantify the

removal efficiency for fine sediment and nutrients in the Trout Creek and Upper Truckee River watersheds.
2. Determine the features of floodplains which have the largest impact on fine sediment and nutrient removal (e.g. residence time, vegetation density and distribution, turbulence sources).
3. Use the model to design methodologies to maximize the efficiency of floodplains as BMPs.
4. Evaluate the basin wide potential and costs of floodplains as BMPs.

Objectives

1a. Develop a SWMM model for urban areas adjacent to Trout Creek watershed
1b. Calibrate and validate SWMM model output using data collected by the ongoing storm water measurement program
2a. Develop and test water quality/sediment retention algorithms for floodplain model
2b. Produce set of measured boundary and initial conditions for the Trout Creek watershed model domain using combinations of measured and modeled inputs
2c. Calibrate hydrodynamic model for Trout Creek floodplain using measured USGS data and project specific data. Validate model with data from second event.
3a. Produce set of measured boundary and initial conditions for the Upper Truckee River watershed model domain using combinations of measured and modeled inputs.
3b. Compare UTR model output inundation, sediment retention etc. with measurements currently being conducted on the UTR (Nicole Beck, personal communication)
4. Investigate fine sediment removal potential of several hypothetical UTR restoration scenarios based on recommendations of Agency staff.

Hypotheses

1. Floodplains have the potential to remove a large fraction of fine sediment and nutrients.
2. A 2-D hydrodynamic model is sufficient to capture the dominant floodplain processes.
3. The performance of floodplains as an effective BMP in the Tahoe basin can be optimized by accurate 2-D models of floodplain hydrodynamic and water quality features.
4. Properly engineered floodplains are a high effectiveness, low cost and low maintenance option for restoration of lake clarity and terrestrial habitat.

d. APPROACH, METHODOLOGY AND LOCATION OF RESEARCH

Approach

This is primarily a modeling study, although some limited data collection is needed. Using existing and ongoing storm water measurements, an urban stormflow model (SWMM) will be set up for the urban areas that drain to the Trout Creek floodplain site. SWMM can provide inputs for those local drainages that are not being monitored. The SWMM model inputs inputs, combined with the USGS measured stream inflows and data collected from turbidity sensors and bottle samples at the upstream and downstream model boundaries (see Fig. 3), and the topographic survey and vegetation distribution will provide the necessary boundary conditions for the 2-D floodplain model, SIFT2D-WQ. These boundary conditions will specifically include flow, TSS, particle size distribution down to 0.5 micron, and nutrient concentrations (additional sampling and analysis will be conducted as part of this project and more extensive monitoring on Trout Creek is part of a separate SNPLMA proposal (Nicole Beck, personal communication)). High water levels during overtopping events, combined with measurement of sediment deposition on monitoring plates throughout the floodplain, and particle size distribution and concentration at the downstream end of the model domain will provide the ground truthing necessary for model calibration and validation. Once calibrated and validated for Trout Creek, SIFT2D-WQ will be used to examine hypothetical scenarios on the UTR. Boundary conditions will be derived from data, and scenarios will be based on the EDAW and ENTRIX (2003) recommendations.

Location

The Upper Truckee watershed has the highest fraction of relatively flat land and the highest level of urban development, making it the ideal location to evaluate the potential of this BMP. It also has the highest loads of fine particles of any stream in the Tahoe basin (Rabidoux, 2005) and it is currently under consideration as the location for a series of proposed riverine restoration projects. Unfortunately, the UTR has lost most of its floodplain habitat due to urbanization, channel straightening, and subsequent channel incision. The Trout Creek Stream Restoration and Wildlife Enhancement Project site provides a suitable location for model calibration and validation, as its restoration ensures annual overbanking.

Methodology

The proposed methodology can be broken down into five tasks: (1) urban stormwater modeling; (2) 2-D floodplain model development; (3) 2- D floodplain model calibration and validation; (4) 2- D floodplain model application; and (5) field measurements.

1. Urban stormwater model

The EPA Storm Water Management Model (SWMM) will be utilized (http://www.epa.gov/ednnrmrl/models/swmm/index.htm). SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. SWMM has four principle hydrologic/hydraulic processes:

- Precipitation – Can be applied to different sub-watersheds.
- Rainfall losses – Evaporation, storage, interception, and infiltration can be varied with impervious or pervious surfaces, degree of saturation, etc.
- Runoff transformation – Converts excess precipitation (including snowmelt) into runoff, based on watershed area, slope, and surface roughness.
- Flow routing – Transports hydrograph downstream through culverts and roadways.

