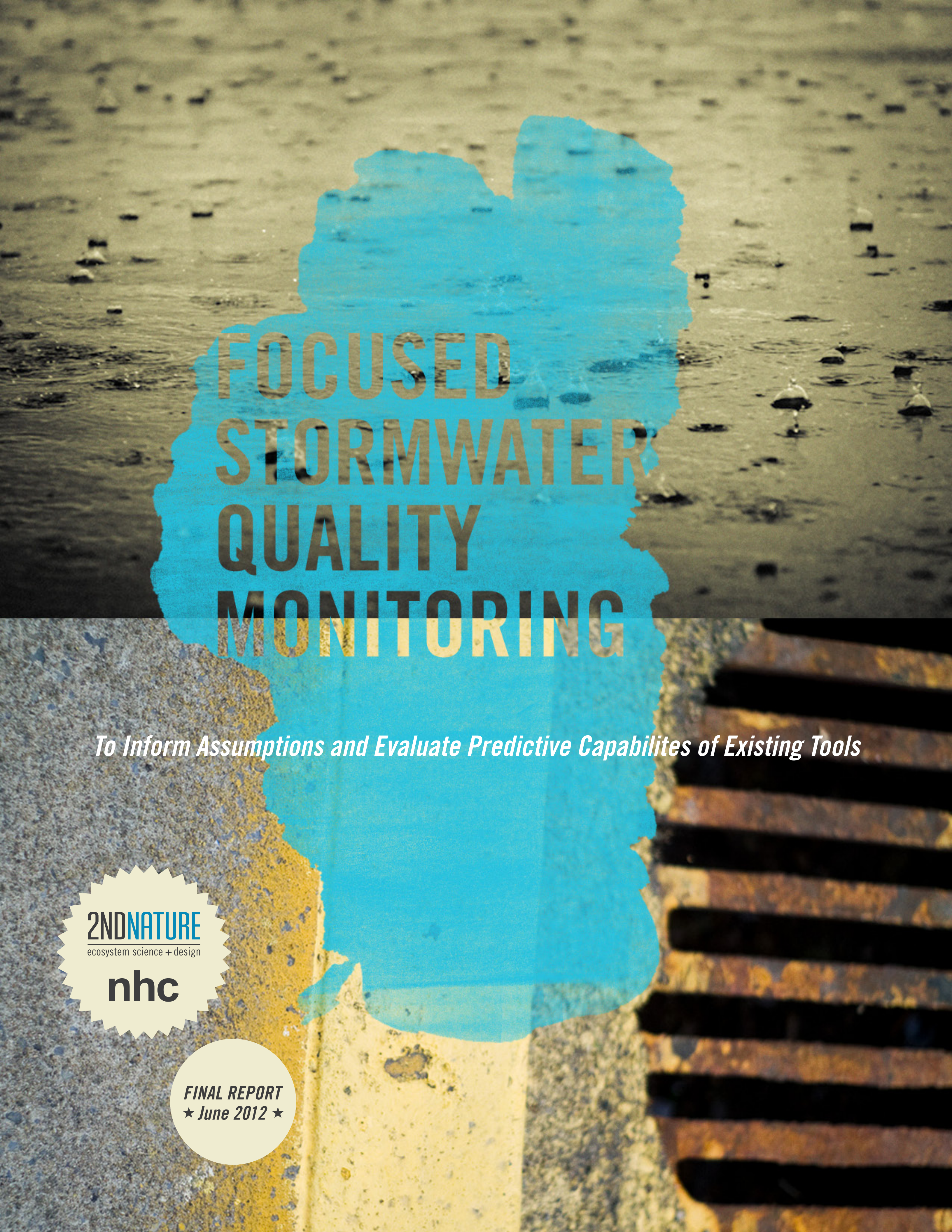

FOCUSED STORMWATER QUALITY MONITORING

To Inform Assumptions and Evaluate Predictive Capabilites of Existing Tools

2NDNATURE
ecosystem science + design

nhc

FINAL REPORT
★ *June 2012* ★

Focused Stormwater Quality Monitoring to Inform Assumptions & Evaluate Predictive Capabilities of Existing Tools

Final Technical Report
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LIST OF KEY ACRONYMS AND TERMS

A&T Tool	TMDL Accounting & Tracking Tool; Data management tool that stores, tracks and reports credit information and load reduction achievement over time in association with the Crediting Program.
Baseline	Baseline Condition; Conditions present during TMDL baseline period, Oct 1, 2003 – May 1, 2004.
BMP RAM	Best Management Practice Maintenance Rapid Assessment Methodology; Tool for Tahoe Basin urban stormwater community to determine relative condition of an urban stormwater BMP.
CEC	Characteristic Effluent Concentration; Represents the effluent concentration typically achieved by a SWT facility in PLRM dependent upon the type of SWT facility specified.
CICU	Commercial/Industrial/Communications/Utilities; Land use designated in Tahoe Basin TMDL.
CRC	Characteristic Runoff Concentration; Representative concentration for a pollutant of concern in runoff from a specific land use and associated land use condition in PLRM.
Credit	Lake Tahoe Clarity Credit; Related to pollutant load reductions and used to evaluate progress towards TMDL.
Crediting Program	Lake Tahoe Clarity Crediting Program; Tahoe Basin program that defines system to track and evaluate pollutant load reductions and related credits within context of TMDL by urban catchment.
DCIA	Directly Connected Impervious Area; Impervious surfaces draining through a direct hydraulic connection to a surface water drainage system.
Existing	Existing Condition; Conditions present during the development of this Strategy Report, Oct 1, 2010 – May 1, 2011.
FSP	Fine Sediment Particle; Mass fraction of TSS concentration <16µm.
LRWQCB	Lahontan Regional Water Quality Control Board; California regulatory agency overseeing Tahoe Basin TMDL implementation.
MFR	Multi-Family Residential; Land use designated in Tahoe Basin TMDL.
NDEP	Nevada Division of Environmental Protection; Nevada regulatory agency overseeing Tahoe Basin TMDL implementation.
PLRM	Pollutant Load Reduction Model; Tool for Tahoe Basin urban stormwater community to estimate pollutant load reductions associated with catchment-scale water quality improvement actions.
Road RAM	Road Rapid Assessment Methodology; Tool for Tahoe Basin urban stormwater community to determine the condition of impervious road surfaces.
Road Risk	PLRM term that incorporates road characteristics to describe relative risk of pollutant generation and transport downslope from impervious road surfaces.
SFR	Single Family Residential; Land use designated in Tahoe Basin TMDL.
SNPLMA	Southern Nevada Public Lands Management Act; Key funding source of this research.
SRP	Soluble Reactive Phosphorous; Also known as orthophosphate, it is the dissolved inorganic fraction of total phosphorous that is biologically available to primary producers.
SWMM	Storm Water Management Model; EPA-developed dynamic rainfall-runoff simulation model used for single event and long term (continuous) simulation of surface hydrology quantity from primarily urban/suburban areas.
SWT	Stormwater Treatment Facility; Treatment BMP designed to reduce urban stormwater volumes and/or pollutant concentrations from a concentrated stormwater flow path.
TMDL	Tahoe Basin Total Maximum Daily Load; Implementation plan that establishes pollutant load reduction allocations for urban stormwater to improve Lake Tahoe clarity.
TSS	Total Suspended Sediment; Mass of sediment contained in a known volume of water.
UPC	Urban Planning Catchment; A contiguous area containing urban land uses with runoff draining to a surface water body. Any single square foot of land is included in only one urban catchment
WQIP	Water Quality Improvement Project; Typically a suite of improvements (pollutant source control, hydrologic source control, and stormwater treatment facilities) implemented within an urban catchment to reduce the pollutant loading to surface waters.

CHAPTER 1. EXECUTIVE SUMMARY

The primary focus of this research was to obtain a representative and reliable stormwater dataset to compare to applicable predictions from the Pollutant Load Reduction Model (PLRM; NHC et al 2009) and provide road specific data to inform the development of Road Rapid Assessment Methodology (Road RAM; 2NDNATURE et al 2010). These currently are the only tools approved for use by the Lake Clarity Crediting Program (Crediting Program; LRWQCB and NDEP 2009), a program intended to incentivize and measure progress toward the attainment of urban stormwater load reductions established in the Lake Tahoe TMDL (LRWQCB and NDEP 2010). However the initial versions of each tool were developed with known limitations. The research documented herein is the culmination of three years of intensive experimental design, stormwater data collection, modeling efforts and data analysis that has greatly improved our understanding of Tahoe Basin urban stormwater quality. This report serves as the final deliverable for a USDA Forest Service Pacific Southwest Research Station grant using SNPLMA Round 9 funding, but relevant information and data obtained from preceding efforts are included in the following analyses when applicable to improve interpretations.

Chapters 2, 3 and 4 provide the background, research context and methods employed. **Chapter 2** provides the research purpose, funding mechanisms, and an overview of the function and structure of the stormwater tools that support the Lake Tahoe TMDL as it relates to the research conducted herein. **Chapter 3** documents site selection, data collection, data management, data analysis techniques, and other relevant methods employed in extensive detail. **Chapter 4** summarizes the specific water year conditions critical to interpreting the context of these monitoring results, including weather and road maintenance practices as documented by the jurisdictions. Since PLRM was designed to be a relatively simple tool to predict average annual potential pollutant load reductions from stormwater quality improvement projects in the Tahoe Basin over a long-term continuous simulation, water year specific hydrology and water quality data is inherently challenging to relate to average annual PLRM predictions generated using the 18 year historic dataset.

Chapter 5 reviews the data and associated findings from land use specific data collection and modeling. PLRMv1 estimates pollutant loads by integrating catchment runoff and land use specific estimates of water quality concentrations for pollutants of concern to lake clarity. PLRMv1 contains a database of characteristic runoff concentrations (CRCs) for each land use type and for a range of land use conditions by pollutant. A significant amount of the land use research was focused on our ability to estimate pollutant generation from roadways, due the assumption that roads in the Tahoe Basin are the largest source per unit area of the primary pollutant of concern, fine sediment particles (FSP; < 16um), impairing Lake clarity (LRWQCB and NDEP 2010). Key road research findings include:

1. Comparison of road specific sampling and mixed land use catchment water quality data support assumptions that the average FSP and TSS concentrations from roads per unit area are significantly higher than the average mixed land use signal. In contrast, the average SRP concentration is lower, suggesting that roads may not be a primary source of SRP to catchment pollutant loads.
2. Roadway condition (as measured by the concentration of FSP obtained from the portable simulator and/or Road RAM) has a significant seasonal variability with the poorest road conditions consistently observed during winter months (see Figure 5.3). Given that the observed roadway conditions consistently improve at all road segments through the summer and fall, all available information suggests road condition is most sensitive to, and controllable by, winter road maintenance practices (see Figure 5.4). Poor road condition in the late winter/early spring can result in a substantial downslope water quality risk when rains efficiently

transport these pollutants into the stormwater system, requiring treatment and/or retention to prevent FSP from reaching the Lake.

3. Periodic evaluations of road condition from winter 2009 through summer 2011 and records of annual road abrasive application volumes by jurisdictions suggest a trend of decreasing abrasive application and improved winter road condition for water quality. This trend was found despite a sequential increase in winter snowfall totals each of the monitored years.

4. The range, minimum and maximum road CRC values in PLRMv1 Road Methodology appear reasonable given the road specific dataset obtained. PLRMv1 bounds anticipated runoff quality and achievable runoff quality through improvements in road conditions based on the concept of road risk. Comparison of the volume weighted average FSP concentrations from this study indicates that the PLRMv1 guidelines for defining and categorizing road risk may be insufficient to reasonably capture differences in operational practices across jurisdictions and detailed recommendations for PLRMv1 user guidance improvements are recommended. The obtainment of consistent road condition observations over a range of water year types on roads maintained in a consistent manner (same road prescriptions across years) would greatly improve our ability to compare annual estimates of road FSP concentrations to PLRM CRC predictions.

5. Comparisons of observed and calculated FSP concentration ranges suggest that frequent street sweeping may provide greater FSP reductions than currently allowed in PLRM; however, more research would be necessary to determine potential adjustments to PLRM CRCs as a result of street sweeping actions. Observations support previous assumptions that increased sweeping frequency during the winter months removes coarse material delivered to road surface prior to pulverization. Observations and discussion with road maintenance personnel suggest the opportunity exists between winter storms to sweep roads where material accumulation occurs. The lowest observed FSP concentrations were actually on high and moderate risk roads where high abrasive applications were coupled with frequent sweeping with high efficiency sweepers.

6. Road surface integrity is not a factor included in PLRM v1, but there is anecdotal evidence that suggests poor road surface integrity can increase the downslope water quality risk as a combination of reduced sweeper effectiveness and the degrading pavement being an additional source of FSP.

7. Two potential long-term PLRM Road Methodology improvements are suggested.

   a. Revise the PLRM Road Methodology to a user defined CRC. A road network classification would be conducted by jurisdictions based on road maintenance practices, and PLRM user inputs would be the specific road condition and associated FSP CRC expected. The main benefits of a condition based approach to the PLRM Road Methodology are the alignment between model inputs and observations that can be verified in the field, and the elimination of the need for PLRM developers to estimate the incremental benefit of individual actions on the long-term average road condition. A number of information and data gaps exist and detailed user guidance on how observation data should inform CRC inputs would need to be developed. This is the preferred recommendation of the research team and technical advisory committee.

   b. PLRMv1 adjusts CRCs from road land uses based on a set of user-defined actions, which reduce CRCs in the model assuming that user-defined actions improve water quality by either reducing pollutant sources or increasing pollutant sinks. Future improvements would replace road risk classification with a grouping based on road maintenance prescriptions by road network and adjust action-specific algorithms to estimate the reduction in the expected CRC as a result of a series of maintenance actions. The main advantages of continuing with an action-based approach to the PLRM Road

Methodology are: 1) user familiarity with the current approach; 2) ease of model use as model inputs can be readily defined with some certainty; and 3) a manageable system to link and track PLRM modeling assumptions with actual road maintenance practices. The main challenges for continuing with an action-based approach would be (1) continued shortcomings linking field observations of road condition, which ultimately drives road runoff quality, with PLRM predictions and (2) overcoming the inherent difficulty in estimating the incremental benefit (or CRC reduction) of specific actions (e.g., modifications to abrasive specifications, changes in road shoulder condition, differences in sweeper efficiency, etc.).

Chapter 5 private parcel research experienced a myriad of challenges associated with cost-effectively sampling the runoff quality from pervious land use types. Given the objectives and the resources available for this effort, an appropriate and cost effective technique to obtain water quality data from pervious surfaces to compare to PLRMv1 CRC values was, unfortunately, not identified. Realistically, the greatest influence on stormwater pollutant load reductions from private parcels will result from implementation and maintenance of private parcel BMPs that infiltrate runoff volumes and provide effective source controls on site, reducing the necessary capacity and treatment capabilities of downstream public stormwater treatment BMPs.

The land use specific research (**Chapter 5**) also developed a framework for refining user inputs and adapting PLRMv1 technical algorithms to better represent pervious road shoulder condition and its effect on infiltration and runoff calculations in the model. A simple method was developed to categorize pervious road shoulder compaction at a road shoulder to guide the PLRM user to infer a default K_{sat} in PLRM. Suggested revisions to the PLRM user guidance are provided; however, no changes to the model technical algorithms have been made at this time.

Chapter 6 reports the results from the stormwater treatment BMP research that obtained cost-effective hydrologic and water quality datasets from nine different treatment BMPs (termed SWTs in PLRM) within the Tahoe Basin in a manner that would allow comparisons of measured data to PLRM hydrologic predictions and inform the PLRMv1 characteristic effluent concentration (CEC) values.

8. A comparison of seasonal estimates generated from 3 water years of SWT hydrology data collection to PLRM predictions show a very strong correlation (significant above 99% confidence) between measured and modeled treated outflow volumes across a range of hydrologic conditions experienced by dry and wet basins (see Figure 6.2B). Given that treated outflow is the hydrology metric used in PLRM to adjust pollutant loads as a result of SWT construction, this is a valuable finding. However, the current PLRM hydrology module was not developed to simulate baseflow, and during wet water years and associated times of high seasonal groundwater the model will likely underestimate actual inflow and therefore overestimate the hydraulic capture performance of the SWT. When the modeled to measured hydrologic comparisons are limited to seasons when baseflow is negligible, the alignment between measured and modeled hydrologic performance greatly improves (see Figure 6.3). Future PLRM improvement should consider allowing a user to define a baseflow component for a modeled SWT facility.
9. PLRM algorithms include static rates of infiltration and flow through treatment outlets over the long-term continuous simulation. These static rates assume that SWTs are maintained over time to ensure continued function at some standard level of performance. However, as noted by this research team and others previously, consistent maintenance of SWTs in the Tahoe Basin is lacking (see Chapter 3.1.4 and Table 3.5). A number of hydrologic functional issues were noted in the monitored SWTs from lack of inspections and maintenance to ensure proper conveyance, maintain storage capacity and preserve expected infiltration rates. Anecdotal evidence obtained from this research and previous research efforts suggests that SWTs in the Tahoe Basin are generally not maintained to the level of maintenance assumed

in PLRMv1. Implementation of the Best Management Practice Maintenance Rapid Assessment Methodology (BMP RAM; 2NDNATURE et al. 2009) can assist stormwater managers and regulators with ensuring that SWTs are maintained to the level of maintenance assumed in PLRM.

10. PLRMv1 currently assigns a static CEC value to all treated effluent volumes for each pollutant modeled based on the type of SWT facility modeled. Results suggest that: 1) the PLRMv1 CEC FSP and TSS values are currently lower than achievable effluent quality from wet basins and dry basins for typical Tahoe Basin maintenance practices; and 2) the treatment capability to achieve effluent FSP concentrations < 100 mg/L are limited when inflow concentrations are relatively elevated (> 300 mg/L) (see Table 6.8). These findings support the assumption that effective pollutant source control actions in the catchment will reduce the concentrations and loads of pollutants delivered to public stormwater treatment systems, thereby increasing their effectiveness and duration of adequate performance prior to maintenance needs. Future PLRM modifications may need to include algorithms that vary CECs as a function of incoming catchment water quality while maintaining limits on the maximum achievable quality of treatment runoff.

11. To ensure that modeled estimates of SWT performance are reasonable, user inputs for PLRM should reflect a strong understanding of the hydrologic function of an SWT based on actual observations and measurements taken after construction of the SWT and not rely upon design specifications. SWT design and function is frequently more complicated than can be readily modeled in PLRM or assumed during design. Therefore, users of the PLRM will typically need a strong understanding of actual SWT function and the PLRM algorithms to develop a reasonable model representation. Future improvements to PLRM SWT modeling should consider allowing a PLRM user to input customized stage-discharge relationships for SWTs and potentially allow a user to define more than one treatment outlet or bypass outlet structure.

There are inherently many limitations and assumptions in the both the data collection and data analysis approaches necessary to express observed data in a manner comparable to PLRM predictions, which are based on long-term (18 yr) continuous simulations. Identified deviations between PLRM and observed data are attributable to both limitations of the data and the models representation of complex environmental systems. The ability to validate and improve a water quality model that is based on physical hydrologic processes and pollutant fate and transport assumptions with site-specific datasets will be improved as the spatial and temporal resolution of the data is increased. There is no question that achieving sustained pollutant load reductions in the Tahoe Basin require continued commitments to source control actions and frequent inspections and maintenance of treatment facilities to ensure they perform, on average, in a manner consistent with the functional condition represented in PLRM.

CHAPTER 2. RESEARCH BACKGROUND

Recently a suite of Tahoe Basin urban stormwater management tools has been developed and adopted by the Lake Clarity Crediting Program (Crediting Program; LRWQCB and NDEP 2009) to support the implementation and tracking of pollutant load reduction actions associated with the Lake Tahoe TMDL. The Lake Tahoe TMDL analysis has identified that fine sediment particles (<16 µm; FSP) are the primary pollutant of concern impacting lake clarity and stormwater runoff originating in urban areas is estimated to contribute 72% of the annual FSP pollutant load to Lake Tahoe (LRWQCB and NDEP 2010). The Crediting Program recommends the use of the Pollutant Load Reduction Model (PLRM; NHC et al. 2009a), Road Rapid Assessment Methodology (Road RAM; 2NDNATURE et al. 2010c) and Best Management Practice Maintenance Rapid Assessment Methodology (BMP RAM; 2NDNATURE et al. 2009a) by local jurisdictions and regulators to estimate and track urban load reductions over time. These currently are the only tools approved for use by the Lake Clarity Crediting Program (Crediting Program; LRWQCB and NDEP 2009), a program intended to incentivize and measure progress toward the attainment of urban stormwater load reductions established in the Lake Tahoe TMDL (LRWQCB and NDEP 2010). However the initial versions of each tool were developed with known limitations. This research has been funded to allow focused testing and evaluation of specific components of these tools to improve their accuracy, precision and compatibility.

RESEARCH FUNDING SOURCES

Since 2009, 2NDNATURE and Northwest Hydraulic Consultants (NHC) have conducted research to test, inform and validate a number of critical assumptions and data gaps for PLRM and Road RAM. Two complementary research contracts have allowed focused stormwater data collection to improve the scientific basis of the water quality algorithms used in PLRMv1 and inform the technical development of Road RAM. Phase I, funded by the US Army Corps of Engineers (US ACE), included the development of the monitoring strategy and initial data collection efforts during 2009. The final Phase I Technical Report was released in March 2010 (*Focused Stormwater Monitoring to Validate Water Quality Source Control and Treatment Assumptions*; 2NDNATURE and NHC 2010a). Prior to completion of Phase I, the USDA Forest Service Pacific Southwest Research Station awarded 2NDNATURE a grant using SNPLMA Round 9 funding to build upon the Phase I data collection from late 2009 through 2011. The majority of this final report includes methods, results and recommendations from the US ACE and SNPLMA funding.

Subsequent to this funding, in 2010 the US ACE funded *The Pilot Catchment Validation Study* to test the integration of the urban stormwater management tools on a single urban catchment for WY2011. The primary objective of the *Pilot Catchment Validation Study* was to develop, test and refine data collection protocols, PLRM modeling techniques, and data analysis approaches to facilitate a catchment scale comparison of pollutant load observations with PLRM predictions. The methods, results and recommendations from this research are provided in a separate, complementary final report entitled *Pilot Catchment Validation Study* (2NDNATURE and NHC 2012). A SNPLMA Round 11 research grant was awarded in November of 2011 to build upon the US ACE-funded study, resulting in the instrumentation, PLRM modeling and analysis of 3 urban catchments from March 1 2012 to February 28, 2013, with a final report expected by the end of 2013.

2.1 TOOL OVERVIEW

Below we provide a simple overview of the PLRM and Road RAM approach and key components addressed by objectives of this research.

2.1.1 POLLUTANT LOAD REDUCTION MODEL (PLRM)

NHC, 2NDNATURE, and Geosyntec Consultants released the initial version of the PLRM (NHC et al. 2009a) in October 2009 through grants provided by the US ACE and the Nevada Division of Environmental Protection (NDEP). The latest versions of the PLRM software and supporting documentation are available for download at: http://www.tiims.org/TIIMS-Sub-Sites/PLRM/docs-downloads.aspx.

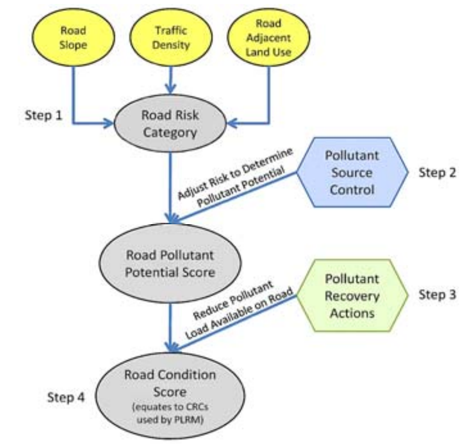
The PLRM provides Tahoe Basin resource managers with a tool to compare stormwater quality improvement alternatives in an urban catchment based on predicted load reductions for pollutants of concern to Lake Tahoe clarity. The desktop estimation tool combines SWMM (Storm Water Management Model) hydrology with a customized water quality module to predict the average annual pollutant loads from the outfall of a mixed land use catchment (NHC et al. 2009a). The continuous simulation model uses local 18-year historic meteorological datasets (WY1989-WY2006) to generate urban hydrology and pollutant loading and provide average annual loads at the catchment outlet for 6 pollutants of concern (total suspended solids [TSS], fine sediment particles [FSP], total nitrogen [TN], dissolved inorganic nitrogen [DIN], total phosphorous [TP], and soluble reactive phosphorous [SRP]). A variety of user inputs are required to represent the modeled urban catchment, including physiographic characteristics, land use distribution and condition, hydrologic source controls, and design characteristics of stormwater treatment BMPs.

The PLRM estimates pollutant concentrations in urban catchments using two primary water quality algorithms: characteristic runoff concentrations (CRCs) and characteristic effluent concentrations (CECs). CRCs are representative average runoff concentrations expected from a specific land use and associated land use condition, while CECs represent the average treated outflow concentrations for stormwater treatment BMPs (SWT) commonly used in the Tahoe Basin. The *PLRM Model Development Document* (NHC et al. 2009a) identifies the need to obtain Tahoe specific land use and SWT data to evaluate the appropriateness of the CRC and CEC algorithms and estimation approaches included in the initial version of PLRM. Also, at the time of PLRM development there was very limited stormwater data available for fine sediment particles in particular (see the *PLRM Model Development Document* (NHC et al. 2009a) for more details).

The PLRM hydrology module (SWMM-based) integrates the native soils and relative permeability of land surfaces within an urban catchment to generate a continuous time-series of surface runoff. The algorithms in PLRM provide a simple method to estimate saturated hydraulic conductivity (K_{sat}) based on soil type and land use type. However, current PLRM algorithms for estimating the fraction of precipitation that becomes surface runoff have two primary limitations: 1) hydrologic properties of soil are based on the 2006 Tahoe Basin Soil Survey (Soil Survey), which is a dataset for undisturbed soils; and 2) algorithms used to adjust saturated hydraulic conductivity (K_{sat}) apply compaction factors that vary by land use and do not consider site-specific conditions. While the PLRM Drainage Conditions Editor (NHC et al. 2009b) allows the modeler to override the suggested default value for K_{sat} derived from technical algorithms in PLRM by land use, little guidance has been provided on how to adjust K_{sat} to better represent site-specific soil conditions that have been altered by development. The *PLRM Model Development Document* (NHC et al. 2009a) identifies the need to better characterize hydrologic properties of soil impacted by development to inform simulations of infiltration in PLRM.

LAND USE POLLUTANT GENERATION

The PLRMv1 Road Methodology assumes that the CRC for pollutants of concern generated by roads can be predicted based on the integration of physiographic characteristics and the distribution of pollutant source controls, road abrasive application practices, and pollutant recovery actions (i.e., sweeping practices) (see schematic at right). Each factor has a variable level of influence on the predicted road condition and associated CRC within PLRM. The combination of user inputs to the Road Methodology results in an expected CRC for each road risk category. Figure 2.1 illustrates the road condition to CRC rating curves using in PLRM for FSP, TSS and SRP, respectively. At the time of PLRM development, the identified data limitations included: (1) minimal FSP data from roads available, (2) the majority of urban water quality monitoring stations measured runoff from mixed land use catchments, and (3) the relative condition of the land uses within the sampled catchment had not been documented concurrent with water quality monitoring. This research developed and implemented a sampling protocol to isolate the pollutant concentration emanating from a road surface at the time of sampling. These techniques were used to consistently sample a series of Tahoe road segments over 3 water years and evaluate the range and shape of the FSP, TSS and SRP CRC rating curves, as well as compare observed FSP concentrations to PLRM predictions.



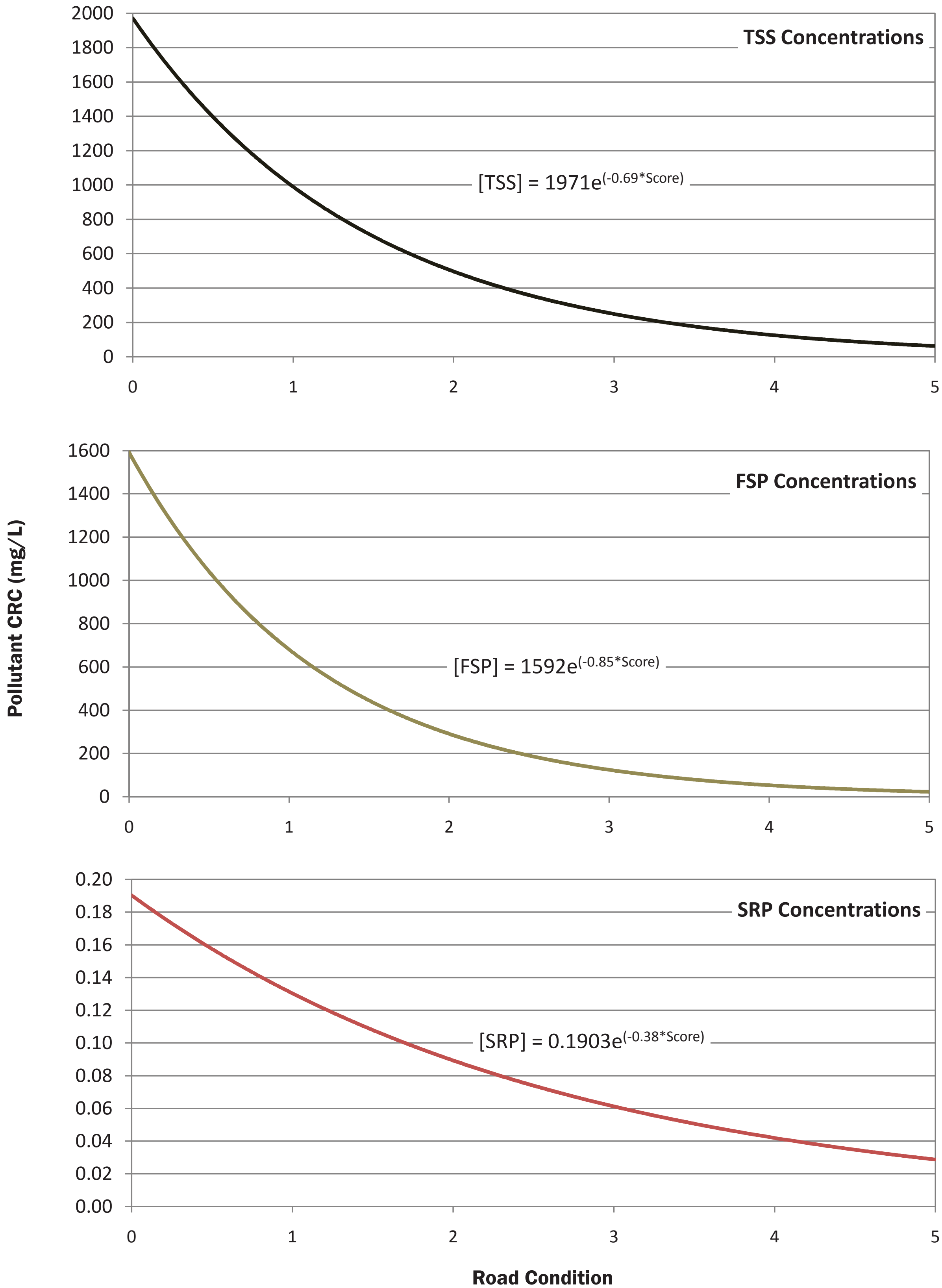
Simplified schematic illustrating PLRM Road Methodology approach.

The PLRM Parcel Methodology defines private parcel land use condition based on the presence/absence of private party pollutant best management practices (BMP) for the other 4 urban land uses: single-family residential (SFR), multi-family residential (MFR), commercial-industrial-communication-utilities (CICU), and vegetated turf. PLRM applies the Tahoe TMDL existing conditions event mean concentration values for parcels without BMPs and the Lake Tahoe TMDL Treatment Tier 1 values for parcels with BMPs (LRWQCB and NDEP 2008b). The initial PLRM private parcel CRC values are not based on a continuum of private parcel condition and are not distinct for the pervious and impervious fractions of the land use types. This research tested a variety of sampling techniques to identify viable methods for improving estimates of FSP CRC values used in PLRM (Table 2.1).

Table 2.1. PLRM land use parcel FSP CRCs with and without parcel BMP implementation certificates issued by TRPA. BMP certification includes both Source Control Certificates and BMP Retrofit Certificates **(**http://www.tahoebmp.org/Default.aspx**)**. CRC values are derived from the TMDL existing condition EMCs (no BMP certification) and Tier 1 EMCs (BMP certification) (LRWQCB and NDEP 2008b).

Land Use Type	**FSP CRC (% TSS by mass)**	
	No BMP certification	BMP certification
SFR	20.3 (36%)	14.0 (36%)
MFR	87.0 (58%)	32.7 (58%)
CICU	186.7 (63%)	128.5 (63%)
Vegetated Turf	4.3 (36%)	4.3 (36%)

PLRM v1 Road Condition to CRC Curves



Equations used in PLRMv1 Road Methodology (NHC et al. 2009a) based on limited Tahoe Basin catchment water quality data and associated road distribution and conditions.

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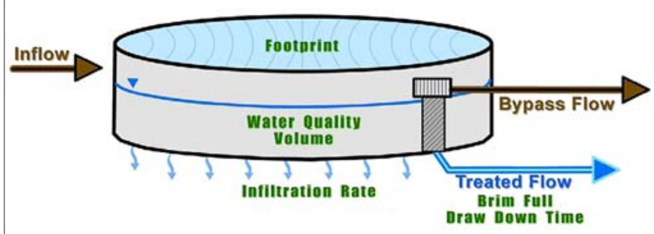
STORMWATER TREATMENT BMPS



PLRM Dry Basin schematic illustrating inflow, bypass flow through the bypass outlet structure, and treated flow through the treatment outlet.

PLRM defines a stormwater treatment BMP (SWT) as a facility that reduces pollutants of concern from a concentrated stormwater flow path and defines 6 specific SWT types: dry basin, infiltration basin, wet basin, treatment vault, cartridge filter, and bed filter. PLRM estimates SWT treatment performance based on the time series of surface runoff from catchments, runoff quality from catchments, SWT type and design characteristics, and a static characteristic effluent concentration (CEC) for each pollutant of concern for runoff routed through the treatment outlets of an SWT. Based on SWT type and key design attributes (Table 2.2), PLRM predicts the average annual volume captured and treated by the SWT (treated flow) and the average annual volume bypassed (see schematic above). SWT types, by definition, rely upon different physical processes to reduce pollutant concentrations in stormwater runoff and decrease stormwater runoff volumes (see Table 2.2). A critical component of PLRM SWT load reductions is the calculation of volume reductions via infiltration and the proportion of stormwater runoff estimated to be treated relative to the volume estimated as bypass. This research included continuous hydrology monitoring of select SWTs to develop measured event, seasonal and annual water budgets to compare with PLRM predictions.

Table 2.2. Examples of PLRM SWT types and key design attributes that the PLRM user inputs.

SWT Type	Description	Key Design Attributes
Dry Basin	Volume-based SWT designed to detain runoff for an extended period of time to allow particle settling. Provides pollutant load reductions through (1) volume reduction via infiltration and (2) effluent concentration reduction via particle capture.	• Water Quality Volume (cu-ft) • Footprint (sq-ft) • Infiltration Rate (in/hr) • Brim Full Draw Down Time (hr)
Wet Basin	Volume-based SWT with a permanent or seasonal pool of water. Provides pollutant load reductions through effluent concentration reduction via particle capture and nutrient cycling.	• Wet Pool Volume (cu-ft) • Wet Pool Footprint (sq-ft) • Minimum Hydraulic Residence Time of Wet Pool (hr) • Surcharge Basin Volume (cu-ft) • Brim Full Draw Down Time (hr)
Cartridge Filter	Flow-based SWT that houses a number of cartridges that contain engineered filtration media. Provides pollutant load reductions through effluent concentration reduction via media filtration.	• Maximum Treatment Flow (cfs)

This research obtained SWT water quality monitoring data from a number of dry basins, wet basins and one cartridge filter to evaluate the CEC values presented in Table 2.3. CEC values are expected to specifically represent only treated outflow concentrations. While a significant amount of SWT high resolution water quality monitoring had been conducted in the Tahoe Basin prior to 2006, past monitoring did not focus on separately analyzing the water quality of treated versus bypassed flows, which is necessary to assess the SWT methodologies and CECs used in PLRM. Furthermore, very little FSP stormwater data was available at the onset of this research. Therefore, resources were prioritized to target FSP data collection and to separately evaluate the quality of stormwater runoff considered to be either treated or bypassed by a SWT.

Table 2.3. PLRM SWT CEC values for FSP, TSS and SRP (NHC et al. 2009a).

SWT Type	FSP (mg/L)	TSS (mg/L)	SRP (mg/L)
Dry Basin	25	25	0.05
Wet Basin	10	10	0.04
Cartridge Filter	13	13	0.04

2.1.2 ROAD RAM

Road RAM is a simple, standardized and repeatable tool to determine the relative condition (i.e., downslope water quality risk) at the time of observation of urban roads in the Tahoe Basin. Road condition is determined by the integration of a series of standardized rapid visual proxies and simple measurements, and Road RAM results can be expressed as a road condition score (0-5) or a corresponding expected FSP concentration at the time of observations (Table 2.4). 2NDNATURE, NHC, and Environmental Incentives released the initial version of the Road RAM (2NDNATURE et al. 2010c) in November 2010 through grants provided by the California Tahoe Conservancy (CTC) and Nevada Division of Environmental Protection (NDEP). The technical document and user's manual can be downloaded at: http://ndep.nv.gov/bwqp/tahoe8.htm and the online tool is located at www.tahoeroadram.com. A portion of the road specific water quality sampling and data collection to inform Road RAM protocols was funded by the SNPLMA Round 9 research grant. *Chapter 6: Experimental Validation of Road RAM Concepts and Protocols* of the *Road RAM Technical Document* (2NDNATURE et al. 2010c) details the data collection and research findings used to support Road RAM protocols. These details are not repeated within this final report. The *Road RAM Technical Document* (2NDNATURE et al. 2010c) identified the need for an analysis of user precision, which is summarized and presented herein.

Table 2.4. Road RAM scores relative to road condition and relative risk to downslope water quality.

Road RAM Score	Condition	FSP Concentration (mg/L) Range
0 - 1.0	Poor	1,592-680
>1.0 - ≤ 2.0	Degraded	679-291
> 2.0 - ≤ 3.0	Fair	290-124
> 3.0 - ≤ 4.0	Acceptable	123-53
> 4.0 – 5.0	Desired	52-23

Road specific sampling techniques, including Road RAM, were used to compare observed and PLRM-predicted road FSP concentrations. Road RAM was intentionally developed to be complementary and consistent with PLRM v1 Road Methodology to the extent possible. However, PLRM predicts a likely average annual road FSP CRC, while Road RAM allows discrete temporal condition assessments at the time of observation. Road RAM scores can be converted to an estimated FSP concentration based on the correlations and statistical analysis conducted during Road RAM development (see Table 2.4). The road-specific FSP sampling and Road RAM observations conducted at a collection of Tahoe road segments over 3 water years for this research are integrated to represent a single observed volume-weighted average FSP concentrations and compared to PLRM predictions. These results provide additional insight for future PLRM Road Methodology recommendations.

2.2 RESEARCH OBJECTIVES

Below we provide the research objectives for the SNPLMA Round 9 research funding. The location where the specific objective has been addressed in the technical report is provided for easy reference. Data collection, management, and analysis techniques implemented for this research are presented in *Chapter 3 (Methods)*.

1. Expand and apply the urban road monitoring dataset to:
   a. Test and refine the PLRM v1 Road Methodology assumptions regarding the role urban road factors may have on urban roadway water quality condition (Chapter 5.1.1);
   b. Inform PLRM v1 estimates of the total (TSS) and fine sediment particles (FSP; TSS< 16 µm) CRCs from roads varying in condition, with inclusion of soluble reactive phosphorous (SRP) analyses as resources allow (Chapter 5.1.1);
   c. Improve the breadth and quality of urban stormwater data on the generation, fate and transport of TSS and FSP, as well as SRP where resources allow (Chapter 5.1.1); and
   d. Collect focused and controlled data from urban roads to inform and improve the Road RAM tool (see *Chapter 6: Experimental Validation of Road RAM Concepts and Protocols* of the *Road RAM Technical Document*; 2NDNATURE et al. 2010c).
2. Apply cost-effective and comparable sampling techniques to increase our understanding of FSP generation from other urban land use types, including commercial and residential surfaces, and their variability of condition (Chapter 5.2).
3. Expand and apply the SWT monitoring dataset to:
   a. Improve the understanding of water quality treatment performance, specifically with respect to FSP, and SRP as resources allow, based on SWT type and key design parameters (Chapter 6.2);
   b. Inform and improve the PLRM v1 CEC estimates based on SWT type and key design parameters (Chapter 6.2); and
   c. Link average annual infiltration rates with measured CHP saturated hydraulic connectivity values to inform PLRM v1 infiltration input requirements (Chapter 6.1.2).
4. Apply the PLRM v1 to estimate and compare hydraulic capture among SWTs monitored. Hydraulic capture is estimated in the PLRM using basic design information for each SWT facility and the drainage conditions of the catchment(s) tributary to each SWT. Information on hydraulic capture allows the research team to estimate the frequency and magnitude of storm events that cause bypass to occur at each SWT, which is a key consideration when developing improved CECs based on the monitoring data collected from this study (Chapter 6.1.1).
5. Collaborate with academic researchers in data and sample sharing for their development of appropriate numeric conversions from FSP concentrations and loads to # of particles.[1]

Above are the original research objectives developed in fall of 2008, which are fairly broad in scope. The research team continued to refine these objectives as new information was gained or priorities shifted, with the intent of maximizing the knowledge and data obtained to meet pressing management, modeling and tool development needs. An additional objective was identified during Phase II development:

6. Develop data collection techniques to inform PLRMv1 modeling assumptions regarding the infiltration rate (i.e., K_{sat}) of compacted pervious road shoulders. Create a framework for refining user inputs and adapting PLRM technical algorithms to allow for better representation of road shoulder condition and its effect on infiltration and runoff calculations in PLRM (Chapter 5.3).

[1] DRI researchers have been provided access to all stormwater samples collected for this research effort. Coordination and data sharing of necessary sample information has been offered to DRI researchers for when they choose to conduct any additional particle count analysis of the stormwater samples provided.

CHAPTER 3. METHODS

To address the current data gaps within the Tahoe Basin urban stormwater management tools and improve upon existing land use and stormwater treatment BMP datasets, the 2NDNATURE team tested cost-effective protocols to maintain the quality of the hydrologic and chemical datasets, but minimize the need for high-resolution stormwater monitoring instrumentation and laboratory analysis. The methods described below focus on generating a reliable dataset with which to compare land use pollutant generation and SWT treatment performance from a range of monitoring sites. Some methods, particularly the roadway water quality data collection techniques, were more effective than others, and the research team will continue to develop, test and refine standardized and consistent data collection methodologies that provide scientifically defensible analyses of sites with varying characteristics at minimal cost.

3.1 DATA COLLECTION

The 2NDNATURE team developed a complete data collection strategy, including monitoring goals and objectives, site selection justification, detailed instrumentation and field monitoring protocols, sample QA/QC requirements and data management specifications. The Phase I Final Monitoring Plan, funded by ACOE, was produced in July 2009 (2NDNATURE and NHC 2009c); the Phase II Monitoring Plan (Appendix A), funded by SNPLMA Round 9, was completed in July 2010 with updated protocols based on the lessons learned from Phase I. Below we provide a summary of these methods for the monitoring and analysis of roadway water quality, road shoulder infiltration, private parcel water quality, and stormwater treatment BMP data. Please refer to Appendix A for specific sampling techniques and detailed protocols.

3.1.1 ROADWAY WATER QUALITY

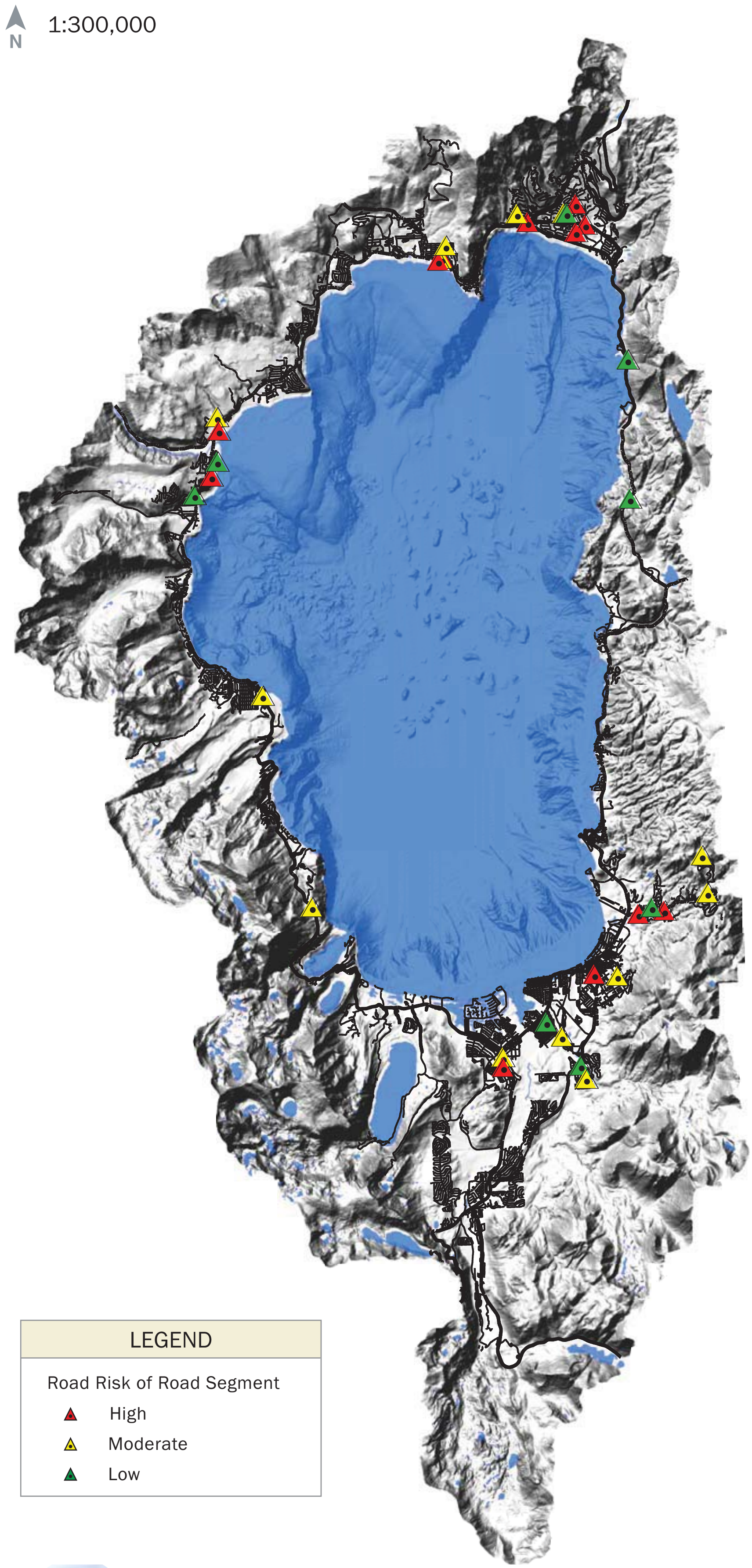
2NDNATURE field personnel collected roadway-specific water quality data at a range of road sites throughout the Lake Tahoe Basin. The following describes the process by which the sites were selected and field measurements were collected and analyzed.

ROAD SEGMENT SELECTION AND CHARACTERIZATION

Using GIS, the research team selected thirty-four (34) road segments, including thirty-two (32) roads and two (2) commercial parking lots (Figures 3.1-3.2), to represent a range of attributes including: road type (primary, secondary); jurisdictions responsible for maintenance; and road risk (high, moderate, and low) as defined in PLRMv1 using road slope, traffic density, and adjacent land use. A road segment is defined as 10,000 ft^2 and includes all continuous lateral impervious area within the right of way. The road segments were selected during the Phase I effort funded by US ACE and additional details on road segment selection and characterization can be found in *Chapter 3.1* of the *Phase I Technical Report* (2NDNATURE and NHC 2010a).

ROAD SEGMENT FIELD DATA COLLECTION TECHNIQUES

Figure 3.3 summarizes the road characteristics and data collected in the field at each urban road segment. The following provides a summary of the data collected; detailed protocols are provided in the *Phase II Monitoring Plan* (see Appendix A).



Road segment sampling sites by jurisdiction, road type, and road risk (as calculated September 2009).[1]

Jurisdiction	# High Risk		# Mod Risk		# Low Risk	
Road Type[2]	***P***	***S***	***P***	***S***	***P***	***S***
Caltrans	4		2			
City of South Lake Tahoe		2		1		1
KGID				2		1
El Dorado County		1			1	1
NDOT	3				2	
Placer County		2		4		
Washoe County		2		2		1

[1] Table does not include the 2 commercial parking lot sites under private jurisdiction.

[2] P= Primary Road; S = Secondary Road

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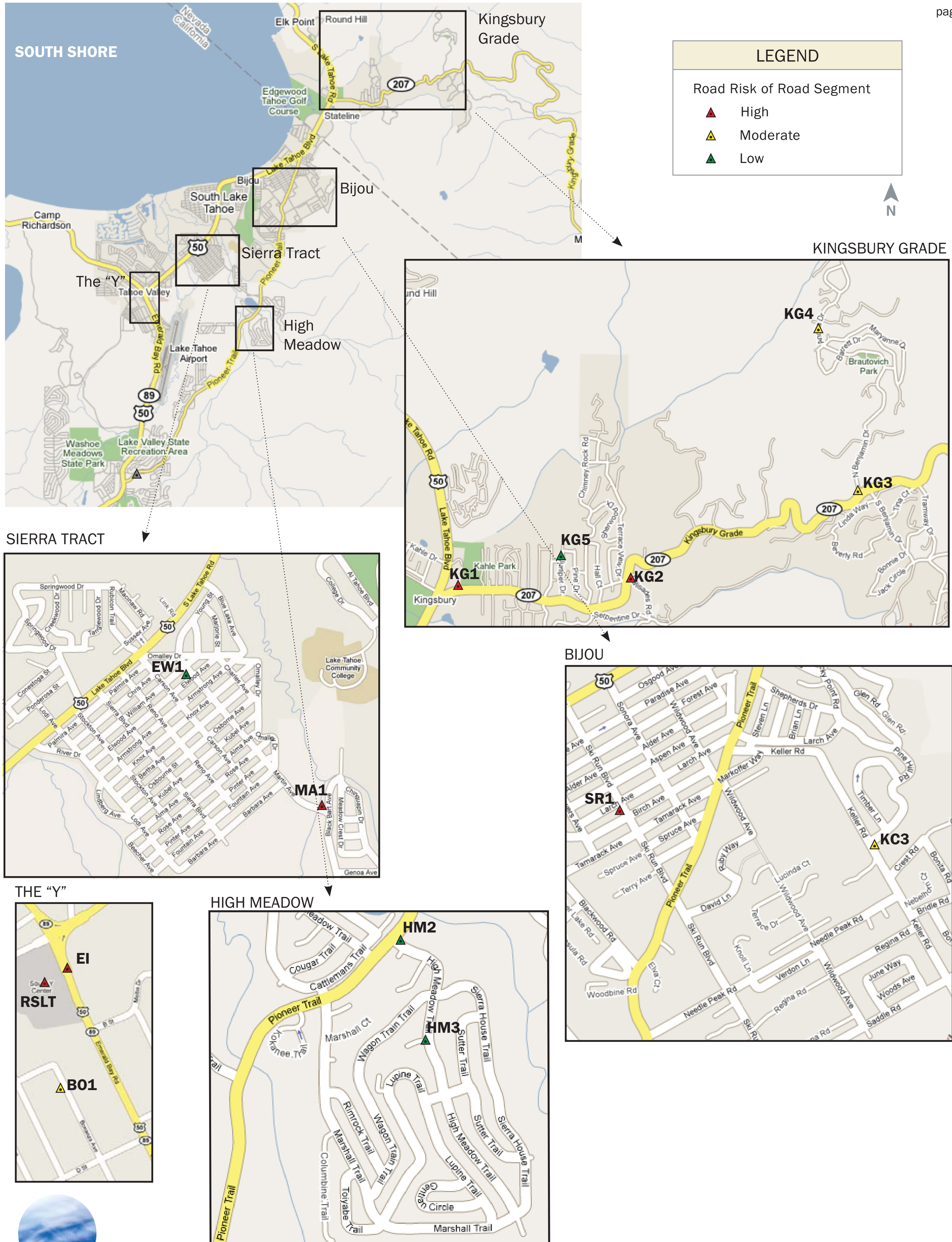
ROAD SEGMENTS - OVERVIEW

FIGURE 3.1



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ROAD SEGMENTS - SOUTH SHORE FIGURE 3.2A

N

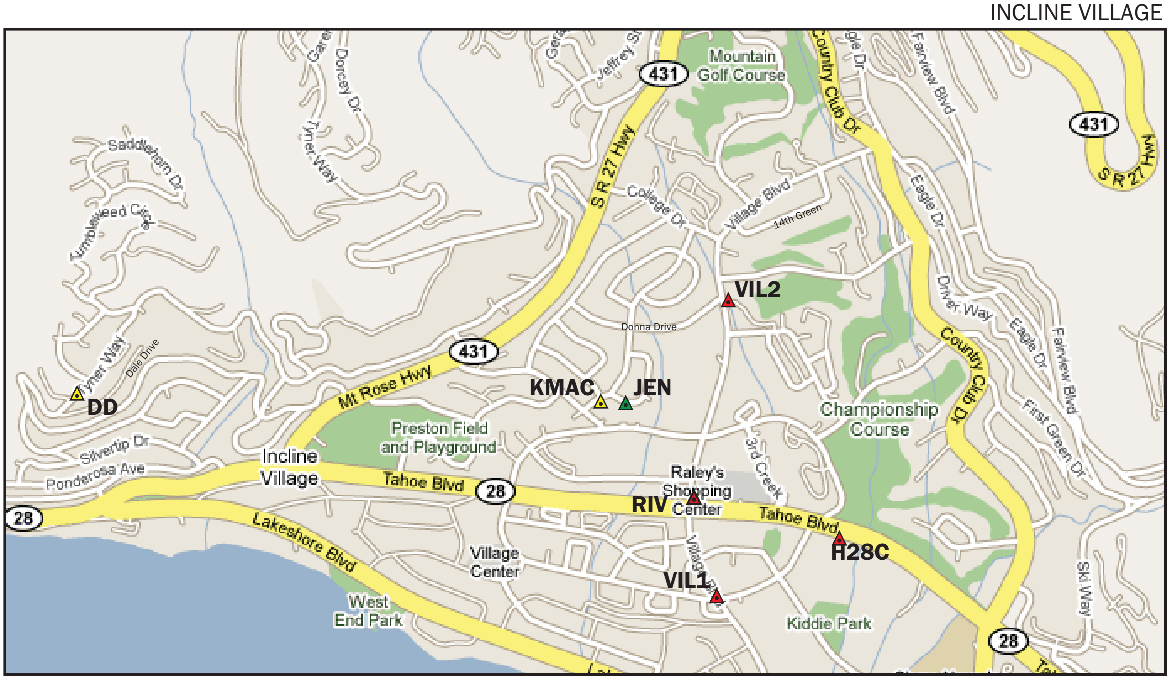
LEGEND

Road Risk of Road Segment

- High
- Moderate
- Low

KINGS BEACH

INCLINE VILLAGE



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ROAD SEGMENTS - EAST AND NORTH SHORE

FIGURE 3.2B

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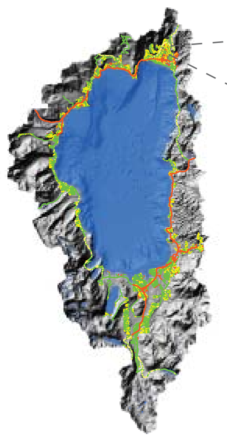
ROAD SEGMENTS - WEST SHORE

FIGURE 3.2C

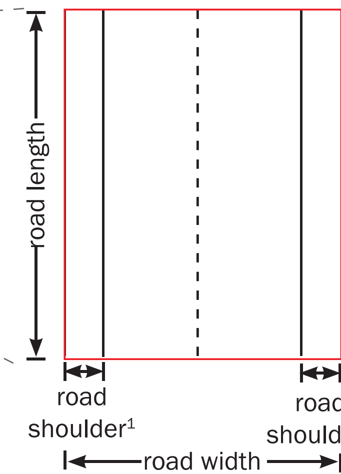
ROAD SEGMENT CHARACTERIZATION

Lake Tahoe Basin



GIS analysis of:
- Road Type [Primary, Secondary]
- Road Risk
  - [PHR, PMR, PLR/SHR, SMR, SLR]
- Jurisdiction

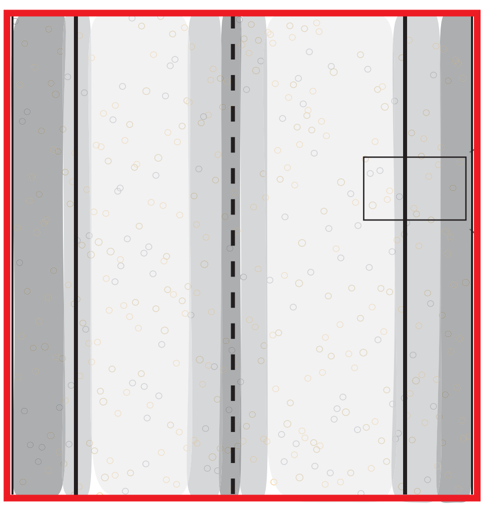
Road Segment (10,000 ft²)



Field characterization of:
- Right and Left Road Shoulder[1] Condition
  - [1, 3, 4, 5]
- Road Surface Integrity
  - [H, M, L]

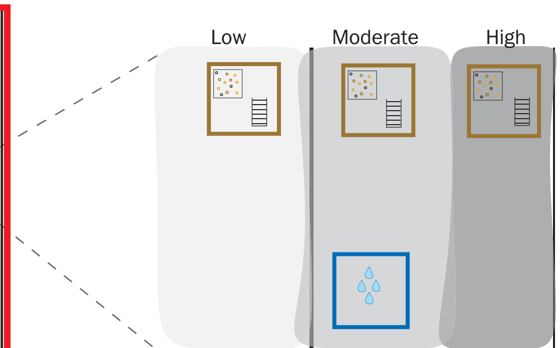
ROAD SEGMENT MONITORING EFFORTS

Road Segment (10,000 ft²)



Road RAM STEP 4B visual observations of material accumulation distribution on road segment of up to 3 material accumulation categories:
- High
- Moderate
- Low

Representative 1'x1' squares within each Material Accumulation Category



Road RAM STEP 4B visual observations of proxies for FSP concentration:
- Volume/Mass [ml, mg]
- Degree of Fines [H, M, L]
- Particle Size Distribution (limited)

Controlled experiments using portable simulator to obtain water quality sample from 1 (typically moderate) material accumulation category:
- TSS and FSP Concentrations [mg/L]
- Turbidity [ntu]
- Particle Size Distribution [% of TSS]

[1] PLRM defines the road shoulder to include the pervious area of the right-of-way. For the purposes of this monitoring and to be consistent with Road RAM, the road segment is defined by the width of the impervious surface area between the two edges of pavement and includes bike lanes or sidewalks if the impervious surface is continuous from the drive lane outward. The road length is determined based on the road segment width and the standardized road segment area of 10,000 ft².

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ROAD MONITORING DATA COLLECTION SCHEMATIC

FIGURE 3.3

Road segment characteristics determined in the field during the initial site visit included right and left road shoulder condition as defined by PLRM (erodible, protected, stable, stable and protected; NHC et al. 2009a) and road surface integrity (high, moderate, and low) based on a visual assessment of the pavement condition.

During each road segment monitoring effort, both road condition evaluations and controlled water quality experiments were conducted. Road condition evaluations included visual observations consistent with Road RAM protocols, which can be found in detail in *STEP 4B* of the *Road RAM User Manual* (2NDNATURE et al. 2010d). Visual observations include the % distribution of high, moderate, and low material accumulation categories on the road segment and observations of volume of material and degree of fines within 1 ft^2 area of each material accumulation category. A limited number of the material samples were kept and submitted to Cooper Analytical Laboratory for particle size distribution analysis. Controlled water quality experiments were conducted using a portable simulator (described below). The controlled experiments were at a minimum conducted in the moderate accumulation category to ensure consistency in comparisons across sites and observation periods. Water quality samples were analyzed for turbidity (ntu) in the field using a Hach 2100P portable turbidimeter, TSS and SRP concentrations were analyzed by WETLAB, and particle size distribution analysis was performed by DRI.

Road segment monitoring efforts conducted for this research are summarized in Table 3.1, including both Road RAM observations for road condition evaluations and water quality sample collection via controlled experiments using the portable simulator.

Table 3.1. Summary of road segment monitoring efforts conducted at 34 road segments from March 2009 through April 2011.

Road Segment Monitoring	Number
Condition evaluations (road segment score as defined by Road RAM)	310
1 ft^2 controlled water quality experiments (Field turbidity and/or laboratory TSS, FSP, SRP concentrations)	315[1]

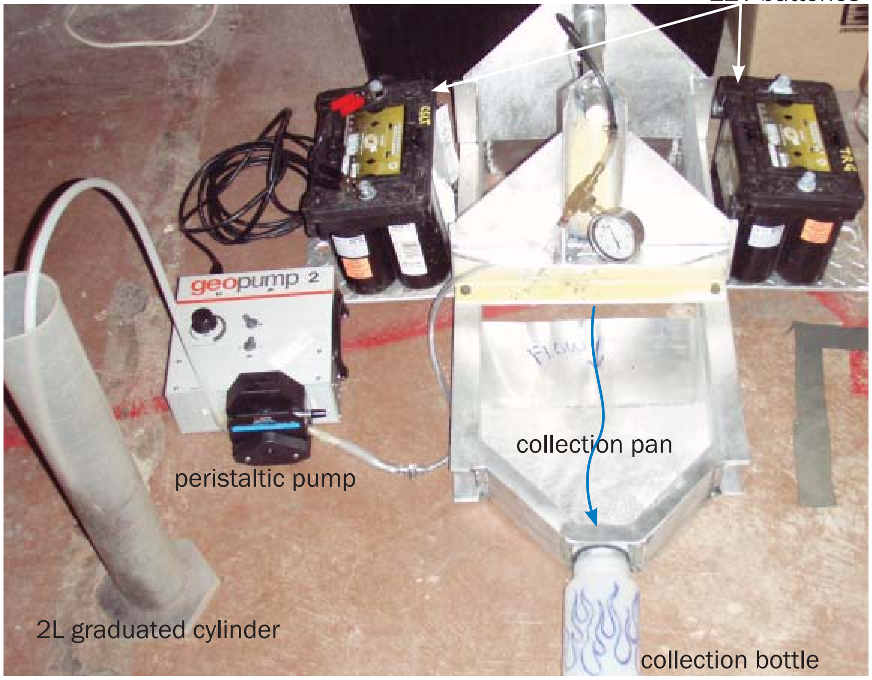
[1] Controlled experiments were not conducted during every road segment monitoring effort either due to weather or resource constraints. However, multiple controlled experiments were conducted at some road segments during each observation period for precision analyses.

PORTABLE SIMULATOR

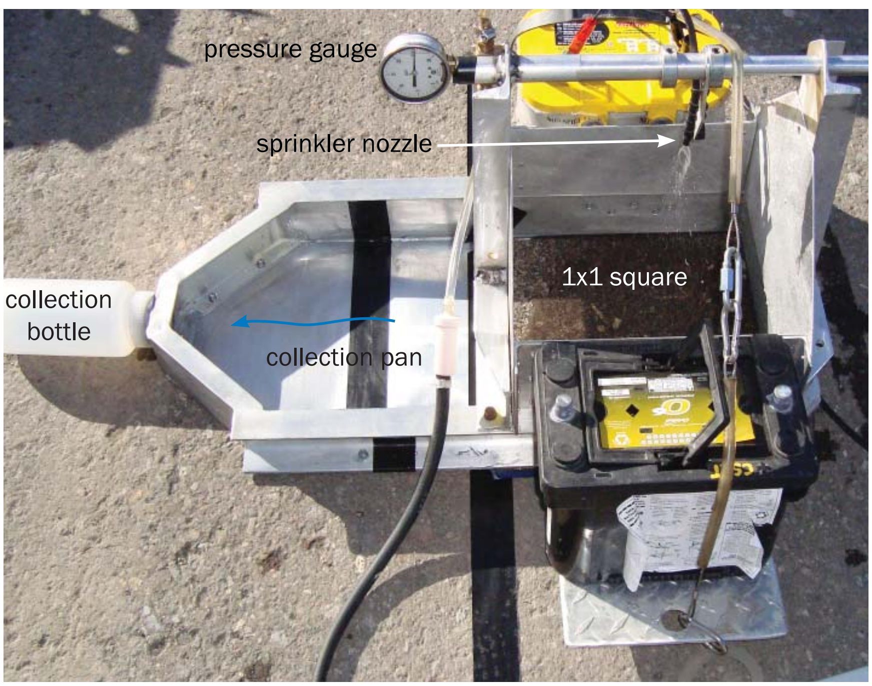
Using a custom-built portable runoff simulator designed and fabricated with assistance by Liquid Innovations and El Dorado County (Figure 3.4), field personnel collected water quality samples from a 1 ft^2 area on the road surface (typically in the moderate accumulation category) to provide a consistent, repeatable, rapid and cost-effective technique to sample the TSS, FSP and SRP concentrations derived from urban roads. Detailed protocols are documented in the *Phase II Monitoring Plan* (see Appendix A), including sample collection, bottle labels, and chain of custody. Key objectives of the portable simulator design included:

- Obtain water quality samples from over 30 Tahoe Basin urban roads in less than 3 days by 2 field personnel.
- Consistently sample a number of urban roads while keeping the water application rate, intensity, contributing area, and water sample collection methods constant. Constraining these primary hydrologic parameters increases our confidence that the measured differences in water quality constituents are due to differences in roadway pollutant mass and not due to sampling variability.
- Recover a minimum of 600ml of water from the simulation for proper analysis by the analytical laboratory.

PORTABLE SIMULATOR - FRONT VIEW



PORTABLE SIMULATOR - TOP VIEW



SIMULATOR IN ACTION IN THE FIELD

site set-up

simulation

sample collection

transfer to collection bottle

collection pan rinse

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PORTABLE SIMULATOR USED IN CONTROLLED EXPERIMENTS

FIGURE 3.4

The above design characteristics require that the portable simulator was run at an estimated intensity of 5 in/hr. While this intensity is higher than rain events in the Tahoe Basin, this increased rate is necessary to minimize the sampling duration and remain cost-effective. The relatively high intensity of simulated rainfall was assumed to be a reasonable trade off that compensates for our inability to simulate runoff from the entire road segment, including sheet flow across the road surface, which is common on impervious surfaces and efficiently entrains and transports pollutants.

ROAD SEGMENT DATA COLLECTION FREQUENCY

2NDNATURE field personnel conducted road sampling at each of the 34 road segments during a total of 10 observation periods from March 2009 through April 2011. Table 3.2 summarizes the 310 road observations completed during this research by road type, jurisdiction in charge of road maintenance, and month of sample collection. Due to a variety of reasons, including road construction and inclement weather, not all road segments were monitored during every observation period.

Table 3.2. Road segment monitoring summary by road type, jurisdiction in charge of road maintenance practices, and observation period. As noted, not all 34 road segments were monitored during every observation period due to inclement weather and/or road construction.

Road Type	Jurisdiction	Mar 09	Apr 09	May 09	Jul 09	Oct 09	Jan 10	Feb 10	Mar 10	Jan 11	Apr 11	Jurisdiction Totals	Road Type Totals
Primary	Caltrans, CA	4	5	6	6	6	4	6	5	5	6	53	121
	El Dorado County, CA	0	1	1	1	1	1	1	1	1	1	9	
	NDOT, NV	4	4	3	4	5	4	3	4	5	5	41	
	Private	0	2	2	2	2	2	2	2	2	2	18	
Secondary	CSLT, CA	4	4	4	4	4	4	4	4	4	4	40	189
	Douglas County, NV	1	3	3	3	3	2	3	3	3	3	27	
	El Dorado County, CA	2	2	2	2	2	2	2	2	2	2	20	
	Placer County, CA	5	6	6	6	6	4	6	5	4	6	54	
	Washoe County, NV	4	5	5	5	5	4	5	5	5	5	48	
Monthly Total		**24**	**32**	**32**	**33**	**34**	**27**	**32**	**31**	**31**	**34**	**310**	

3.1.2 ROAD SHOULDER INFILTRATION MEASUREMENTS

NHC field personnel collected measurements of K_{sat} and soil compaction across a range of Lake Tahoe Basin road shoulder conditions. The following summarizes the site selection process and the field data collection methods; more complete documentation is provided in Appendix B (*Measuring Road Shoulder Saturated Hydraulic Conductivity to Inform and Refine PLRM Algorithms*).

ROAD SHOULDER SITE SELECTION & CHARACTERIZATION

The characteristics of the 42 sites selected to evaluate if correlations between soil type or road shoulder condition could be related to measured K_{sat} are summarized in Table 3.3. Factors used to select sites included: soil type based on dominant texture, road type (primary or secondary road), and observed road shoulder condition.

Table 3.3. Summary of the road shoulder infiltration sites and key characteristics, including soil type, road shoulder condition, and road land use type.

Neighborhood	Texture of Soil Horizon	PLRM Road Shoulder Conditions	Road Type	# Sites
West Sunnyside, Placer County	Gravelly Medial Sandy Loam	Erodible, Stable, Stable and Protected	Secondary	5
Dollar Point, Placer County	Very Cobbly Sandy Loam	Erodible, Stable and Protected	Secondary	3
Sierra Tract, City of South Lake Tahoe	Loamy Coarse Sand	Erodible, Stable and Protected	Secondary	14
Montgomery Estates, El Dorado County	Gravelly Loamy Coarse Sand	Stable, Stable and Protected	Secondary	4
Meyers, El Dorado County	Coarse Sandy Loam	Erodible, Stable, Stable and Protected	Secondary	8
Gardner Mountain, City of South Lake Tahoe	Loamy Coarse Sand	Erodible	Secondary	2
Highway 89, City of South Lake Tahoe	Loamy Coarse Sand	Erodible	Primary	6
			Total	**42**

ROAD SHOULDER FIELD DATA COLLECTION TECHNIQUES

Simultaneous compaction and saturated hydraulic conductivity (K_{sat}) measurements were conducted at each site 3-5 foot from the edge of the impervious road surface (e.g., asphalt travel lane, bike lane, top back of curb). Compaction was measured using an analog cone penetrometer to measure the relative resistance of soil at each sample site to infer the degree of compaction. Each measurement was taken in dry soil using the ½" tip for the cone penetrometer and at many sites multiple readings were averaged to ensure that soil heterogeneity did not bias the depth of penetration recorded. K_{sat} was measured using a constant head permeameter (CHP) in accordance with NRCS guidelines (NRCS 2010) at approximately 6" below the soil surface. Readings were taken at the shallowest depth the CHP would allow to better infer surface infiltration conditions.

To test the hypothesis that K_{sat} is lowest near the impervious edge of the road surface and increases with distance from the road shoulder, 24-foot transects were established at several sites extending perpendicular to the road shoulder to evaluate if declining soil compaction and increasing K_{sat} could be observed. Compaction measurements were taken at roughly one foot intervals. K_{sat} measurements were taken at a distance of 3-5 feet and at 24 feet from the impervious edge of the road surface, with a third measurement taken along the transect if a notable change in soil compaction was identified along the transect.

3.1.3 PRIVATE PARCEL WATER QUALITY

The research team aimed to develop a cost-effective data collection and analysis technique to evaluate the relative water quality risk from pervious urban land use types in the Tahoe Basin and inform the CRC values used in PLRMv1 for private parcels. The primary objective of the data collection effort was to test various data collection techniques in order to identify viable methods for improving estimates of FSP CRC values used in PLRM for the private parcel land uses targeted.

PRIVATE PARCEL SITE SELECTION & CHARACTERIZATION

Thirty six sites were selected throughout the Tahoe Basin to represent a range of observed existing conditions on the private parcel land uses (CICU, MFR, SFR). In addition to the private parcel land uses, non-urban land uses (EP1-5) were also selected to provide a greater range of surface conditions. Vegetated turf was not included because PLRM assumes that improved water quality management of turf surfaces does not result in a reduction in FSP generation from this land use (see *Table 6.5* in *PLRM User Manual*, NHC et al. 2009b). Field personnel categorized the relative condition of each site based on visual observations of the degree of exposed, disturbed and potentially erodible soils on the parcel (see photos at right). This approach was used to expand upon the binary concept in the PLRM Parcel Methodology, which is based on whether or not a site has received a TRPA BMP Certificate of Completion, and to determine relative condition based on the assessment of the site at the time of observations. For each land use type, 3 sites were selected in each condition category (good, moderate and poor). In addition to the private parcel water quality methods described below, 2 commercial parking lot sites (see sites RIV and RSLT in Figure 3.2) were included in the roadway water quality research described above in Chapter 3.1.1, and are included in the summary shown in Table 3.2.

Range of private parcel conditions observed.

PRIVATE PARCEL FIELD DATA COLLECTION TECHNIQUES

Field personnel collected land use data over the course of 3 observation periods – October 2010, April 2011 and June 2011, visiting each site once. Initial testing of data collection techniques included the use of the portable simulator on pervious surfaces to determine if the simulator could improve comparisons across land use types by reducing sampling variability. However, the use of the portable simulator on pervious surfaces was discarded because of (1) the high and variable water volume required to generate enough runoff to collect an adequate volume for laboratory analysis, and (2) the difficulty in sealing the portable simulator to ensure runoff is not lost underneath the collection pan and out the sides of the sampling area.

At each site, a representative 1 ft^2 area was selected, similar to the methodology used for road data collection (see Chapter 3.1.1). The relative condition within the square was documented, considering level of disturbance or compaction and type of material. Approximately 200 ml of material was collected from the upper soil layer and stored in a labeled Ziploc bag for future analysis. In some locations, a runoff test, similar to the protocols detailed in the *BMP RAM User Manual* (2NDNATURE et al. 2009b), was conducted to measure the length of time it takes for 1 L of water to infiltrate. Two analysis methods were tested using the dry material sample collected from each site:

- Particle grain size analysis (described in Chapter 3.1.5) by Cooper Testing on 23 samples from a range of land use types representing poor and good conditions.

- Turbidity measurements on a subset of 24 samples by adding 10 g of material to 1 L of water, with the hypothesis that the dry material samples with a greater fraction of FSP would yield higher turbidity values.

3.1.4 STORMWATER TREATMENT BMPS (SWTS)

2NDNATURE designed and implemented stormwater monitoring at 3 typical Lake Tahoe SWT types (as defined by BMP RAM (2NDNATURE et al. 2009a) and PLRM (NHC et al. 2009a)): dry basins, wet basins, and cartridge filters. Cost-effective data collection included continuous surface water hydrology monitoring, event-based surface water sampling, and treatment BMP condition evaluations. Field data was used in the analysis of SWT treatment performance and as inputs to the modeling techniques described in Chapter 3.2 of this technical report.

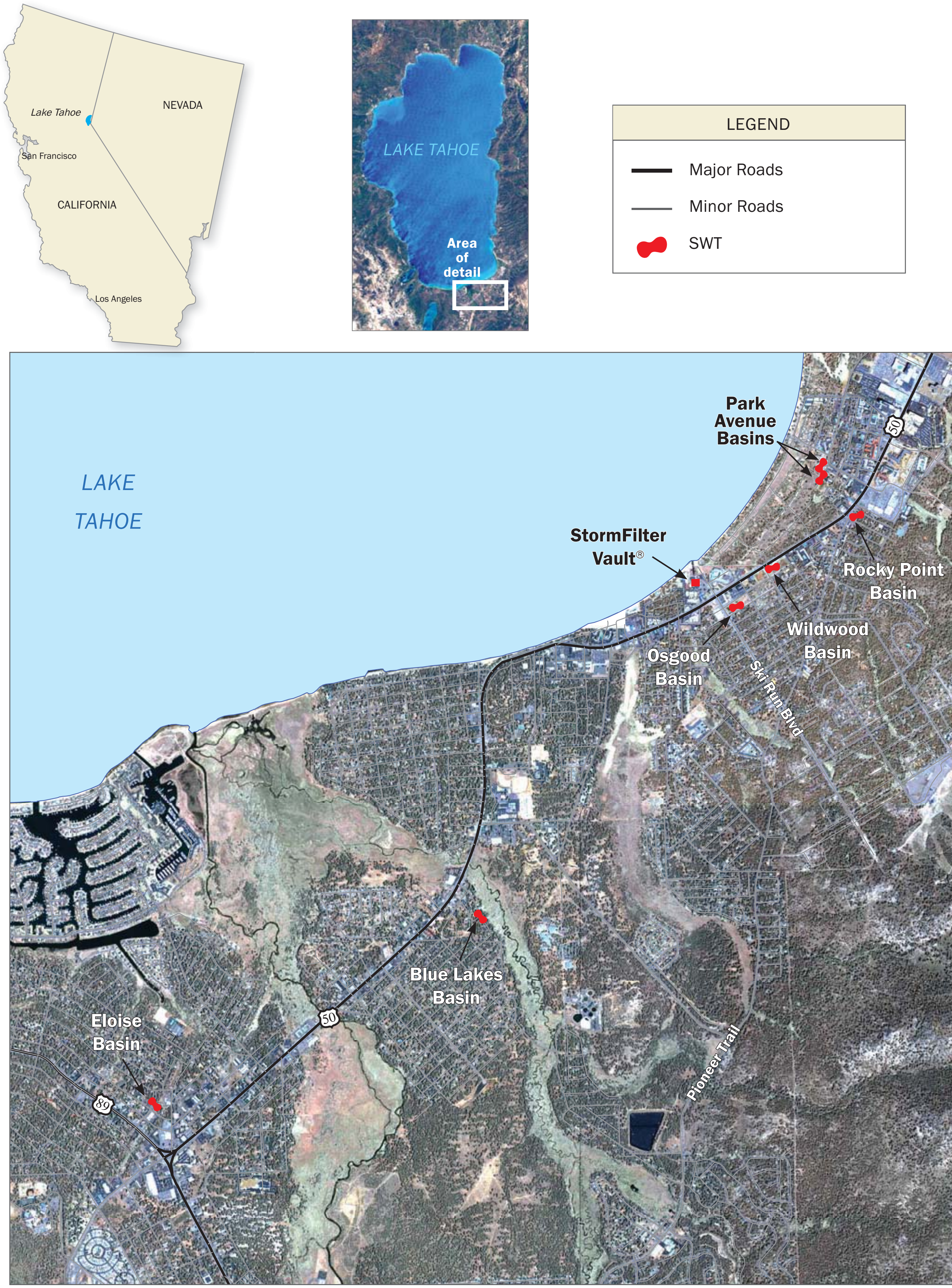
SWT SITE SELECTION & CHARACTERIZATION

2NDNATURE developed a site prioritization matrix based on overall research cost effectiveness and considered a number of factors, including site proximity, team familiarity with the site, and ease of instrumentation, when making the final site selections. A total of 9 SWTs (Figure 3.5) were monitored during this research: 4 sites (Osgood Basin, Park Avenue Upper [PA1] and Lower [PA2] Basins, and Stormfilter® Vault) were monitored from WY09 through WY11 and 5 sites were added in WY10-WY11 (Rocky Point Basin, Eloise Basin, Blue Lakes Basin, Wildwood Basin, and Coon Basin).

To compare the treatment performance to PLRM predictions, key characteristics of the contributing catchment and SWT design were detailed for each SWT (Tables 3.4-3.5). The urban catchment contributing to the BMP was delineated (Figures 3.6A-B) and a GIS analysis was performed to calculate the total area, average slope, land use distribution, % impervious area, and dominant soils (see Table 3.4) as described in the PLRM Applications Guide (NHC et al. 2010). Reconnaissance level field inspections were used to validate PLRM inputs derived from the GIS data and to inform PLRM input parameters that cannot be developed from a GIS analysis (e.g., stormwater treatment (SWT) parameters). Key stormwater treatment BMP design attributes, as well as construction and maintenance history, were also cataloged based on field visits, existing design reports, and conversations with jurisdiction public works personnel (see Table 3.5).

The following key points should be noted about the monitoring sites (see Tables 3.4 and 3.5):

- Catchment area ranged from 1.7 acres (Stormfilter) to 340 acres (Osgood).
- Catchment % impervious area ranges from 18% (Rocky Point) to 81% (Stormfilter), while total impervious area ranges from 1.4 acres (Stormfilter) to 118 acres (Eloise).
- Roads, including primary and secondary roads, typically account for 10-20% of the total catchment area. Both Osgood and Rocky Point catchments are dominated by non-urban land uses (e.g., EP1-5) (43 and 56%, respectively) and residential land uses (39 and 29%, respectively). Residential land uses account for approximately 50% of the total area in the Blue Lakes and Wildwood catchments, while the percent of commercial land use is highest in Park Avenue and Eloise catchments (19 and 27%, respectively).
- The cartridge filters in the Stormfilter® Vault were replaced in 2008. Based on conversations with CSLT personnel, there has been no recent maintenance activity at any of the other SWTs monitored.
- 2NDNATURE has monitored the Park Avenue basins almost continuously since 2004 (2NDNATURE 2008). During this time, the basin treatment train has never functioned completely as designed, as the water inflowing from the Rocky Point inlet bypasses PA1 more frequently than intended and the total volume of water outflowing from PA1 does not reach the inlet of PA2 as designed because of notable infiltration occurring at the joints in the storm drain pipe connecting PA1 to PA2.



A ninth SWT (Coon Basin) was also monitored; however it is located on the north shore in Kings Beach, CA, and therefore is not shown on this map.

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SWT MONITORING SITE LOCATION MAP

FIGURE 3.5

Catchment Name[1]	Osgood	Park Avenue	Eloise	Rocky Point	Blue Lakes	Wildwood	Stormfilter
Location	South Lake Tahoe, CA	South Lake Tahoe, CA	South Lake Tahoe, CA	South Lake Tahoe, CA	South Lake Tahoe, CA	South Lake Tahoe, CA	South Lake Tahoe, CA
Total Area (ac)	341	225	281	169	17.3	108	1.7
Impervious Area (%, ac)	23% (79 acres)	30% (67)	42% (118)	18% (30)	35% (6.1)	43% (46)	81% (1.4)
Average Slope (%)	9%	7%	1%	10%	2%	4%	2%
Land Use Distribution (% Total Area)							
Primary Roads	3%	1%	0%	1%	0%	1%	
Secondary Roads	11%	12%	13%	10%	19%	20%	
Commercial Industrial Communications Utilities (CICU)	4%	19%	27%	4%	9%	14%	90%
Multi-Family Residential (MFR)	14%	9%	23%	8%	30%	20%	
Single Family Residential (SFR)	25%	16%	4%	21%	24%	27%	
Unimpacted Vegetation (EP 1-5)	43%	44%	32%	56%	18%	17%	10%
Catchment Soils							
Dominant Soil Type	Cassenai; Cagwin Rock	Cassenai; Christopher-Gefo	Ubaj; Christopher-Gefo	Cassenai; Cagwin Rock	Christopher-Gefo	Oneidas; Marla	Marla
Private Parcels (% TRPA Certification)							
CICU	27%	0%	6%	0%	0%	2%	0%
MFR	21%	4%	0%	6%	7%	10%	0%
SFR	20%	16%	13%	17%	71%	14%	0%

[1] Given inconsistent instrument data collection at Coon Basin, a GIS analysis of the catchment was not performed.

SWT Name	Osgood	PA1	PA2	Eloise	Rocky Point	Blue Lakes	Wildwood	Coon[1]	Stormfilter
PLRM Inputs									
SWT Type	Wet Basin	Wet Basin	Dry Basin	Wet Basin	Dry Basin	Dry Basin	Dry Basin	Dry Basin	Cartridge Filter
Water Quality / Wet Pool Volume (ac-ft)	0.07	0.47	0.96	0.35	0.27	0.17	2.25		-
Footprint / Wet Pool Footprint (sq-ft)	2,250	25,100	27,600	19,700	8,200	2,400	98,000		-
Infiltration Rate (in/hr)	-	-	0.40	-	0.1	0.15	0.02	n/a	-
Min Wet Pool HRT (hrs)	24	24	-	24	-	-	-	-	-
Surcharge Basin Volume (ac-ft)	0.43	0.73	-	1.05	-	-	-	-	-
Brim Full Draw Down Time (hrs)	48	48	48	60	41.2	170	96	n/a	-
Max Treatment Flow (cfs)	-	-	-	-	-	-	-	-	0.75
Additional Details									
Year Constructed	1985; mod. 1997	2001; mod. 2003	2001; mod. 2003	1980s					2001
Morphology	Max flow path; pre-treatment settling forebay	Max flow path	Max flow path	Max flow path	Max flow path	Max flow path	Max flow path	Max flow path	Enclosed Rect-angle
Outlet Type	20' Rect. Weir w/ 3 6" orifices	1 2.5' Perf. CMP; 1 5' CMP	1 2.5' Perf. CMP	1 6' CMP	2' Rect. Weir w/ 1 3" hole	1 3' Perf. CMP	Notch Weir	1 5' CMP	Weir
Treated Depth (ft)	1.90	0.58	1.04	-	0.65	1.69	-	-	0.5
Bypass Depth (ft)	2.85	1.66 / 1.76	2.04	4.68	2.68	2.94	2.06	2.96	2.00
Discharges to	Ski Run Marina	PA2/North Ditch	North Ditch	SEZ/Tahoe Keys	PA1	Trout Creek SEZ	Wilwood Basin #3	Culvert to Lake Tahoe	Ski Run Marina
Last Known Maintenance	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2008 (replaced filters)
Research Monitoring Details									
Date Surface WLR Installed	Dec 2008	Dec 2008	Dec 2008	Sept 2009	Sept 2009	Sept 2009	Sept 2009	Sept 2009	n/a
Date of Topo Survey	July 2009	Aug 2011	Aug2011	June 2010	June 2010	Aug 2011	June 2010	Oct 2010	n/a
# Inlet PS Installed (Date)	3[2] (Nov 2009)	2[3] (Jan 2009)	2[3] (Jan 2009)	4 (Nov 2009)	5 (Sept 2009)	4 (Sept 2009)	n/a	n/a	n/a
# Outlet PS Installed (Date)	3[2] (Nov 2009)	2[3] (Jan 2009)	3[3] (Jan 2009)	4 (Nov 2009)	4 (Sept 2009)	4 (Sept 2009)	n/a	n/a	n/a
Monitoring Summary	Water Budget & CEC data	Water Budget & CEC data	Water Budget & CEC data	Water Budget & CEC data	Water Budget & CEC data	CEC data only; poor WLR data	CEC data only; poor WLR data	CED data only; poor WLR data	CEC data only; poor WLR data

[1] Given inconsistent instrument data collection at Coon Basin, a a full analysis of the basin was not performed.

[2] Originally, 3 inlet and 2 outlet passive samplers were installed at Osgood Basin in Jan 2009. However, following Phase I research, it was determined the passive samplers had not been installed at the correct elevations and new passive samplers were installed in Nov 2009. All 3 inlet passive samplers were moved, and 1 additional outlet passive sampler was installed.

[3] Based on lessons learned during Phase I monitoring, the elevations of the Park Avenue basin passive samplers were modified to more appropriately sample the inlet and outlet surface waters.

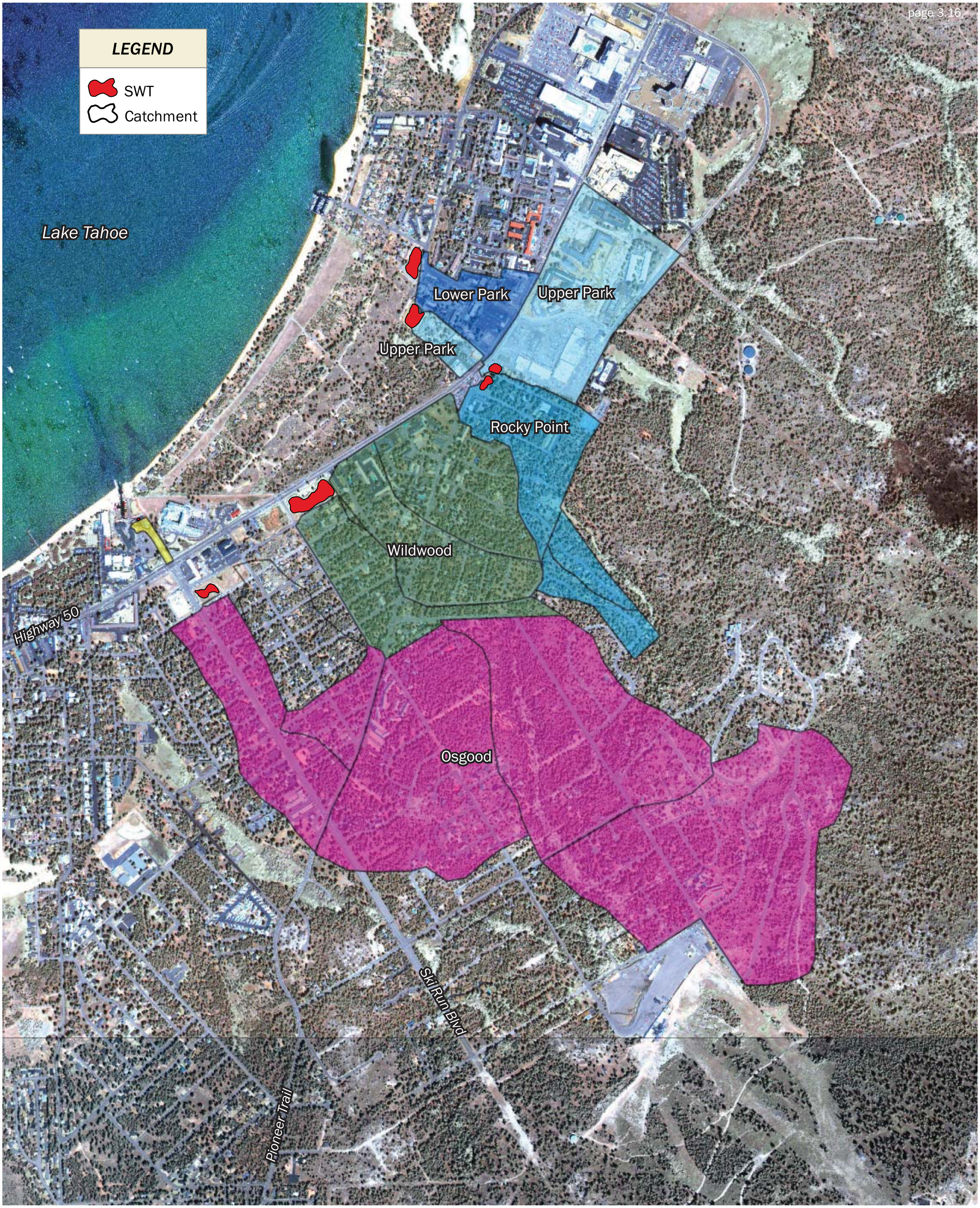

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Figure 3.6A. SWT Catchment Location Map - South Lake Tahoe, East

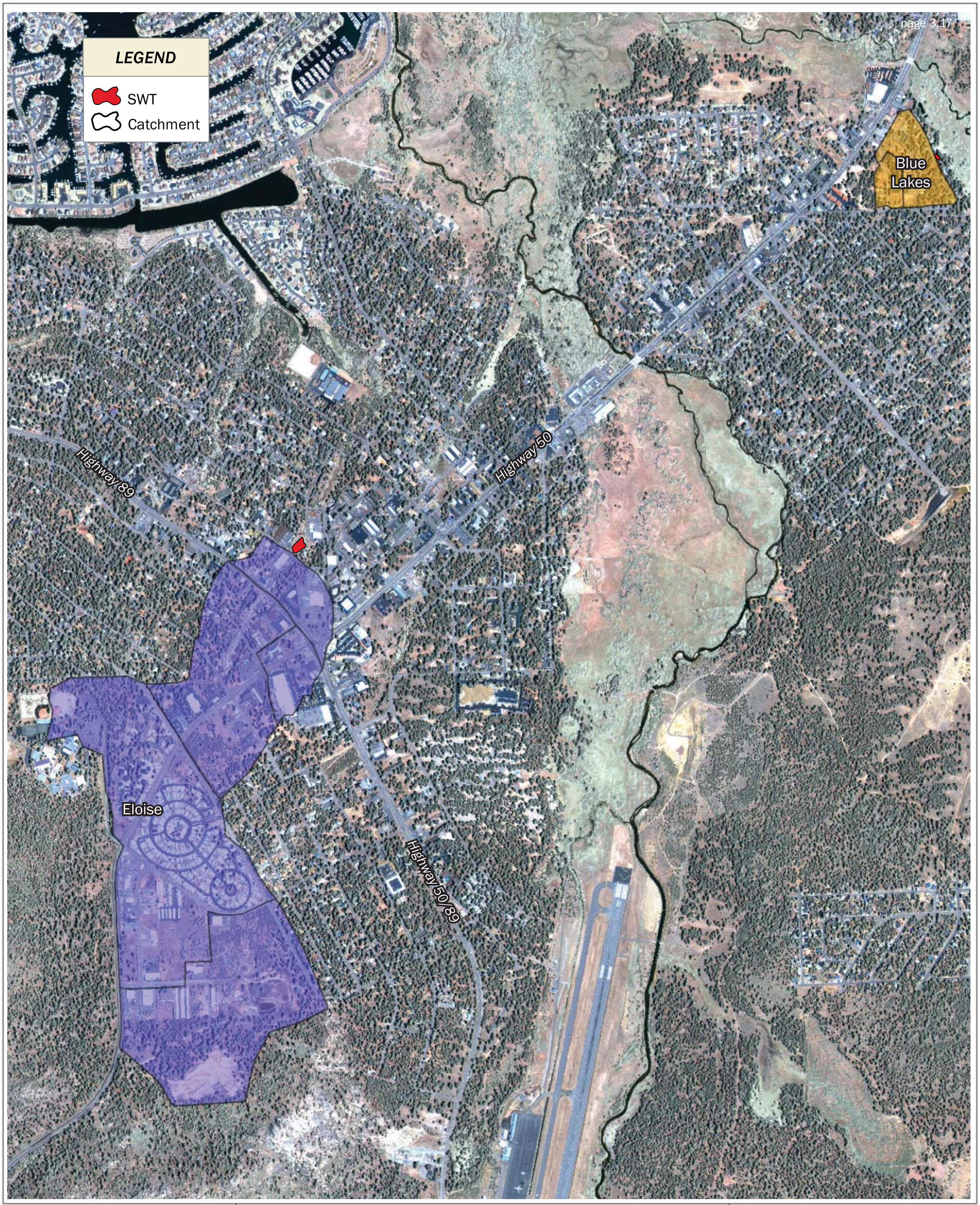

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Figure 3.6B. SWT Catchment Location Map - South Lake Tahoe, West

SURFACE WATER HYDROLOGY DATA COLLECTION TECHNIQUES

At all nine SWTs, an unvented In-Situ LevelTroll 500 and staff plate were installed to record water depth on 15-minute intervals. An In-Situ BaroTroll maintained at the offices of Environmental Incentives in South Lake Tahoe, CA recorded barometric pressure on the same time interval to correct the SWT depth data for changes in atmospheric pressure. All instrument gages were downloaded and maintained regularly during site visits, and the staff plates were used to visually verify instrument performance and complete data QA/QC. Accuracy of the water level recorders is ±0.05 ft, as documented in the manufacturer's specifications. Due to the cold climate and frequent freeze/thaw conditions, several level recorders did not perform reliably during the winter months. Data from Blue Lakes, Wildwood and Coon Basins could not be consistently correlated to staff plate measurements and, therefore, were not used in this research analysis (see Table 3.5). Data collection from the Stormfilter® Vault was also unreliable, as there is constant backwatering within the outlet and accurate depth readings were not obtained.