The development of a SWMM model has been the subject of part of the Lake Tahoe TMDL program (Brent Wolfe, NHC, personal communication). That work will be used as the basis of the present effort.

GIS coverages from the TMDL science program (Roberts and Reuter 2007) will be used as the basis of creating the SWMM model domains. The subset of those urban areas, shown schematically in Fig. 3, that drain directly into Trout Creek or its floodplain will be those modeled. Meteorological data are available from the nearby UC Davis meteorological station at Timber Cove pier and an additional meteorological station to be installed on the Trout Creek floodplain (see Fig. 3).

2. 2-D floodplain model development

The SWMM water quality model will be integrated into a previously developed floodplain hydrodynamic model, SIFT2D (Andrews, 2007). The hydrodynamic model solves the two-dimensional, depth-averaged and Reynolds-averaged form of the conservation of mass, conservation of momentum and scalar transport equations. The model was specifically developed for freshwater floodplains to model flow in both the highly advective channel environment and the vegetated, shallow water, and complex topography environment of floodplains. The model solves the 2-D governing equations on a staggered Cartesian grid using the semi-implicit time integration method and the advection scheme of Stelling & Duinmeijer (2003). Terms arising from vegetative drag in the momentum equations are absorbed into a parameterization of bottom friction, and the surface roughness values are calculated after Mason et al. (2003), which accounts for reductions in drag as vegetation deflects with increases in flow velocity. Other floodplain-specific methods include a higher order turbulence closure scheme, and the ability to handle subcritical to supercritical flow transitions and the wetting and drying of computational cells. The performance of SIFT2D has been evaluated on several model test cases designed to simulate floodplain specific flows and has been successfully applied to a restored floodplain on the Lower Cosumnes River (Andrews, 2007).

Vegetation is usually accounted for through an increase of the resistance/conveyance coefficient (e.g.

Manning's *n*) thereby converting that coefficient into a sort of repository for non-modeled processes. Models with explicit consideration of vegetation through a drag force in 1-D models have been presented recently (see García, 1996; McGahey and Samuels, 2004). However, vegetation effects are highly non-linear, and the usual methods to determine suitable values of Manning's *n*, based on the linear method by Cowan (V. T. Chow, 1959) may likely lead to incorrect values of the resistance coefficient (Yen, 1992). In addition, part of the flow is blocked, whereby only spatially-averaged velocities are physically meaningful. Two limiting cases can be identified for vegetation: emergent and deeply submerged. In the first case, the vegetation resists via drag throughout the water column almost exclusively, while in the second case the resistance is through shear at the bottom and banks, like a roughness effect (Kouwen, 1989). In these two cases the resistance does not depend on depth. In situations in between these two limiting cases the resistance does depend on depth (Howe and Rodríguez, 2006). In submerged vegetation, a shear layer develops at the top of the vegetation that penetrates within the canopy (Sukhodolov and Sukhodolova, 2006; Sukhodolova et al., 2006). Turbulent stresses peak close to the top of the canopy (López and García, 2001). There is an important momentum transfer between vegetated and non-vegetated areas in the horizontal directions.

Rather than using larger values of Manning's *n*, vegetation will be incorporated in the model via a force that accounts for the mechanisms mentioned above. The research will therefore determine as a first stage suitable expressions for the force originated by vegetation, based on previous experimental, theoretical, and numerical works (García, 1996; Nepf, 1999; McGahey and Samuels, 2004; Kirkil et al., 2005; Dunn et al., 1996). The drag force will be determined as a function of the density of plants and mechanical properties of the vegetation.

The main focus of this work will be on the extension of the hydrodynamic model to include transport and transformation processes affecting suspended sediment, nitrogen and phosphorus (SIFT2D -WQ). This will necessitate the modeling of additional water quality constituents, including temperature, dissolved oxygen, and algae, but will allow for the creation of a more robust model for future examination of other water quality issues, such as the creation of fish spawning habitat.

The state variables that will be explicitly modeled include the physical variables of water temperature and suspended sediment (separated into several size classes), the biological variables representing phytoplankton and periphyton populations, and the chemical variables of dissolved oxygen, ammonium, nitrate, particulate organic nitrogen, dissolved organic nitrogen, orthophosphate, refractory phosphorus, particulate organic phosphorus, and dissolved and particulate organic matter. For modeling fine particles, historical approaches involve calculating deposition using empirical relations and resuspension as a function of shear stress created by mean flow velocities or wave orbital motion (Lopez & Garcia, 1998; Kadlec & Knight, 1996). Most of these methods result from analysis of planar sediment beds with no extraneous objects and thus do not apply for vegetated floodplain environments. A more empirical approach employed by previous suspended sediment models will therefore be used to calculate net deposition, and an additional removal term is added to account for the filtering effects of vegetation (Thonon et al., In Press; Ziegler & Nisbet, 1995). The effect of floodplain processes on the particle size distribution (PSD) is one of the key questions to be explored through this project. The model approach to dealing with this will initially follow the approaches adopted by Swift et al. (2006) and Jassby (2006) to attempt to model the evolution of changing PSD.

For the chemical and biological constituents, similar modifications are needed due to the large influence of the sediment layer and vegetative area in proportion to the depth. Modifications to the standard nutrient modeling approaches (see for example Hamilton and Schladow 1996; Schladow and Hamilton 1996; Swift et al. 2006) include analytically accounting for sediment processes such as oxidation of organic matter, sorption and precipitation of phosphorus, and nitrification in the aerobic sediment zone, and methanogenesis and denitrification in the anaerobic sediment zone using approaches suggested by Di Toro et al. (1991). Periphyton will be explicitly modeled because they can potentially have large effects on nutrient fluxes along major flowpaths where hydrologic residence times are not high enough to generate significant algal growth (Warwick et al., 1999). Nutrient flux terms due to macrophytes will not be explicitly included in the equations as part of the current work, unless field measurements indicate they are a major influence. Although macrophytes are highly important in long-term biogeochemical cycling, they uptake most of their inorganic nutrients from below the sediment surface and release nutrients by decay and leaching of leaf litter over time scales much longer than a typical flood event (Kadlec & Knight, 1996).

(3) 2- D floodplain model calibration and validation

Model calibration and validation will be undertaken with two independent events during which Trout Creek overtops its banks and floodplain inundation occurs. Initially the hydrodynamic model will be calibrated, against stream and floodplain stage heights by adjusting the floodplain roughness. The water quality calibration is a more difficult and extensive process, as it requires the assignment of numerous rate constants pertaining to all the modeled processes. The primary calibration test will be the degree of match to measured water quality constituents at the downstream boundary condition (measured by USGS) and the distribution and particle size distribution of sediment on the floodplain settling tiles. Model validation will be achieved by running the model using input data from a second overbanking event. Model validation will be considered as having been accomplished when no adjustment of the calibration coefficients is needed to produce as satisfactory match to measured conditions in the second event.

(4) 2- D floodplain model application

Once calibrated and validated, SWMM and SIFT2D-WQ will be used on specific reaches of the UTR, depending on specific agency interests and project needs at that time. Two sites that will be considered are the “golf course reach”, where State Parks is planning stream restoration, and a site further upstream that is currently being studied as part of an ongoing SNPLMA project (Nicole Beck, personal communication). In addition, the model will be used to provide an upper bound on the full potential of engineered floodplains as BMPs on the UTR, and specifically where those BMPS need to be installed i.e., the model will be used to provide a better estimate than that the simple calculation presented above.

(5) Measurements (using existing UC Davis instrumentation)

A meteorological station will be set up on the former City of South Lake Tahoe water quality sampling station near the Trout Creek/Cold Creek confluence. Parameters to be sampled include wind speed and direction, air temperature, relative humidity, atmospheric pressure, shortwave solar radiation and water temperature. Data will be recorded at 15 minute intervals and downloaded by spread-spectrum radio.

Water Depth and Flow Data: the USGS currently operates two real-time water depth/flow gages, at the upstream end of the field site on Trout Creek (USGS 10336775) and at the downstream end (USGS 10336780). Water depth will be measured at the upstream end of Cold Creek using an Onset HOBO U20 Water Level logger to provide the final model hydrodynamic boundary condition. Water depth at four locations within the boundaries of the floodplain will be recorded by other YSI 6600 sondes and Branker TG-410 data loggers to provide data for model calibration and validation.

Turbidity will be measured at the two upstream boundaries (one for Trout Creek, one for Cold Creek) and the downstream boundary, as well as four interior points for calibration/validation using the YSI and Branker data loggers.