2NDNATURE field personnel surveyed the three wet basins and four dry basins to obtain detailed topography and elevations of critical features (inlet(s), outlet(s), instrumentation, etc.) for each basin. The basin topographic data was tied to the water level recorder elevation to create a basin stage to storage rating curve using the ArcGIS 3D Analyst surface volume tool and the subsequent development of a continuous basin water storage time series and detailed water budget (described below in Chapter 3.2.1). Site instrumentation details for each SWT are provided in Table 3.5, and Figures 3.7A-G illustrates site-specific topographic contours and monitoring locations.

WATER QUALITY SAMPLE FIELD DATA COLLECTION TECHNIQUES

A total of 299 water quality samples were collected from the nine SWTs during WY09-WY11 using a combination of passive samplers, grab samples, and automated instrumentation and submitted to Western Environmental Testing Laboratory (WETLAB).

As indicated in Table 3.5, passive samplers (Nalgene® Stormwater Samplers) were installed at 6 SWTs to characterize the inlet and outlet water quality. Passive samplers are a low-cost method to collect discrete water quality samples associated with a specific basin water surface elevation. Samplers collect the rising limb of the hydrograph (standardizing sample collection across all sites) and are self-sealing to preserve the sample until field personnel can safely visit the site (top half of Figure 3.8). In some instances, water samples collected from passive samplers may be slightly higher than event mean concentrations (EMCs) because they sample the rising limb and do not represent the entire hydrograph. However, the reduced cost of passive sampler installation and lower data management complexity compared to flow-weighted automated samplers allow for a significant increase in the number of sites monitored and the temporal extent of monitoring for the resources available.

Two to three passive samplers were installed at both the inlet and outlet of each basin (bottom half of Figure 3.8) and sample collection is standardized based on relative basin stage. Inlet/outlet pairs were installed at near equivalent water surface elevations to ensure collection of samples occurs at a similar location on the storm hydrograph and the difference pollutant concentrations between the inlet and outlet pair can be attributed to the water quality treatment as a result of flow through and interaction with the treatment BMP (Figures 3.9A-B). Sampler elevations are determined relative to the treatment and bypass outlet elevations of the SWT, in order to compare treated and bypass flow, as defined by PLRM.

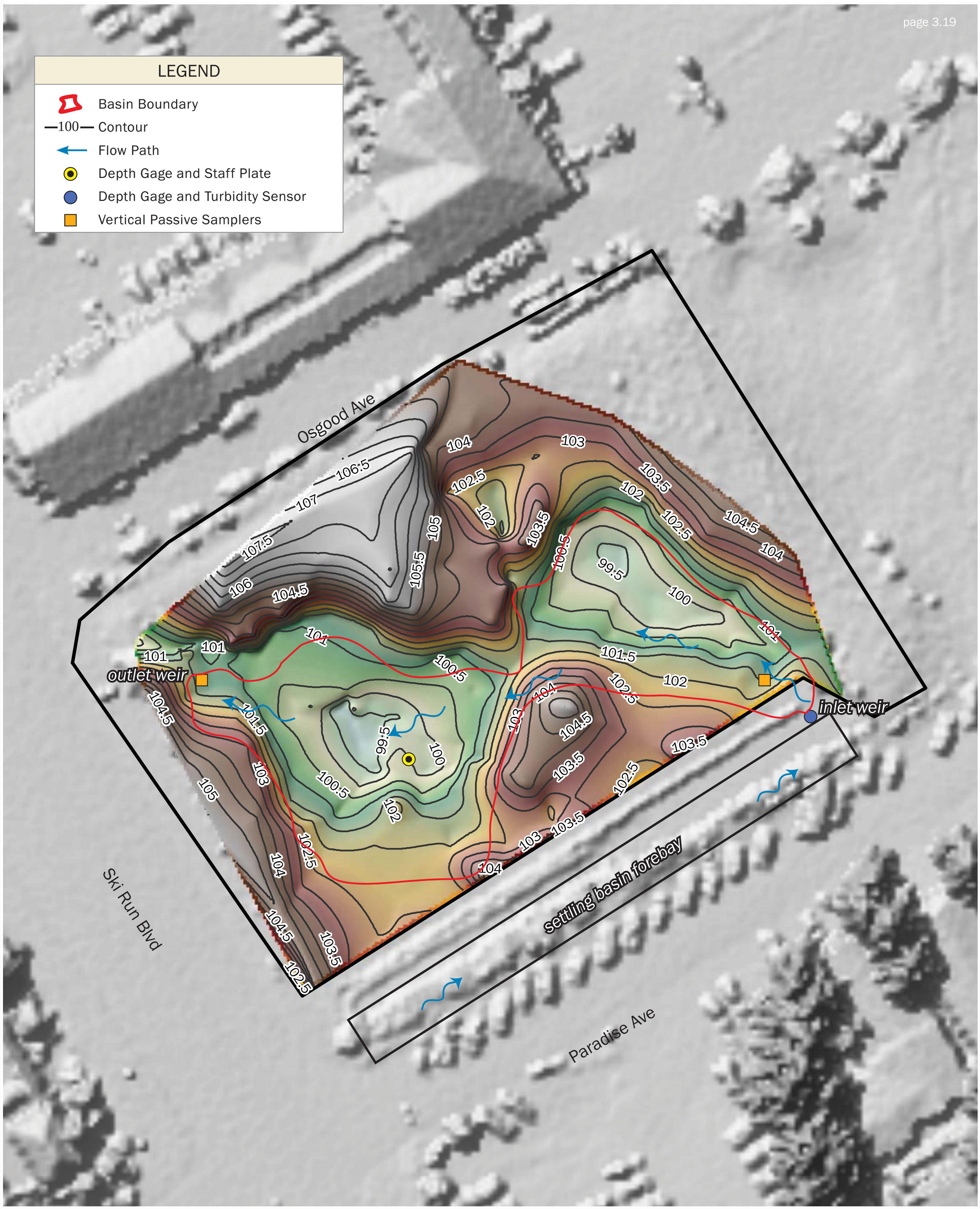

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Figure 3.7A. Osgood Basin Site Map Shaded topographic contours of Osgood Basin plotted over a 2010 LiDAR data. Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 100ft elevation

Feet
0 15 30 60
N

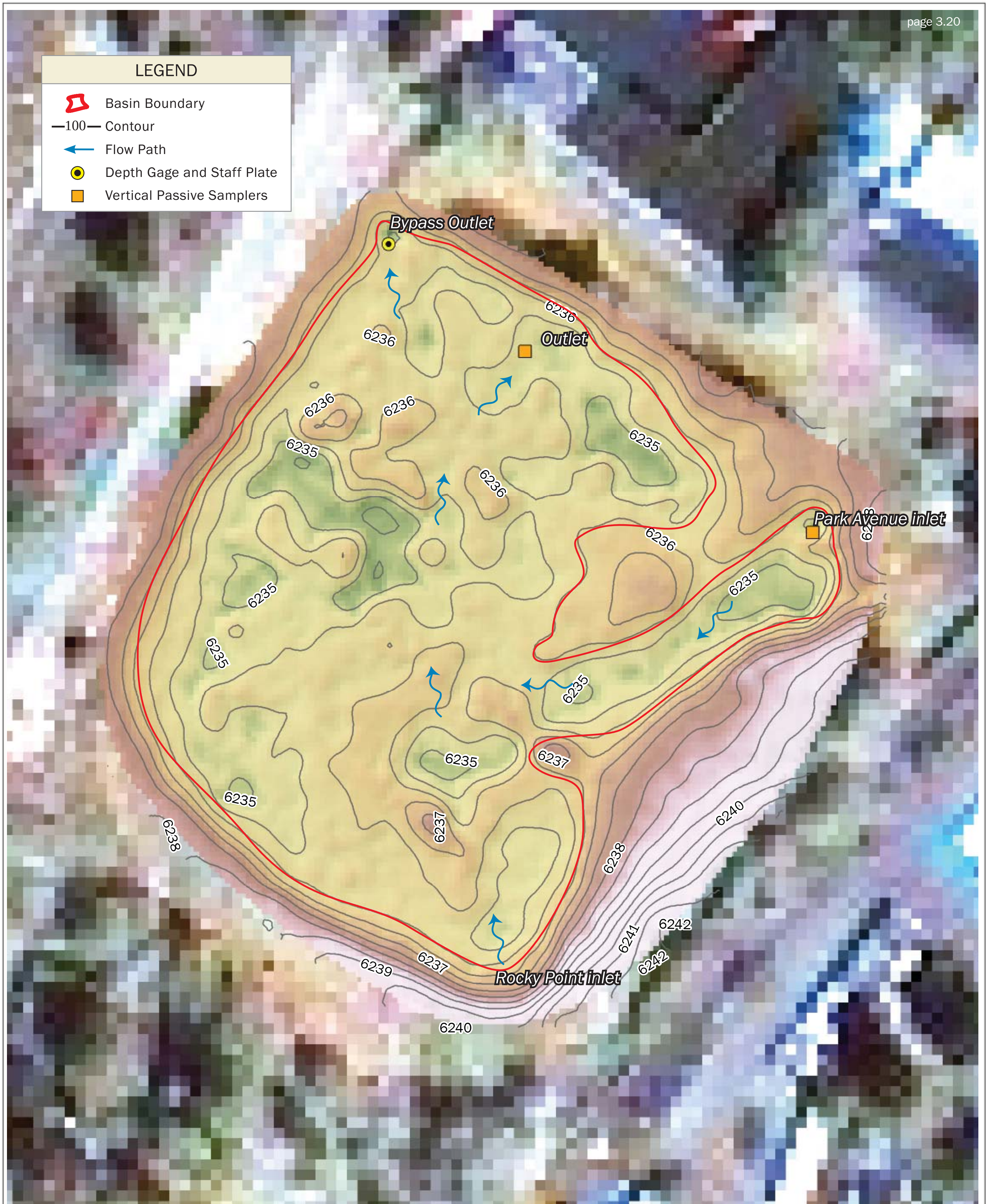

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Figure 3.7B. PA1 Basin Site Map Shaded topographic contours of Upper Park Basin (PA1). Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 6234.5 ft elevation

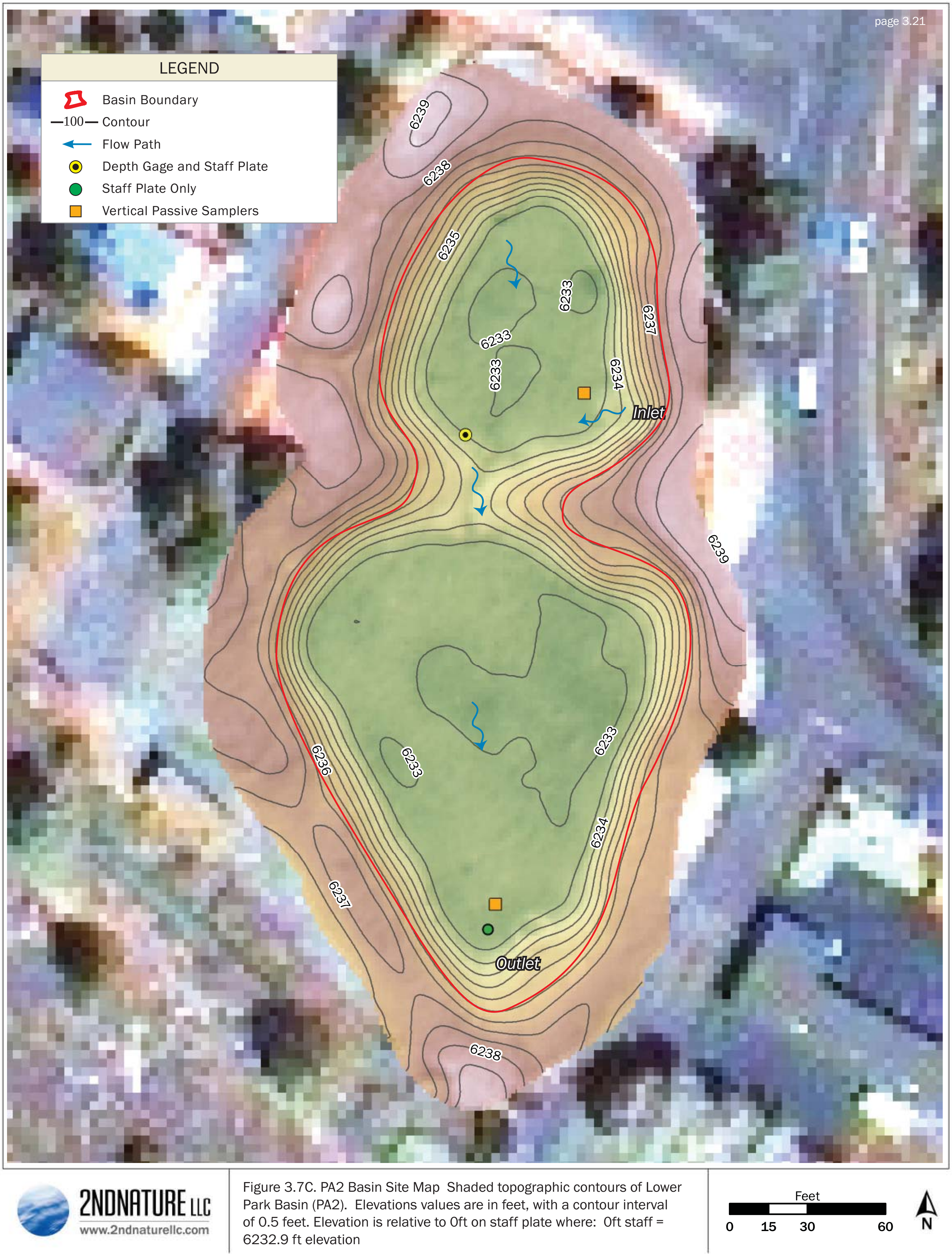

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Figure 3.7C. PA2 Basin Site Map Shaded topographic contours of Lower Park Basin (PA2). Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 6232.9 ft elevation

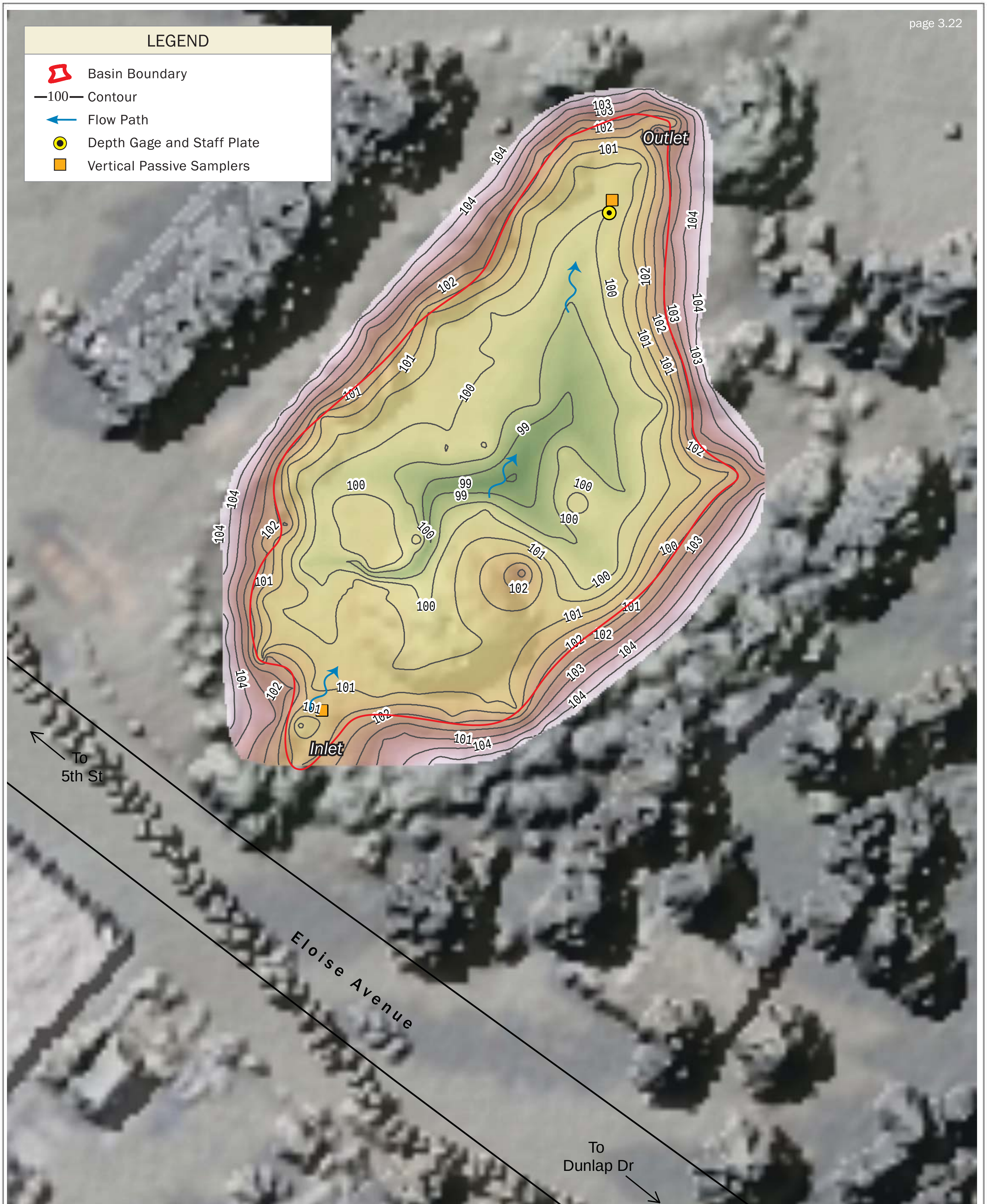

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Figure 3.7D. Eloise Basin Site Map Shaded topographic contours of Eloise Basin. Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 100 ft elevation

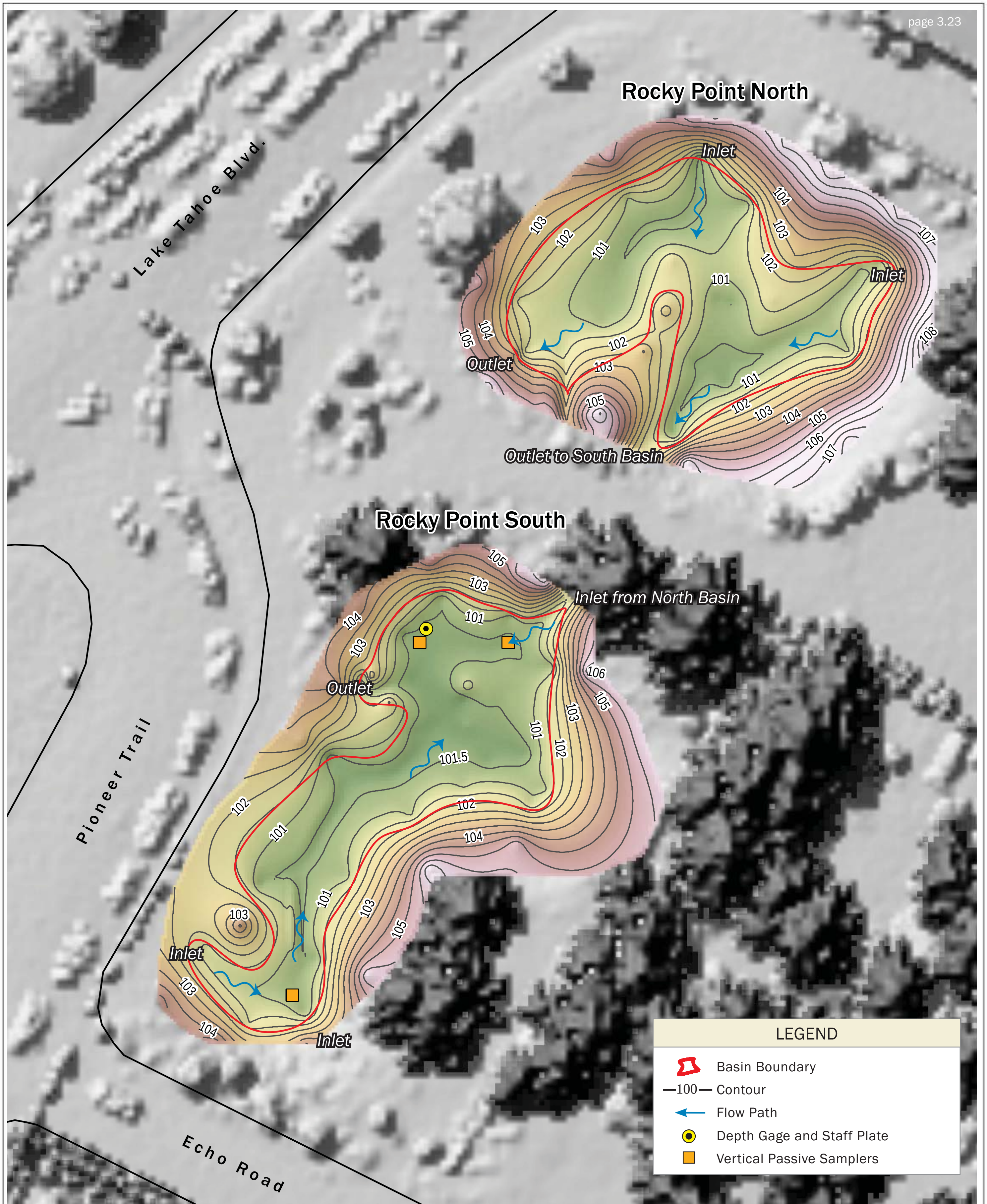

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Figure 3.7E. Rocky Point Basins Site Map Shaded topographic contours of Rocky Point Basins. Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 100 ft elevation

Feet
0 12.5 25 50
N

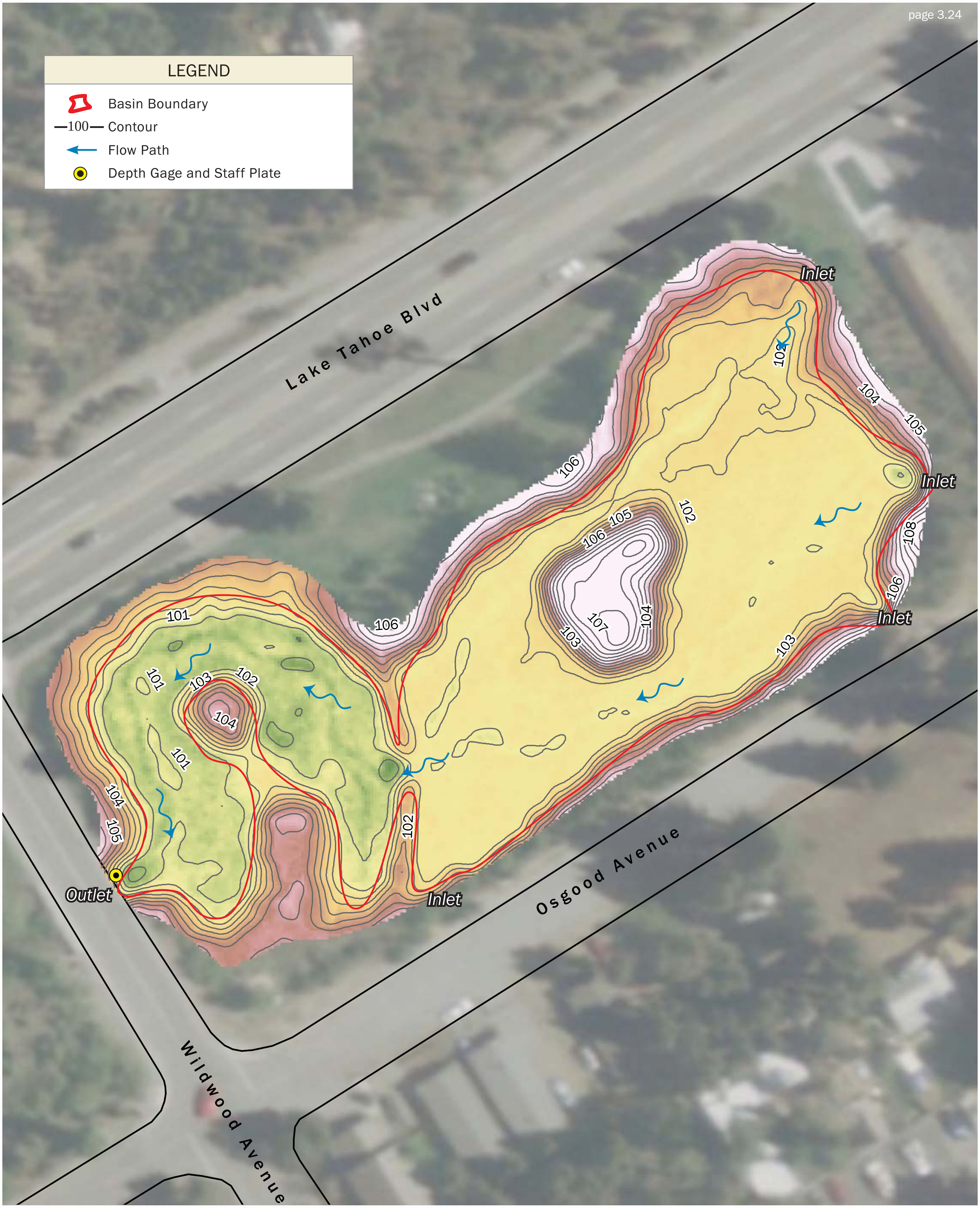

Figure 3.7F. Wildwood Basin Site Map Shaded topographic contours of Wildwood Basin. Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 100 ft elevation

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Feet
0 25 50 100
N

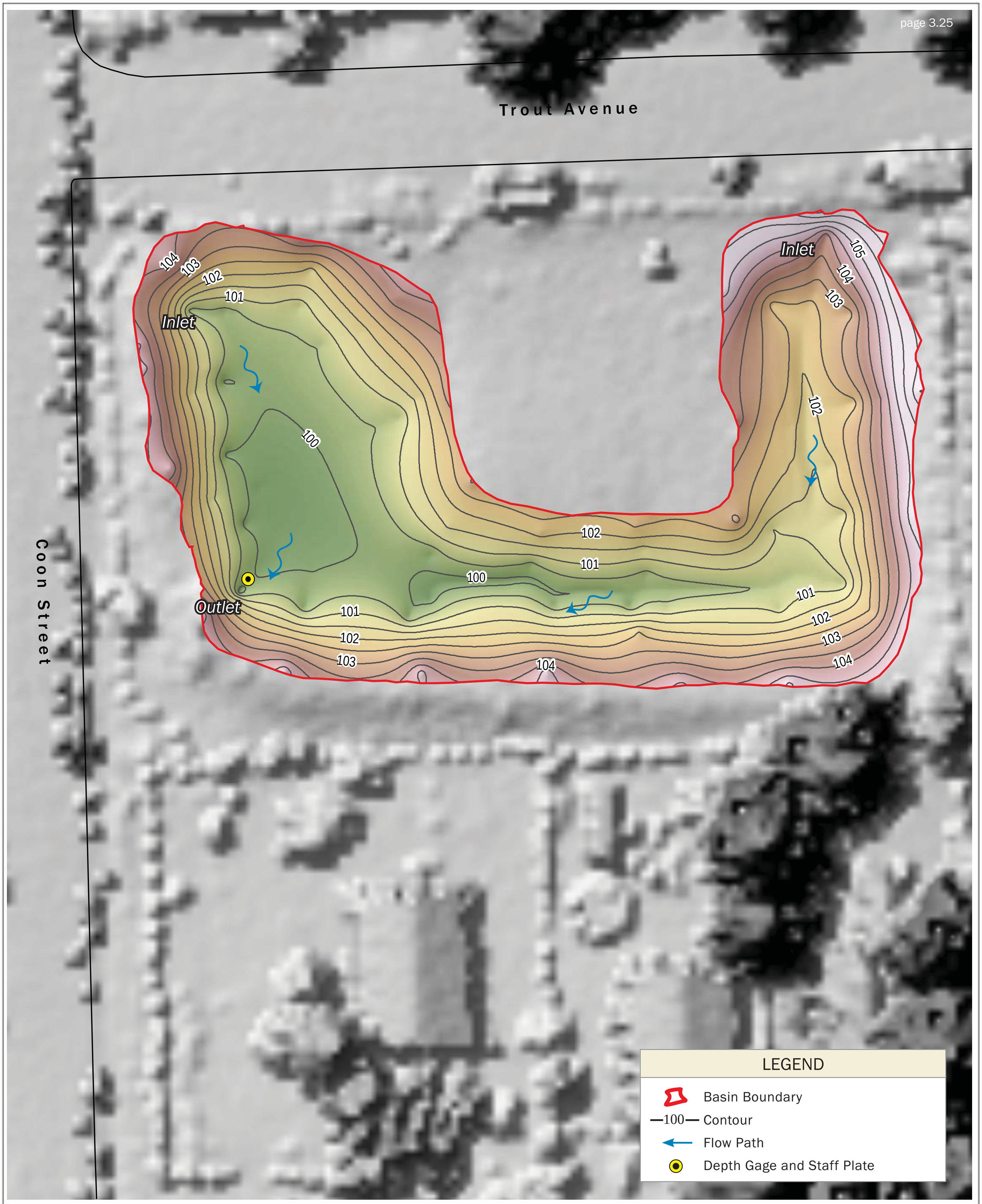

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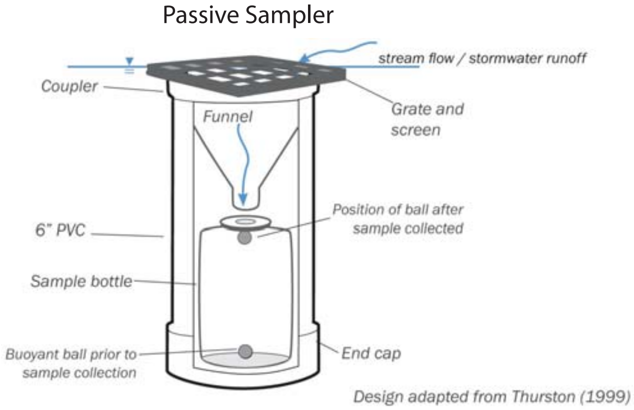
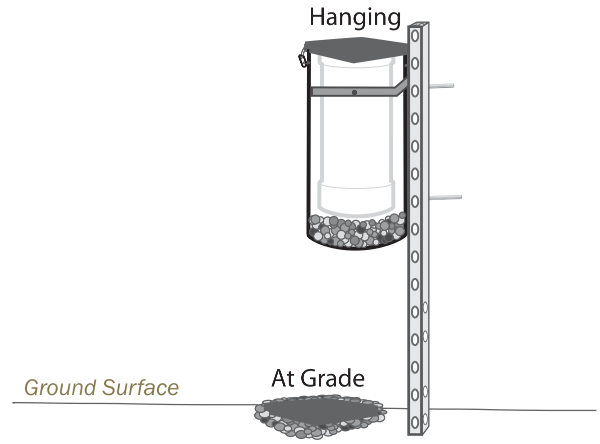
Figure 3.7G. Coon Basin Site Map Shaded topographic contours of Coon Basin. Elevations values are in feet, with a contour interval of 0.5 feet. Elevation is relative to 0ft on staff plate where: 0ft staff = 100 ft elevation

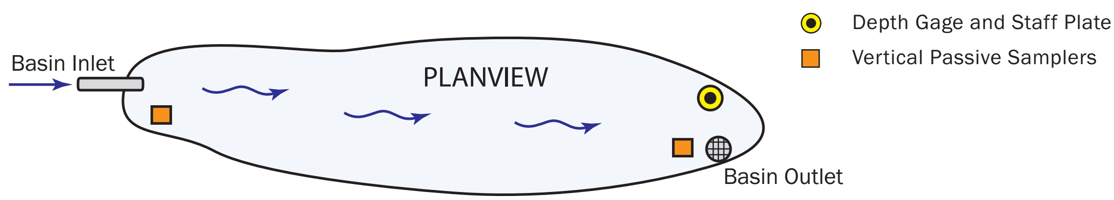
BASIN SWT PASSIVE SAMPLER DESIGN

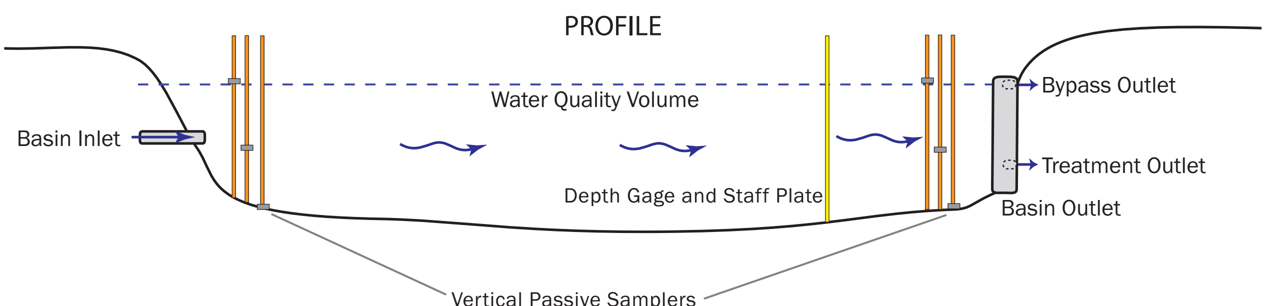




- Passive samplers can be custom fabricated to meet site-specific needs, but typically are Nalgene Stormwater Samplers®.
- Passive samplers can be (1) buried in the flow path to collect sample at grade or (2) secured to vertical sign post to collect a sample at a targeted stage elevation (i.e., hanging).
- Sample is collected when water surface exceeds elevation of top of sampler. Sample flows over grate, through funnel and into bottle. As bottle fills with water during the event, the ping pong ball floats to the top and plugs the hole in the lid and seals the sample until it is collected by field personnel.

BASIN SWT



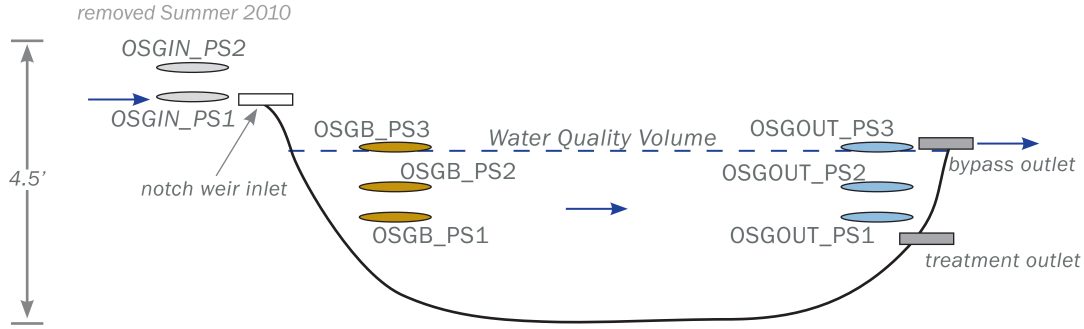


SITE INSTRUMENTATION

- Depth Gage installed in basin to record water depth continuously on 15-minute intervals and create surface water hydrology time series.
- Staff Plate is installed to QA/QC depth data.
- 4 - 8 Basin Passive Samplers are installed within basin (2-4 at inlet and 2-4 at outlet, depending on basin depth at invert of bypass outlet).
  - Samplers are installed to collect samples at various water surface elevations to standardize sampling based on relative basin stage.
  - Inlet and outlet sampler elevations are matched as closely as possible to create inlet/outlet sample pairs. This technique assumes that at the same basin stage, the inlet/outlet sampler pairs are collecting samples at a similar location on the storm hydrograph and observed water quality differences between the samples is the result of flow through and interaction with the SWT.

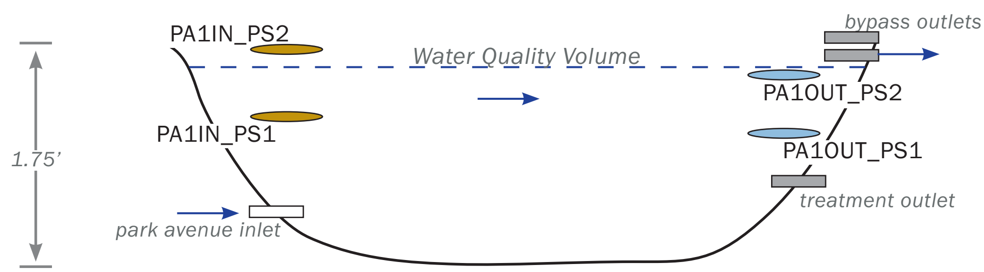
1.

Osgood Basin



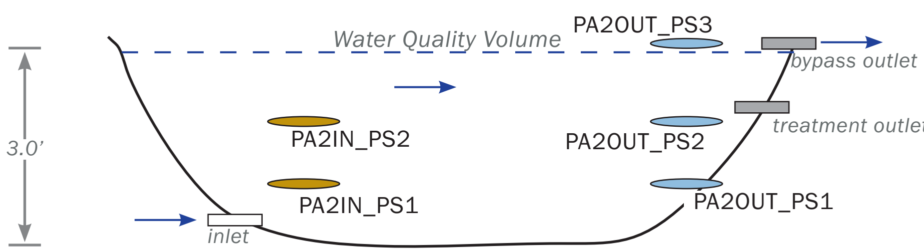
2.

Park Avenue Upper Basin (PA1)



3.

Park Avenue Lower Basin (PA2)



LEGEND
▭ Conveyance Structure
⬭ Passive Sampler

Note: Schematics drawn to show relative elevation within each SWT. Horizontal dimension is not drawn to scale.

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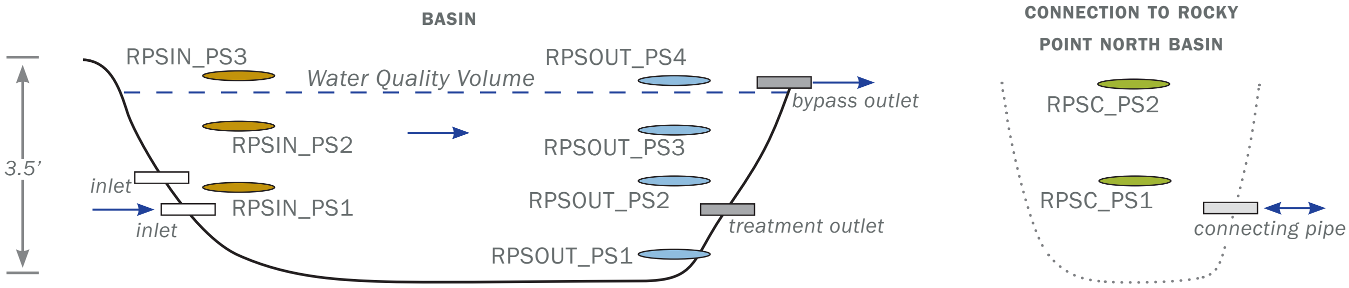
CROSS SECTION SCHEMATICS OF SWT SAMPLE COLLECTION

FIGURE 3.9A

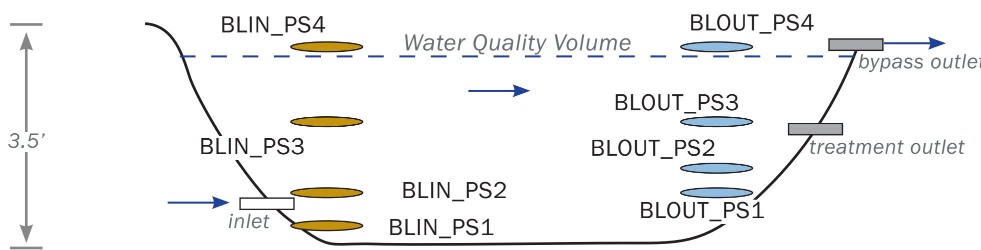
4.

Rocky Point South Basin



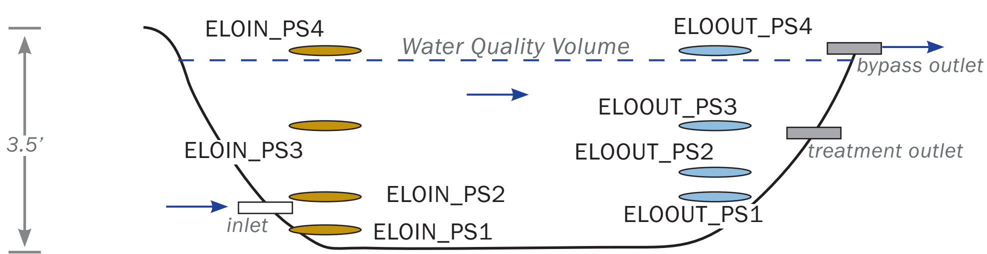
5.

Blue Lakes Basin



6.

Eloise Basin



LEGEND	
▭	Conveyance Structure
⬭	Passive Sampler

Note: Schematics drawn to show relative elevation within each SWT. Horizontal dimension is not drawn to scale.

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CROSS SECTION SCHEMATICS OF SWT SAMPLE COLLECTION

FIGURE 3.9B

Grab samples were periodically collected at the treatment and bypass outlets of all nine SWTs throughout WY10-WY11. The date and time of sample collection was noted and compared to the SWT volume time series to determine hydrograph position. These water quality results are compared to the passive sampler results to address any bias introduced by the passive sampler monitoring technique, as well as provide water quality data for those SWTs where passive samplers were not installed.

At Osgood Basin and the Stormfilter® Vault, Sigma 900 series automated samplers also collected inlet and outlet water quality samples during WY09. The two samplers at Osgood Basin were originally installed by the CSLT in November 2007 for other monitoring needs and remained in place until winter 2010. 2NDNATURE field personnel installed the automated samplers at the Stormfilter® Vault in March 2009 because the passive sampling technique was not feasible within the cartridge filter. However, due to backwatering effects at both the inlet and outlet, reliable water quality data was not obtained and the instruments were removed in October 2009. Subsequently, grab samples from the outlet were collected during runoff events instead.

SWT CONDITION FIELD DATA COLLECTION TECHNIQUES

2NDNATURE field personnel performed the field observations (STEP 4) of the Best Management Practices Maintenance Rapid Assessment Methodology (BMP RAM) at each SWT every summer per the protocols detailed in the BMP RAM User Manual v1 (2NDNATURE et al. 2009b). BMP RAM observations were conducted in September 2009, July 2010, June 2011, and August 2011 to evaluate the condition of each SWT. While BMP RAM scores could not be calculated because score calculation requires jurisdictional input to develop benchmark and threshold values (STEP 3), valuable information on the relative changes in SWT condition over the multiple years of monitoring were acquired. As noted above, communications with responsible jurisdictions and frequent SWT observations indicate none of the SWTs included in this research have had any level of maintenance in the past 4 years.

SWT INFILTRATION FIELD DATA COLLECTION TECHNIQUES

Discrete soil sample collection and simultaneous saturated conductivity measurements were conducted within each of the six dry basins to improve our technical understanding of infiltration volumes, CHP measurements, and SWT treatment performance over time. The data is used to calculate average annual infiltration rates within SWTs and to compare these measured values to the water budget estimates of infiltration (described below in Chapter 3.2.1). A total of 53 soil samples were collected and stored in labeled Ziploc bags and a subset of 34 samples were submitted to Cooper Laboratory (see Chapter 3.1.5) for particle grain size analysis. In accordance with BMP RAM protocols, 2NDNATURE field personnel measured saturated conductivity (Ksat) at a depth of approximately 6” below the soil surface using a CHP fabricated according to NRCS specifications.

3.1.5 SAMPLE ANALYSES

A total of 614 water quality samples collected during controlled road experiments or SWT event-based sampling and a subset of these were analyzed for turbidity in the field and submitted to WETLAB for TSS (mg/L); particle size distribution [PSD] (% by mass for the following particle sizes: <1 µm, <10 µm, <16 µm, <20 µm, <63 µm, <100 µm and <1000 µm); and soluble reactive phosphorous [SRP] (mg/L) analysis. A fraction of the dry material samples collected during Road RAM observations, private parcel sampling, and SWT basin infiltration monitoring were kept and submitted to Cooper Analytical Laboratory for PSD (% mass <16 µm). The particle size analysis (ASTM D 422-63) includes a combination of sieves (for particles >75 µm) and a hydrometer (particles <75 µm), and the resulting data was provided as % sand (63 µm – 2 mm), % silt and clay (<63 µm), and estimated % FSP (<16 µm). Laboratory standard operating procedures are provided in *Appendix B* of the *Phase II Monitoring Plan* (2NDNATURE and NHC 2010b). Table 3.6 summarizes the sample analyses and frequency of analysis for all samples collected for this research. All water samples obtained for FSP analyses have been submitted to DRI for analysis and DRI researchers were encouraged to use the samples for additional particle size research efforts. Coordination and data sharing of necessary sample information has been offered to DRI researchers should they conduct additional analyses.

Table 3.6. Research analytical laboratory details and frequency of pollutant constituent analysis.

Constituent	Analytical Laboratory	Analytical Method	Frequency of Analysis (n)	Detection Limit
Water Quality Samples				
Turbidity (Field)	n/a	Hach 2100P or Lamotte 2020 portable turbidimeter[1]	87% (535)	0.1 ntu
Total Suspended Sediment (TSS)	WETLAB	SM 2540D	90% (550)	1 mg/L
Soluble Reactive Phosphorous (SRP)	WETLAB	EPA 365.3	47% (288)	10 µg/L
Dissolved Phosphorous (DP)	WETLAB	EPA 365.3	27% (167)	10 µg/L
Total Phosphorous (TP)	WETLAB	EPA 365.3	27% (166)	10 µg/L
Particle Size Distribution	DRI	Saturn Digitizer 5200	89% (547)	1 mg/L
Dry Material Samples				
Particle Size Distribution	Cooper Laboratory	ASTM D422	23% (210)	n/a

[1] The measurement range for the Hach 2100P is 0-1000 ntu, while the Lamotte 2020 is 0-4000 ntu. For samples <1000 ntu field measurements were taken using the Hach 2100P and for samples >1,000 ntu the Lamotte turbidimeter was used in the field.

FIELD QA/QC

Field precision of the portable simulator was calculated by performing field triplicates at 18 road segments over the course of the research (Table 3.7). The road segments represented a range of conditions and road risks. The instances of greatest deviation in measured FSP concentration occurred when the amount of material on the road was high or road surface integrity was poor, allowing water to seep out through the sides of the sampler. Since the distribution of material even within an accumulation area is not completely uniform, we expect some error in our field precision due to the difficulty in selecting and sampling three 1 ft^2 areas with an equal amount of material.

Six field blanks were collected over the course of the research and submitted blind to WETLAB. Distilled water was poured onto the collection pan of the sampler (see Figure 3.4) and collected in a clean sample bottle. The field blank turbidity, TSS and FSP results represent the minimum values measured during the research project, indicating there is likely little sample contamination during field sampling. The average SRP concentration is higher than the analysis detection limit (0.017 mg/L vs. 0.01 mg/L) suggesting the potential for sample contamination during monitoring; however, the average is based on a very limited number of samples. If future monitoring includes SRP analysis, field research will ensure all bottles are pre-rinsed with DI water prior to SRP sample collection and are thoroughly washed by the analytical laboratory.

Table 3.7. Field QA/QC results. Pollutant field precision is expressed as percent error based on field replicate samples and sample integrity is evaluated as the measured concentration of field blanks.