Sediment deposition will be measured at up to 10 locations within the floodplain with the use of plastic grass sediment traps. Sediment removal due to impaction on biofilms present on vegetation will be measured using two artificial floodplain plant setups. In both cases, the sediments accumulated on both types of device will be collected, sonicated (to reduce to primary particles) and then analyzed for particle size distribution and concentration using the same techniques we have developed for Tahoe streams.

Water temperature will be measured at all model boundaries as well as interior points within the channel and on the floodplain using 30 OnSet HOBO Water Temp Pro v2 loggers, housed in PVC casings. Water temperature is an important floodplain parameter, as it controls many metabolic processes. It is more straightforward to model than are nutrient cycles and sediment distribution, so these measurements provide a ready means to test the scalar transport part of the model.

e. STRATEGY FOR ENGAGING WITH MANAGERS

Following an initial start-up workshop with Agency representatives, we will meet with agency representatives at approximately 3 monthly intervals, coinciding with the presentation of the quarterly reports. Agencies that we intend to meet with include (but are not limited to) the California Tahoe Conservancy, the Tahoe Regional Planning Agency (TRPA), Lahontan Regional Water Quality Control Board, California State Parks, the Tahoe Resource Conservation District, the City of South Lake Tahoe and El Dorado County. We will also report our finding to the Upper Truckee River Watershed Group at regular intervals. We will also coordinate with the TMDL Source Category Integration Committee (LRWQCB, NDEP and TRPA) to discuss and provide updates on pollutant removal opportunities to meet TMDL load reduction targets.

f. DELIVERABLES/PRODUCTS

1. Calibrated and validated urban stormwater model and floodplain hydrodynamic and water quality model, including manual and sample input datasets.
2. Report quantifying and describing sediment/nutrient removal efficiencies and mechanisms on the Trout Creek floodplain.
3. Report describing the performance of hypothetical floodplain projects on the UTR, methodologies for improving their performance, and their benefits in fine sediment removal and the costs of such projects relative to other BMPs for sediment removal.
4. Exhibit to be displayed at the UC Davis TERC outreach center describing wetland function, based on the study results.

g. SCHEDULE OF MILESTONES/DELIVERABLES

	Month from Start of Project																							
TASK	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1. Start-up meeting and workplan	🟦																							
2. Agency workshop		🟦																						
3. Install & operate monitoring equipment		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
4. SWMM model	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦							
5. SWMM Final Report																		🟦						
6. SIFT2D-WQ Development	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦												
7. SIFT2D-WQ Calibration/Validation									🟦	🟦	🟦	🟦	🟦	🟦										
8. SIFT2D-WQ Trout Creek Analysis												🟦	🟦	🟦	🟦	🟦	🟦							
9. SIFT2D-WQ UTR application & analysis																	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
10. Exhibit/outreach development																						🟦	🟦	🟦
11. Quarterly Rpt and Invoice			🟦			🟦			🟦			🟦			🟦			🟦			🟦			🟦
12. Agency meetings			🟦			🟦			🟦			🟦			🟦			🟦			🟦			🟦
13. Drafts of publication manuscripts																							🟦	
14. Final Report and Invoice																								🟦

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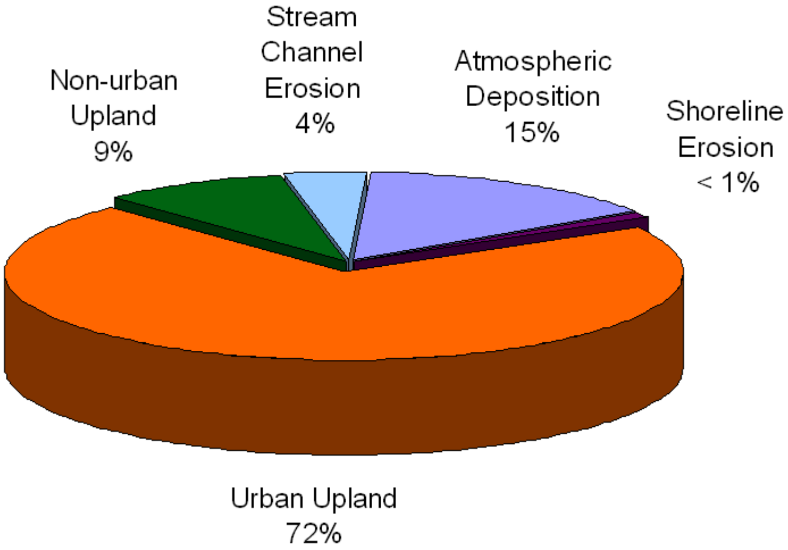

Figure 1. Percentage contribution of fine particles (<20 microns) entering Lake Tahoe by source category. From LRWQCB and NDEP (2007).