Constituent	Field Precision % Error (n)	Sample Integrity Concentration (n)
Field Turbidity	10.1% (42)	1.2 ntu (6)
TSS	12.5% (40)	2.0 mg/L (6)
FSP[1]	12.2% (40)	1.1 mg/L (5)
SRP	10.7% (14)	17 ug/L(3)

[1] Samples are submitted to laboratory for TSS concentration and particle size distribution. FSP concentrations is calculated as TSS (mg/L) * % of TSS < 16 μm.

Laboratory QA/QC

Laboratory analytical precision calculations and method blank analysis for all water quality samples collected during this research are presented in Table 3.8. The analytical laboratory performs regular quality control efforts that include method blanks, matrix spikes, laboratory duplicates and external standards. The complete laboratory quality assurance plan is provided in *Appendix A* of the *Phase II Monitoring Plan* (2NDNATURE and NHC 2010b). Instrument precision was tested on the field turbidimeter using triplicate subsamples from individual field samples.

Table 3.8. Laboratory QA/QC results. Laboratory precision is expressed as percent error based on replicate samples and sample integrity is evaluated as the measured concentration of method blanks. Number of samples used in calculation is noted in parentheses.

Analysis	Lab Precision % Error (n)	Sample Integrity Concentration (n)
TSS	6.5% (50)	0.93 mg/L (31)
FSP[1]	n/a	n/a
SRP	n/a	10 ug/L (40)
DP	n/a	10 ug/L (14)
TP	n/a	10 ug/L (14)

[1] Samples are submitted to laboratory for TSS concentration and particle size distribution. FSP concentrations is calculated as TSS (mg/L) * % of TSS < 16 μm. Lab replicate and method blank data for particle size distribution is not available.

3.1.6 ROAD RAM USER PRECISION

During two observations periods (January 2011 and April 2011) 2-4 trained field personnel conducted 46 simultaneous, independent Road RAM observations to determine the variation in road segment scores as a result of reasonable differences in user field observation inputs. Field observations of percent distribution of material accumulation categories, volume measurements, and degree of fines observations between field personnel differed by varying degrees depending upon the categorization of the high, moderate and low areas of accumulation and the selection of the representative 1ft^2 area. The average difference in the road segment condition score was 0.3 (Table 3.9) and never greater than 0.6. For 17 observations (or 37%), field personnel observations resulted in the users arriving at the road segment score +/- 0.1. These analyses of field observation precision should continue to be conducted to validate the Road RAM scoring process and improve the observation protocols, particularly during other times of the year. However, these initial results provide confidence that the Road RAM is a simple, repeatable tool with standardized field observations, consistent with statements in the

Road RAM Technical Document (2NDNATURE et al. 2010c) that the field observation precision between two trained field personnel is within ±0.5 of a road segment condition score.

Table 3.9. Results of Road RAM field observation precision analysis completed in WY2011.

Number of Observation Periods	Number of Observations	Road Segment Condition Score (0-5)				
		Average Difference	Standard Deviation	Maximum Difference	Minimum Difference	Frequency Difference ≤0.1 Score (n)
2	46	0.3	0.2	0.6	0.0	37% (17)

3.1.7 DATA MANAGEMENT

All data collected during this research have been managed in a digital Microsoft Access relational database (CRC.accdb for land use data and CEC.accdb for SWTs; Figure 3.10). Controlled experiment data, road condition data, private parcel site conditions, SWT condition observations and staff plate measurements, and field notes were recorded in field notebooks or custom datasheets during all sampling activities. Instrument data downloads and maintenance activities were recorded on pre-printed data logs. Upon return to the office, office personnel QA/QC'd all data for accuracy and completeness before integration into the database. The laboratory submitted electronic results of analyses, which office personnel checked for data quality and completeness, verified against the chain of custody record, and then entered into the database. Following development of the Road RAM data management tool, field personnel have recorded Road RAM observations directly into the online database in the field (www.tahoeroadram.com).

3.2 MODELING TECHNIQUES

2NDNATURE and NHC staff used cost-effective modeling techniques to develop stormwater datasets to further the analysis of the data collected in the field. Detailed surface water budgets were created for each monitored SWT using the continuous water level data, topographic survey data, and spot measurements described in Chapter 3.1.4 above. PLRM models developed for each drainage catchment were adapted using the EPA's Storm Water Management Model (SWMM), which is the parent model to PLRM, to facilitate analysis of output from the long-term continuous simulations of surface water runoff on seasonal and annual time periods.

3.2.1 WATER BUDGET CALCULATIONS

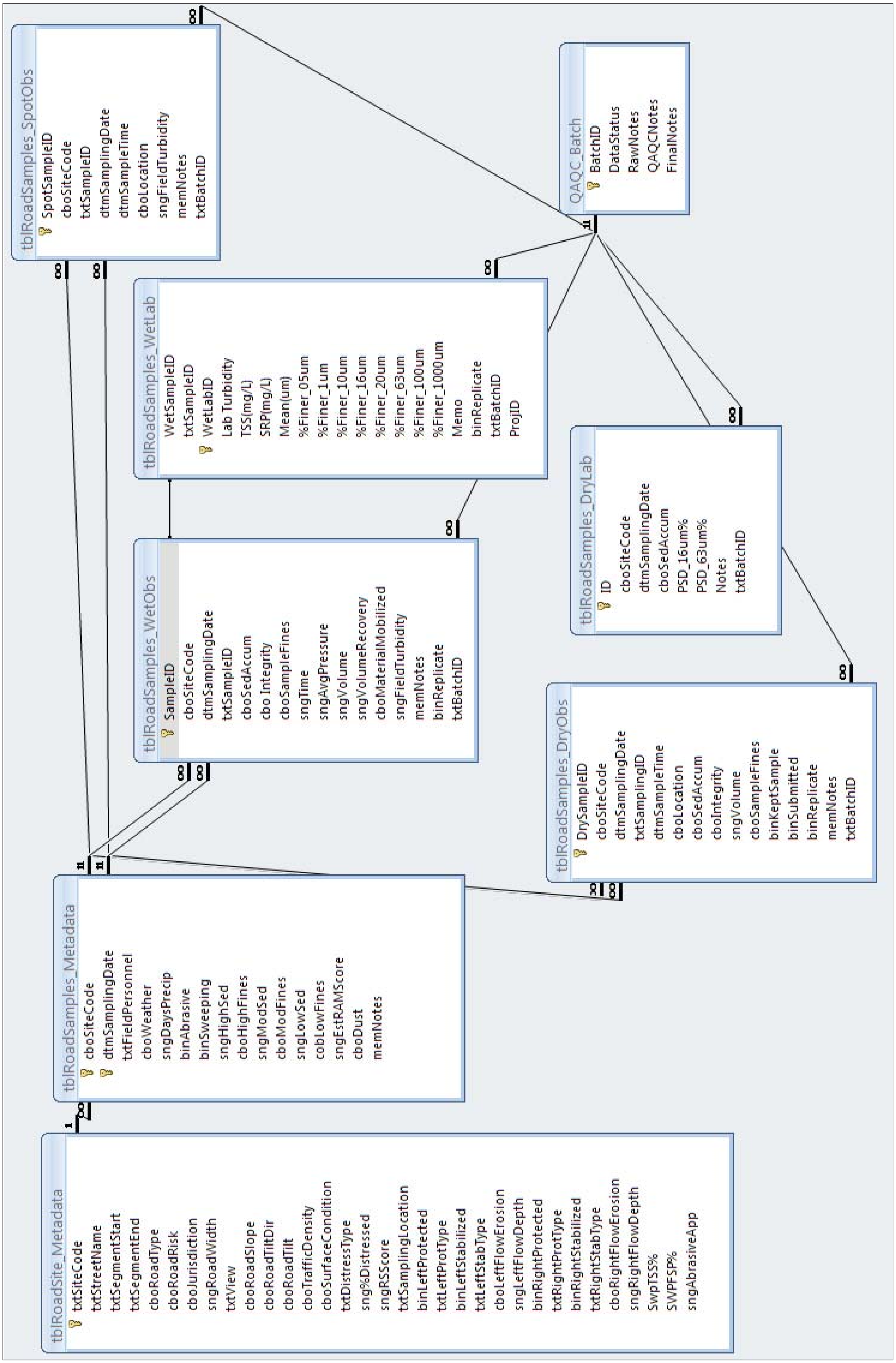
Below we provide a brief overview of the methodology used to created detailed surface water budgets for Osgood, PA1, PA2, Rocky Point and Eloise Basins. A detailed description of the methodology is provided in Appendix C, along with a complete list of all variables defined below, with descriptions and units.

The continuous water surface elevation and associated storage time series obtained from pressure transducers recording water depth on 15-min intervals are used to calculate a surface water budget for each SWT using the following mass balance equation:

Change in SWT Storage = Water Inputs – Water Losses

or

$$\Delta V_{SWT} = V_{INPUT} - V_{LOSS} \text{ (EQ 3.1A)}$$



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DATA RELATIONSHIP STRUCTURE FOR RESEARCH DATABASES

FIGURE 3.10

Change in storage is a continual balance of water inputs and losses to the SWT. When water inputs are greater than water losses, the SWT will fill with water over time and the SWT storage volume will increase. Conversely, when losses are greater than inputs, the water storage volume within the SWT will decrease over time. Water inputs and losses can be calculated using the following equations:

$$V_{INPUT} = V_{IN} + V_{PRECIP} \text{ (EQ 3.2)}$$

and

$$V_{LOSS} = V_{OUT\_B} + V_{OUT\_T} + V_{INF} + V_{ET} \text{ (EQ 3.3)}$$

thus

$$\Delta V_{SWT} = (V_{IN} + V_{PRECIP}) - (V_{OUT\_B} + V_{OUT\_T} + V_{INF} + V_{ET}) \text{ (EQ 3.1B)}$$

where water inputs include inflow through the constructed SWT inlet (V_{IN}) and direct precipitation on the SWT surface area (V_{PRECIP}), and water losses include outflow through the constructed bypass (V_{OUT_B}) and treated (V_{OUT_T}) outlets, infiltration through the subsurface (V_{INF}), and evapotranspiration (V_{ET}).

Each of the volume terms is the sum of a water flux over a given time period, and can be written as:

$$V = \Sigma\, Q * t \text{ (EQ 3.4)}$$

where Q is the rate (cf/min) of volume change over discrete time intervals (t) defined for the time period of interest (e.g., event, month, season, water year). For example, if the inflow rate (Q_{IN}) is 1 cf/min for an event lasting 10 minutes, then the total inflow volume equals 10 cf (V_{IN}).

To simplify the calculation of seasonal volume losses average water loss rates (Q) are calculated for the evapotranspiration, infiltration, and treated outflow loss terms and standard engineering equations are used to calculate bypass outflow. Water inputs (direct precipitation and inflow) are variable and will depend upon climatic factors in the contributing catchment including precipitation rate, runoff and stormwater transport. In fact V_{PRECIP} is considered negligible on the seasonal-scale (less than 2% of total input volume) and is not included in these calculations. Therefore, the change in basin storage (ΔV_{SWT}) for each time step can be determined using the WSE time series and each water loss rate can be estimated as a function of the water surface elevation of the SWT (WSE). By rearranging the water mass balance equation (EQ 3.1B), the input volume for any time step can be solved:

$$V_{IN} = \Delta V_{SWT} + \Sigma\, (Q_{LOSS} * t) \text{ (EQ 3.5)}$$

where Q_{LOSS} is the SWT total loss rate, summing all of the loss terms shown in EQ 3.3. Total inflow volumes can thus be calculated over any time period of interest (e.g., event, month, season, etc.). Having solved for all variables in EQ 3.5 for every time step when data is available, the desired volume metrics can be calculated including:

- Seasonal volume totals (cf) for all input and loss terms,
- Seasonal infiltration rates (in/hr) as [Seasonal infiltration volumes (V_{INF}) / SWT footprint (sq-ft)],
- SWT hydraulic capture (%) as [Treated outflow volumes (V_{OUT_T}) + infiltration volumes (V_{INF})]/inflow volumes (V_{IN}), and
- Average seasonal pollutant concentrations (mg/L) * volumes (cf) to calculate pollutant loads (MT).

During development of the water budgets for each SWT, a number of difficulties in calculating the seasonal water volumes were identified:

- Data gaps due to instrument failure: The freeze-thaw conditions of the alpine climate resulted in instrument malfunction, especially in dry basins where the instruments were often exposed to the air. The resulting data gaps can be seen in the basin volume time series for each SWT presented in Chapter 6.1.
- SWT Design: Certain design characteristics, such as multiple inlet and/or outlet structures, can complicate the quantification of volume fluxes. Additionally, a number of SWTs do not function as designed. For example, a bypass pipe was installed at the Rocky Point inlet to PA1 to bypass the basin during high-flow events. However, due to the elevation of the structure, water has been observed flowing out of the basin through this pipe during certain times of year. These types of unconstrained characteristics presented challenges to the water budget calculations.
- WLR placement: The locations for WLR installation were determined by (1) the SWT topography to ensure the recorded depth was representative, (2) the ease of instrument maintenance and download during all times of year, and (3) the location of previous instrumentation to improve comparisons to existing data. In some instances, access resulted in the WLR not being installed at the low point of the SWTs. For example, at Eloise Basin the WLR was installed over 1.5’ above the base of the basin, which represents 0.1 ac-ft of volume or 10% of the total volume capacity. These missed volumes were not included in the water budget seasonal and annual totals.
- SWT Maintenance: The lack of consistent maintenance at these SWTs complicated the calculation of treated outflow rates. At some SWTs, including Osgood Basin and PA1, the treated outlets are clogged due to sediment accumulation around the outlet structure. In these instances, treated outflow rates were calculated using the water volume time series, because engineering equations based on the outlet design were not appropriate. Additionally, corrosion of the Eloise CMP results in some volume loss through the leaky CMP, which was estimated based on field measurements and accounted for in the water budget calculations.
- Given the large number of variables used in the water budget calculations and the inherent difficulty in isolating each variable, there is some uncertainty associated with the inflow volumes calculated using the water budget methodology. Our SWT hydrologic monitoring illustrated that each SWT has a series of nuances associated with how stormwater enters and leaves the SWT. Future SWT monitoring should include additional field measurement techniques to obtain accurate manual measurements of inflow, treated outflow and bypass outflow rates when possible to calibrate water budget estimates.

3.2.2 SWMM HYDROLOGY ESTIMATES

PLRM uses the EPA’s Storm Water Management Model (SWMM) to execute a long-term continuous simulation of stormwater runoff conditions defined through user inputs describing land use conditions, including: pollutant source controls, hydrologic source controls, and stormwater treatment facilities. PLRM output is reported as average annual values based on the results of the entire 18-year continuous simulation (1989-2006). Detailed analysis of the results from the continuous simulation generated by PLRM can be accomplished by running the PLRM input file directly in SWMM and post-processing the time-series outputs generated by SWMM. Running a PLRM model directly in SWMM allows for assessment of output on any time scale, which is useful when comparing modeled output to collected field data.

PLRM INPUTS

The PLRM inputs for each catchment and SWT are detailed in Tables 3.5 and 3.6, respectively. Input data for each PLRM model was developed using: GIS data and reconnaissance level field assessments of drainage conditions and design attributes of the stormwater treatment facilities modeled. The following described the key steps and methods used to develop PLRM inputs.

1. GIS data was queried to develop input data for each PLRM catchment within a model (e.g., land use distribution, soil distribution, average slope, road risk, etc.). The GIS processes and algorithms used to develop the input data are described in the PLRM Applications Guide (NHC et al. 2010). The following GIS datasets were used:
   a. *TMDL Land Use GIS Layer*: The layer can be downloaded from the LRWQCB website at http://www.waterboards.ca.gov/lahontan/water_issues/programs/tmdl/lake_tahoe/index.shtml
   b. *2006 Tahoe Basin Soil Survey*: The layer can be downloaded from the Natural Resources Conservation Service (NRCS) website for Soil Survey Symbol = CA693 at http://soildatamart.nrcs.usda.gov/Survey.aspx?State=CA
   c. *PLRM Road Risk Layer*: The 2009 default Road Risk layer was refined by the City of South Lake Tahoe, Washoe County, and Douglas to better reflect actual road operations and road conditions within their respective jurisdictions. The updated March 2011 road risk GIS layer is available for download at http://tiims.org/TIIMS-Sub-Sites/PLRM/docs-downloads.aspx.
   d. *PLRM Road Shoulder Conditions Layer*: The default Road Shoulder Conditions layer, which reflects conditions in the summer of 2010, was used for model development. The GIS layer is available at http://tiims.org/TIIMS-Sub-Sites/PLRM/docs-downloads.aspx.
2. Reconnaissance level field inspections were used to validate PLRM inputs derived from the GIS data listed above and to inform PLRM input parameters that cannot be developed from a GIS analysis (e.g., stormwater treatment (SWT) parameters). The following are examples where field inspections were used to develop PLRM input data.
   a. *Impervious Area Connectivity of CICU, SFR, and MFR Land Uses:* The amount of impervious area associated with SFR, MFR, and CICU land uses that is directly connected impervious area (DCIA) was estimated through field inspection. Note that a GIS layer is not available for this PLRM input.
   b. *SWT Input Parameters:* PLRM inputs that define the function of each SWT facility modeled (e.g., water quality volume of a dry basin) were estimated through field inspection. For each SWT facility monitored for this study, topographic surveys were conducted (see Chapter 3.1.4) to calculate relationships between water depth and storage volume in each basin.
3. Information on the degree of private property BMP implementation, as of 2011, was received from CSLT. This information was post-processed in GIS to estimate the percentage of private property BMP compliance by land use within each modeled drainage catchment.
4. The publicly available version of the PLRM includes a meteorological record that extends to water year 2006. In order to compare modeled output to field data collected in water years 2009 through 2011, the meteorological record of the PLRM database was extended. The process was completed as follows:
   a. Precipitation and temperature data were downloaded from the NRCS website for the Fallen Leaf and Hagan's Meadow SnoTel gages, which are the two SnoTel gages used in PLRM to generate meteorological data for simulations within the area of interest.
   b. The data was quality assured and added to the PLRM database for the two SnoTel gages.
   c. The PLRM meteorological algorithms were re-run to generate a new time series of meteorological data that extended through water year 2011 for the developed models.

POST-PROCESSING OUTPUT FROM SWMM SIMULATIONS

Running a PLRM model directly in SWMM allows for assessment of output at any time scale, which is useful when comparing modeled output to collected field data for specific events or time periods. To assess time-series output the following process was used:

1. The PLRM program develops an input file that is run by SWMM (“tempSwmm.inp”). This input file was run directly in SWMM to provide access to the time-series output generated by SWMM.
    a. The file “tempSwmm.inp” was saved to a new directory. For a specific PLRM Project and PLRM Scenario, this file is located in the folder: C:\Program Files\PLRM\Projects\Project1\Scenario1.
    b. The “tempSwmm.inp” was opened and run in SWMM version 5.0.014, with the simulation period revised to extend through water year 2011. Note that version 5.0.014 is the specific version of SWMM that PLRM runs. Running a PLRM input file in a different version of SWMM may not generate comparable output relative to that reported by PLRM.
2. The time-series output generated by SWMM was extracted from the program at specific points of interest (e.g., catchment outfalls, SWT treatment junctions) by using the “Report” functions available in SWMM.
3. The time-series output was imported into Microsoft Excel and analyzed for specific events and time-periods against available monitoring data collected during the research effort.

CHAPTER 4. ENVIRONMENTAL SETTINGS

This research focused on data collection and analysis of stormwater quality, land use conditions, and effluent quality from SWTs. In order to appropriately compare hydrology and water quality monitoring data across water years or to inform average annual PLRM predictions, it is critical to constrain the drivers that inherently influenced the data. The primary uncontrollable system driver is the weather where daily, seasonal and water year variations introduce variability into hydrologic, water quality and land use condition observations. We provide a simple approach to put WY09, WY10 and WY11 into a relative hydrologic context by a simple comparison to the long-term Tahoe City precipitation dataset (1911-2011), as well as to the 18 years (1989-2006) used in PLRM simulations. Another uncontrollable influence on the spatial and temporal results of the roadway research is the jurisdictional road maintenance practices, which are assumed to have a high influence on the relative amount of sediment (and FSP) available on a road surface in the Tahoe Basin. The actual road maintenance practices implemented on roads vary within and across jurisdictions. The research team made a significant effort to document the road maintenance practices implemented by each jurisdiction on specific road segments included in this study.

4.1 WATER YEAR CONTEXT

The climatic differences between water years have a direct impact on the resulting urban stormwater runoff observed during the study. Providing climatic context for the monitored years assists the research team with interpretation of these results and will assist researchers with comparisons of these data to future water year observations. The Tahoe City gage, operated by Western Regional Climate Center (WRCC) (http://www.wrcc.dri.edu/), provides the longest period of record for Tahoe Basin climate data. A precipitation frequency analysis was conducted on the 101 years of Tahoe City precipitation data to determine the recurrence intervals (RI) of annual precipitation totals. The water year type definitions were created using reasonable recurrence intervals to bracket average precipitation totals and ensure the extreme (very wet and very dry) categories have less than a 10% probability of occurring (Table 4.1). The Tahoe City gage may not exactly represent the weather conditions experienced at a specific water quality monitoring station included in this research, however, the Tahoe City data is a reliable and easily accessible long-term record that likely provides a reasonable representation of water year types for the Tahoe Basin urban areas as a whole for the purposes of this research.

Table 4.1. Frequency analysis of Tahoe City precipitation gage using 101 years of data and classification of water year types based on recurrence interval (RI) breaks.

WY Type	RI (yr)	Tahoe City[1] WY Precipitation (in)
Very Dry	< 1.1	<18.4
Dry	1.1 - 1.5	18.4 - 24.5
Average	>1.5 - 3.0	>24.5 - 35.0
Wet	>3.0 - 10.0	>35.0 - 49.0
Very Wet	> 10.0	> 49.0
Minimum WY precipitation (in)		8.8
Maximum WY precipitation (in)		69.2
Mean WY precipitation (in)		31.6
Median WY precipitation (in)		30.0

[1] Tahoe City gage (#48758) operated by WRCC.

Using the definitions presented in Table 4.1, Table 4.2 summarizes the total water year precipitation and water year type over the past 5 years, from WY07-WY11.

Table 4.2. Water year types for WY07-WY11 based on frequency analysis, WY definitions (see Table 4.1) and total WY precipitation at Tahoe City gage.

Metric	WY07	WY08	WY09	WY10	WY11
Tahoe City WY precipitation (in)	19.7	19.3	27.2	37.9	45.0
Water year type[1]	Dry	Dry	Average	Wet	Wet

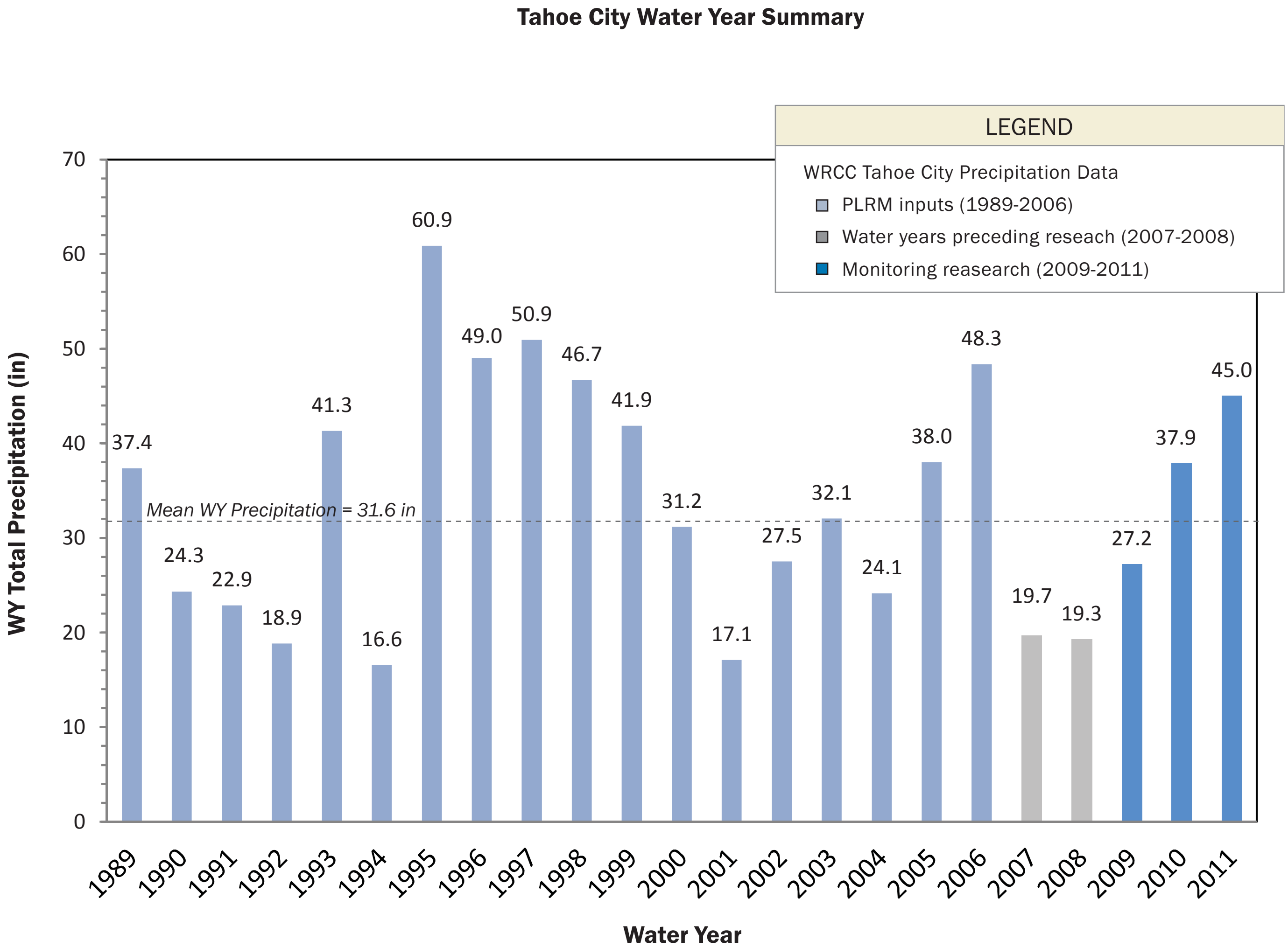
Figure 4.1 graphically presents the Tahoe City gage data for the water years used in the PLRM 18 year simulation, as well as WY07-WY11. The 18 water years used in PLRM simulations represent a range of water year types: 9 years are average or drier and 9 years are above average. WY07 and WY08 were not monitored during this research, but notably were two consecutive dry years. WY09 to WY11 progressively got wetter, which influenced the data obtained and analyzed during this research. The considerations of antecedent and actual water year weather conditions are used in our hydrologic and water quality data interpretations herein.

4.2 WEATHER CONDITIONS

Figure 4.2 presents the relevant precipitation and air temperature data from the CSLT City Lab weather station over the duration of the research data collection to provide the climatic context for the urban road and SWT monitoring that occurred from December 2008 through September 2011. The City Lab weather station is located on Lake Tahoe Boulevard and D Street, near the "Y" in South Lake Tahoe and is assumed to be relatively representative of the general winter and spring weather conditions within the Tahoe Basin and adequate for the purposes of this study.

These data were used to determine how weather condition might influence road research findings, and the following describes the meteorological conditions and road maintenance activities leading up to each observation period for road condition evaluations. Road maintenance activities are estimated based on field observations and discussions with jurisdiction road maintenance personnel.

- **March 2009**: There were multiple winter snow storms and instances of winter road abrasive applications. The most recent was 14 days prior to monitoring.
- **April 2009:** Prior to monitoring, meteorology data suggests only one major winter storm occurred. During the monitoring, a minor rain/snow event fell on the North Shore and eliminated the sampling of certain sites. However, field personnel did not observe active abrasive application during this event.
- **May 2009**: Warmer temperatures in late spring eliminated the need for abrasive applications and it was estimated that no abrasives were applied between the April and May monitoring. A rain event exceeding 2 inches occurred prior to monitoring and likely transported sediment accumulated on the road surface downslope, thereby improving the road conditions observed following spring rains.
- **July 2009**: A few summer thunderstorm events occurred in June, again likely improving road conditions due to wash off of material from the roadways. The July monitoring event occurred over 3 months after the last winter storm when road abrasives were applied to select urban roads, and the warmer temperatures allowed some jurisdictions to conduct consistent pollutant recovery actions.
- **October 2009:** Following the dry summer months, fall rain storms began in the 2 weeks leading up to the sampling, including a large rain event (2.6 in) one week prior to monitoring. These rain storms likely washed off any sediment that had been accumulating on the road surfaces.



Water year total precipitation is provided from the WRCC Tahoe City weather station for the 18 years (1989-2006; pale blue) used for PLRM simulations, the 2 years preceding the research effort (2007-2008; grey), and the 3 years of the research effort (2009-20011; dark blue). The 18 years of data used in PLRM represent a range of precipitation values, including 2 very dry, 4 dry, 3 average, 6 wet, and 3 very wet years (see Table 4.1 for water year type definitions). The two years prior to our monitoring research were dry years, followed by increasingly wet years in 2009, 2010, and 2010. Understanding the meteorological context of data collection is critical to intrepreting the water quality and hydrology data results presented in this technical report.

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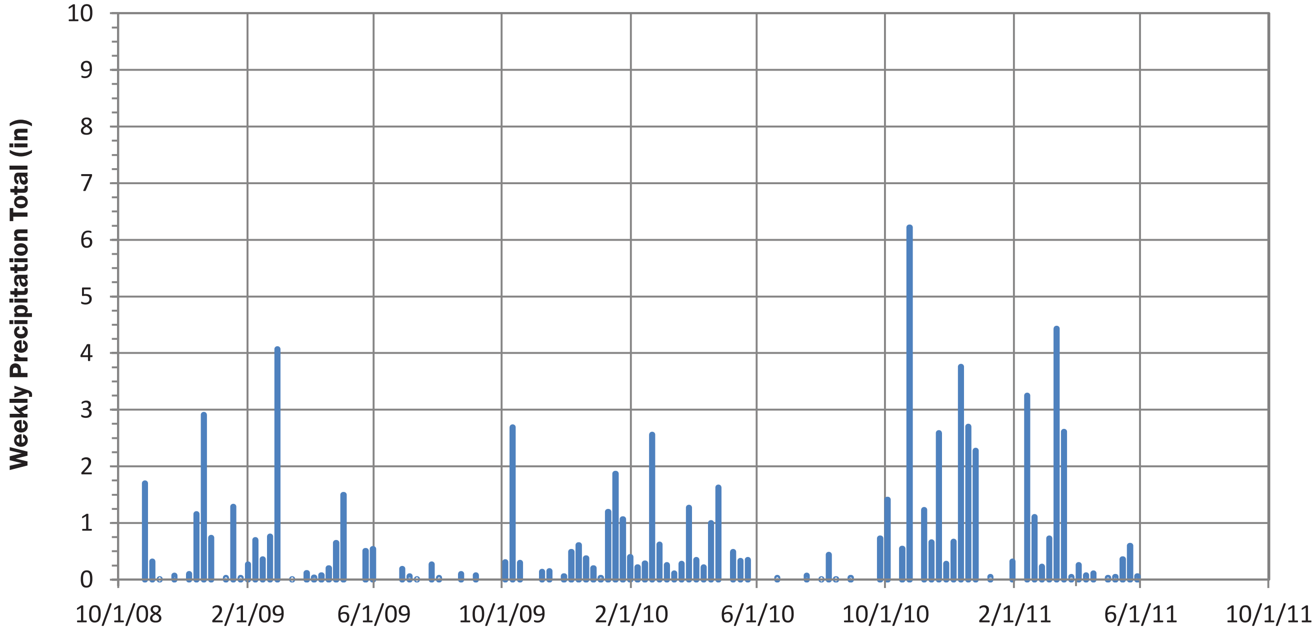
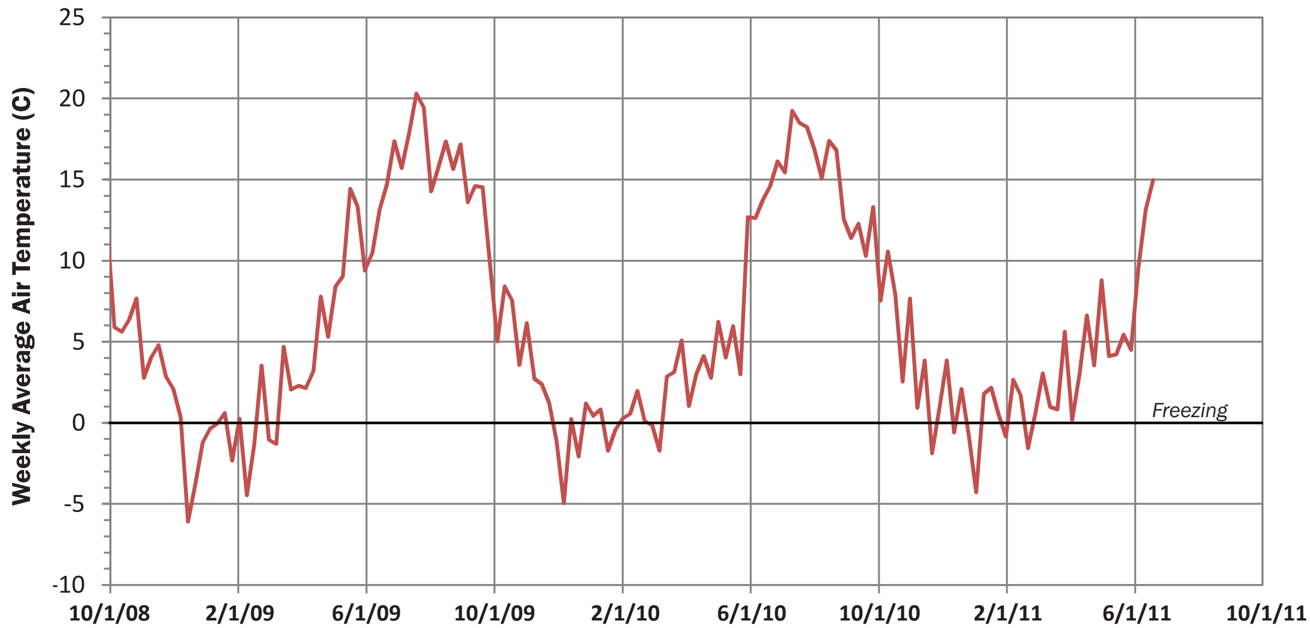
TAHOE CITY TOTAL WATER YEAR PRECIPITATION; 1989-2011

FIGURE 4.1

CSLT City Lab Data[1]





[1]CSLT City Lab weather station is located at Lake Tahoe Blvd and D Street near the South Y.

- **January 2010:** In the month prior to the observation period, there were multiple winter snow storms and instances of winter road abrasive applications. The most recent was 7 days prior to monitoring.
- **February 2010:** Prior to monitoring, there were several winter snow storms and instances of winter road abrasive applications. The most recent road abrasive application was 9 days prior to monitoring.
- **March 2010:** In the month leading up to the sampling, there were several winter snow storms, including one large event (>1 in). The most recent was a relatively small event (0.2 in) 2 days prior to monitoring.
- **January 2011:** There were several large snow events in December 2010, but in the weeks prior to monitoring there was little precipitation. However, daily average temperatures were frequently below freezing and it is unlikely that pollutant recovery was occurring with much regularity during this time period.
- **April 2011:** There were frequent snow storms requiring abrasive application throughout the months of March and April. The most recent storm, which resulted in intermittent abrasive application, occurred the day preceding sampling.

The weather conditions also provide the context to conduct event intensity, duration and total magnitude comparisons of catchment and SWT hydrologic volumes and pollutant loads.

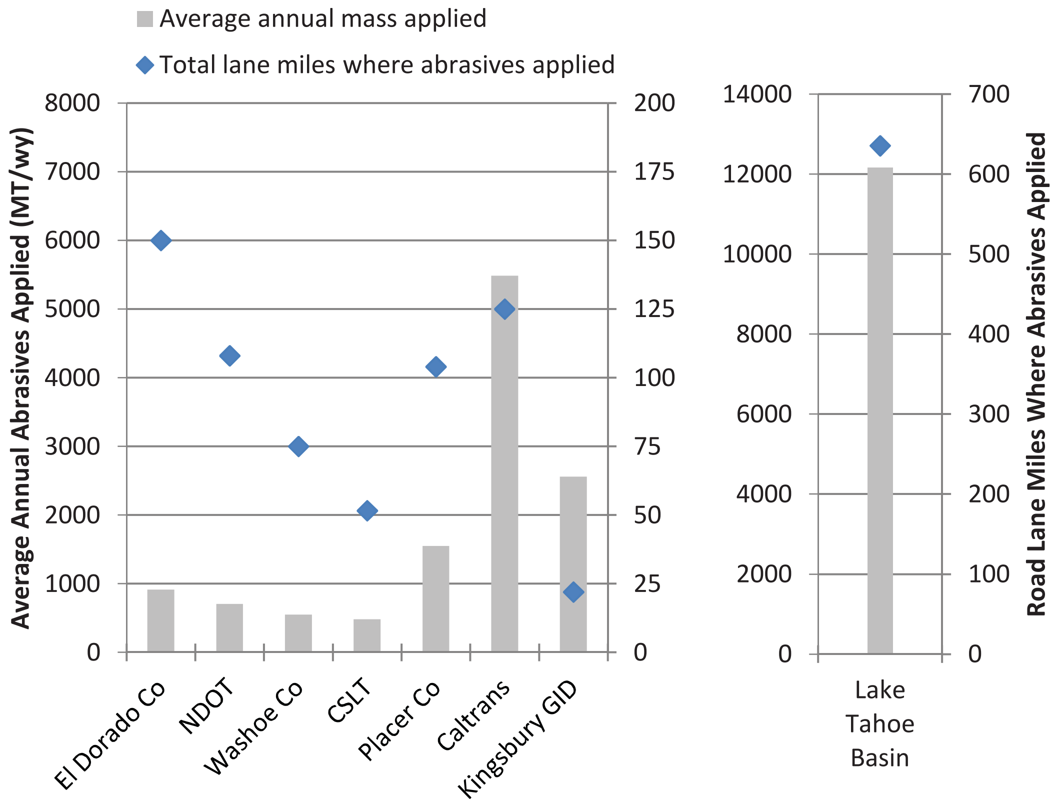
4.3 TAHOE BASIN ROAD MAINTENANCE PRACTICE DOCUMENTATION, WY09-WY11

The *Phase I Technical Document* (2NDNATURE and NHC 2010a) identified accurate documentation of jurisdiction maintenance practices as a significant data gap inhibiting interpretation of road condition data. The observed condition of each urban road is assumed to be the integrated signal of pollutant inputs (sources) and outputs (sinks). The primary maintenance practices implemented on short-time scales are road abrasive application and sweeping, and these two practices can vary widely by jurisdiction, road priority, and weather conditions. Ideally, the specific chronology of these actions on each road segment sampled for this study would be documented, including abrasive application dates and amount applied per unit area, and pollutant recovery dates, sweeper type, and amount of material recovered per unit area. However current documentation practices by most jurisdictions does not allow for this level of spatial and temporal detail.

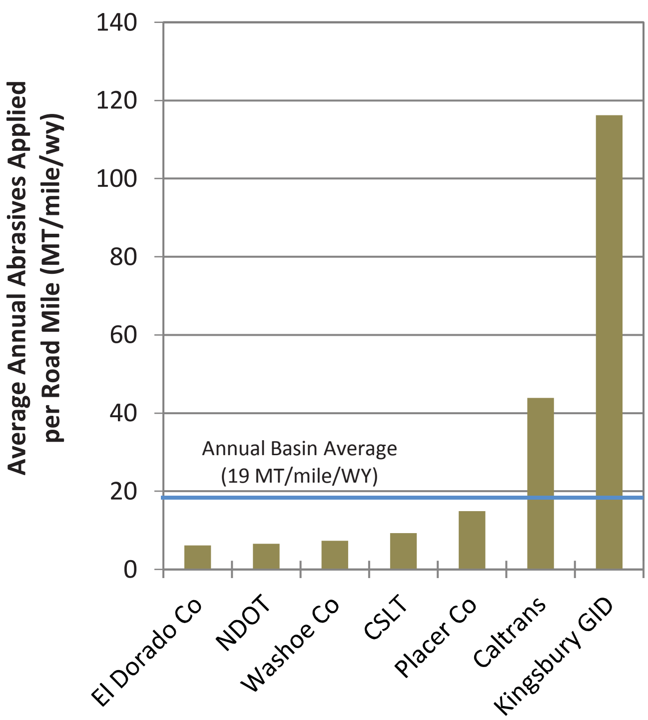
2NDNATURE compiled abrasive application data from the annual road maintenance reports and existing data for all Tahoe Basin urban jurisdictions from WY2001-WY2011. Data suggests the average annual mass of anthropogenic road abrasives applied to Tahoe Basin roads over the last decade is 12,160 MT per water year or 9,850[2] yd^3/wy (Figure 4.3). This mass of road abrasives is brought into the Tahoe Basin and chronically added to the annual stormwater sediment budget each year. Records from the past decade indicate that in recent years jurisdictions have been able to reduce their abrasive application per unit area of road, while maintaining traffic safety as indicated in Figure 4.4. The 2011 Basin-wide total (9,400 MT) was 43% lower than the 2002 amount, despite twice as much winter snowfall in WY2011 compared to WY2002 (see Figure 4.4).

Table 4.3 summarizes the general jurisdiction-wide road maintenance practices for the 7 Tahoe Basin urban jurisdictions. While this data does not provide temporal or spatial-specific data with which to evaluate road segment condition results by observation period, it does provide a relative comparison of the Basin-wide practices with which to evaluate trends in the observed road datasets. In the future, jurisdictions should consistently report annual mass and/or volume of abrasives actually applied to roads. Use of advanced spreader equipment (e.g., user controlled application, GPS-enabled spreaders) would provide the most accurate abrasive application records.

[2] Density of dry sand assumed to be 1.6 g/ml; 2,700 lbs/yd^3.



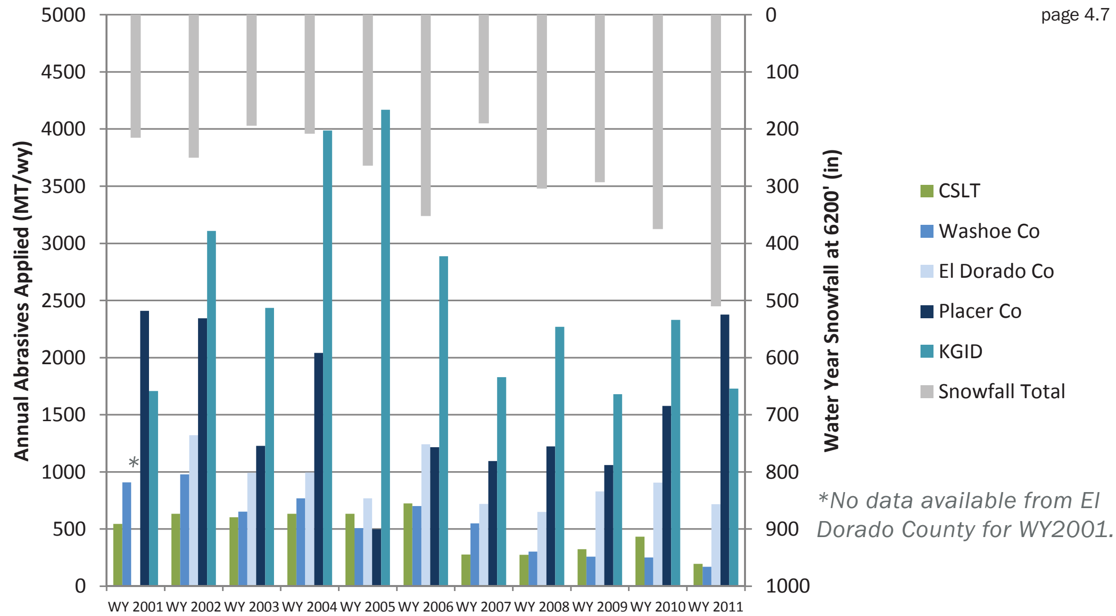
A. Average annual abrasives applied by jurisdiction based on annual reports from 2001-2011, compared to the total road lane(primary and secondary) miles within each jurisdiction where abrasives are applied. Based on this data, the 635 lane miles are treated with 12,160 MT (9,850 yd^3) of road abrasives on average each water year.



B. Average annual abrasives applied by jurisdiction per road mile where abrasives are typically applied. Based on this data, these road miles are treated with 19 MT of road abrasives on average each water year.

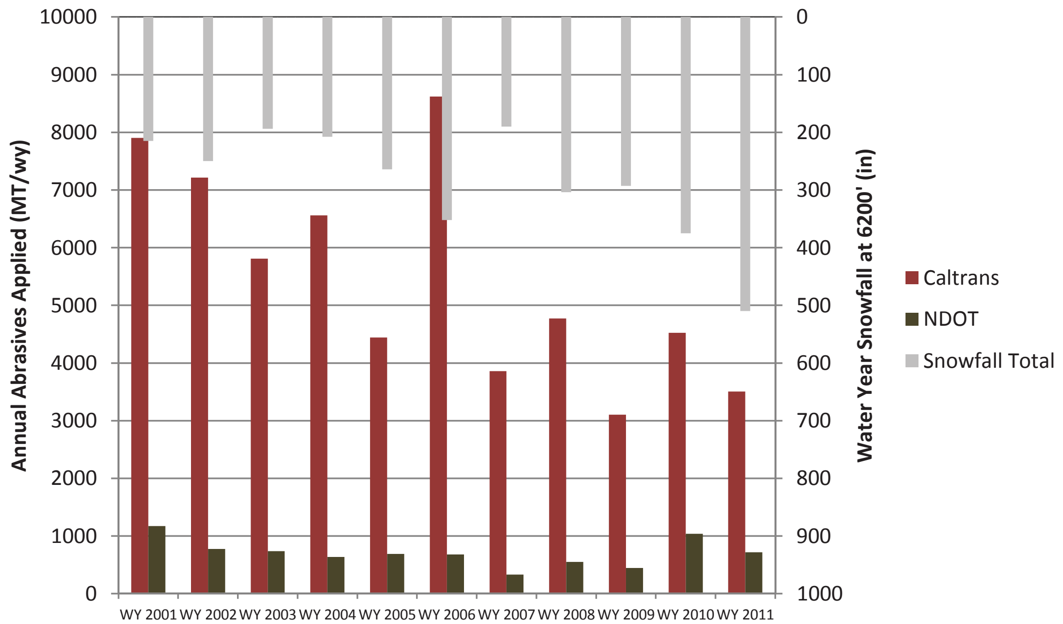
NOTE: In Douglas County, the general improvment districts (GID) are in charge of road maintenace practices within their designated areas. To maintain consistency with the road segments monitored by 2NDNATURE (2010a, 2010b), data from Kingsbury GID is used for comparison to other Lake Tahoe urban jurisdicitions.

A. Tahoe Basin jurisdictions annual road abrasives applied by WY as documented in road maintenance annual reports. WY snowfall totals are also provided for climate context (Squaw Valley, 2011).



*No data available from El Dorado County for WY2001.

B. Local Transportation agencies annual road abrasives applied by WY as documented in each road maintenance annual report. WY snowfall totals are also provided for climate context (Squaw Valley, 2011).



C. Total annual abrasives applied each WY in Tahoe Basin. WY snowfall totals are also provided for climate context (Squaw Valley, 2011).

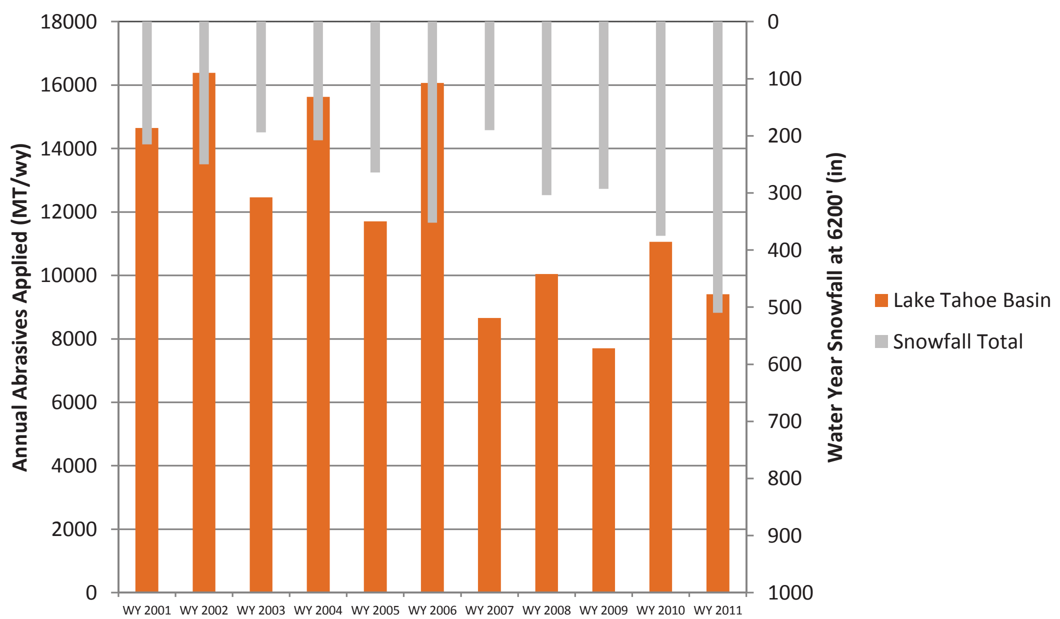


Table 4.3. Summary of Tahoe Basin urban jurisdiction road maintenance practices. For each jurisdiction, key components of their abrasive application and pollutant recovery practices are provided.

Jurisdiction	Abrasive Application			Pollutant Recovery			
	Spreader Equipment	Abrasive Type	Lane Miles where applied (% of Jurisdiction)	Action Types	Sweeper Equipment	Frequency	Location
California Department of Transportation (Caltrans)	Sander + Muncie Controller	De-icing sand; salt/brine	125 miles (100%)	Snow Haul; Sweeping	Allianze 4000	Winter – Event-Based	All Roads
City of South Lake Tahoe (CSLT)	Monroe Spreader + Plow	Eagle Valley Basin Volcanic Cinders; Huck Salt	52 miles (20%)	Sweeping	Tymco (regen air); Athey Mechanical Broom	Winter – Event-Based; Summer – 2x	All Roads
El Dorado County	Truck with hopper	Washoe Sand / Volcanic Cinders	150 miles (40-60%)	Sweeping	Elgin Waterless Eagle	Winter – Event-Based & Weekly; Summer – Every 2 weeks (primary) & 1x (secondary)	All Roads
Kingsbury General Improvement District (KGID)	Truck with hopper	5:1 Concrete Sand and Salt	22 miles (50%)	Drain Cleaning; Sweeping	Schwarze AR8000	Winter – Weather-Based; Spring/Summer – 2x; Fall – 1x	All Roads
Nevada Department of Transportation (NDOT)	3 Epoke 3500/440; 6 Flink	Western Material Spec B Sand; Huck Salt	108 miles (100%)	Snow Haul; Sweeping	Tennant Centurion (mechanical w/ vacuum assist)	Winter – Event-Based; Summer - Monthly	All Roads
Placer County	Truck with hopper	Hansen Brothers De-Icing Sand	140 miles (68%)	Sweeping	Johnson 4000 (mechanical); Tennant Centurion (mechanical w/ vacuum assist)	Winter – Event-Based; Summer – 2x	Roads where abrasives applied
Washoe County	Epoke	Western Material Spec B Sand; Huck Salt	75 miles (50%)	Sweeping	Tymco DST6; Tennant Sentinel	Winter – Daily as weather allows; Summer – Every 6 weeks	Primary roads first, then all roads

CHAPTER 5. LAND USE SPECIFIC RESEARCH

PLRMv1 estimates pollutant loads by integrating catchment runoff and land use specific estimates of water quality concentrations for pollutants of concern to lake clarity. PLRMv1 contains a database of characteristic runoff concentrations (CRCs) for each land use type and for a range of land use conditions. The PLRMv1 values were determined using available Tahoe specific data, which in some cases was limited. In particular, the current database was developed using an extremely limited set of FSP concentration data for Tahoe land uses and road conditions. The Lake Tahoe TMDL (LRWQCB and NDEP 2010) and other stormwater research suggest roadways are the greatest potential source of FSP per unit area, and thus the CRC research contained herein focused on improving the breadth and quality for FSP pollutant generation data from impervious roads. Less intensive research was conducted on other pollutants (TSS and SRP) and other land use types. Another priority research area addressed is the default saturated hydraulic conductivity (K_{sat}) values assigned to compacted road shoulders in PLRMv1.

5.1 ROADWAY RESEARCH

5.1.1 ROADWAY RESEARCH RESULTS

The following section presents the findings from road land use monitoring during WY09-WY11, including controlled road experiments and Road RAM observations, and comparisons of the datasets to the PLRMv1 road CRC estimates.

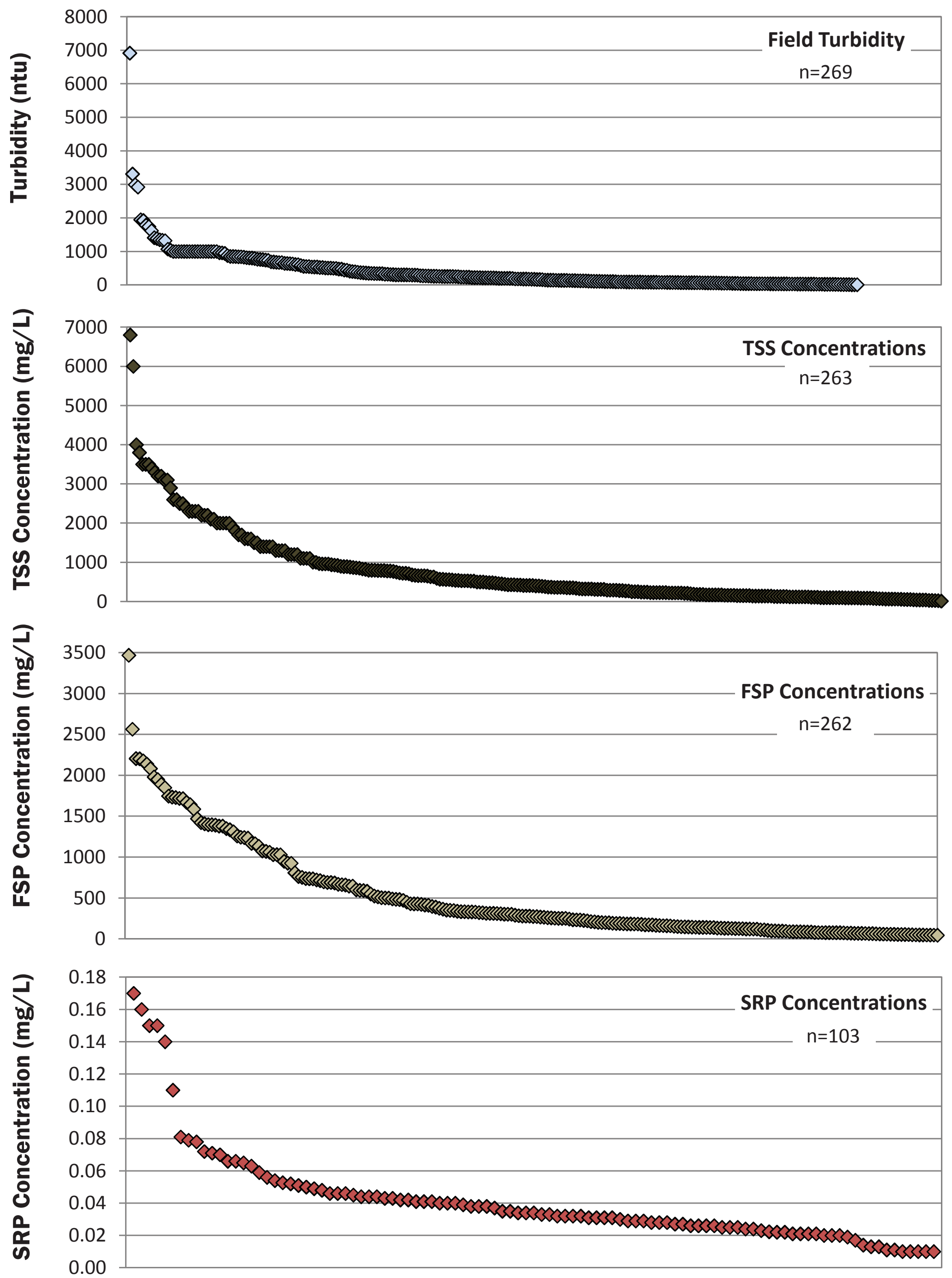
CONTROLLED EXPERIMENT CONCENTRATIONS

Figure 5.1 presents turbidity, FSP, TSS and SRP values obtained from the controlled experiments over the course of the study, ranked from highest concentration to lowest concentration. Figure 5.1 includes all road segments sampled over all observation periods and the number of observations for each pollutant is provided. The analysis of SRP concentrations was included starting in WY2010, and therefore there is less available SRP data compared to the other pollutants of concern.

TURBIDITY TO FSP CONCENTRATION

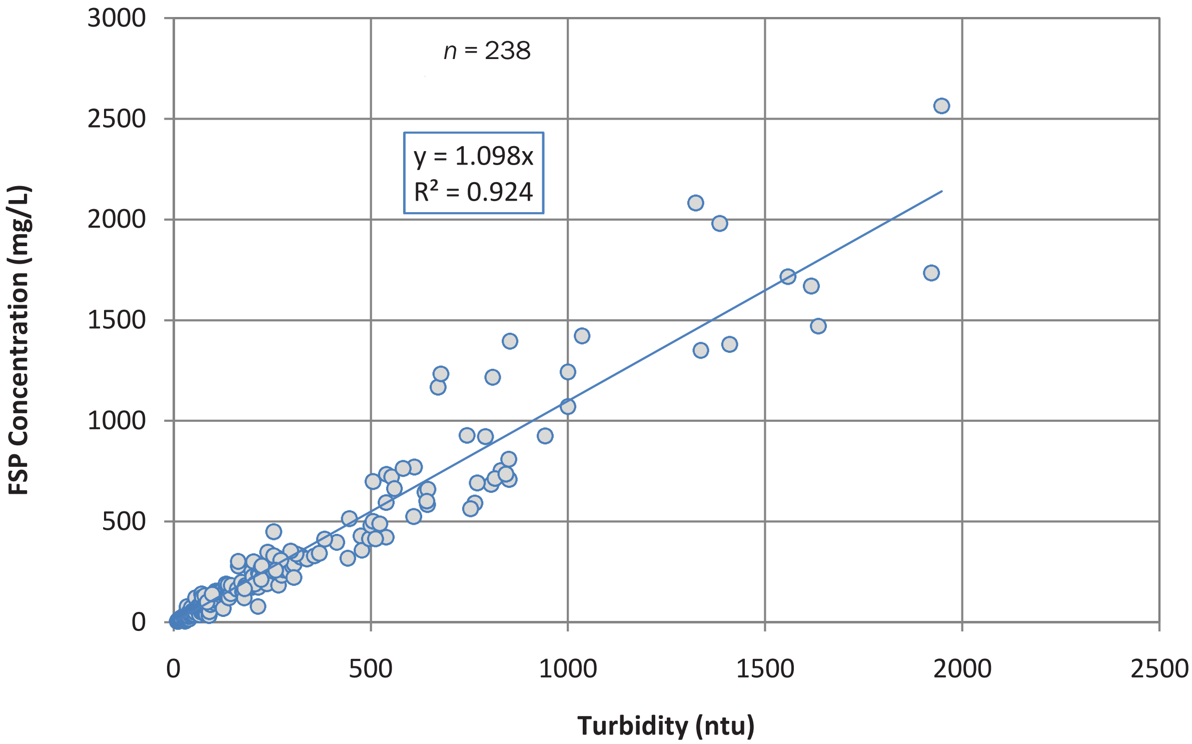
Figure 5.2 correlates the results from controlled experiment samples that were analyzed for turbidity in the field and then sent to the analytical laboratory for FSP concentration analysis. This strong correlation (R^2 = 0.924; n=238) suggests that field turbidity is a promising cost-effective and reliable proxy for FSP concentrations by mass (mg/L) for road-specific runoff samples. Other Tahoe Basin researchers have also found strong FSP (both mass and number of particles) to turbidity correlations in stormwater, streams, and land use data, but the slope of the curve can vary by source of FSP (Kayhanian et al. 2005; 2NDNATURE and NHC 2010a; Heyvaert et al. 2010). El Dorado County stormwater personnel have also found a strong FSP to turbidity relationship during their road monitoring efforts (R. Wigart pers. comm.). Additional data at higher FSP and turbidity values (> 1,000 NTU) and the standardization of analytical methods for both FSP and field turbidity would increase our confidence in using field turbidity as a reliable and cost effective proxy for FSP concentrations.

TAHOE BASIN CONTROLLED ROAD EXPERIMENTS



Range of measured pollutant concentrations from controlled experiments on 1ft^2 areas of moderate accumulation on road surfaces conducted from 2009 - 2011, ranked high to low. Over two years of data collection, it appears a representative distribution of expected 1ft^2 road conditions have been sampled.

TAHOE BASIN CONTROLLED ROAD EXPERIMENTS
TURBIDITY TO FSP RATING CURVE



Correlation plot of turbidity versus FSP concentration based on 238 controlled Tahoe Basin road experiments collected and analyzed in 2009 and 2010 (2NDNATURE and NHC 2010a).

SEASONAL VARIATIONS

Figure 5.3 presents the FSP concentration range obtained from controlled experiments on the area of moderate accumulation for all road segments sampled during each observation period, demonstrating the extreme seasonal variability in FSP concentrations. Of the 315 controlled experiments conducted, which were equally distributed throughout the year, 77% of the observations (105 of 136 samples) that exceeded 300[3] mg/L FSP were observed during the winter months (January through March), and 32% of the observations (44 of 136 samples) exceeded 1,000 mg/L FSP during the same time frame. The 1,000 mg/L is used as the upper threshold, because road segments that exceeded 1,000 mg/L using the portable sampler possessed excessive amounts of fine sediment, the roads are in poor condition and should a runoff event occur it would be considered an extreme downslope water quality risk.

This seasonal trend of peak FSP concentration observed during the winter months aligns with seasonal road maintenance practices, when significant amounts of abrasives, a source of potential FSP, are applied to the road surface to provide traction and protect driver safety. It is likely that tire chains, plowing and other road surface impacts increase the rate of pavement degradation during the winter months as well. Abrasives used on Tahoe Basin roads contain some fraction of FSP prior to application, but it is assumed the greatest generation of FSP on winter roads is the pulverization of abrasives, pavement decay and other material transported to the road surface from vehicle traffic. In addition to an increased source of pollutants, the opportunity and effectiveness of street sweeping to remove abrasives and other material prior to accumulation and pulverization is intermittent and can be challenging given adverse weather conditions and icy road surfaces during the winter.

The maximum FSP concentrations and variability across sites significantly decreases from the winter months through the spring sampling periods (April and May) and summer sampling periods (July and October; see Figure 5.3). By summer, the measured FSP concentrations are reduced to <100 mg/L on nearly all roads sampled, regardless of the road condition prior to the runoff event. This finding is likely the combined result of: (1) warmer temperatures reducing the need for road abrasive applications, (2) jurisdictions having more opportunities to sweep given the length of time since the most recent winter storm and abrasive application, and (3) late spring/summer rain events mobilizing and essentially washing off the sediment accumulated on the road surface. There are some road segments where it is known that winter road abrasives were applied, but it has been confirmed from the jurisdiction that no sweeping actions were conducted at any point during the year. At these sites the measured FSP concentrations were reduced from > 1,000 mg/L during the winter to < 200 mg/L during summer and fall observations. These observations suggest that spring rain events can essentially wash road surfaces and effectively remove material and pollutants from the road surface, transporting them into the stormwater conveyance system. It is likely that high wind events and traffic passing can also transport FSP from the road surface to the shoulder or beyond.

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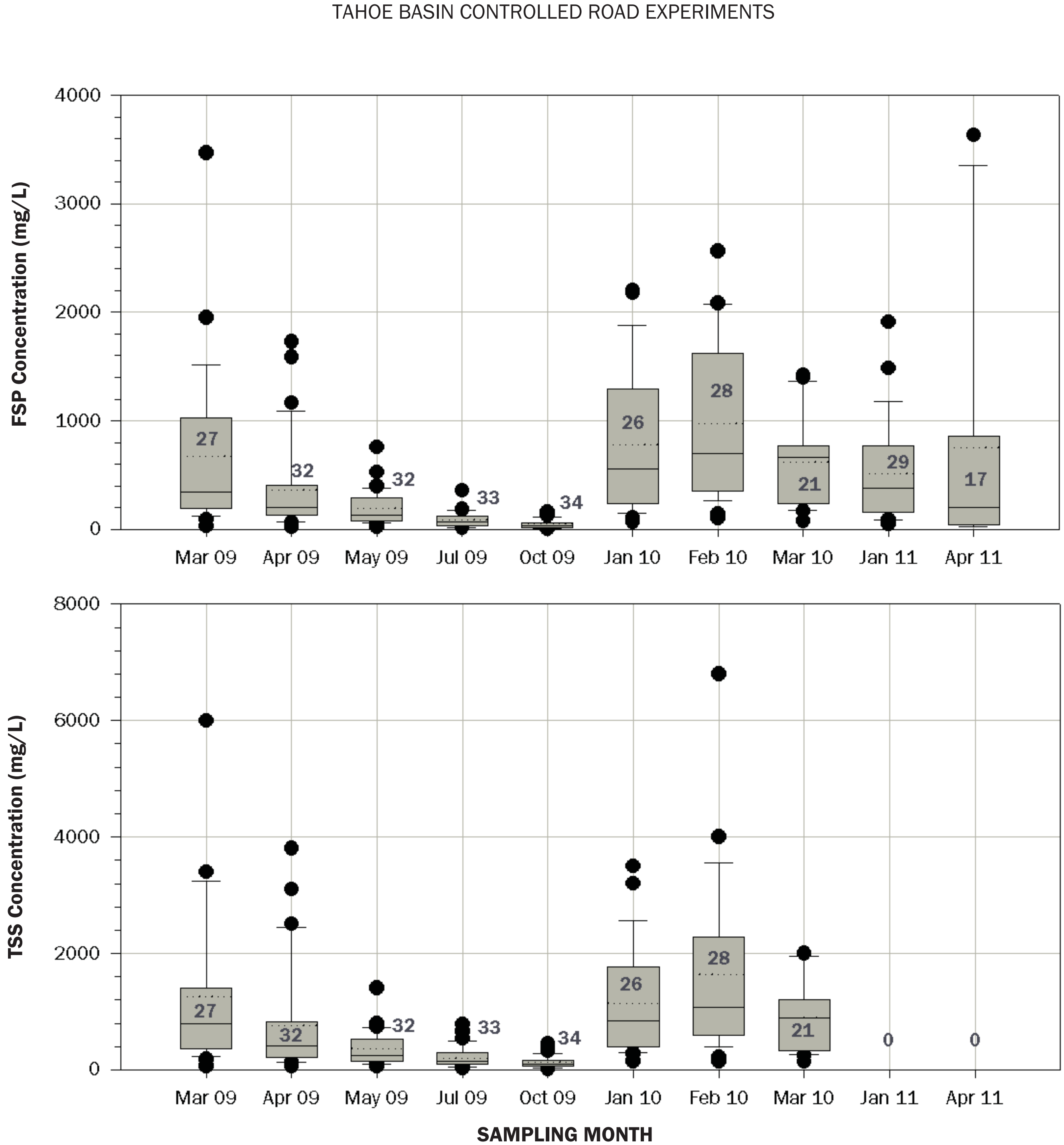
[3] The FSP value of 300 mg/L is used a critical threshold, above which is considered a significant water quality risk of a road surface because a) 300 mg/L is the 60th percentile value given the existing 315 controlled road sampling data points; b) field observations of a road surface that results in a FSP concentration > 300 mg/L visibly appears to have an elevated amount of fine particles on the road surface; c) roads subjected to both road abrasive applications and high sweeping frequency have been observed to be consistently below 300 mg/L during winter observations, therefore indicating that FSP values below 300 mg/L on high risk roads are achievable during winter road conditions; and d) using the mixed urban catchment data obtained from this research, the mean FSP concentration is 128 mg/L and 300 mg/L is the 89th percentile, indicating 300 mg/L is relatively elevated given available data.



The strong seasonal pattern of FSP and TSS concentrations from road surfaces is demonstrated by the box and whisker plots of Tahoe Basin road FSP and TSS concentrations measured during the controlled experiments from WY2009-WY2011. In 2011, water quality samples were not submitted to the laboratory for analysis. FSP concentrations are determined using field turbidity results and the turbidity to FSP concentration rating curve shown in Figure 5.2. No TSS concentration data is available for those 2 observations periods.

JURISDICTIONAL DIFFERENCES

FSP

The seasonal trends of FSP suggest that the winter and early spring road conditions provide the greatest opportunity to manage the risk to downslope water quality by local jurisdictions. During this time, roads have the greatest amount of pollutants following winter storm abrasive application and there is the greatest risk of pollutant transport into the stormwater system during the subsequent spring rains. Eight-six percent (or 44 of 51) of the samples that exceed a FSP concentration of 1000 mg/L (see Figure 5.3) were measured in the winter months. Table 5.1 provides the distribution of these 51 samples by jurisdiction in charge of road maintenance. The jurisdictions are ordered from left to right by increasing average annual abrasive application by lane mile (see Figure 4.3). There is an increasing trend that as a jurisdiction's abrasive application rate increases the frequency of samples >1000 mg/L in that jurisdiction increases, suggesting that abrasive application has a direct effect on the discrete observed FSP concentration on the road surface.

Table 5.1. Comparison by jurisdiction of total number of FSP samples that exceeded 1000 mg/L with the average annual abrasive application rate per lane mile (MT/mile/WY; see Chapter 4.3).

Jurisdiction	El Dorado County	NDOT	Washoe County	CSLT	Placer County	Caltrans	KGID
# of samples > 1000 mg/L FSP	1	6	1	1	13	16	13
Average annual abrasive application per lane mile (MT/mile/WY)	6.1	6.5	7.3	9.3	14.9	43.9	116.2

While increased FSP concentrations are to be expected during the winter months when the sources (i.e., abrasives) are the highest, road segments where low FSP concentrations are observed during the winter months provide insight into how to reduce FSP accumulation on the road surfaces. The research team conducted a closer examination of these 44 winter observations <300 mg/L FSP with respect to the specific road maintenance practices implemented at those road segments. While the exact chronology of practices conducted at the road segment prior to our observations are not maintained by the jurisdictions, the implementation of road maintenance practices that minimize abrasive applications and maximize sweeping frequency with more efficient sweepers were confirmed for the majority of the road segments where those 44 observations occurred.

- Fourteen of the 44 winter road segment observations <300 mg/L were conducted on lower risk roads where road abrasives are not typically applied and observations by field personnel confirmed no evidence of recent abrasive applications. Typically these are low sloped roads in residential areas with low traffic densities.
- Of the 9 winter observations where FSP <100 mg/L, 4 observations were on high risk roads (EI and VIL1, see Figures 3.2A-B) where road abrasives are frequently applied; however, these segments were subjected to frequent street sweeping using high-efficiency sweepers when conditions allowed.
- The lowest measured winter FSP concentration (28 mg/L) was observed in March 2009 on Highway 50 at the South Y in South Lake Tahoe (road segment EI, see Figure 3.2A and photo at right). During this time Caltrans was testing the use of a high efficiency regenerative air sweeper at this heavily trafficked intersection (L. Waters, pers. comm.) and multiple passes were observed by 2NDNATURE field personnel along the road segment prior to the controlled experiment.

EI Road Segment, March 2009: Lowest measured FSP Concentration (28 mg/L)

The upper graphic in Figure 5.4 presents the integration of the controlled experiment FSP concentration data from 5 winter observations (March 2009, January 2010, February 2010, March 2010 and January 2011) arranged from highest to lowest average FSP concentration by Tahoe Basin jurisdiction. Sampling sites where abrasive applications were unlikely or infrequent (low gradient residential roads with low traffic density) were removed from the dataset presented in Figure 5.4. There is a discernible trend in the maximum, average and minimum FSP concentration values observed across jurisdictions, although the distribution of road risk categories sampled for each jurisdiction is similar (see Figure 3.1).

TSS

The TSS concentrations from the controlled experiments show a similar seasonal and jurisdictional pattern to the FSP concentrations with peak values in the winter and reductions observed through the spring and into summer (see Figure 5.3). The two highest measured concentrations are observed in February 2010 (6800 mg/L) and March 2009 (6000 mg/L), and the monthly average TSS concentration during the winter months (January through March) is >800 mg/L. By the summer and early fall (July through October), the average monthly TSS concentration is <150 mg/L and there are frequent observations (11 samples, or 16%) of TSS concentrations <50 mg/L. Winter TSS concentrations from controlled experiments are provided on the bottom half of Figure 5.4 and indicate a jurisdictional trend similar to the FSP concentration data.

SRP

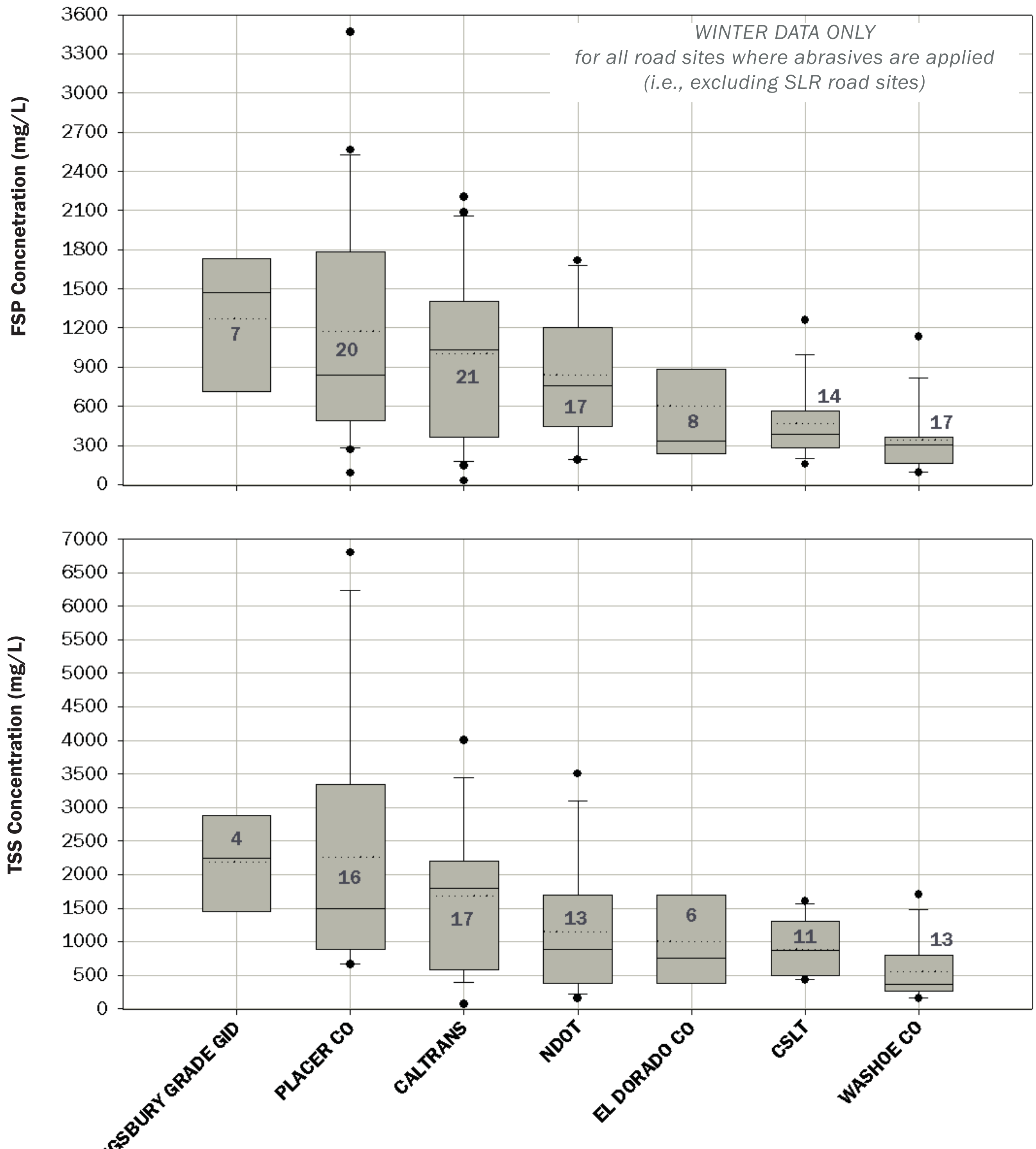
The SRP concentrations from 103 controlled experiments are plotted in a box and whisker plot by jurisdiction in Figure 5.5A. Given the limited SRP sampling, the SRP box and whisker plot shows all road segments for all observation periods (October 2009, January 2010, and February 2010). The data is arranged from highest to lowest average SRP concentration, resulting in a different jurisdiction order than shown in Figure 5.4, and demonstrates some variability but no significant difference in the SRP concentrations across jurisdictions.

Figure 5.5B illustrates that there is no correlation between SRP and FSP concentration, suggesting the factors influencing SRP concentrations on Tahoe Basin roads are different from the factors driving observed FSP concentrations. Perhaps more importantly is the concentrations of SRP measured from roads are significantly lower than those observed from other land uses. With a mean SRP of 0.04 mg/L for 103 samples, road SRP concentrations are over an order of magnitude lower than the SRP mean concentrations (0.6 mg/L) measured from a fertilized ball field in Incline Village (2NDNATURE 2007) and well below the Tahoe Regional Planning Agency surface water discharge standard for dissolved phosphorous (DP) of 0.1 mg/L (TRPA 2007).

Since the Lake Tahoe TMDL regulates total phosphorous (TP) and not the biologically available dissolved fraction (SRP), there is some interest in understanding the potential implications of the finding that roads are a low priority source of SRP relative to the potential of TP source loading from this land use. Given the extensive breadth of this data collection effort, TP was not analyzed in order to reduce analytical costs and therefore we have no consistent road specific data to make an inference of the expected TP loading from roads. However, the biogeochemical behavior of phosphorous species and existing Tahoe stormwater datasets can be used to infer two possible scenarios.

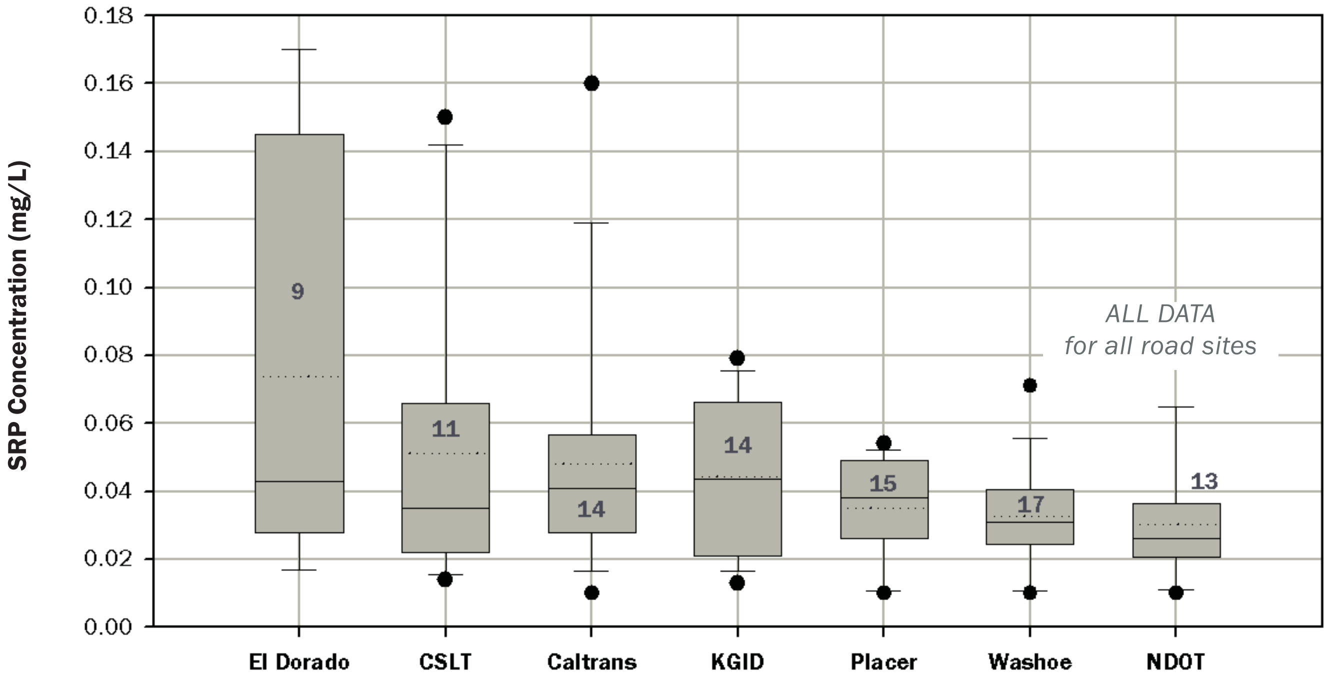
1. Using the compilation of stormwater data from 12 typical urban mixed land use Tahoe catchments (see Table C1 in 2NDNATURE 2006), the average ratio of SRP:TP was 0.12 ± 0.07. Applying this ratio to the SRP mean road concentration of 0.04 mg/L from this research yields an estimated TP concentration of 0.33 mg/L from roads. The watershed model used to support the TMDL (LRWQCB and NDEP 2010) estimated primary and secondary road EMCs as 1.98 mg/L and 0.588 mg/L, respectively. This tenuous comparison suggests TP loading from road surfaces may be lower than originally assumed; however road-specific TP

TAHOE BASIN CONTROLLED ROAD EXPERIMENTS

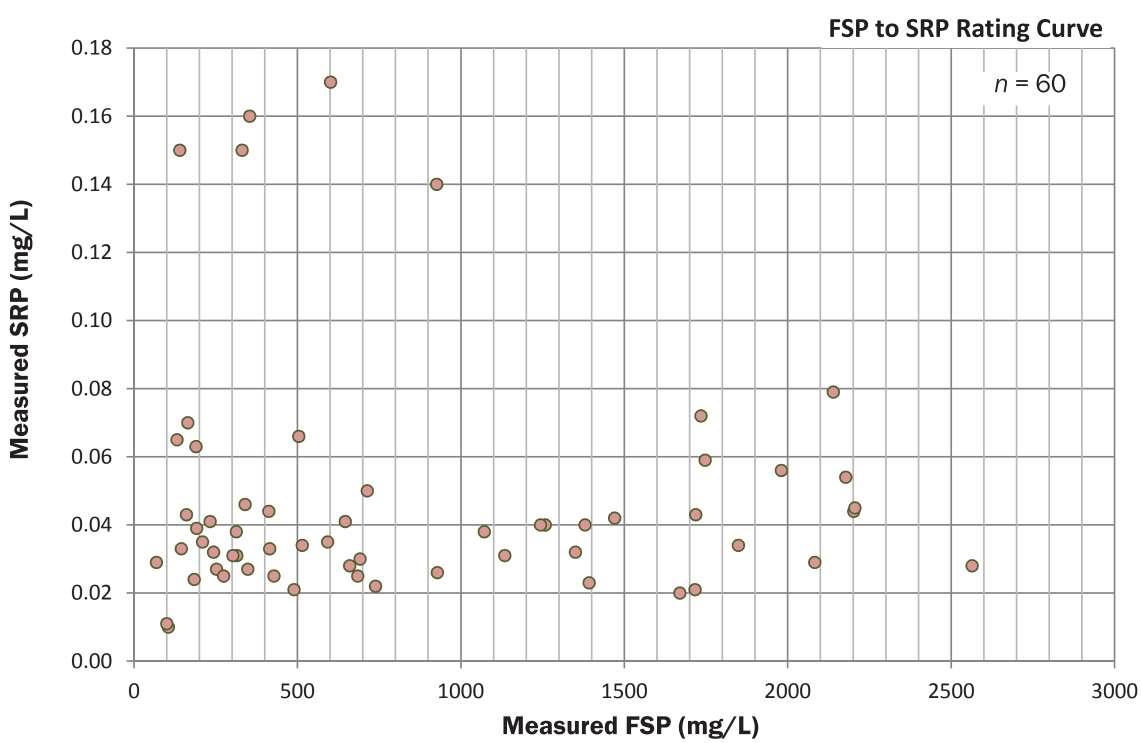


Data above was obtained from March 2009, January 2010, February 2010, March 2010, and January 2011 controlled road sampling efforts. Water quality data is presented by jurisdiction, ranked from left to right in order of decreasing mean concentration. In 2011, water quality samples were not submitted to the laboratory for analysis. FSP concentrations are determined using field turbidity results and the turbidity to FSP concentration rating curve shown in Figure 5.2. No TSS concentration data is available for those 2 observations periods.

(A) Data above was obtained from October 2009, January 2010, and February 2010 controlled road sampling efforts. Water quality data is presented by jurisdiction, ranked from left to right in order of decreasing mean concentration.



(B) SRP concentrations are plotted against measured FSP concentrations for 60 samples where both data are available. The data shows no correlation between FSP and SRP, suggesting there are different factors influencing SRP concentrations in road surface runoff than those that affect FSP concentrations.



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research is necessary prior to any recommendations to revise road TP CRCs in PLRM. If TP concentrations are consistent with the SRP findings that roads are not a significant source, then phosphorous source control efforts should be focused elsewhere (i.e. fertilizer reductions, car washing etc).

2. If this estimation approach is incorrect, and roads are a significant source of TP, it would be in the form of particulate phosphorous[4] (PP). Particulate phosphorous is bound to the small particles (i.e., FSP) and thus implementation strategies focused on reducing the amount of FSP available on road surfaces prior to stormwater runoff events would be equally effective at reducing PP and thus TP from this land use type.

ROAD POLLUTANT CONCENTRATIONS RELATIVE TO LAKE TAHOE TMDL LAND USE EMCS

Table 5.2 provides a comparison of the Lake Tahoe TMDL land use EMCs used in the Watershed Model (LRWQCB and NDEP 2010) to the mean concentrations of the sample datasets obtained using the portable simulator on Tahoe roads for each pollutant. This comparison has a number of limitations, but it does provide an initial evaluation of how Lake Tahoe TMDL EMCs align with a land use specific dataset. The greatest deviation is associated with the observed FSP concentrations on secondary roads being 4 times higher than the original Lake Tahoe TMDL EMC FSP values. The Lake Tahoe TMDL EMC values for residential and vegetated turf land uses are also provided in Table 5.2 to illustrate how average pollutant concentrations from road land uses compare to average pollutant concentrations across all urban land uses in the Tahoe Basin.

Table 5.2. FSP, TSS and SRP EMC values used by the watershed model (LRWQCB and NDEP 2010) by urban land use type. Mean concentrations obtained from this research using the portable simulator on impervious roads and two select CICU parking lots are provided for comparison. Note that the dissolved phosphorous (DP) and SRP numbers are not directly comparable as SRP is the biologically available fraction of DP.

Land use type	Watershed Model EMCs			WY09-WY11 Research Mean concentrations		
	FSP (mg/L)	TSS (mg/L)	DP (mg/L)	FSP (mg/L)	TSS (mg/L)	SRP (mg/L)
Primary roads	566	952	0.096	624	866	0.039
Secondary roads	89	150	0.144	434	767	0.044
Road spatial average*	164	276	0.136	464	783	0.043
CICU (Pervious and Impervious)	176	296	0.078	193	287	0.023
MFR (Pervious and Impervious)	92	150	0.144	Not evaluated		
SFR (Pervious and Impervious)	30	56	0.144			
Vegetated Turf	5	12	0.263			

The road spatial average* weights the primary and secondary road EMCs based on 110 miles of primary roads and 590 miles of secondary roads in the Tahoe Basin.

ROAD RAM DEVELOPMENT

The research contained herein contributed to the development of Road RAM and correlation of road condition scores to road segment FSP concentrations (mg/L) at time of observations. The insight and value of this research is detailed in the Road RAM Technical Document (2NDNATURE et al. 2010c) and not repeated herein. The portable

[4] TP = PP + SRP+ dissolved organic phosphorous (DOP) see Figure 2 (2NDNATURE 2006). It is reasonable to assume DOP source loading from roads would be extremely low, making PP the critical compound influencing TP concentrations from roads.

simulator was a critical component of the Road RAM field observation development, where the statistical significance of a series of rapid observations was tested to evaluate their capability to predict the FSP concentration measured by the simulator on the same $1ft^2$ road surface. Road RAM (2NDNATURE et al. 2010c) is a complete standardized tool to rapidly determine and track road condition over time. Road condition is defined as the relative amount of FSP available on the road segment at the time of observation and is determined using a series of experimentally derived visual proxies. Table 5.3 presents the final categorical Road RAM to FSP concentration relationship and Figure 5.6 graphically presents the empirical equation. Figure 5.6 is a similar FSP to pollutant potential score relative to PLRMv1 Road Methodology (NHC et al. 2009a). This empirical equation allows a simple and reliable translation between Road RAM scores and road segment FSP concentrations.

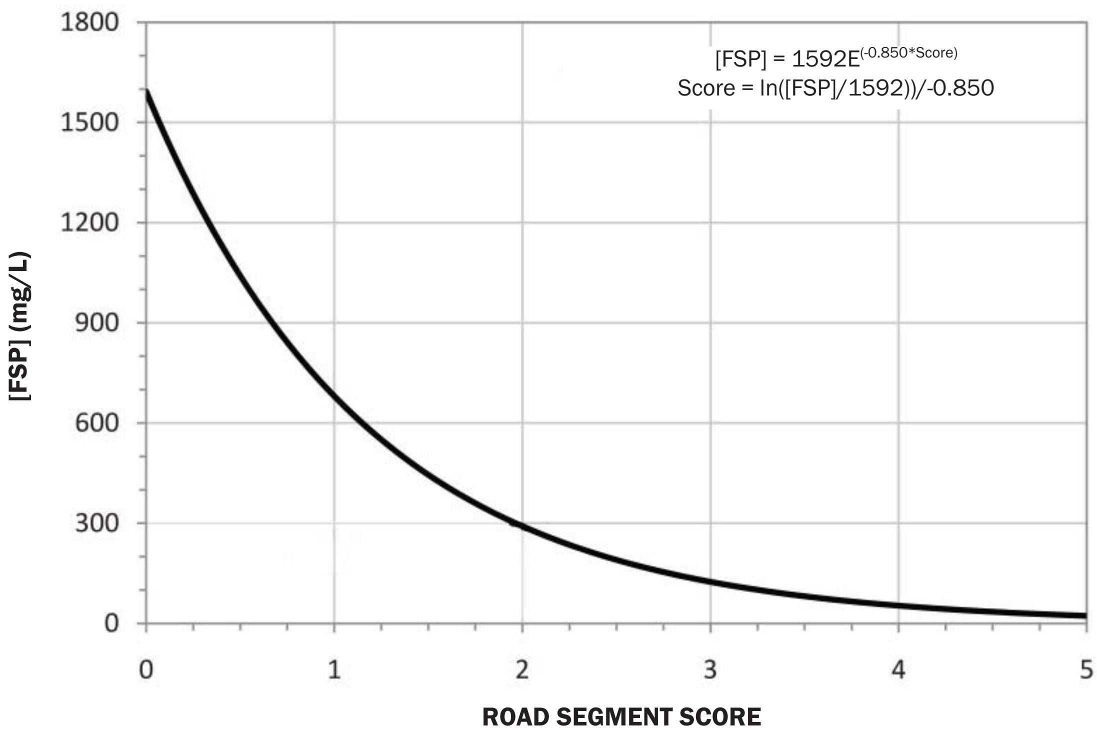
Table 5.3. Road RAM scores relative to road condition and relative risk to downslope water quality.

Road RAM Score	Condition	FSP Concentration (mg/L) Range
0 - 1.0	Poor	1,592-680
>1.0 - ≤ 2.0	Degraded	679-291
> 2.0 - ≤ 3.0	Fair	290-124
> 3.0 - ≤ 4.0	Acceptable	123-53
> 4.0 – 5.0	Desired	52-23

Each Road RAM score is correlated to an expected FSP concentration from the road segment if the segment were sampled in a manner consistent with the controlled experiments. The translation of road segment FSP concentrations to a 0-5 RAM score simplify communication of relative condition, while preserving the quantitative alignment to the concentrations of the pollutant of concern. Table 5.4 compares differences in Road RAM scores throughout the 0-5 range to the equivalent differences in FSP concentrations using the relationship shown in Figure 5.6. While the absolute FSP concentration differences vary depending upon the Road RAM score, the percent difference in the FSP concentrations is consistent, i.e., for every 0.1 change in Road RAM score there is a consistent 8.1% FSP concentration change. The smaller differences in absolute FSP concentrations at higher RAM scores (RAM >2 or FSP concentration <300 mg/L) are consistent with our ability to measure these differences in the field using the portable sampler. Much higher field precision (<8% error) is observed when there is less material on the road surface and RAM scores are above 2). Field sampling error significantly increases when the amount of material on the roadway is excessive, creating micro gullies and transport variability from the road surface to the sampler collection device. For simplicity’s sake, road condition observation results are provided as Road RAM scores throughout this document. However, using Table 5.4 the reader can easily translate RAM scores to FSP concentrations.

The combination of the Road RAM visual proxies and controlled experiment data results were used to create a series of Basin-wide maps of road condition for 4 observations periods at the road segments monitored (Figure 5.7). Each symbol represents a specific road segment and the color designates the score range, consistent with Table 5.3. Similar to the seasonal trends shown in Figure 5.3, road conditions that minimize pollutant generation appear to be best during the summer observation period and worst during the winter observation period, where the overwhelming majority of the road segments have road condition scores deemed degraded or poor. Spatial variations during any particular observation period are also apparent. Any road segment score can be converted to an FSP concentration using the exponential equation presented in Figure 5.6. The Road RAM map outputs provide a simple communication tool to easily convey the time progression of relative road condition around the Tahoe Basin, and hopefully inform the prioritization of future actions to improve water quality from road surfaces.