Figure 2. Aerial photo showing suspended sediment plume entering Lake Tahoe from the Upper Truckee River. From Goldman et al. (1974).

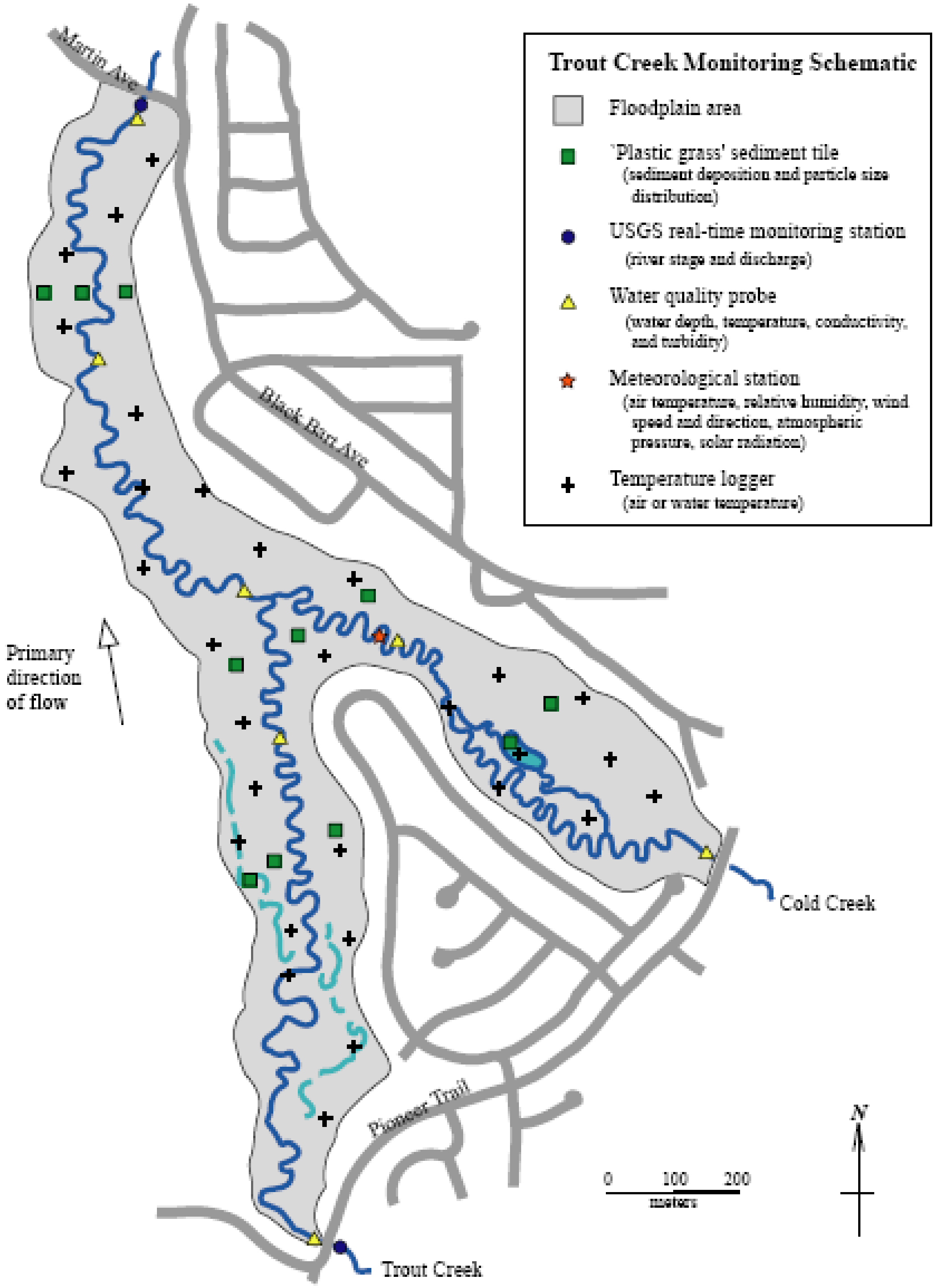

Figure 3. Schematic of Trout Creek floodplain area, showing proposed location of instruments. Instrumentation is provided by UC Davis and is not requested as part of this proposal.