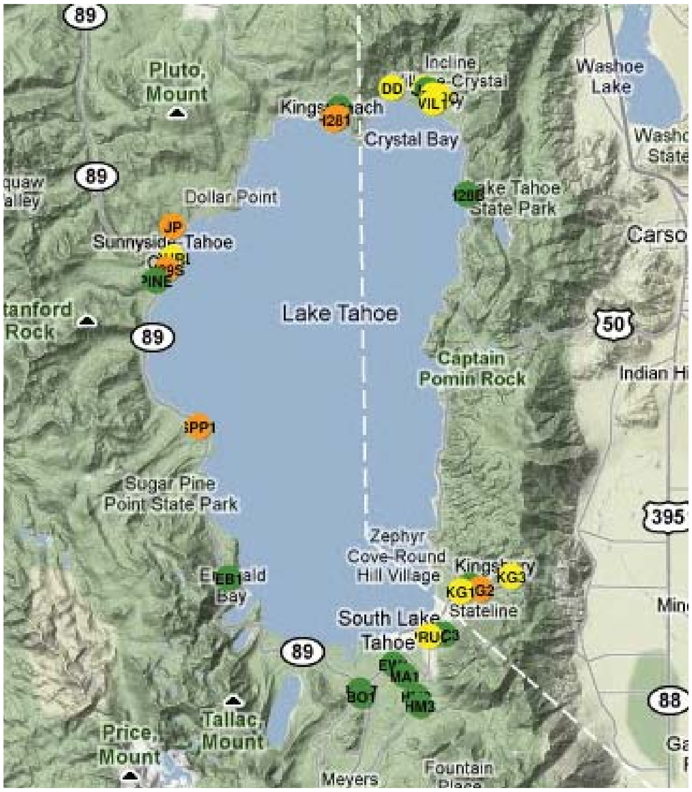
ROAD RAM SCORE TO FSP CONCENTRATION RELATIONSHIP



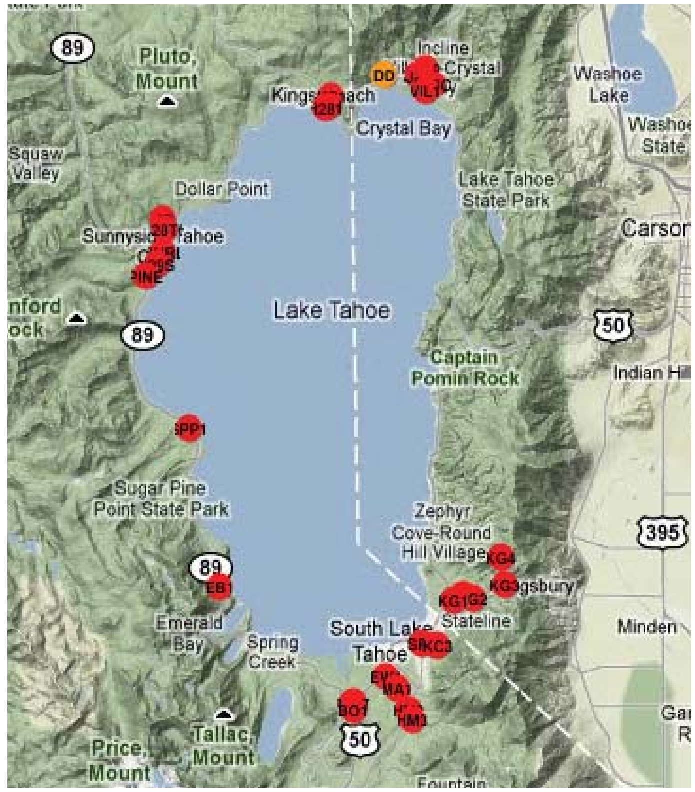
The road segment score represents the observed condition of the road segment at the time of observation. The road segment FSP concentration is converted to a road segment score by the Road RAM database using the same concentration to score relationship used in PLRMv1.

ROAD RAM ROAD SEGMENT CONDITION SCORES

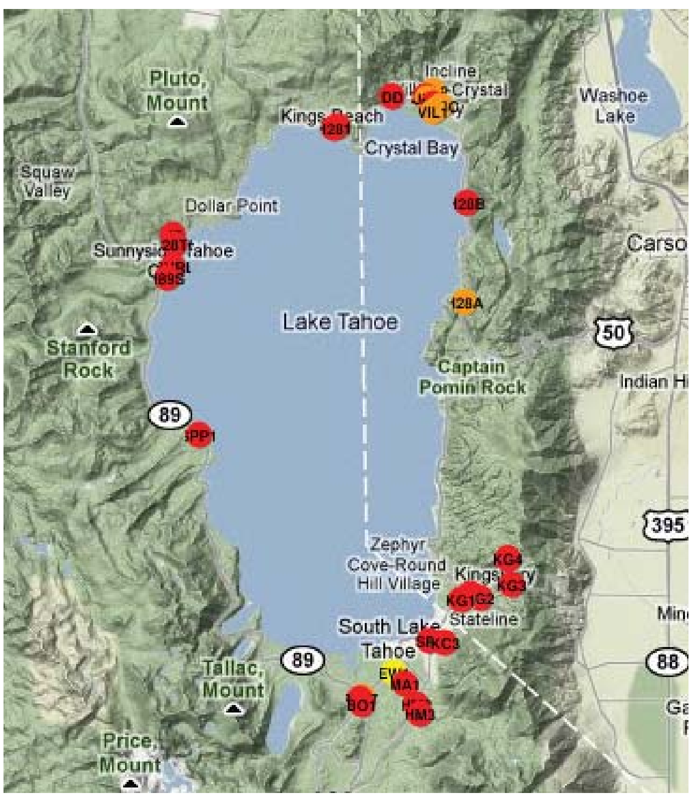
July 2009 Observation Period



February 2010 Observation Period



January 2011 Observation Period



April 2011 Observation Period

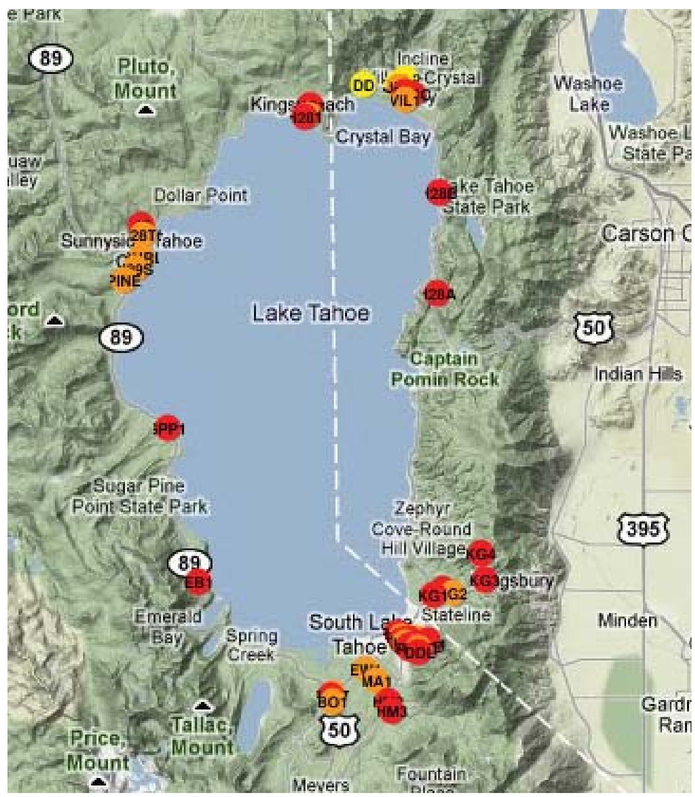


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FIGURE 5.7

Table 5.4. Comparison of differences in Road RAM scores to equivalent magnitude and percent differences in FSP concentrations. While the absolute FSP concentration difference on a ± 0.1 RAM score interval ranges from 130 mg/L to 2 mg/L as the expected FSP concentration decreases, the absolute deviation is consistently ± 8.1%.

Road RAM Score	FSP Concentration (mg/L)	FSP Concentration Difference	% Difference	Road RAM Score	FSP Concentration (mg/L)	FSP Concentration Difference	% Difference
0	1592	-	-	2.6	175	-15	-8.1%
0.1	1462	-130	-8.1%	2.7	160	-14	-8.1%
0.2	1343	-119	-8.1%	2.8	147	-13	-8.1%
0.3	1234	-109	-8.1%	2.9	135	-12	-8.1%
0.4	1133	-101	-8.1%	3	124	-11	-8.1%
0.5	1041	-92	-8.1%	3.1	114	-10	-8.1%
0.6	956	-85	-8.1%	3.2	105	-9	-8.1%
0.7	878	-78	-8.1%	3.3	96.3	-9	-8.1%
0.8	807	-72	-8.1%	3.4	88.5	-8	-8.1%
0.9	741	-66	-8.1%	3.5	81.3	-7	-8.1%
1	680	-60	-8.1%	3.6	74.6	-7	-8.1%
1.1	625	-55	-8.1%	3.7	68.6	-6	-8.1%
1.2	574	-51	-8.1%	3.8	63.0	-6	-8.1%
1.3	527	-47	-8.1%	3.9	57.8	-5	-8.1%
1.4	484	-43	-8.1%	4	53.1	-5	-8.1%
1.5	445	-39	-8.1%	4.1	48.8	-4	-8.1%
1.6	409	-36	-8.1%	4.2	44.8	-4	-8.1%
1.7	375	-33	-8.1%	4.3	41.2	-4	-8.1%
1.8	345	-31	-8.1%	4.4	37.8	-3	-8.1%
1.9	317	-28	-8.1%	4.5	34.7	-3	-8.1%
2	291	-26	-8.1%	4.6	31.9	-3	-8.1%
2.1	267	-24	-8.1%	4.7	29.3	-3	-8.1%
2.2	245	-22	-8.1%	4.8	26.9	-2	-8.1%
2.3	225	-20	-8.1%	4.9	24.7	-2	-8.1%
2.4	207	-18	-8.1%	5	22.7	-2	-8.1%
2.5	190	-17	-8.1%				

PLRMV1 CRC RANGE AND SHAPE

A CRC, or characteristic runoff concentration, is a runoff concentration for a pollutant of concern from a specific land use and associated land use condition over a range of stormwater runoff events and seasons. A CRC is similar in concept to an event mean concentration (EMC), but a CRC is calculated as the long-term pollutant load divided by the long-term runoff volume. For example, CRCs in PLRM are assumed to be representative of the pollutant load divided by the runoff volume generated by the continuous 18-year simulation that PLRMv1 currently executes. Conversely, EMCs attempt to characterize the average concentration in runoff for a specific event, which typically lasts a few hours or days. In order to accurately quantify a CRC, the research would need to determine the volume weighted average of EMCs over multiple years for a particular site that captures a land use specific EMC across all event types for a specific condition. Multiple sites that cover a range of potential land use conditions would be necessary. Because this approach is cost, time and likely logistically prohibitive, various methods are used to compare our series of discrete measured pollutant concentrations on road surfaces appropriately to PLRMv1 CRC values.

The first comparison uses the complete dataset of measured road pollutant concentrations over the course of the research to evaluate the shape, minimum, and maximum values of current PLRM CRCs for road land uses. The shape of the exponential decay of the FSP CRC algorithm is presented in Figure 5.6. The measured FSP concentration values were obtained from 1ft^2 on the moderate accumulation area from 32 road segments during 10 observation periods for a range of meteorological conditions. The complete dataset (see Figure 5.1) is relevant to assess the range and exponential shape of CRCs in PLRM relative to road condition for the following reasons: 1) the series of road segments cumulatively represent the spatial range of observed road conditions across all jurisdictions in the Tahoe Basin; and 2) each road segment was sampled over a range of weather conditions during a 3-year period.

Table 5.5 compares these PLRM estimates to the values measured during road sampling for TSS, FSP and SRP concentrations. The results suggest the high bookend PLRM CRC values are within reason, while the PLRM minimum CRCs are within the range of measured concentration on Tahoe roadways. The high frequency of SRP samples measured at the minimum value (40 samples below 0.03 mg/L) suggests the analytical detection limit is too high to detect variations in the road SRP data. However, given comparisons of SRP concentrations on roads to other land uses in the Basin, it is likely not a stormwater monitoring priority to continue SRP sampling on road surfaces. Based on the available measured data, the PLRMv1 TSS, FSP and SRP CRCs appear to be representative of the observed range of concentrations from Tahoe roads.

Table 5.5. Comparison of PLRMv1 CRC values to measured concentrations for TSS, FSP and SRP collected during controlled experiments.

	TSS (mg/L)	FSP (mg/L)	SRP (mg/L)
PLRMv1 MAX CRC	1398	1014	0.16
Measured MAX concentration (n)	6800 (263)	3468 (262)	0.17 (103)
Frequency measured MAX > PLRMv1 MAX (n)	18% (51)	16% (43)	1% (1)
PLRMv1 MIN	63	22	0.03
Measured MIN concentration (n)	10 (263)	4 (262)	0.01 (103)
Frequency measured MIN < PLRMv1 MIN (n)	6% (16)	6% (16)	39% (40)

The CRC to road condition score) rating curves and equations for TSS, FSP, and SRP CRCs used in PLRMv1 (see Figure 2.1) show the inverse relationship between score and concentration (i.e., concentrations exponentially decline with an increase in road condition score on a 0-5 scale). The experimental field data in Figure 5.1 verifies that the exponential shape of the CRC to score relationships used in PLRMv1 for these pollutants is reasonable. This research finding also supports the FSP to score equation used in Road RAM (Figure 5.6).

CALCULATED AVERAGE FSP CONCENTRATION ESTIMATES

In order to compare observed road FSP concentration data and the PLRM predicted values for a specific road segment, we must ensure the observed data is expressed in a manner that is spatially and temporally comparable to a PLRM FSP CRC. Road RAM includes a spatial extrapolation technique to determine road condition (RAM score or FSP concentration) of a 10,000 ft^2 road segment based on visual observations in representative 1ft^2 areas (see *Road RAM Technical Document Chapter 9*; 2NDNATURE et al. 2010a). The road segment area is a standardized 10,000 ft^2 and the % area contribution of each accumulation category (high, moderate, low) is estimated for each road segment evaluated. The moderate accumulation area FSP concentration was measured using the simulator, and Road RAM visual proxies were used to predict the FSP concentration on the low and high areas of accumulation. The results are spatially weighted to estimate the road segment FSP concentration, a spatially comparable value to PLRM CRCs and these are the values shown for specific observation periods in Figure 5.7.

Road RAM temporal extrapolation techniques are used to compare a series of measured FSP concentration values at one road segment, which are concentrations representing discrete measurements at a specific location at a specific point in time, into a seasonally flow weighted concentration we believe to be comparable to PLRM FSP CRCs. Road RAM includes a temporal extrapolation technique to integrate a series of discrete observations at one road segment conducted over a water year and estimate the flow weighted annual FSP concentration or road condition (see *Road RAM Technical Document Chapter 8: Spatial and Temporal Extrapolation of Observations* (2NDNATURE et al. 2010a)). The weighting of FSP concentration data by season (Table 5.6) was informed by the seasonal road condition variations and the relative annual contribution of surface runoff in each season. Estimates of seasonal surface runoff from urban areas in the Tahoe Basin was derived from an analysis of long-term (18-year) time-series output of hourly surface runoff in EPA SWMM for representative PLRM scenarios. EQ 5.1 summarizes how the measured FSP concentration values were integrated to calculate volume weighted average FSP concentration at each road segment.

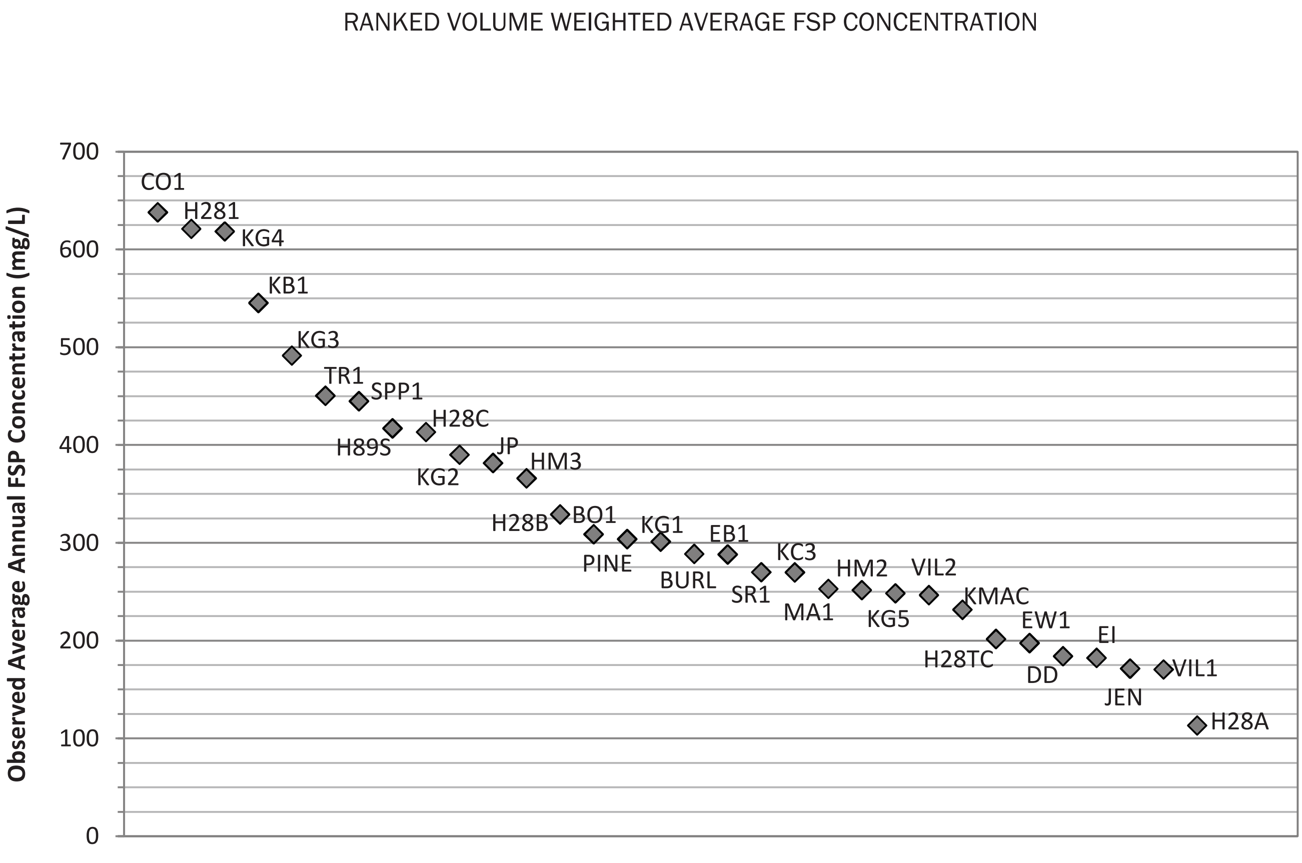
$$[FSP]average = [FSP]_{s/f} fRV_{s/f} + [FSP]_w fRV_w + [FSP]_{ws} fRV_{ws} + [FSP]_{ss} fRV_{ss} \qquad \text{EQ (5.1)}$$

where [FSP] annual is assumed to be our best representation of an annual average FSP concentration given the available dataset, $[FSP]_i$ is the average FSP concentration of all observations made within the respective seasons and fRV_i is the fraction of the total average annual urban runoff volumes for each season indicated in Table 5.6.

Table 5.6. Temporal integration of discrete road condition observations to estimate the calculated volume weighted average FSP concentrations (slightly modified from Road RAM; 2NDNATURE et al. 2010a).

Season (months)	fRV_i
Summer/Fall (s/f: Aug-Dec)	20%
Winter (w: Jan-Feb)	20%
Late Winter/Early Spring (w/s: Mar-Apr)	40%
Spring/Summer (s/s: May-July)	20%

Using all available road segment data over 3 water years with the total number of observations per segment ranging from 5 to 10, the annual volume weighted observed FSP concentration is calculated per EQ 5.1 for the 32 road segments and plotted categorically from high to low in Figure 5.8. The 32 sites cumulatively represent a reasonable range of road risk types across all jurisdictions. The observed volume weighted average annual FSP concentrations range from 113 mg/L to 638 mg/L. Sixteen of the 32 sites had a calculated volume weighted FSP concentration > 300 mg/L and 31 of the 32 sites (66%) exceed the FSP EMC road average (164 mg/L) as determined from mixed catchment stormwater data (Gunter 2005) and used in the Watershed Model (see Table 5.2).



Ranking from high to low of the calculated volume weighted average road segment FSP concentration for the 32 road segments. Discrete road segment concentrations are temporally weighted based on the values presented in Table 5.5 to calculate an annual value.

CALCULATED FSP CONCENTRATION LIMITATIONS

The calculated volume weighted average FSP concentrations are based on data generated using field observations with known limitations. The calculated values are generated using a number of spatial and temporal extrapolation techniques to integrate a series of discrete observations to estimate the volume weighted annual FSP concentration for specific road segments. Given the infeasibility of continuously sampling the stormwater runoff from a road segment over all event types for a number of years, we believe we provide a reasonable and appropriate approach to integrate the available series of temporally discrete FSP concentration measurements to compare to PLRMv1 CRCs predictions for the same road segments.

Figure 5.9 illustrates the time series of observed FSP concentration values and the calculated volume weighted average FSP value for a number of road segments included in the research. The actual fluctuation of FSP concentrations on the road surfaces are much more variable than the dataset represents and obviously the more frequent the road condition observations the better the temporal resolution of the dataset to estimate a volume weighted average concentration. The variability of road condition on daily or weekly timescales is significant during times when abrasives are applied or immediately following effective sweeping efforts. Controlled measurements of the amount of FSP on the road surface conducted immediately prior to and following sweeping efforts using a regenerative air sweeper in Washoe County suggested a 42% immediate reduction in the FSP on the road surface (NTCD 2011). The number of days since sweeping and/or abrasive applications on a specific road segment prior to the observed FSP concentration by field personnel can have a significant influence on the results. However, the research team was not able to obtain a chronology of the practices by the responsible jurisdictions to better understand the maintenance context prior to each of our observations. The sequence of happenings matters, such that the number of days since abrasive applications, sweeping efforts, snow hauls, runoff events, etc. and relative amount of traffic will result in a potentially different road condition. The calculated volume weighted averages presented herein assume that the general condition has been captured by the series of observations spanning WY09-WY11 for each road segment. The total precipitation for each of the water years 2009-2011 were above average (see Chapter 4.1) suggesting the road conditions during these winter months in the study may have been relatively worse than other years due to the increased frequency and amount of abrasive applications and reduced opportunity for sweeping.

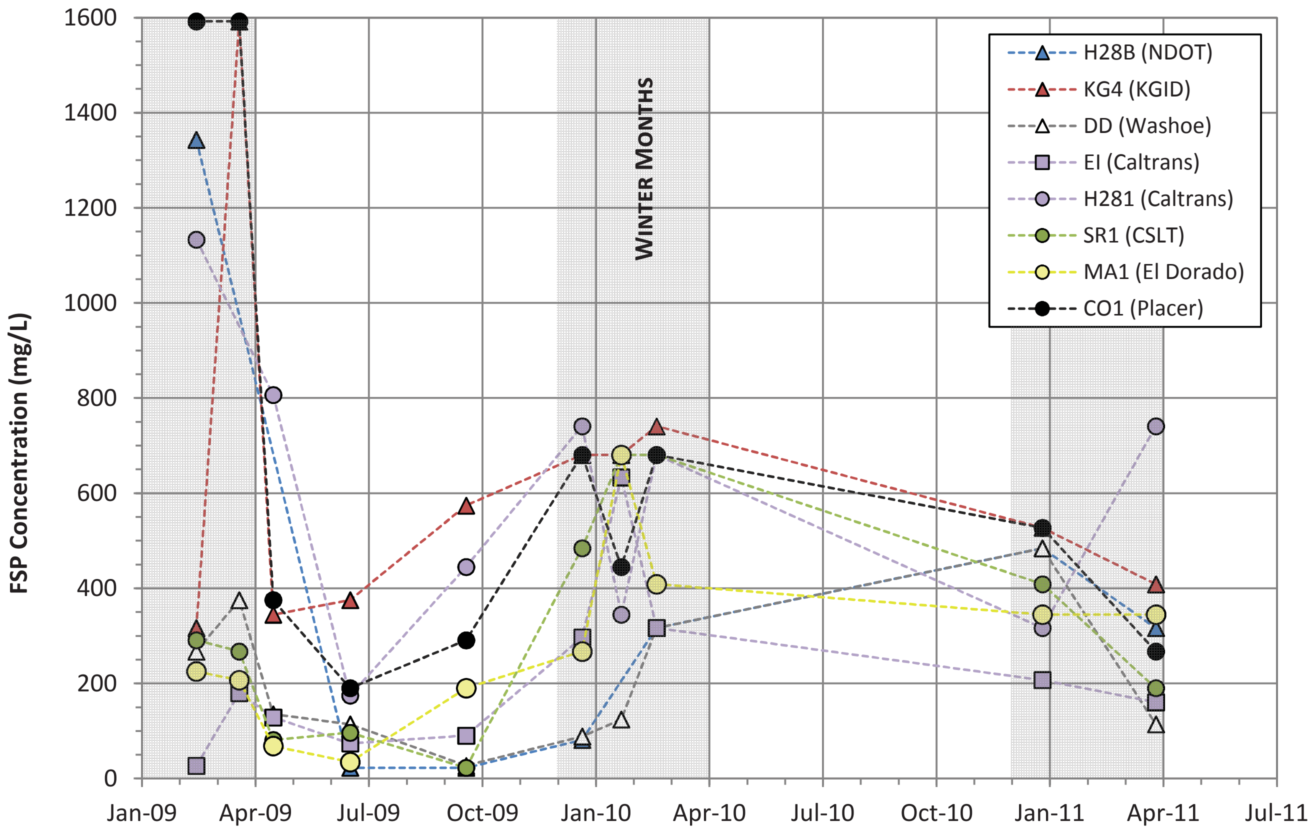
PLRM CRC PREDICTIONS COMPARED TO OBSERVED

PLRMv1 Road Methodology was used to predict the CRC for each road segment where seasonal observations had been made. We note that PLRM was not intended to predict the CRC for a specific road segment, but rather represent an average for a road risk type. A series of PLRM input assumptions were completed by the research team and compared to the calculated volume weighted average FSP concentrations. The analysis of each scenario yielded additional insight on how PLRM inputs drive expected road CRCs and how to best use PLRMv1 to compare predicted values to the calculated volume weighted FSP concentrations using the series of discrete observations. However, the obtainment of consistent observations over a range of water year types on roads maintained in a consistent manner (same road prescriptions across years) would greatly improve our ability to compare annual estimates of road FSP concentrations to PLRM CRC predictions.

PLRM SCENARIO A

Table 5.7 presents the PLRM inputs for each road segment grouped by jurisdiction. Road risk for each segment was determined using the March 2011 PLRM road risk layer, and road shoulder condition is representative of 2011 field observations. The abrasive strategy for all roads and all jurisdictions is set at minimal to remove the influence of one variable on the PLRM predictions. The sweeper type and sweeping frequency were informed by the

OBSERVED ROAD SEGMENT FSP CONCENTRATION TIME SERIES



Time series of observed road segment FSP concentrations for 8 road segments, representing each of the Tahoe Basin urban jurisdictions. For comparative purposes, road segments with the most frequent observations, greatest variability, and located in high traffic areas were selected for display. Caltrans site EI is also included because the March 2009 observation of 28 mg/L is the lowest observed winter FSP concentration at all sites from WY09-WY11 and according to Caltrans personnel (L. Waters pers. comm.) followed rigorous testing of a high efficiency sweeper at the South Y. Shading signifies winter season. Below the calculated volume weighted average road segment FSP concentration is provided for each site.

Site (Jurisdiction)	Calculated Average FSP Concentration (mg/L)
H28B (NDOT)	329
KG4 (KGID)	619
DD (Washoe)	184
EI (Caltrans)	182
H281 (Caltrans)	621
SR1 (CSLT)	270
MA1 (El Dorado)	253
CO1 (Placer)	638

Site	March 2011 Risk[1]	March 2011 Road Shoulder Condition[2]	Sweeper Type[3]	Sweeping Frequency[4]	PLRM FSP CRC (mg/L)	Calc [FSP] (mg/L)
Caltrans						
EB1	PLR/SHR	5	Broom	Often	208	288
EI	PHR	5	Vacuum	V. Frequent	348	182
H281	PHR	5	Broom	Frequent	472	621
H89S	PHR	1	Broom	Frequent	1010	417
SPP1	PLR/SHR	1	Broom	Frequent	472	445
CSLT						
BO1	SMR	1	Tandem	Often	204	309
EW1	SMR	1	Tandem	Often	204	198
KC3	PLR/SHR	4	Tandem	V. Frequent	229	270
SR1	PLR/SHR	5	Tandem	V. Frequent	200	270
El Dorado						
HM2	PLR/SHR	5	Regen	Frequent	194	252
HM3	SMR	5	Regen	Frequent	84	366
MA1	SMR	5	Regen	Frequent	84	253
KGID						
KG3	PLR/SHR	4	Broom	Rare	242	492
KG4	PLR/SHR	5	Broom	Rare	211	619
KG5	SLR	5	Broom	Rare	31	248
NDOT						
H28A	PMR	5	Vacuum	Frequent	235	113
H28B	PMR	5	Vacuum	Frequent	235	329
H28C	PHR	5	Vacuum	Frequent	376	364
KG1	PHR	5	Vacuum	Frequent	376	301
KG2	PHR	4	Vacuum	Frequent	432	390
Placer County						
BURL	SMR	4	Broom	Occasional	105	289
CO1	PLR/SHR	5	Broom	Often	208	638
JP	PLR/SHR	4	Broom	Often	239	382
KB1	PLR/SHR	5	Broom	Occasional	211	545
PINE	PLR/SHR	4	Broom	Often	239	304
TR1	SMR	5	Broom	Occasional	92	450
Washoe County						
DD	PLR/SHR	5	Vacuum	Occasional	189	184
JEN	SLR	5	Vacuum	Rare	29	172
KMAC	PLR/SHR	3	Vacuum	Occasional	268	232
VIL1	PMR	1	Vacuum	V. Frequent	491	171
VIL2	PMR	5	Vacuum	V. Frequent	217	247

[1] Combination of Type: P= primary road; S= secondary road and Risk: H= high risk; M= moderate risk; L= low risk
[2] Road Shoulder Condition: 1= erodible; 3= protected only; 4= stable only; 5= stable & protected
[3] Sweeper Type: Vacuum= High-efficiency vacuum-assisted (dustless); Regen= Regnerative air; Tandem= Tandem operation (mechanical broom + vacuum); Broom= Mechancical Broom
[4] Sweeping Frequency: Rare= 1-2 times summer only; Occasional= 1-2 times per season; Often= monthly winter & twice summer; Frequent= twice monthly winter & 2 times summer; V. Frequent= ASAP winter & monthly summer

COMPARISON OF **SCENARIO A** PLRM PREDICTED FSP CRCS TO CALCULATED VOLUME WEIGHTED AVERAGE FSP CONCENTRATIONS (WY09-WY11).

TABLE 5.7

jurisdiction's general road maintenance practice information provided (see Chapter 4.3), with site-specific adjustments based on the research team's observations throughout WY09-WY11.

Figures 5.10A-C presents the comparison between the calculated average FSP concentrations and the PLRM Scenario A predictions by jurisdiction, risk, and road shoulder condition, respectively. The solid line indicates agreement, below the line indicates PLRM CRC estimates are lower than the observed FSP concentration, and above the line indicates PLRM CRC values are higher. The dotted lines indicate a 20% difference, which is proposed as an aggressive target to judge the extent of deviations between observed and predicted values on a site-specific basis while recognizing the limitations in both estimates.

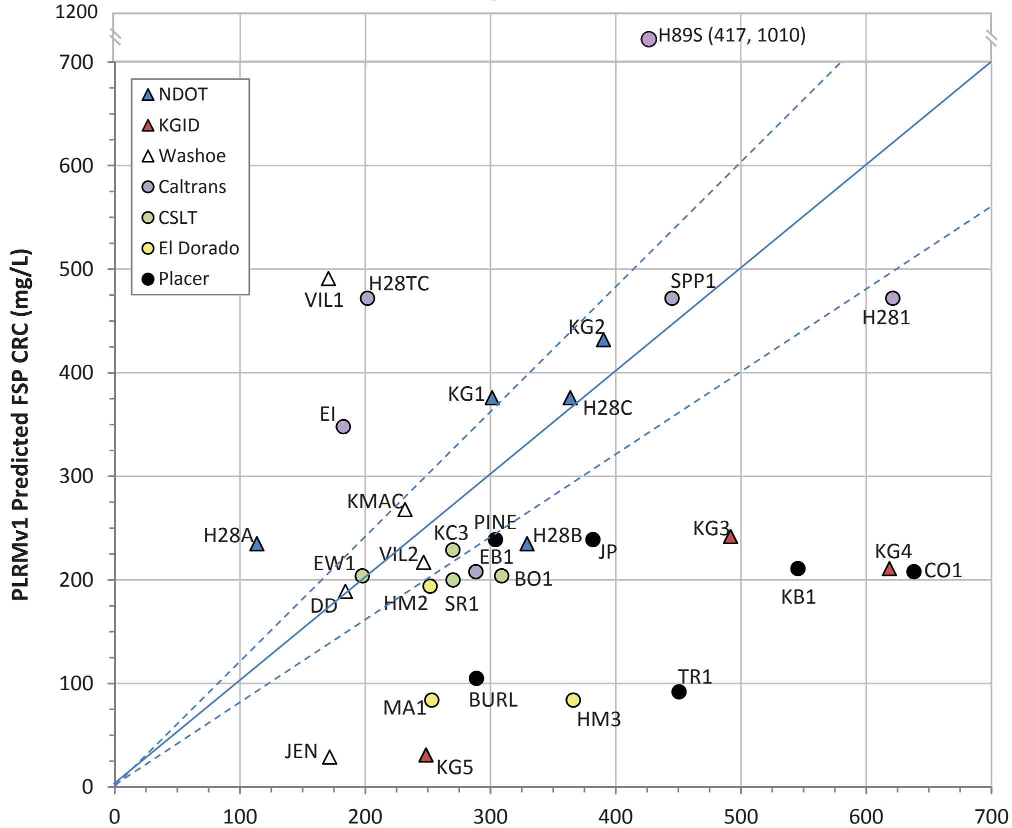
Of the 32 sites, 24 are outside of the 20% envelope. The most prevelant pattern of outliers is the frequent occurance of PLRM predictions lower than calculated FSP values for secondary road risk types (see Figure 5.10B), suggesting that secondary roads tend to accumulate more FSP than PLRM predicts. The secondary roads that fall below the line are frequently jurisdictions with relatively high annual abrasive application rates per road mile realtive to other jursidictions, namely Placer County and Kingbury Grade (see Figure 4. 3). For example, KG4 is a very steep residential road managed by KGID and is defined as a high risk secondary road. This road segment is heavily sanded but rarely swept, and measurements resulted in some of the highest discrete FSP concentrations during the study period (see photo at right). These findings led to a critical evaluation of the designation of road risk across jurisditions and PLRM Scenario B.

Road segment KG4 in April 2011. Note the significant accumulation of abrasives on the road surface and adjacent snow bank.

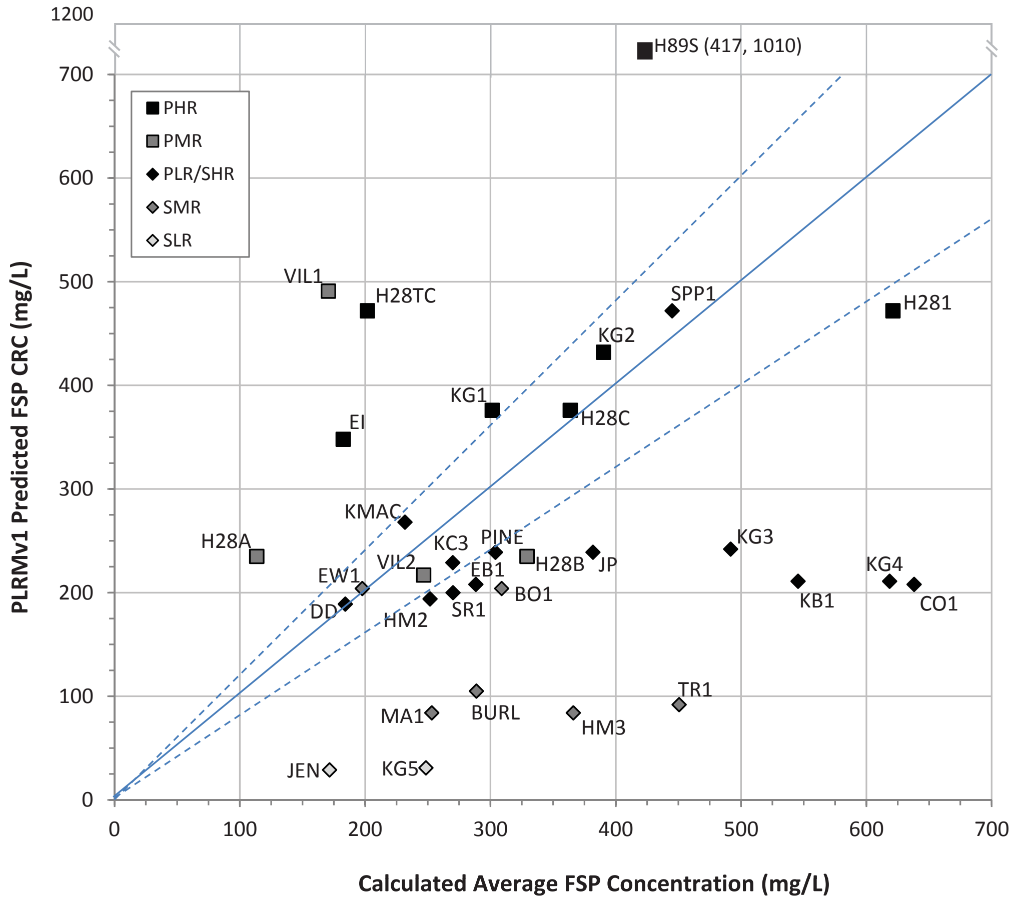
PLRM SCENARIO B

In PLRM Scenario B, we revise the March 2011 default road risk designations based on PLRM user guidance and our technical understanding of the road segment locations gained during this research. PLRMv1 categorizes roads based on road risk as a starting point of expected road condition based on the relative potential sources of pollutants (both abrasives applications and native road shoulder erosion). PLRMv1 essentially includes 5 different road risk types with incremental decreases in the initial CRC with a reduction in risk (PHR, PMR, PLR/SHR, SMR, and SLR). The expected road CRC is then further reduced in PLRM as result of source control and pollutant recovery actions conducted on the road segment. Through the application of PLRM and stormwater research (2NDNATURE and NHC 2010 and this research) it has been determined that across jurisdictions roads of the same risk type are not maintained using consistent techniques and a large deviation exists on the type, amount, frequency and spatial application of abrasives across jurisdictions in the Tahoe Basin (see Figure 4.4). PLRM user manual (NHC et al. 2009b) provides some guidance to critically assess the initial road risk designations included in PLRMv1 to improve the risk classification based on the jurisdiction's specific abrasive application procedures. We apply this guidance in PLRM Scenario B, along with our existing knowledge of the geographical context and observations of relative abrasive application by jurisdiction across sites. Additionally, we disregard the designation of primary or secondary road type. Rather, road risk was considered a continuum where the annual amount of abrasives applied relatively to all roads in the Tahoe Basin decreases incrementally from PHR to SLR. Based on information available and continued road segment observations over the 3 water years, the research team made assumptions for each jurisdiction based on the expected relative risk of their road networks and the specific roads included in the research. The exception to the jurisditional adjustments was the assignment of all sites located on the main arterial

(A) By jurisdiction in charge of road maintenance operations



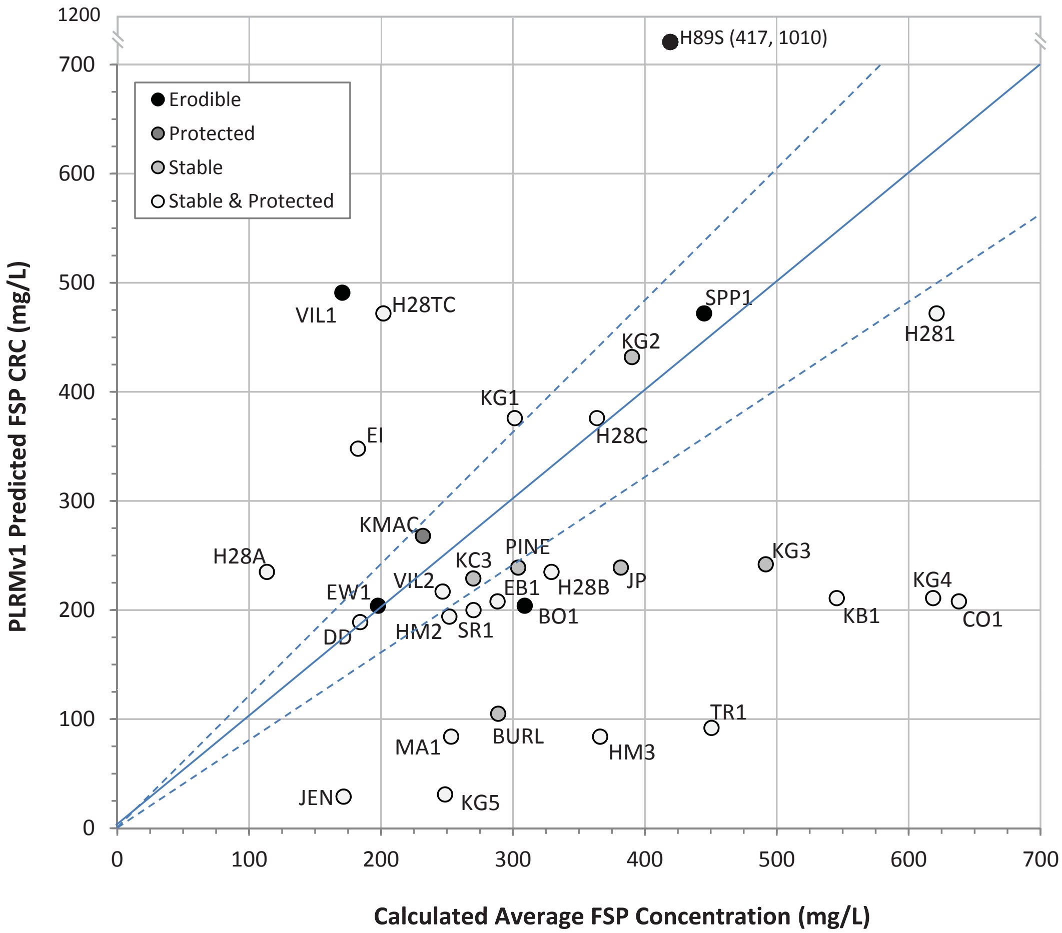
(B) By road risk



See Table 5.7 for PLRM inputs for Scenario A.

SCENARIO A

(C) By road shoulder condition



See Table 5.7 for PLRM inputs for Scenario A.

roads in the Basin (i.e., Highways 50, 89, 28, 207 and 267) as PHR regardless of jurisdiction as a result of the high amount of winter tourist traffic on these roads. Table 5.8 is organized by jurisidiction and includes the assumptions regarding juridisctional risk classifications. No other input modifications to PLRM are made from Scenario A. Figures 5.11A-C presents the comparison of the calculated volume weighted concentrations and PLRM Scenario B predictions by jurisdiction, risk and road shoulder condition, respectively. Of the 32 sites, 17 are outside of the 20% envelope, an improvement from Scenario A results.

PLRM SCENARIO C

The final adjustment to the PLRM inputs was the designation of all segments with stable and protected road shoulder condition. Scenario B (Figure 5.12A-C) shows no discernible trend with respect to road shoulder condition. This modification was tested because the controlled experiment data and Road RAM observations do not evaluate condition on pervious road shoulders so isolating PLRM predictions to just the impervious area may be a more robust comparison. No other changes were made to PLRM inputs in Scenario B (see Table 5.8) and the differences in the PLRM predictions in Scenario C are now limited to road risk type and pollutant recovery actions variations (see schematic on page 2.3). The removal of road shoulder condition reduced the predicted CRC for a number of segments and resulted in a slight improvement in agreement between predicted and calculated values (14 of 32 with a deviation > ± 20%). Scenario C exhibits a strong correlation between the predicted and calculated values (Kendall's tau of 0.5, significant above 99% confidence). In this case Kendall's tau, a ranked correlation coefficient, is used since the data show non-normal distributions (rather than Pearson's r which assumes normal distributions).

The comparisons between the PLRM predictions and calculated FSP concentrations are used to evaluate the relative effect of road characteristics on FSP concentrations.

ROAD SURFACE INTEGRITY

A number of road segments below the 1:1 line (higher calculated values than PLRMv1 predictions) are for roads with poor surface integrity. The research team has observed relatively elevated measured FSP concentrations on roads with high degree of cracking and pavement failure. HM3, BO1, and JP all have significant pavement cracking, and all three were observed to have a higher calculated average FSP concentration than predicted by PLRM (see Figure 5.12).

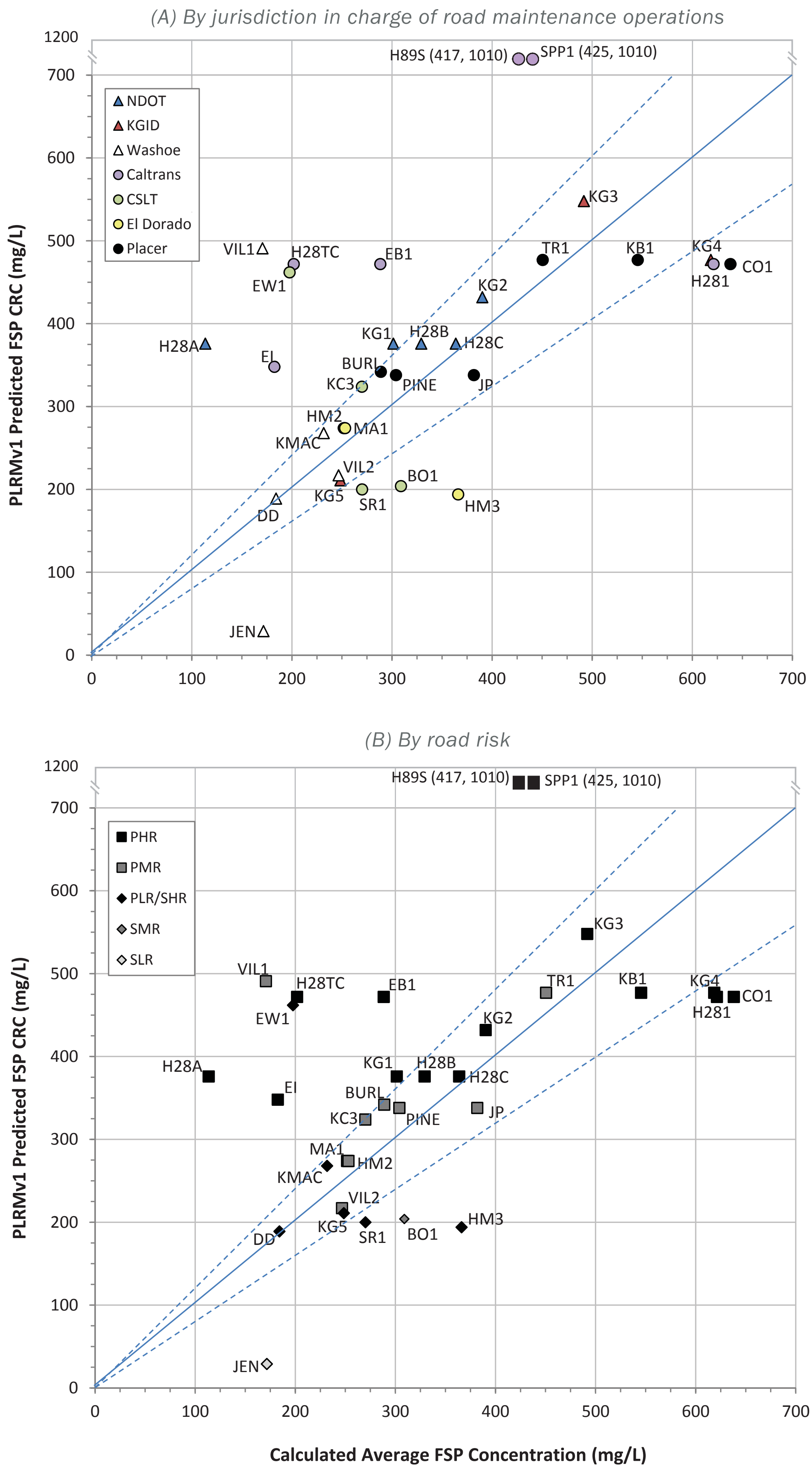
Road Segment HM3; Poor road surface integrity

Both discrete and average results suggest that maintaining road surface integrity can have a significant benefit to reducing the FSP generation of a road. Observations suggest poor road surface integrity may result in relatively elevated observed average FSP concentrations to: (1) decreased effectiveness of pollutant recovery actions as material cannot be effectively removed from the cracks using current sweeper technology, wind, traffic or any other mechanism besides wash off that transports FSP from the road surface to the shoulder; and (2) the elevated contribution of FSP locally from accelerated pavement degradation. Figure 5.13 presents the time series of observations from 3 of the road segments with poor integrity, illustrating the relatively elevated winter FSP concentrations (> 600 mg/L) for moderate to low risk roads, yet summer observations yield FSP concentrations <50 mg/L, suggesting road washoff during spring rains can effectively mine the cracks of stored material and transport pollutants downslope. Also included in Figure 5.13 is the time series data for site TR1, a poor integrity road that was repaved in Summer 2010, corresponding to a dramatic reduction in the subsequent winter observations in

Site	Adjusted Risk[1]	Sweeper Type	Sweeping Frequency	PLRM FSP CRC (mg/L)	Calc [FSP] (mg/L)	Points of Interest
Caltrans: Relatively high annual abrasive application and responsible for main arterial roads in Basin.						
EB1	PHR	Broom	Often	472	288	
EI	PHR	Vacuum	V. Frequent	348	182	One very low winter observation (28 mg/L) has significant influence on calculated FSP.
H281	PHR	Broom	Frequent	472	621	Main arterial road, PHR.
H28TC	PHR	Broom	Frequent	472	202	Main arterial road, PHR.
H89S	PHR	Broom	Frequent	1010	417	Main arterial road, PHR.
SPP1	PHR	Broom	Frequent	1010	445	
CSLT: Relatively moderate to low road abrasive application; No PHR roads						
BO1	SMR	Tandem	Often	204	309	Poor road surface integrity
EW1	PLR/SHR	Tandem	Often	462	198	Poor road surface integrity
KC3	PMR	Tandem	V. Frequent	324	270	Steep road.
SR1	PLR/SHR	Tandem	V. Frequent	200	270	High traffic density. Parking along road may affect sweeper's ability to sweep entire road width.
El Dorado: Relatively moderate to low road abrasive application; No PHR roads.						
HM2	PMR	Regen	Frequent	274	252	Located at intersection near school, high priority for abrasives.
HM3	PLR/SHR	Regen	Frequent	194	366	Poor road surface integrity.
MA1	PMR	Regen	Frequent	274	253	Located on dangerous curve, high priority for abrasives.
KGID: Relatively high annual abrasive application; High risk categories used						
KG3	PHR	Broom	Rare	548	492	Dangerous intersection.
KG4	PHR	Broom	Rare	477	619	Steep road.
KG5	PLR/SHR	Broom	Rare	211	248	
NDOT: Relatively moderate to low abrasive applications but responsible for arterial highways in Basin.						
H28A	PHR	Vacuum	Frequent	376	113	Main arterial road, PHR.
H28B	PHR	Vacuum	Frequent	376	329	Main arterial road, PHR. One very high concentration (>1,300mg/L) in LW/ES is influencing calculated FSP.
H28C	PHR	Vacuum	Frequent	376	364	Main arterial road, PHR.
KG1	PHR	Vacuum	Frequent	376	301	Main arterial road, PHR.
KG2	PHR	Vacuum	Frequent	432	390	Main arterial road, PHR.
Placer County: Relatively high annual abrasive application; High risk categories used.						
BURL	PMR	Broom	Occasional	342	289	
CO1	PHR	Broom	Often	472	638	
JP	PMR	Broom	Often	338	382	Poor road surface integrity.
KB1	PHR	Broom	Occasional	477	545	Steep road.
PINE	PMR	Broom	Often	338	304	
TR1	PMR	Broom	Occasional	477	450	Poor road surface integrity.
Washoe County: Relatively moderate to low abrasive applications; No PHR in jurisdiction						
DD	PLR/SHR	Vacuum	Occasional	189	184	Steep road.
JEN	SLR	Vacuum	Rare	29	172	
KMAC	PLR/SHR	Vacuum	Occasional	268	232	
VIL1	PMR	Vacuum	V. Frequent	491	171	High traffic density.
VIL2	PMR	Vacuum	V. Frequent	217	247	High traffic density.

See Table 5.7 for footnotes. Note, road shoulder condition is unchanged from Scenario A; see Table 5.7 for road shoulder conditions by site.

SCENARIO B



See Table 5.8 for PLRM inputs for Scenario B.

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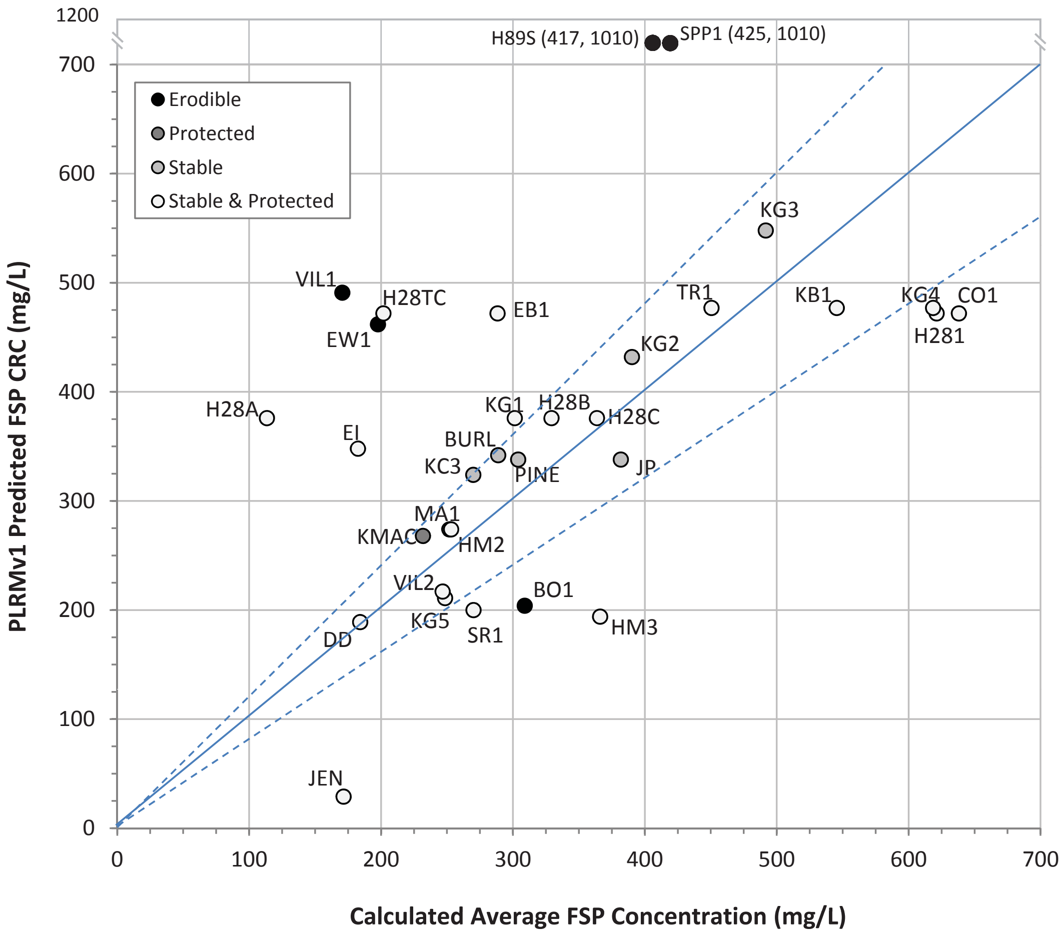
SCENARIO B: PLRM PREDICTED FSP CRCS TO CALCULATED VOLUME WEIGHTED AVERAGE FSP CONCENTRATIONS (WY09-WY11); PAGE 1 OF 2

FIGURE 5.11

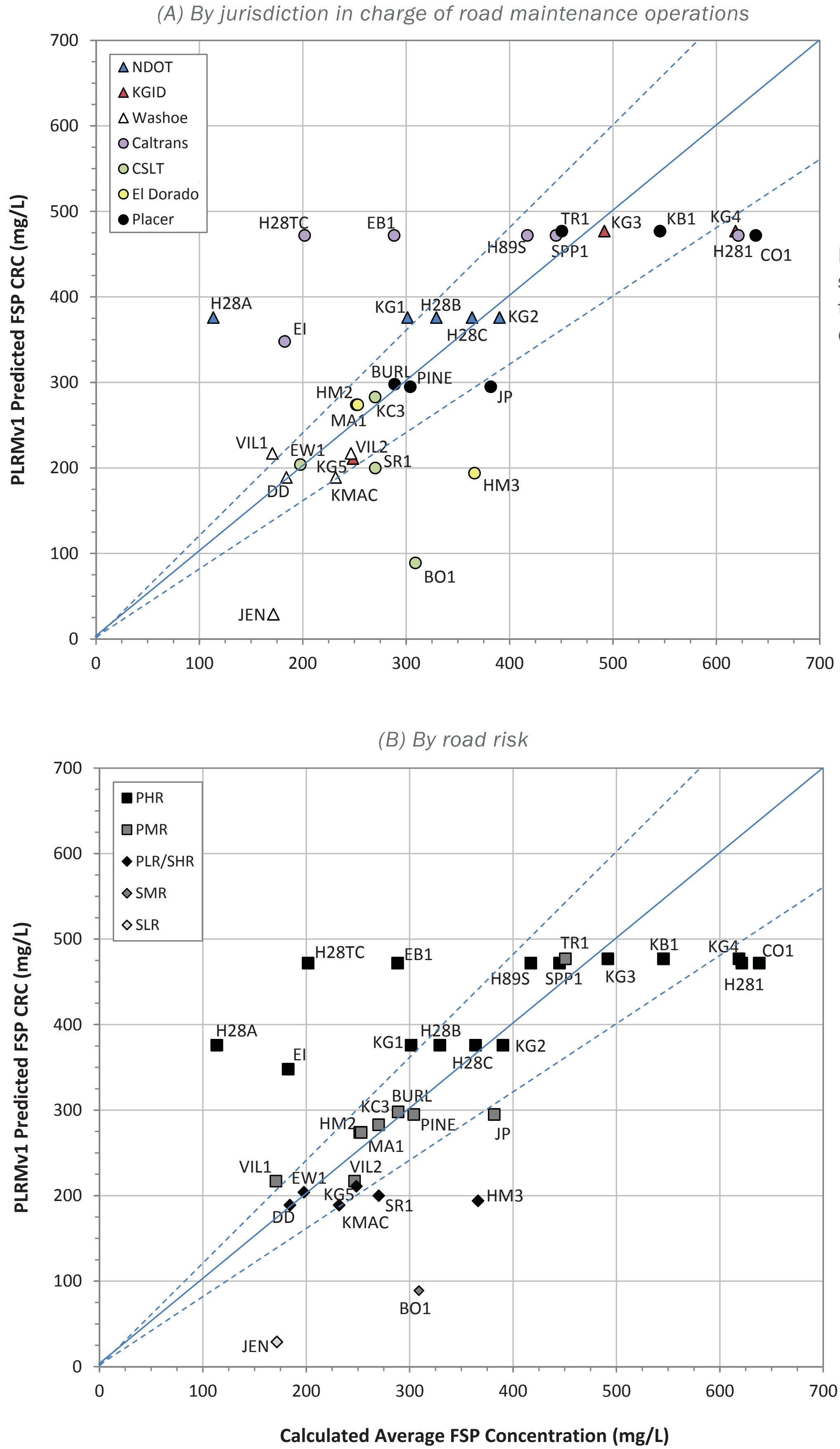
SCENARIO B

(C) By road shoulder condition



See Table 5.8 for PLRM inputs for Scenario B.

SCENARIO C

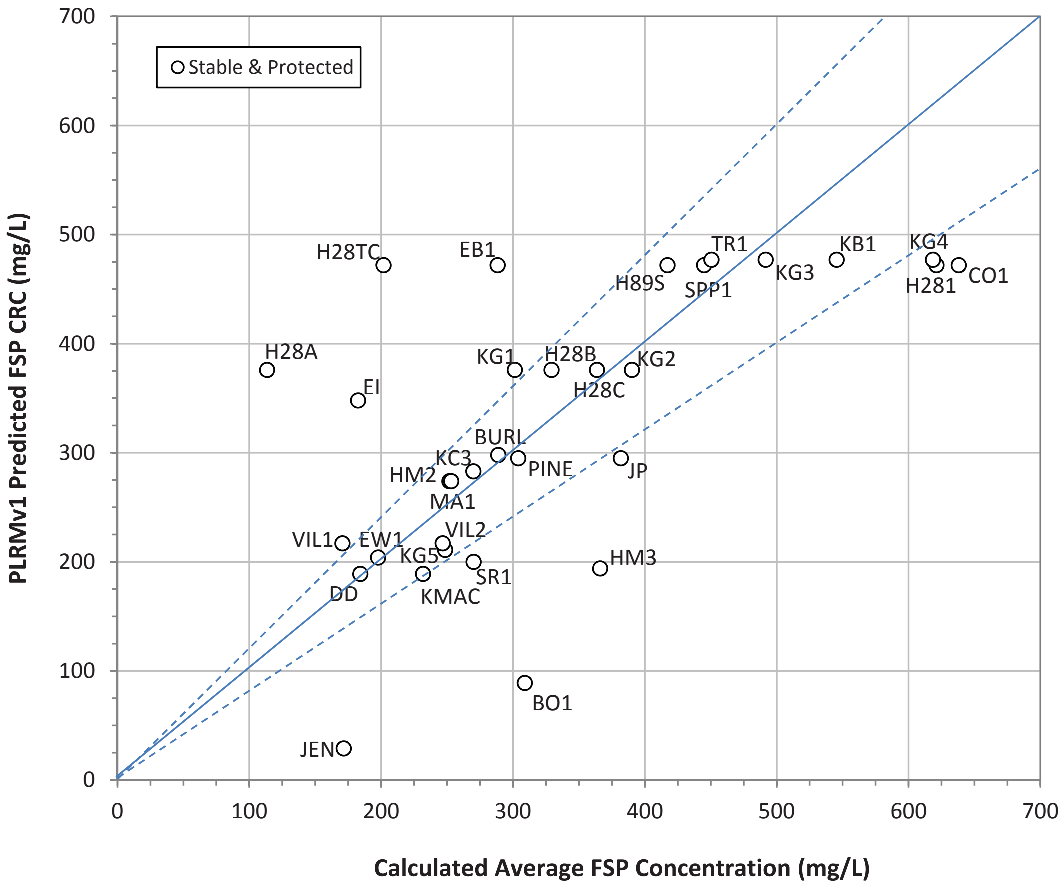


Kendall's tau = 0.51, suggesting a strong correlation, significant above 99% confidence.

PLRM inputs for Scenario C are the same as Scenario B, except all road shoulder conditions have been designated as stable and protected.

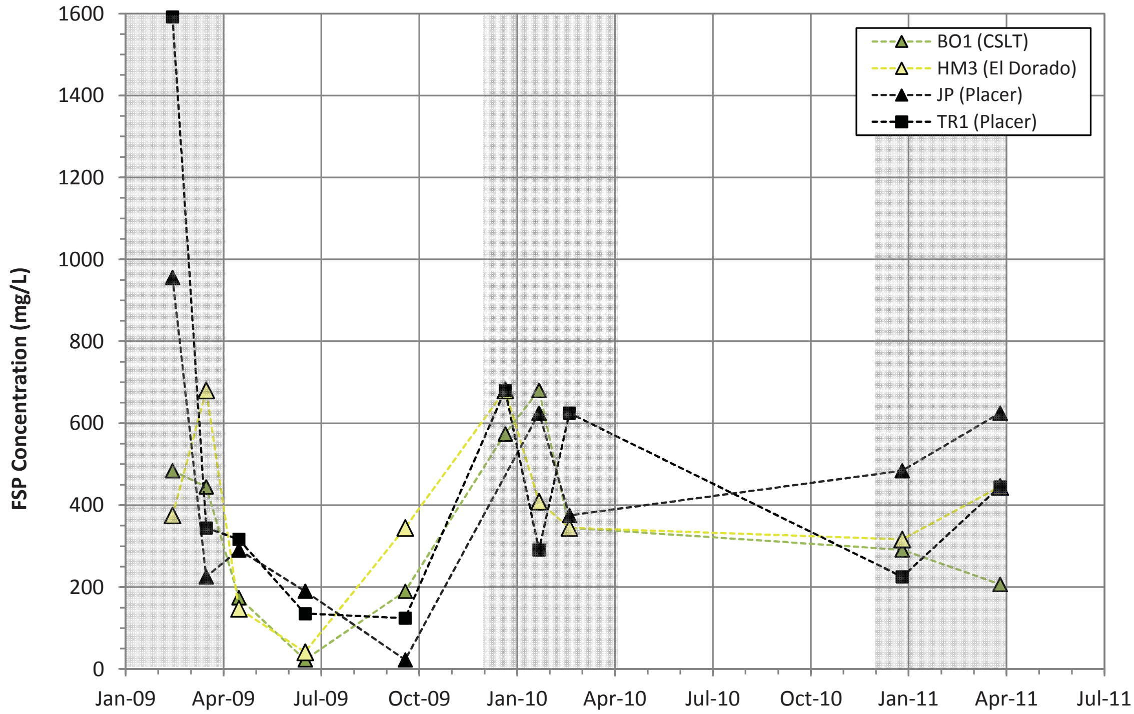
SCENARIO C

(C) By road shoulder condition



PLRM inputs for Scenario C are the same as Scenario B, except all road shoulder conditions have been designated as stable and protected.

OBSERVED ROAD SEGMENT FSP CONCENTRATION TIME SERIES AT SITES WITH POOR ROAD SURFACE INTEGRITY



Time series of observed road segment FSP concentrations for 3 road segments with poor road surface integrity, in addition to TR1, which was repaved in Summer 2010. Shading signifies winter season.

BO1

HM3

JP

TR1 March 2009

TR1 January 2011

WY11 (from an average of 700 mg/L in previous winters to 225 mg/L in January 2011). Road surface integrity is not a factor included in PLRM to estimate average annual road condition, but visual and measured FSP accumulation on these road segments suggests poor road surface integrity can increase the downslope water risk.

SWEEPING EFFECTIVENESS

One outlier that persists throughout all PLRM scenarios is site EI, a Caltrans PHR road segment located at the South Y where high abrasive applications and very high traffic density exist. During the winter observations in 2009, Caltrans was rigorously testing a high efficiency sweeper and multiple passes were observed at the site prior to the lowest winter road segment FSP concentration measurement to date (28 mg/L; see Figure 5.4). This data point, combined with observations in Washoe County of good road conditions, where sweeping practices are consistently more frequent with high efficiency vacuum assist or regenerative air sweepers compared to other jurisdiction in the Tahoe Basin, supports the hypothesis that increased sweeping frequency with vacuum assist sweepers on roads that require frequent abrasive applications to protect driver safety can be maintained in a relatively good condition. While the direct cause and effect dataset does not exist, these data illustrate that relatively low (< 50 mg/L) FSP concentrations on a PHR road are achievable in the winter and based on the seasonal runoff volume distribution, low winter FSP concentrations are expected to result in a relatively lower amount of FSP transported into downslope stormwater.

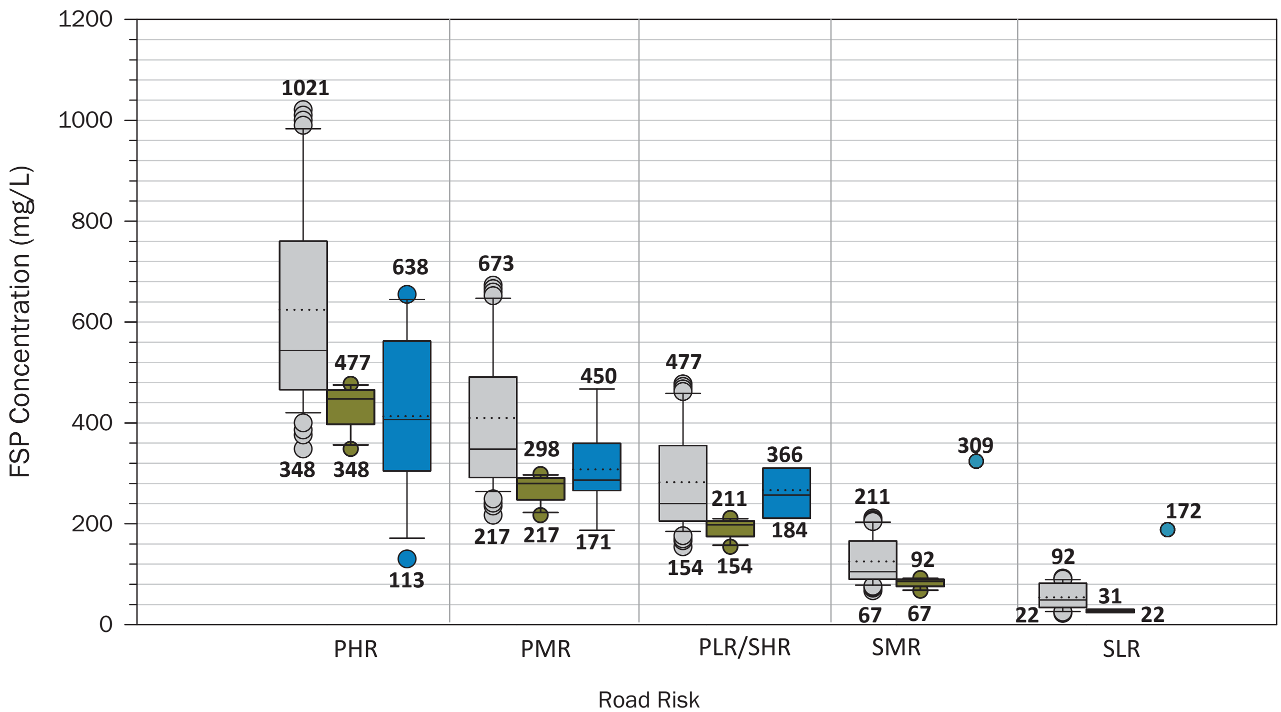
ROAD RISK AND ROAD SHOULDER CONDITION

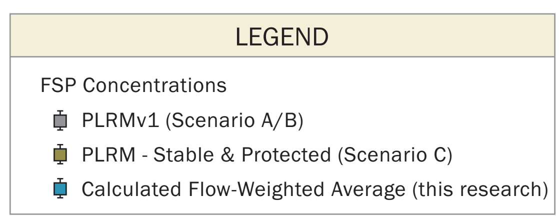
Scenarios B and C improve the agreement between PLRM and calculated FSP values; however, with the adjustments to road risk, only two sites are designated as either SMR or SLR road segments. The implications of this upward shift of all of the roads to relatively moderate to high road risk is that even roads in residential neighborhoods with relatively low traffic were observed to have higher FSP concentrations than PLRM algorithms originally assumed. The population of road segments for this research were selected to ensure a range of potential risk across the Tahoe Basin, but these data suggest that the current spatial distribution of relatively low risk roads is lower than originally expected.

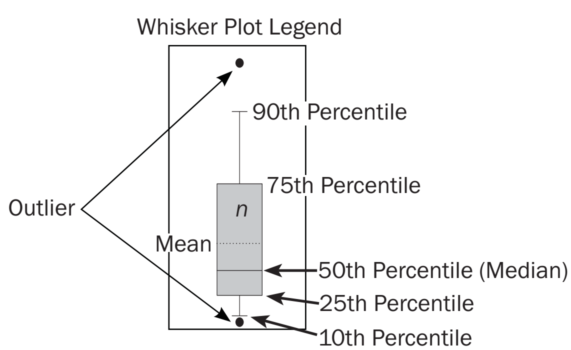
Given all of the limitations associated with the calculated volume weighted FSP value, we present a simple comparison of the potental PLRM FSP CRC range by road risk type for Scenario A, B and C and the observed FSP values. Figure 5.14 contains 3 box and whisker plots. The grey is the complete potential range of FSP CRCs used in Scenarios A and B. The green is the restricted range of potential FSP CRCs when the road shoulder condition is assumed to be stable and protected for all roads (Scenario C). The blue is the range of calculated FSP concentrations from the observed data. Figure 5.14 yields the following points:

- The PLRMv1 restriction that primary high risk (PHR) roads cannot have an FSP CRC lower than 348 mg/L is not representative of all observations. The calculated dataset indicates that primary high risk roads can potentially achieve average FSP concentrations approximately 65% lower than PLRMv1 currently allows and the mean calculated FSP concentration (396 mg/L) is below the 25th percentile of PLRMv1 CRCs for that risk category. Considering that WY09-W11 were relatively high snow winters (see Figure 4.4), the occurrence of some low discrete winter observations and volume-weighted FSP values below the PLRM minimum suggests that PLRM may need to accommodate even lower CRCs for high risk primary roads where more intensive source control and recovery actions are implemented.
- As discussed above and shown in Figure 5.12B, the WY09-WY11 volume weighted annual FSP concentrations for secondary moderate risk (SMR) and secondary low risk (SLR) roads are considerably higher than the current maximum FSP CRCs set by PLRMv1 for these road risk categories. This may

COMPARISON OF FSP CONCENTRATION RANGES







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- indicate that the PLRMv1 user guidelines for characterizing roads in the Tahoe Basin as secondary moderate risk and secondary low risk roads may need to be reevaluated and potentially adjusted.
- The impact of changes in road shoulder condition on the potential range of FSP CRCs for each risk type in PLRMv1 can be significant. Figure 5.14 shows how the ranges of FSP CRCs by road risk category are narrowed for stable and protected roads, significantly decreasing the maximum FSP CRC. The calculated FSP concentration ranges by risk category indicate a greater observed range than what is currently possible if PLRM predictions are restricted to only stable and protected values. While the data collection did not adequately address the contribution of material eroded from pervious road shoulders, this comparison illustrates the difficulty with adequately attributing incremental FSP CRC reductions to specific actions when our observations of road condition evaluate the integrated cumulative signal of many interrelated actions.

5.1.2 ROADWAY RESEARCH FINDINGS

1. This research (see Figure 5.2) supports other Tahoe Basin studies (Kayhanian et al. 2005; 2NDNATURE and NHC 2010a; Heyvaert et al. 2010; El Dorado County, R. Wigart pers. comm.) that suggest field turbidity may be a cost-effective and reliable proxy for FSP concentrations measured in stormwater and streams. Due to the relatively high FSP concentrations observed on roads, the development of consistent methods to obtain and translate field turbidity to FSP concentrations should be a future management priority to reduce monitoring costs while increasing the availability of data.
2. The average pollutant concentrations obtained from roadway sampling were 451 mg/L, 783 and 0.04 for FSP, TSS and SRP respectively. These concentrations can be compared to average samples collected in stormwater runoff from mixed land use catchments of 120 mg/L, 350, and 0.06 respectively (2NDNATURE 2006b, Gunter 2005, and data from this research in Chapter 6*)*. This comparison suggests that the average FSP and TSS concentrations from roads are significantly higher than the average mixed land use signal. In contrast, the average SRP concentration is slightly lower suggesting that roads may not be a primary source of SRP to catchment pollutant loads.
3. Research findings confirm both the range and shape of the road CRC values used in the PLRM v1 database (see Figure 2.1) are consistent with the calculated observed values. While discrete measurements using the portable simulator are not directly comparable to the PLRM CRC values given spatial and temporal differences, the range of measured values can provide insight into the general shape and maximum and minimum values used in PLRMv1. The measured FSP, TSS and SRP values (see Figure 5.1) show a similar distribution to the values used in PLRM (see Figure 2.1) demonstrating an exponential decay in concentrations as road condition improves, and the measured maximum and minimum values indicate that the PLRM minimum CRC values are achievable and the maximum CRC values are within reason when compared to discrete observations (see Table 5.5).
4. Roadway condition (as measured by the concentration of FSP obtained from the portable simulator and/or Road RAM) has a significant seasonal variability with the poorest road conditions consistently observed during winter months (see Figure 5.3). Given that the observed roadway conditions consistently improve at all road segments through the summer and fall, all available information suggests road condition is most sensitive and controllable from winter road maintenance practices (see Figure 5.4).
5. Road condition was periodically evaluated at 32 sites from the winter 2009 through summer 2011. The winter snowfall totals increased each of these years, yet the datasets identifying the total amount of road abrasives applied as reported by the jurisdictions (see Figure 4.4) and road condition both suggest a trend of

decreasing application of road abrasives and improved winter road condition for water quality (see Figures 5.9 and 5.13). The increased focus on roads as the primary source of FSP generation in the Tahoe Basin appears to have had a positive influence on road maintenance practices conducted for water quality protection. The co-occurrence of reduced abrasive application volumes and improved road conditions over the course of this research provide another piece of evidence to suggest road maintenance practices have a significant influence on winter road conditions.

6. PLRMv1 bounds anticipated runoff quality and achievable runoff quality through improvements in road conditions based on the concept of road risk, which in PLRMv1 allows a user to select from six different categories of road risk. Comparison of the volume weighted average FSP concentrations from this study indicates that the PLRMv1 guidelines for defining and categorizing road risk may be insufficient to reasonably capture differences in operational practices across jurisdictions in the Tahoe Basin. In order to better estimate road runoff quality across jurisdictions in the Tahoe Basin: 1) the concept of road risk would need to be modified to account for differences in operational practices across jurisdictions, or 2) jurisdictions would need to agree upon a standard set of operational practices that would be performed for specific types of roads and physiographic characteristics.

7. Comparisons of predicted and calculated FSP concentration ranges (see Figure 5.14) suggest that frequent street sweeping can provide greater FSP CRC reductions than currently allowed in PLRM. For example, the lowest calculated FSP concentrations were actually on high and moderate risk roads where high abrasive applications were coupled with frequent sweeping with high efficiency sweepers. Given the recent findings that improved road condition is a cost-effective pollutant load reduction strategy for Tahoe jurisdictions (2NDNATURE and NHC 2011B), additional research that is capable of defensibly testing and quantifying the cause and effect linkages between road maintenance prescriptions, subsequent road condition and associated stormwater FSP loads would be extremely beneficial for the Tahoe Basin.

8. Road surface integrity is not a factor included in PLRM v1, but there is anecdotal evidence that suggests poor road surface integrity can increase the downslope water quality risk. Moderate to low risk roads have relatively elevated winter FSP concentrations (>600 mg/L) due to material storage in pavement cracks, yet summer observations are <50 mg/L, suggesting road washoff during spring rains can effectively mine the cracks of stored material and transport pollutants downslope (see Figure 5.13). Pavement conditions are known to significantly affect the pickup performance of street cleaners (Sartor and Boyd 1972). Street sweepers have considerable difficulty effectively picking up particulate material from streets whose pavements are classified as poor, because lots of surface cracks and deep depressions allow material to accumulate where it cannot be recovered effectively by sweepers. The uneven surfaces that accompany poor pavement conditions make it difficult for the sweepers to operate effectively, especially the newer air machines that require a seal contact with the pavement. In order to realize the benefits of better sweeper pickup performance, proper pavement maintenance activities are needed to maintain a minimum pavement condition. In addition, all cracks should be sealed on a regular and ongoing basis. Future research is required to quantify the effect of road surface integrity on road FSP concentrations with perhaps particular attention to how road integrity influences the effectiveness of maintenance practices. Road surface integrity should be incorporated into future PLRM estimations of the effectiveness of sweeping.

9. The minimum and 25% percentile value of all calculated volume weighted FSP values were 113 and 243 mg/L, respectively. These data indicate that improved road conditions within the Tahoe Basin are achievable with improved water quality maintenance techniques. Spatial prioritization of roads with the greatest hydrologic connectivity to Lake Tahoe could be a useful exercise to identify road segments where improved road maintenance would provide the greatest FSP load reduction benefit.

10. Observations suggest that even roads where abrasives are not frequently applied can accumulate FSP as a result of tracking, road surface degradation or other mechanisms and thus continued observations of road condition and responsive recovery mechanisms when necessary are essential.

5.1.3 PLRM ROAD METHODOLOGY RECOMMENDATIONS

Future modifications to PLRM Road Methodology should consider the findings in the above section. Recognizing that there is currently no timeline set for completing improvements to PLRM, recommendations are separated below into: 1) upgrades to user manual guidance for PLRM v1; and 2) potential approaches for long-term improvements.

PLRM V1 USER MANUAL UPGRADES

The WY2009-WY2011 road condition research results presented within this report suggest that the current guidance provided in the PLRM user manual to determine road risk categories within a Tahoe Basin urban catchment may be too confining. Currently, the user begins with the default values for road risk provided in a GIS shapefile associated with the PLRM software, which is based on primary and secondary roads as designated by the Lake Tahoe TMDL land use layer. Current PLRM guidance does provide a list of potential factors that may justify adjustments to the default layer (e.g., bus routes, busy intersections, main access routes to ski resorts, etc.); however, there is no clearly defined mechanism for evaluating differences across road locations. This lack of explicit guidance can result in subjective designations that are not consistent across Tahoe Basin urban jurisdictions.

In the near term, pending resources to integrate the technical improvements recommended below, an upgraded PLRMv1 user manual could help to resolve existing confusion by users and increase the tool usability. However, while this research has identified additional factors which users should consider while designating road risk (provided below), no specific upgrades to the user manual are provided at this time. Prior to providing such guidance, frequent PLRM users should be included in a PLRM user workshop to elicit input on which sections of the current user manual lack clarity and to gain feedback on any suggested upgrades. Without such input, there is the danger that the supplemental PLRM guidance may not decrease the subjectivity of the user inputs and/or may result in a process that is overly burdensome for the user. In the meantime, in addition to the factors provided on pages 54-55 of the current PLRM User Manual (NHC et al. 2009B), this research identifies the following items which should be considered as the user evaluates road risk within their jurisdiction:

- Road risk categories should be considered a continuum ranging from most frequent abrasive applications (PHR) to no abrasive applications (SLR), and users should not be constrained by the TMDL land use designations of primary and secondary roads. Based on the monitoring results of this research, it is possible for smaller local roads in the Tahoe Basin, which are categorized in the default PLRM road risk layer as secondary roads, to exhibit very high FSP concentrations that will require the road to be assigned the classification of a primary road in PLRM.
- Jurisdictions should consider the total average annual abrasives applied per lane mile in their jurisdiction compared to the Tahoe Basin average (see Figure 4.3). Jurisdictions who apply significantly more abrasives than the Tahoe Basin average will likely have roads at the higher end of the risk continuum.
- Roads with minimal to no parking pressure on the road shoulder will likely be a lower risk than roads where parking pressure is higher. Note this criterion is different that the road shoulder condition, as it

looks at the density of cars parked on the road shoulder and not whether or not they are able to park there.

- Arterial neighborhood roads are likely to be in higher risk than neighborhood roads with fewer access points, due to higher local traffic and increased abrasive tracking from nearby high risk roads.
- In general, roads in closer proximity to higher risk roads will likely have an increased risk due to abrasive tracking.
- Significant shade on the road surface, particularly if the shade is present for a majority of the day, will likely increase abrasive application and therefore increase risk.

POTENTIAL APPROACHES FOR LONG-TERM IMPROVEMENTS

Funding for PLRM technical updates and improvements has been secured through a SNPLMA Round 12 research grant for 'Stormwater Tools Improvement Project' and an interagency agreement is currently being negotiated between the Bureau of Land Management and Environmental Protection Agency. Based on the lessons learned from this research, there are two potential approaches to the future structure of the PLRM Road Methodology: 1) allowing a user to define an expected condition of road and thus the expected CRC, which would be verified through subsequent assessments (e.g., Road RAM); or 2) improving the existing approach, which incrementally lowers the CRC for a specific type of road based on a set of user-defined actions. Based upon the structure and advantages and disadvantages of each approach described below, the user defined CRC approach is the preferred recommendation of the research team and technical advisory committee.

ROAD METHODOLOGY APPROACH #1 – USER DEFINED CRC (I.E., ROAD CONDITION)

While a number of limitations associated with the ability to use a series of spatially and temporally discrete observations exist and have been outlined above, there is an opportunity to utilize the available road specific condition assessment tools (i.e., portable simulator and Road RAM) to guide PLRM users to define their own pre- and post-project road condition and associated CRC. Below is the general approach to a user defined road condition.

- Jurisdictions would group roads by the road maintenance practices conducted on a specific network of roads using classification guidance in the Road RAM User Manual as a starting point (see STEP 3 of 2NDNATURE et al 2010). Based on this research, the inclusion of road surface integrity and/or pavement management actions may be considered as a component of road class. Jurisdictions would be required to have very detailed descriptions of the practices conducted that define each class.
- The PLRM user would assign each road class with an FSP CRC depending upon existing or future practices. The research herein would be used as an initial guide to recommend a range of acceptable CRCs for each jurisdiction based on WY09-WY12 practices.
- In the future, the jurisdictions would implement road condition assessment efforts to obtain a series of spatial and temporal observations on specific road classes (characterized by different road maintenance prescriptions) to calculate the flow weighted average FSP concentrations. By applying a number of the techniques developed and implemented under this research effort, jurisdictions could simultaneously test the effectiveness of innovative road maintenance practices implemented on a subset of roads and quantify the expected improved prescription FSP CRCs to inform PLRM inputs. As new road maintenance prescriptions are identified and implemented, this flexible approach allows the incorporation of these

practices directly into PLRM estimates if the appropriate effectiveness assessment has been performed. Sharing of the quantified FSP CRCs by jurisdictions implementing similar prescriptions or interested in similar improvements would be encouraged.

- Road shoulder condition as it relates to road shoulder erosion and/or the stormwater entrainment of FSP on the pervious road shoulder is not adequately addressed by the current field evaluation techniques, and the developers would need to identify a solution to ensure this is still incorporated. The approach to isolating the contribution/influence of road shoulder condition on the road class CRCs presented above would certainly be considered.
- The experimental design and guideline details to provide the jurisdictions with a standardized approach to assessment, data analysis and CRC determination from the data obtained would need to be developed and documented.

The main benefits of a condition based approach to the PLRM Road Methodology are the alignment between model inputs and observations that can be verified in the field, and the elimination of the need for PLRM developers to estimate the incremental benefit of individual actions on the long-term average road condition. The Crediting Program requires jurisdictions to conduct and submit annual verification reports to justify annual credit awards based on their commitments during catchment registration. The current recommended method for verification of road condition is the use of Road RAM or equivalent, thus providing a direct programmatic link between the estimation tool (PLRM), the condition verification tool (Road RAM) and the award of annual credits when these two conditions align. The downsides include the lack of current guidance on how a jurisdiction should determine the appropriate CRC for current and future road practices and the need of future road monitoring to inform and verify the model inputs. In addition, this approach does require more on the ground observations and time spent evaluating road conditions. However, given the cost-effective opportunity for jurisdictions to achieve long-term FSP load reductions as a result of road condition improvements (2NDNATURE and NHC 2011B), continued focus on the water quality effectiveness of road maintenance prescriptions in the Tahoe Basin is likely.

ROAD METHODOLOGY APPROACH #2 – IMPROVE ACTION-BASED CRC ESTIMATIONS

PLRMv1 adjusts CRCs from road land uses based on a set of user-defined actions, which reduce CRCs in the model assuming that user-defined actions improve water quality by either reducing the pollutant sources or increasing the sinks. Based on the research herein, the following modifications would be explored to better align PLRM Road Methodology with factors observed to influence the FSP CRCs.

- The current PLRM Road Methodology merges estimated rates of road abrasive applications and road shoulder erosion into one algorithm to calculate a pollutant potential score in PLRM, which is then translated into a CRC for each pollutant modeled. The current algorithm is challenging to validate because it blends different mechanisms of pollutant generation into one prediction of runoff quality (pollutant build-up and wash-off on the road surface is combined with road shoulder erosion). To improve future PLRM validation efforts the current algorithm could be revised to separately define actions and estimate pollutant generation from the road surface relative to pollutant generation from the road shoulder.
- Based on this research, the current PLRM algorithms may be under-predicting the observed variability of FSP generation based on the condition of the road surface and over-predicting FSP variability from the condition of the road shoulder (see Figure 5.14). Some of the observed variability in FSP generation is due to differences in operational practices among Tahoe jurisdictions, and this variability should be addressed by developing standardized and well-defined approaches to winter road operations (see next bullet). If

road shoulder condition contributions to pollutant loads are isolated in a future version of PLRM, the challenge of quantifying the contribution and ability to recover pollutants from pervious shoulders will remain. The findings and limitations regarding road shoulder condition should be critically assessed when revising the PLRM Road Methodology.

- The road risk approach could be refined or replaced by a more quantifiable classification system defining standards for road maintenance practices. Under this approach, each Tahoe urban jurisdiction would develop a road operations plan that defines specific maintenance practices and seasonal road operations to be performed for each class of roads in their jurisdiction, which would then be linked to the revised classification system. The classification system would estimate the pollutant potential from a road surface based on defined metrics such as abrasive application rates, abrasive types, and potentially other metrics.
- The ultimate effectiveness of FSP recovery from street sweeping and the resulting improvement to an FSP CRC in PLRM is a highly debated topic. Nevertheless, the effectiveness of street sweeping in PLRM algorithms should be revaluated to consider the following factors:
    - Effect of road surface integrity on sweeping effectiveness estimates.
    - Effect of road shoulder condition on sweeping effectiveness estimates.
    - Ability of sweepers other than "high-efficiency" sweepers to recover a greater fraction of FSP on the road surface relative to what PLRM currently predicts. For example, PLRM provides a very minor credit for the use of mechanical broom sweepers for FSP recovery. However, mechanical broom sweepers can operate more efficiently in adverse weather conditions and can potentially recover coarse road abrasives prior to pulverization by vehicle traffic.
    - Maximum recovery credit the PLRM currently allows for "high-efficiency" street sweepers. This recommendation is based on observations during this research. The lowest observed winter FSP concentration was measured at the high risk Caltrans site EI in March 2009, when Caltrans was testing the use of a high efficiency sweeper (see Figure 5.9).

The main advantages of continuing with an action-based approach to the PLRM Road Methodology are 1) user familiarity with the current approach; 2) ease of model use as model inputs can be readily defined with some certainty; and 3) a manageable system to link and track PLRM modeling assumptions with actual road maintenance practices. Furthermore, the action-based approach reinforces to PLRM users the concept that incremental water quality benefits can be realized with specific operational changes to road maintenance practices. The action-based approach presents a significant model calibration and validation challenge as it is extremely difficult to isolate and quantify through monitoring, with reasonable accuracy, the incremental CRC reduction associated with a specific action. The comparisons in this report of calculated volume weighted average runoff concentrations from observed data and PLRM CRCs illustrate the difficulty in adequately attributing incremental FSP CRC reductions to specific actions, because observations of road condition evaluate the cumulative water quality signal of many interrelated actions. Furthermore, the action-based approach is based on the premise that a defined action will improve the condition of a road by some defined degree, which in turn improves the runoff quality predicted by the PLRM. As discussed below, the ultimate effect on water quality is based on the condition of a road and not the actions that might degrade or improve the condition. Consequently, through the action-based approach PLRM will continue to infer expected road conditions, which may not be reflective of actual road conditions when actions performed are more or less efficient at improving road condition relative to a PLRM prediction.

5.2 PRIVATE PARCEL CRCS

5.2.1 PRIVATE PARCEL RESULTS

The primary focus of the private parcel CRC research was to test a variety of sampling techniques to identify viable methods for collecting data that would be consistent with and comparable to the water quality data described in Chapter 5.1. The 2NDNATURE team tested several different sampling techniques, and a discussion of their effectiveness is discussed below.

IMPERVIOUS SURFACES

Two of the 34 road segment sites selected for the controlled experiments and Road RAM observations were located in commercial parking lots, likely the worst case scenario for pollutant generation on private parcels. Table 5.9 provides the observation period and calculated average annual FSP concentration results for these two sites, located in Raley's parking lots in South Lake Tahoe (RSLT) and Incline Village (RIV). Similar to the road water quality results, the 2 commercial parking lots show seasonal trends, with the highest concentrations recorded in the winter months, and lowest concentrations recorded in the summer and fall.

Table 5.9. Commercial parking lot concentrations observed during WY09-WY11 roadway monitoring. Values presented include the observed FSP concentrations by observation period, the average annual concentration based on the seasonal weighting presented in Table 5.6, and the PLRM predicted FSP CRC for CICU impervious surfaces both in existing and improved conditions.

CICU Imp	April 2009	May 2009	July 2009	Oct 2009	Jan 2010	Feb 2010	Mar 2010	Jan 2011	Mar 2011	Ave Annual	PLRM Predicted CRCs	
											Existing	Improved
RIV	147	88.5	105	22.7	574	1040	878	878	680	**417**	187	129
RSLT	57.8	24.7	22.7	22.7	956	291	345	445	317	**218**		

Table 5.9 also presents the comparison of the PLRM predicted FSP CRC values for CICU impervious surfaces to the calculated average annual FSP concentration. While the data is limited, it does suggest that commercial parking lots have the potential to generate relatively high FSP concentrations. It is assumed that parking lots and driveways posses the highest potential FSP loading surface type within commercial or residential land uses. The CICU CRCs used in PLRM are expected to be commercial land use average that would include the contribution of relatively lower FSP generating surface types such as roofs and sidewalks, thus making the PLRM predicted CRCs in Table 5.9 reasonable. Similarly, source control efforts on private parcels should prioritize surfaces where cars transport and deposit FSP potentially accumulated elsewhere.

PERVIOUS SURFACES

The following provides a brief discussion of the pervious monitoring techniques tested during this research, including the pros, cons, and preliminary results when appropriate.

CONTROLLED EXPERIMENTS

The portable sampler was initially tested on pervious surfaces, in the hopes that the sampling methods could be standardize to reduce sampling variability and improve comparisons across land use types. However, as described in Chapter 3.1.3, there were several issues which resulted in our inability to control the volume applied and to capture a standardized amount runoff from the portable simulator on pervious surfaces. Therefore a few other techniques were tested and are explained below.

PARTICLE GRAIN SIZE ANALYSIS

The collection of dry material from a 1 ft^2 area of exposed soil on a private parcel was tested because the technique could be done rapidly, allowing the collection of a large number of samples from a range of locations in a short amount of time. The sampling area can be standardized across all sites, and equivalent to the sampling area used for the controlled experiments on impervious surfaces. However, there were the following disadvantages that resulted in the data being inappropriate for comparisons to PLRM private parcel CRC values:

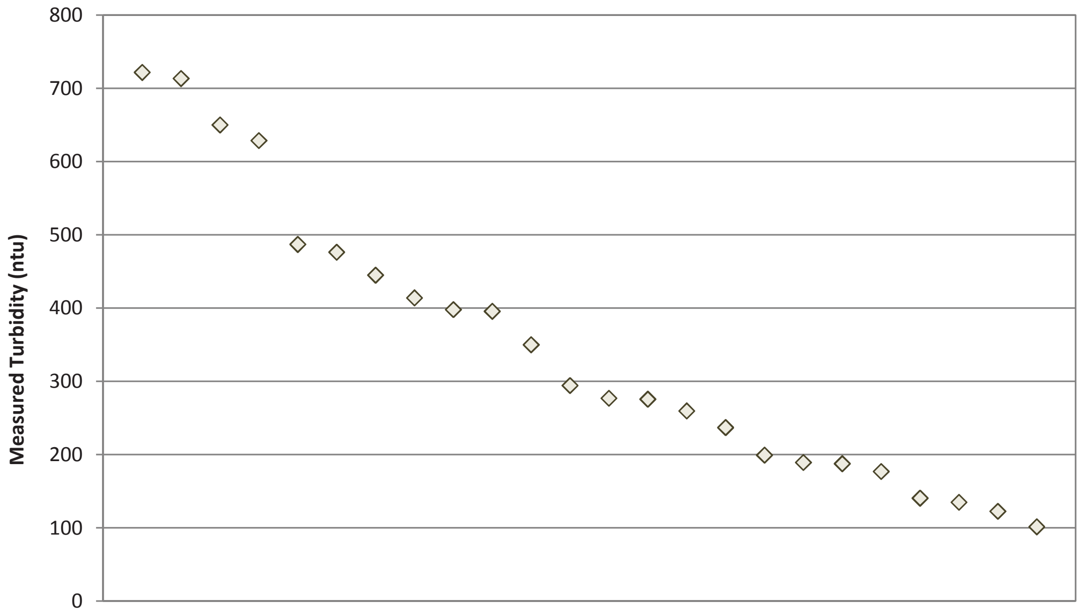
1. Particle grain size distribution is strongly dependent upon the fraction of coarse material present in the sample. All samples were sieved through a 2 mm mesh to standardize the volume and reduce the variability of the grain size distribution of the material submitted to the laboratory. However, the differences in the % of the sample < 16 μm covered a range of less than 15% making our confidence that we could detect differences across sites beyond our sampling error questionable.
2. The submission of the samples to the laboratory for analysis reduces the cost-effectiveness of the sampling technique, and the research team was unable to determine appropriate field observations that correlated to the particle size distribution results to reduce future analytical costs.
3. The collection of samples from exposed surfaces within a private parcel represent the worst case scenario for pollutant generation from a private parcel, whereas PLRM predicts a FSP concentration which integrates all surface types within all parcels of the same land use within a catchment. A technique for spatially weighting the distribution of surface types within a parcel would be necessary to make more suitable comparisons.

WATER QUALITY TURBIDITY TESTS

Similarly to the particle grain size analysis techniques, the water quality turbidity tests had a standardized sampling area that was equivalent to the controlled experiments. The water quality turbidity tests also aimed to address the first disadvantage listed above for the particle grain size analysis technique (the inability to correlate dry material sample results to water quality results). Figure 5.15 ranks the measured average turbidity concentrations of the 24 samples analyzed, and demonstrates the detection of a significant range of turbidity values across sites. Regardless, the turbidity results did not correlate with simple field observations of the relative compaction and/or visual relative degree of disturbance of the pervious surface samples. Disadvantages of this technique include:

1. Measured values shown in Figure 5.15 represent a single 1 ft^2 area within the entire private parcel, while PLRM predicts a parcel average FSP concentration. As shown with the road water quality data, a single 1x1 area is unlikely to represent the average of a larger area. The measured values would need to be spatially weighted based on % distribution within the parcel to be more comparable to PLRM predictions. This is similar to the discussion of the spatial integration of road controlled experiments on a 1ft^2 area to an entire road segment (10,000 ft^2) in Chapter 5.1.
2. Sampling technique is biased due to the collection of all material within a 1x1 square rather than the portable sampler that requires material to mobilized and transported into the sampler simulating a runoff microcosm. Sampling methods therefore assume 100% entrainment of the sediment in stormwater, when in reality the concentrations are likely to be significantly lower due to (1) infiltration through the subsurface and (2) particle capture as the runoff travels over vegetation, organic matter, etc within the parcel.

RANKED PRIVATE PARCEL PERVIOUS SURFACE TURBITY MEASUREMENTS



Range of 25 water quality turbidity measurements, ranked high to low, from pervious surfaces on private parcels representing a range of observed condition. While the measurements indicate a range of observed turbidity values, a meaningful statistical correlation of turbidity to simple field observations of relative compaction and/or degree of disturbance was not identified.

3. Private parcel land use samples were collected in an area of exposed soil, which will preferentially bias the results towards higher concentrations. Areas with erosion control BMPs, such as vegetation, will have less erodible soil and therefore lower generation of FSP.

5.2.2 PRIVATE PARCEL RESEARCH FINDINGS

1. Realistically, the greatest influence on stormwater pollutant load reductions from private parcels will result from implementation of private parcel BMPs that infiltrate runoff volumes and provide effective source controls on site. Future research should prioritize evaluations of how to implement, maximize and maintain the effectiveness of private parcel infiltration BMPs over time.
    - Effective and well maintained infiltration BMPs will significantly minimize the runoff contributions from parcels before it enters the stormwater conveyance system, thereby reducing the necessary capacity and treatment capabilities of downstream treatment BMPs.
    - Effective source control actions will eliminate the introduction of pollutants into the stormwater system. The high number of observations of pervious and impervious surfaces of all land use types during this research suggests that TSS and FSP source control efforts on private land uses should target strategies that reduce the potential accumulation and subsequent transport from impervious surfaces and highly compacted pervious surfaces where cars frequently park, such as driveways and parking lots, particularly in the winter. Strategies that reduce the amount of FSP available on these surfaces prior to subsequent runoff events (such as sweeping and removal) will reduce the distributed contribution of the primary pollutant in stormwater from private land uses.
2. If future water quality monitoring of private land uses occurs, the data collection should focus on the concentrations emanating from the impervious and highly compacted pervious surfaces. These surfaces likely are the biggest influence on pollutant transport from private land uses, as a significant portion of the surface water flowing over pervious surfaces will be infiltrated and never reach the stormwater conveyance system. The portable simulator is a reasonable and repeatable device that can cost-effectively assist with the generation of a large impervious surface water quality dataset, but this effort demonstrates its limitations and poor field precision on even highly compacted pervious surfaces.
3. There are a myriad of challenges associated with cost-effectively sampling the runoff quality from a specific land use type. Ideally the isolated runoff from a series of discrete parcels of a specific land use type and condition could be collected and compared, but the ability to instrument and isolate specific land use types would be technically challenging if not impossible and would result in excessive instrumentation and monitoring cost. Given the objectives and the resources available for this effort, an appropriate cost effective technique to obtain water quality data from pervious surfaces adequate to compare to CRC values was, unfortunately, not identified.

5.3 ROAD SHOULDER INFILTRATION

5.3.1 ROAD SHOULDER RESULTS

COMPARISON TO CURRENT PLRM ALGORITHM

Table 5.10 compares measured K_{sat} to predicted K_{sat} using the PLRM[5] v1 algorithm. As shown in Table 5.10, field measurements of K_{sat} have significant variability across sites and Soil Survey Map Units. The current PLRM algorithms that combine hydrologic properties for a Soil Survey Map Unit and a land-use based compaction factor do not appear to provide an adequate method to estimate the variability observed in K_{sat}. Note that because road shoulders can be highly modified, the soil measured in the road shoulder may not be representative of the Soil Survey Map Unit defined in Table 5.10. This discrepancy may be influencing the interpretation of Table 5.10.

Table 5.10. Comparison of measured K_{sat} to current PLRM algorithm[4].

Map Unit	Texture of Soil Horizon Sampled	PLRM Unimpacted K_{sat} [in/hr]	PLRM Secondary Road K_{sat} [in/hr]	PLRM Primary Road K_{sat} [in/hr]	Field Measured Road Shoulder K_{sat} [in/hr]		
					Max	Min	Median
7172	Gravelly Medial Sandy Loam	5.0	1.5	1.0	13.00	1.00	2.17
7222	Very Cobbly Sandy Loam	3.8	1.1	0.8	12.50	2.33	7.42
7444	Loamy Coarse Sand	12.0	3.6	2.4	1.83	0.08	0.47
7421	Gravelly Loamy Coarse Sand	5.0	1.5	1.0	4.50	0.67	1.83
7491	Coarse Sandy Loam	1.6	0.5	0.3	9.33	0.17	1.25
7471	Loamy Coarse Sand	13.5	4.0	2.7	2.00	0.33	1.22

COMPARISON OF ROAD LAND USE TO MEASURED K_{SAT}

Table 5.11 compares measured K_{sat} for all sites by the type of road land use (secondary or primary road). As shown in Table 5.11, secondary roads have a higher average K_{sat} relative to primary roads and a much larger standard deviation. While additional data collection may be warranted to better assess the variability of K_{sat} for primary roads, it is likely that the variability of measured K_{sat} for secondary roads will remain larger because the condition of road shoulders is relatively uniform for primary roads.

Table 5.11. Road land use type and measured K_{sat}

Road Type	K_{sat} [in/hr]			Standard Deviation	# of Samples
	Max	Min	Ave		
Secondary	13.00	0.08	2.04	3.22	38
Primary	2.00	0.33	1.19	0.76	6

[5] A bug in PLRMv1 was discovered during this research. The values shown in Table 5.11 are the intended values that PLRM is supposed to estimate. Values derived from PLRM version 1.1 for Ksat will be slightly lower than those shown in Table 5.11.

COMPARISON OF COMPACTION MEASUREMENTS TO MEASURED KSAT

Figure 5.16A presents measurements of cone penetrometer depth and K_{sat}. No correlation across cone penetrometer depths with measured K_{sat} is apparent in Figure 5.16A. It should be noted that sites with relatively low cone penetrometer depths (less than two inches) had Ksat measurements below two inches/hour. Conversely, sites with relatively high cone penetrometer depths (greater than three inches) had Ksat measurements at or above two inches/hour. This result may indicate that while cone penetrometer depths cannot be used to infer Ksat for all soil conditions, it may be a useful measurement to quickly distinguish between highly compacted soils with lower Ksat and relatively undisturbed soils with higher Ksat.

COMPARISON OF ROAD SHOULDER CONDITION AND MEASURED KSAT

Table 5.12 compares the observed road shoulder condition defined using the PLRM Road Methodology with measured K_{sat}. While additional data collection may be warranted to increase the sample size to better assess the variability of K_{sat} with observed condition, the following points about the data presented in Table 5.12 are noted:

- Erodible road shoulders have the lowest variability in measured K_{sat}. This observation is likely due to all erodible road shoulders having some level of disturbance by definition, which diminishes the potential for high K_{sat} measurements.
- There is significant variability in measured K_{sat} for stable and stable and protected road shoulders. This observation may indicate that condition alone cannot be used to infer K_{sat} for stable and stable and protected road shoulders. In these cases, soil type may be the dominant factor influencing K_{sat} for road shoulders.

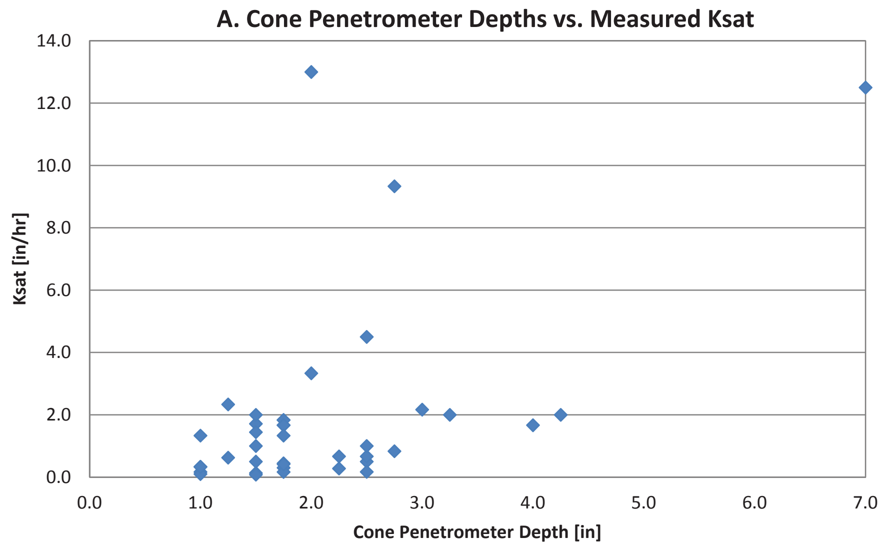
Table 5.12. Road shoulder condition and measured Ksat

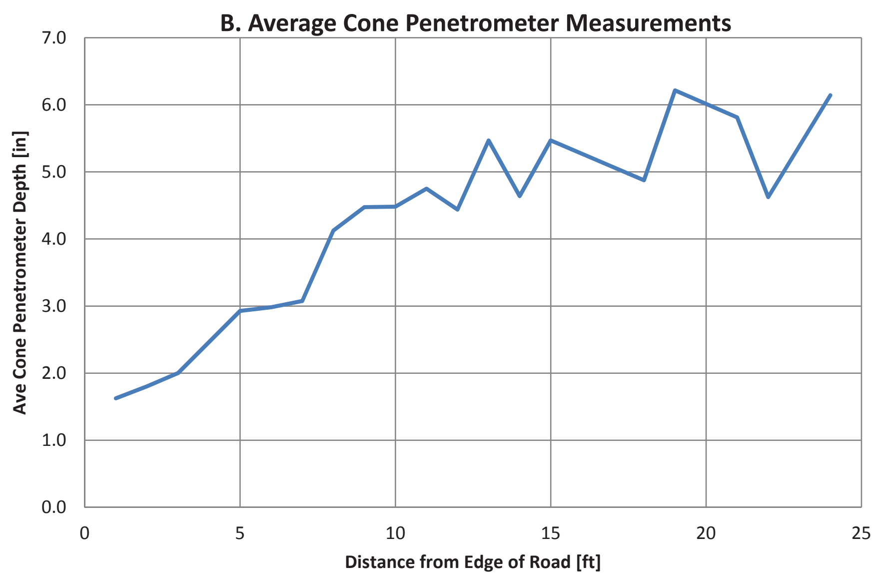
PLRM Road Shoulder Condition	K_{sat} [in/hr]			Standard Deviation	# Samples
	Max	Min	Ave		
Erodible	2.33	0.08	0.97	0.75	28
Stable Only	9.33	0.17	2.83	2.93	8
Stable and Protected	13.00	0.67	6.23	6.03	5

TRANSECTS

Figure 5.16B shows the average cone penetrometer depth for all transects as a function of distance from the edge of the road. Figure 5.16B demonstrates that average soil compaction decreases with distance from the edge of the road surface. Average cone penetrometer measurements had a relatively constant increase until a distance of roughly 12-15 feet from the edge of road. After about 15 feet from the edge of the road, average cone penetrometer measurements varied between 5 and 6 inches but did not demonstrate a trend of continued increase with distance from the edge of the road.

Table 5.13 summarizes statistics for measured K_{sat} within three to five feet of the edge of the road and 24 feet from the edge of the road. Three of the seven K_{sat} values measured at 24 feet from the edge of the road were too rapid to be within the range of accuracy for the CHP. These measurements were included in the analysis assuming a rate of 20 in/hr. As shown in Table 5.13, measured K_{sat} is notably higher with increased distance from the edge of the road.


A. Cone Penetrometer Depths vs. Measured Ksat
Ksat [in/hr]
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Cone Penetrometer Depth [in]


B. Average Cone Penetrometer Measurements
Ave Cone Penetrometer Depth [in]
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
25
Distance from Edge of Road [ft]

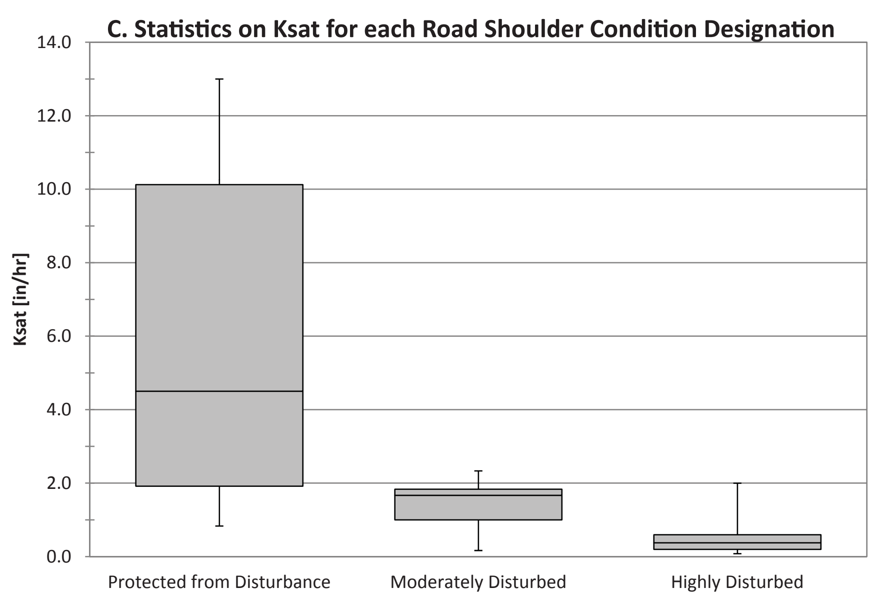

C. Statistics on Ksat for each Road Shoulder Condition Designation
Ksat [in/hr]
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Protected from Disturbance
Moderately Disturbed
Highly Disturbed

Table 5.13. Transects and measured K_{sat}

Distance from Impervious [ft]	K_{sat} [in/hr]			Standard Deviation	# Samples
	Max	Min	Median		
3 or 5	9.33	0.33	1.83	3.10	7
24	20.00	9.50	14.67	4.27	7

5.3.2 ROAD SHOULDER INFILTRATION RESEARCH FINDINGS

Based on the results and interpretation presented above, a simple method was developed to categorize road shoulder condition at each road shoulder site to infer a default K_{sat} in PLRM. Road shoulder condition was defined as either: highly disturbed, moderately disturbed, or protected from disturbance, based on qualitative observations made in the field about the level of disturbance of the majority of the pervious portion of the road shoulder (see Appendix B for a decision tree to identify road shoulder condition).

Statistical results for road shoulders comparing the estimated condition with measured K_{sat} are shown in Figure 5.16C. For conditions defined as either highly disturbed or moderately disturbed, the measured K_{sat} in the road shoulder exhibits a relatively narrow range of values. Conversely, for the condition defined as protected from disturbance, a wide range of measured K_{sat} values was observed. These results appear to indicate the following:

- Road shoulder compaction is likely the primary factor influencing measured K_{sat} values in road shoulder soils with conditions observed as either highly disturbed or moderately disturbed. In these cases, soil type may not strongly influence measured K_{sat} values.
- For road shoulders observed in the protected from disturbance category, soil type is likely the primary factor influencing measured K_{sat} values. In this case, compaction estimates or visual observations of disturbance do not appear to provide strong correlations and cannot be used to infer K_{sat}.

CHAPTER 6. STORMWATER TREATMENT BMP RESEARCH

The stormwater treatment BMP research was conducted to obtain cost-effective hydrologic and water quality datasets from nine different treatment BMPs (termed SWTs in PLRM) within the Tahoe Basin in a manner that would allow comparisons of measured data to PLRM hydrologic predictions and inform the PLRMv1 CEC values particularly for FSP. Based on SWT type and key design attributes, PLRM predicts the average annual volume captured and treated by the SWT (treated flow) and the average annual volume not captured (bypass flow) (see schematic on page 2.6). Treated flow is assigned a CEC for each pollutant based on the type of SWT modeled. Bypassed flow retains the inflowing pollutant concentrations routed to the SWT at each time step, which is calculated by PLRM as the flow-weighted average of CRCs for land uses contributing to the SWT. The CEC values used within the PLRMv1 database (see Table 2.3) were determined using limited Tahoe specific data, particularly for fine sediment particles (FSP), which is the primary pollutant of concern. The results below compare PLRM predictions of SWT performance on event, seasonal and annual time steps for four SWTs for monitoring periods where confidence in the measured data was high. In addition, over 100 treated outflow samples were collected from the nine SWTs over the 3 water years and this data is used to compare measured pollutant concentrations in treated outflow to CEC values used in the PLRMv1.

6.1 SWT HYDROLOGY RESEARCH

6.1.1 COMPARISON OF OBSERVED VERSUS PREDICTED PERFORMANCE

The PLRM hydrology module (SWMM-based) predicts stormwater runoff from urbanized catchments and generates a time-series of surface runoff for an 18-year continuous simulation. At each time step in the simulation, surface runoff from contributing catchments may be routed to SWTs. Based on the user inputs of SWT type and key design attributes, PLRM predicts the average annual volume of water captured by the SWT over the 18-year simulation, where:

$$V_{CAP} = V_{ET} + V_{INF} + V_{OUT\_T} \quad \text{(EQ 6.1)}$$

$$\%_{CAP} = V_{CAP} / V_{IN} \quad \text{(EQ 6.2)}$$

The captured volume (V_{CAP}) includes volume losses due to evapotranspiration (V_{ET}), infiltration (V_{INF}), and outflow through the treated outlet (V_{OUT_T}), and hydraulic capture ($\%_{CAP}$) is defined as the percent of the inflow volume (V_{IN}) treated by the SWT (V_{CAP}). The remaining volume not captured and treated by the SWT is considered bypass (V_{OUT_B}). Definitions for each variable are provided in Appendix C. Table 6.1 presents the PLRM average annual volume estimates for inflow, treated outflow, infiltration and evapotranspiration, and bypass, as well as the predicted % hydraulic capture for 5 SWTs monitored during this research. The PLRM models for each catchment and SWT were built using the information provided in Tables 3.4 and 3.5.

Table 6.1. PLRM average annual hydrology estimates (WY1989-WY2006).

BMP Type	Site	Inflow (ac-ft)	Treated Outflow (ac-ft)	Infiltration + ET (ac-ft)	Bypass Outflow (ac-ft)	Hydraulic Capture (%)
Dry Basin	Rocky Point	16.3	14.4	0.9	1.0	94%
	PA2	39.6	18.1	17.8	3.8	91%
Wet Basin	Osgood	39.4	24.8	0.5	14.1	64%
	Eloise	215.4	44.8	0.4	170.3	21%
	PA1	34.3	26.9	1.1	6.3	82%

Observed hydrologic performance in each SWT was calculating based on water balance equations developed from high resolution (15 min interval) water depth monitoring and detailed topographic surveys of each SWT, which including surveys of inlet and outlet structures that controlled surface water elevations in each SWT. All hydrologic monitoring data collection and the associated analysis methods are detailed in Chapters 3.1.4 and 3.2.1. Instrument failure and data gaps did occur during the monitoring effort, which limited the quality and extent of datasets that that were deemed appropriate to compare to predicted performance in PLRM. Of the 9 SWTs instrumented with depth recorders, three wet basins (Osgood, PA1 and Eloise) and two dry basins (PA2 and Rocky Point) resulted in reliable observed hydrologic data (Figures 6.1A-E). See Table 3.5 and Chapter 3.1.4 for a discussion of the difficulties in calibrating the depth gage data at the other SWTs.

For SWTs and time periods with reliable water depth datasets, observed calculations of hydrologic performance are compared to PLRM estimates of performance (Table 6.2). While Table 6.1 displays annual average PLRM estimates of hydrologic performance, Table 6.2 displays predicted performance from PLRM simulations on an annual and seasonal basis for time periods with reliable monitoring data during water years 2009 through 2011. The seasonal approach was taken to evaluate potential differences in observed and predicted performance from variable meteorological conditions in the Tahoe Basin and the associated differences in hydrologic responses, which include: 1) runoff generated by a mixture of rain and snowmelt (October- February); 2) runoff that includes a significant spring snowmelt component (March-May); and 3) runoff generated by rain events and thunderstorms (June-Sept). The categorization of seasons used by this research is consistent with the season definitions in the RWQCB NPDES permit monitoring requirements (LRWQCB 2011).

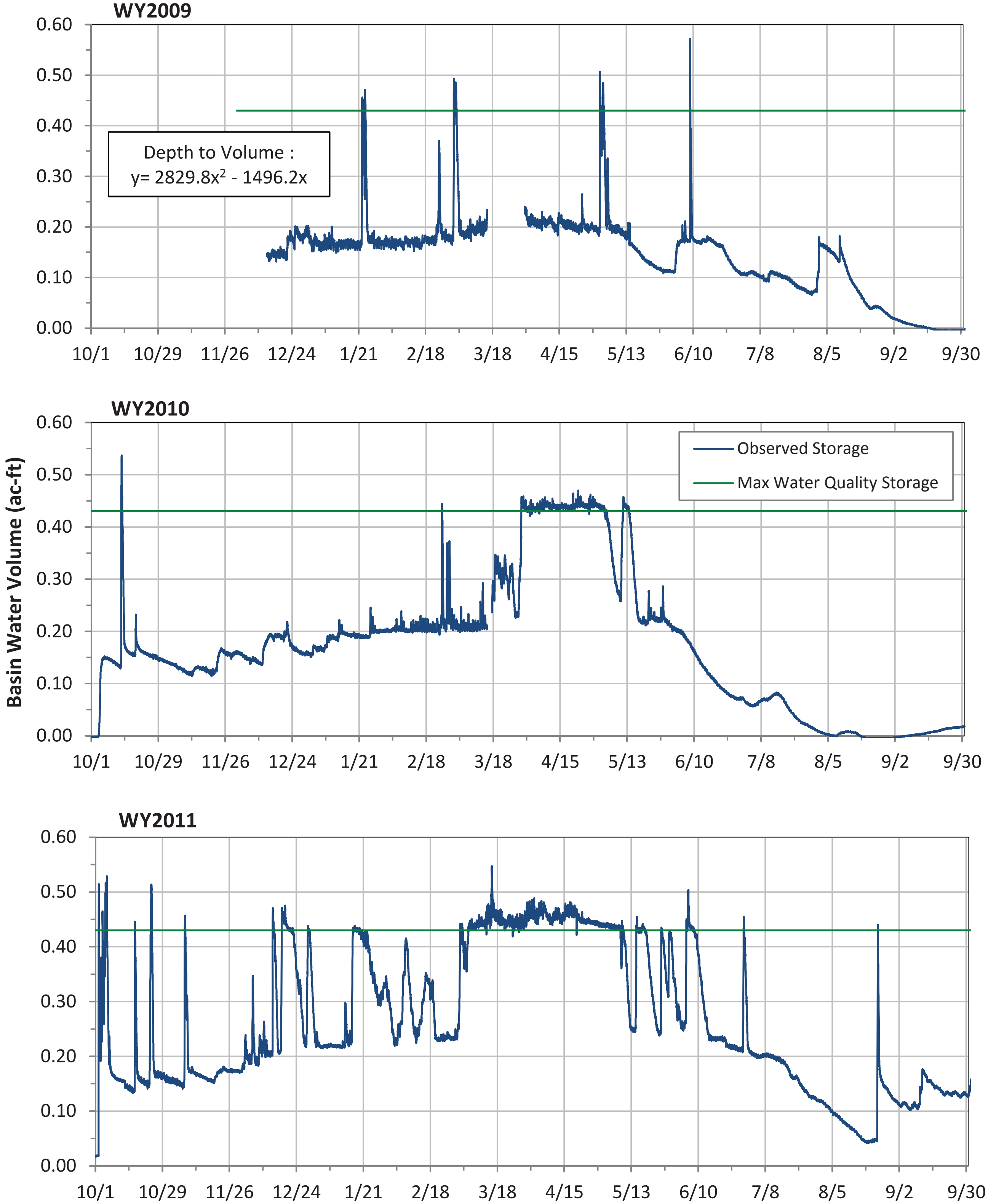
As discussed in Chapter 4.1 and shown in Figure 4.1, the 18-yr PLRM simulation (WY1989-WY2006) represents a range of dry, average and wet water years, while the water years monitored during this research represent one average year and two wet years, with total precipitation increasing in each year during the study from WY2009 to WY2011. Given the difference in the distribution of water year types between the two datasets, the use of standard PLRM outputs that present average annual SWT performance (see Table 6.1) to the observed seasonal estimates (see Table 6.2) is not an appropriate comparison. Therefore, post-processing of output generated by PLRM models was completed in SWMM (see Chapter 3.2.2) to predict the seasonal hydrologic performance of each SWT (see Table 6.2) to compare with the monitoring data, as discussed in more detail below.

LIMITATIONS ASSOCIATED WITH SWT MONITORING AND MODELING

Each SWT monitored during this research has known idiosyncrasies which complicated representations of SWT performance model through PLRM, as well as the calculations of observed hydrologic performance using the water balance equations. Site-specific issues include:

- Rocky Point Basin: The Rocky Point Basin is comprised of two dry basins that are connected via a culvert (see Figure 3.7E). Water levels were recorded in the south basin for this research, which due to the direct hydraulic connection between the two basins also represents water levels in the north basin. The outlet structures of both basins are identical and include a single orifice (treatment outlet) and concrete weir (bypass outlet). The north basin is used by the adjacent commercial properties for snow storage, which complicates the analysis of water level data because the stored snow may have artificially raised recorded water levels during the winter and spring. Furthermore, the single treatment orifice used to drain the basins (treatment outlet) was found to be clogged with debris on at least one occasion, which could have led to variable treatment performance and this variability adds uncertainty to the analysis of water level data and the modeled representations of performance in PLRM.

Osgood Basin Volume Time Series WY2009-WY2011



Frequency of Occurrence: Water Storage Above Outlet Elevation Resulting in Treated Outflow / Bypass Outflow

WY	Season		
	Fall/Winter	Spring	Summer
WY09	55% / 1%*	77% / 2% *	12% / 0%
WY10	46% / 0%	100% / 41%	7% / 0%
WY11	75% / 12%	100% / 83%	39% / 3%

* significant data gaps in observed volume time series

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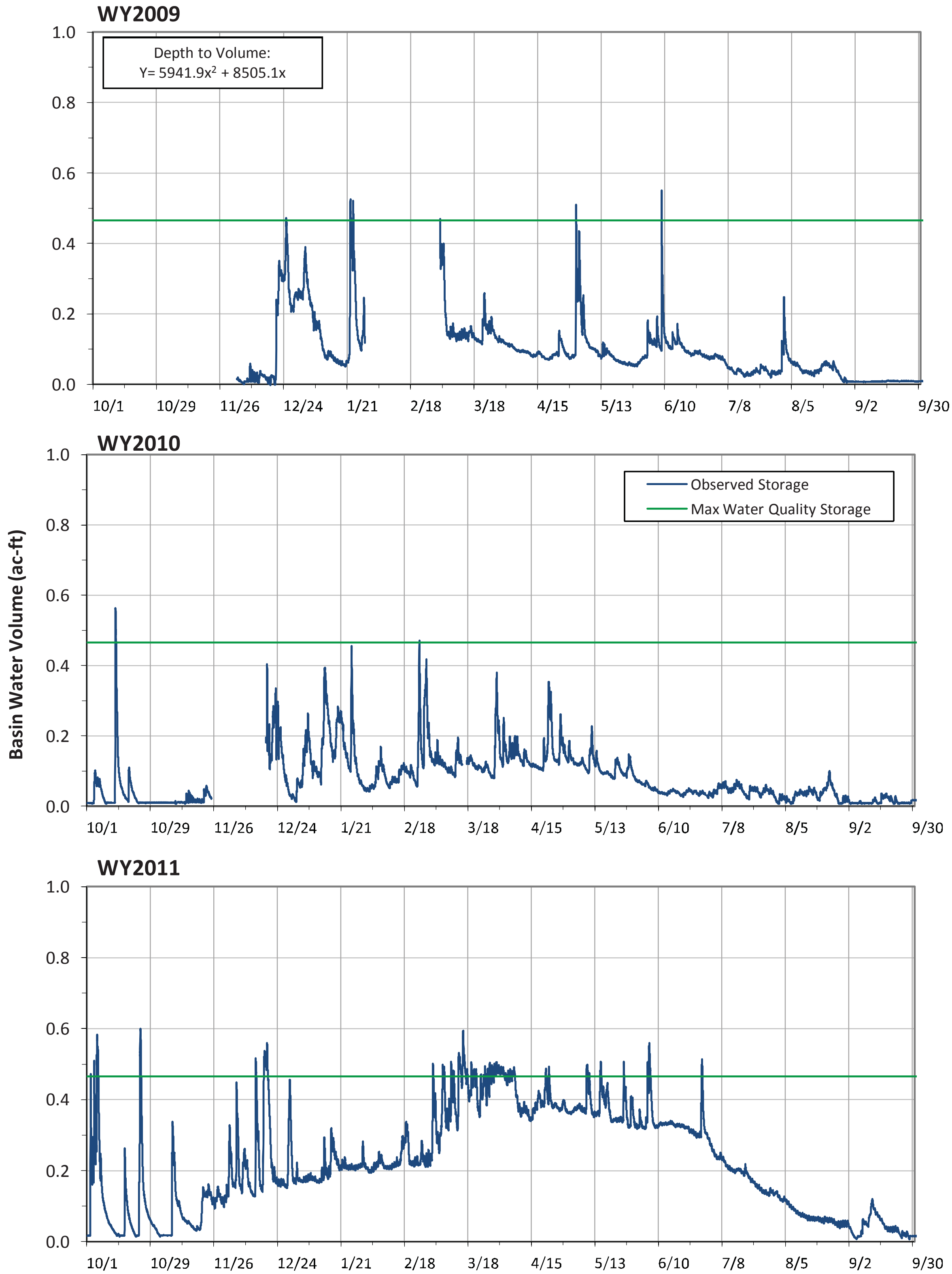
Park Avenue Upper Basin (PA1) Volume Time Series WY2009-WY2011



Frequency of Occurrence: Water Storage Above Outlet Elevation Resulting in Treated Outflow / Bypass Outflow

WY	Season		
	Fall/Winter	Spring	Summer
WY09	59% / 2%*	88% / 1%	32% / 1%
WY10	46% / 1%*	100% / 0%	2% / 0%
WY11	79% / 3%	100% / 33%	61% / 2%

* significant data gaps in observed volume time series

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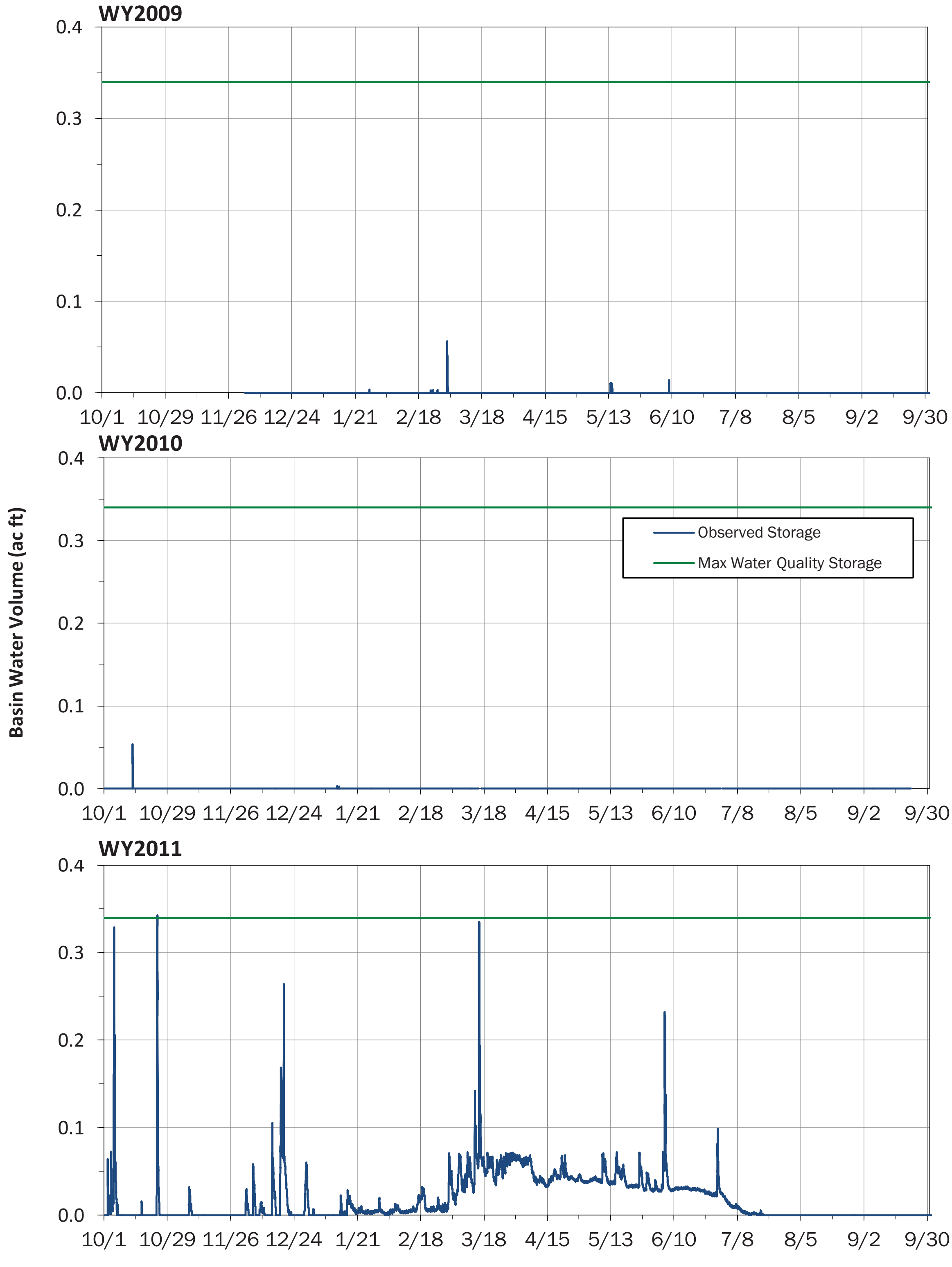
Park Avenue Lower Basin (PA2) Volume Time Series WY2009-WY2011



Frequency of Occurrence: Water Storage Above Outlet Elevation Resulting in Treated Outflow / Bypass Outflow

WY	Season		
	Fall/Winter	Spring	Summer
WY09	0% / 0%	0% / 0%	0% / 0%
WY10	0% / 0%	0% / 0%	0% / 0%
WY11	0% / 0%	0% / 0%	0% / 0%

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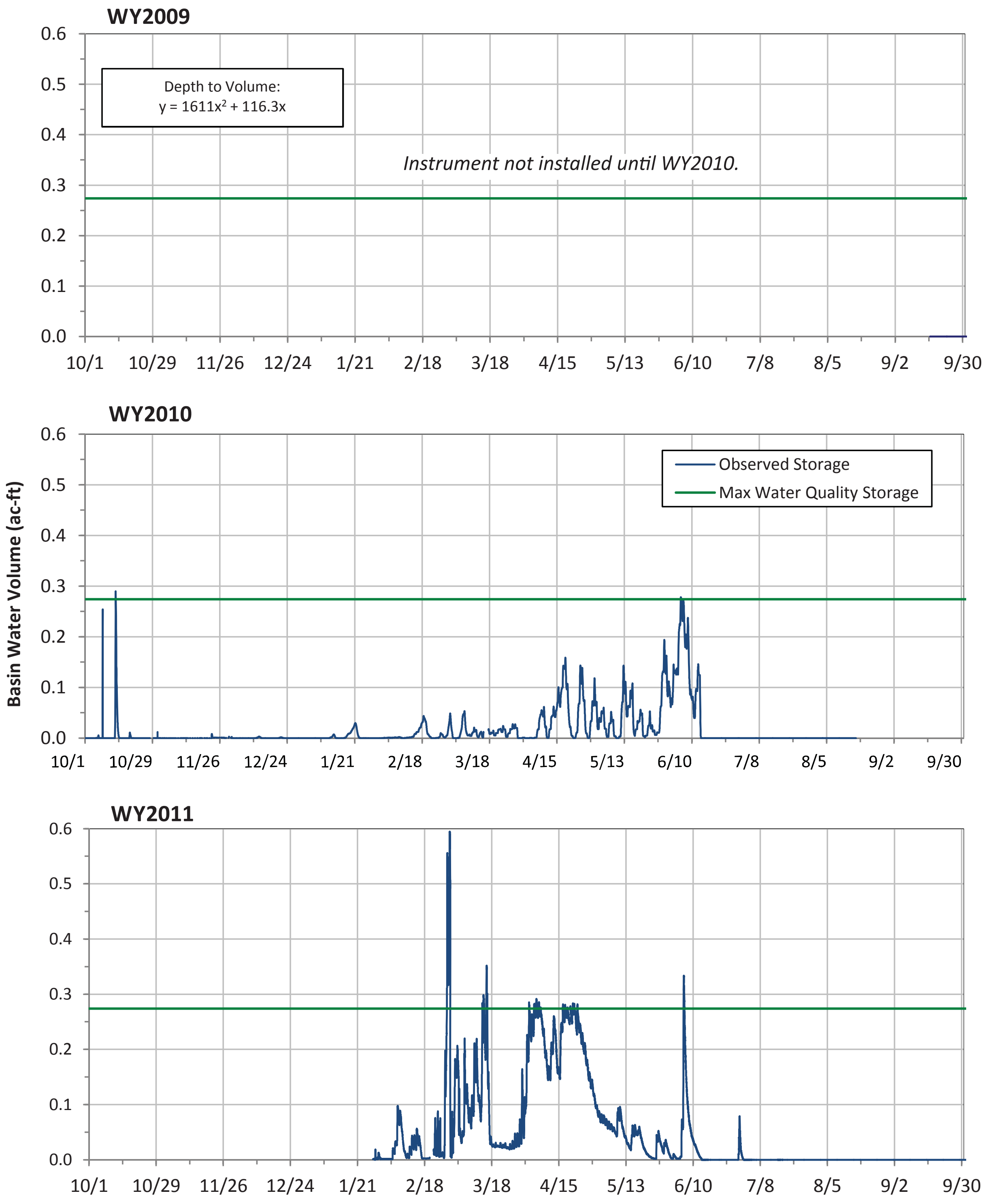
Rocky Point Basin Volume Time Series WY2009-WY2011

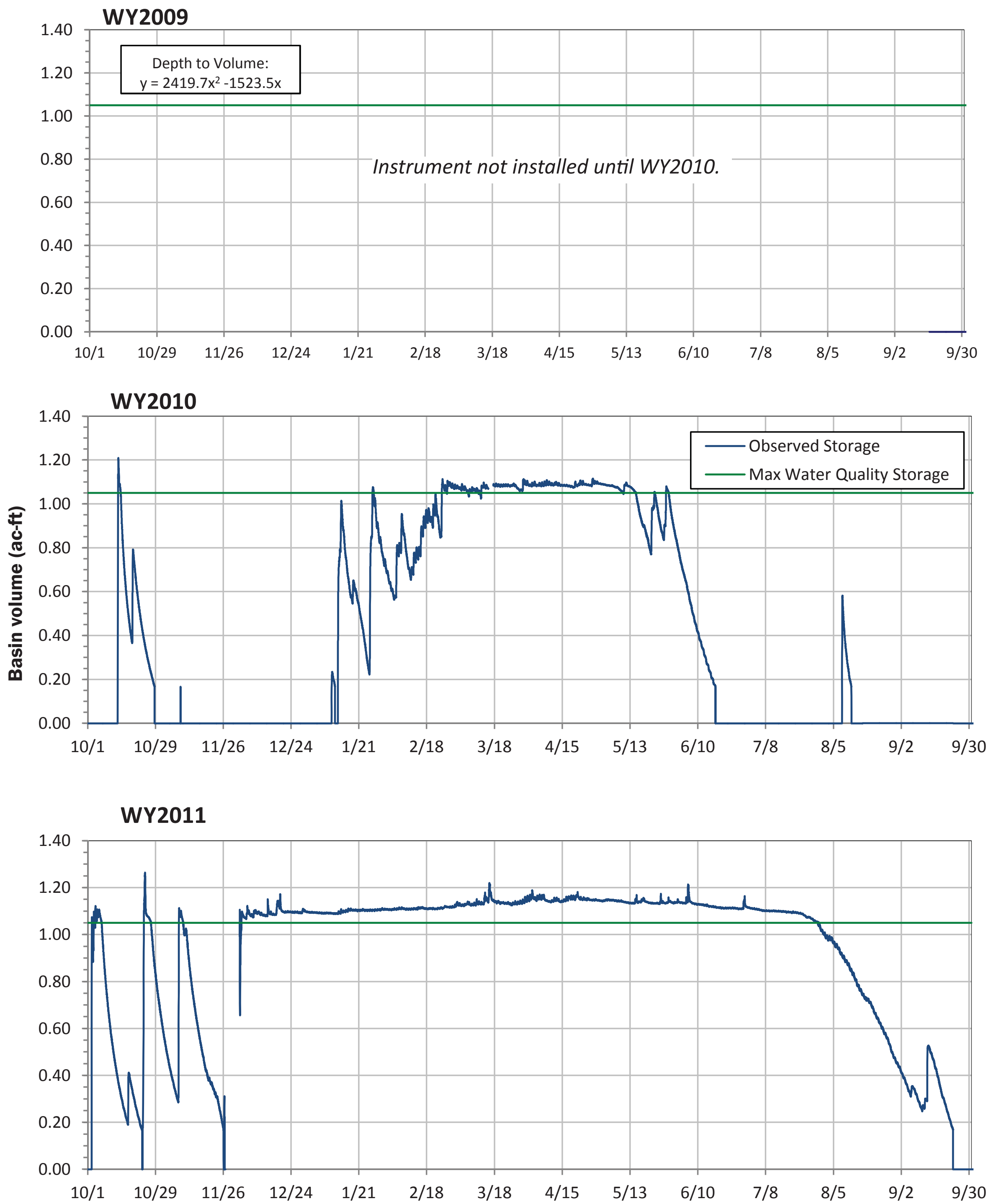


Frequency of Occurrence: Water Storage Above Outlet Elevation Resulting in Treated Outflow / Bypass Outflow

WY	Season		
	Fall/Winter	Spring	Summer
WY09	-	-	-
WY10	5% / 10%	50% / 0%	11% / 1%
WY11	41% / 5%*	91% / 3%	6% / 1%

* significant data gaps in observed volume time series

Eloise Basin Volume Time Series WY2009-WY2011



Frequency of Occurrence: Water Storage Above Outlet Elevation Resulting in Treated Outflow / Bypass Outflow

WY	Season		
	Fall/Winter	Spring	Summer
WY09	-	-	-
WY10	80% / 8%*	100% / 82%	44% / 0%*
WY11	83% / 68%	100% / 100%	73% / 50%

* significant data gaps in observed volume time series

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BMP Type	Site	Season	Start Date	Stop Date	# Days	Observed					PLRM Predicted				
						Inflow (ac-ft)	Treated (ac-ft)	Infiltration + ET (ac-ft)	Bypass (ac-ft)	Hydraulic Capture (%)	Inflow (ac-ft)	Treated (ac-ft)	Infiltration + ET (ac-ft)	Bypass (ac-ft)	Hydraulic Capture (%)
Dry Basin	Rocky Point	Spring WY11	01-Mar-11	31-May-11	92	40.4	38.9	0.2	0.9	96%	9.4	8.6	0.5	0.3	97%
		Summer WY11	01-Jun-11	30-Sep-11	122	3.5	2.9	0.0	0.3	82%	1.8	1.7	0.1	0.0	100%
	PA2	Fall/Winter WY11	01-Oct-10	28-Feb-11	151	2.2	0.0	2.2	0.0	100%	36.6	13.1	13.4	10.1	73%
		Spring WY11	01-Mar-11	31-May-11	92	3.0	0.0	3.0	0.0	100%	23.3	9.6	9.5	4.3	82%
		Summer WY11	01-Jun-11	30-Sep-11	122	1.5	0.0	1.5	0.0	100%	3.9	2.0	1.9	0.0	100%
Wet Basin	Osgood	Summer WY09	01-Jun-09	30-Sep-09	122	3.6	1.9	0.9	0.9	68%	2.6	2.0	0.0	0.6	78%
		Fall/Winter WY10	01-Oct-09	28-Feb-10	151	14.0	9.6	0.8	3.2	74%	23.4	13.5	0.3	9.6	59%
		Spring WY10	01-Mar-10	31-May-10	92	54.7	12.8	0.7	41.2	24%	11.7	10.6	0.1	1.1	91%
		Summer WY10	01-Jun-10	30-Sep-10	122	1.7	1.1	0.8	0.0	97%	1.0	1.0	0.0	0.0	100%
		Fall/Winter WY11	01-Oct-10	28-Feb-11	151	141.6	15.7	0.9	124.8	12%	40.9	14.8	0.1	25.9	37%
		Spring WY11	01-Mar-11	31-May-11	92	900.0	12.8	0.8	886.3	1%	22.4	14.3	0.1	8.0	64%
		Summer WY11	01-Jun-11	30-Sep-11	122	13.5	6.9	1.0	5.7	55%	5.8	2.7	0.0	3.1	47%
	Eloise	Fall/Winter WY10	09-Jan-10	28-Feb-10	51	16.7	7.9	3.0	5.6	64%	57.0	16.1	0.2	40.7	29%
		Spring WY10	01-Mar-10	31-May-10	92	89.9	52.6	4.4	33.1	63%	69.6	18.4	0.0	51.2	26%
		Fall/Winter WY11	01-Oct-10	28-Feb-11	151	250.5	73.4	6.5	170.8	32%	211.5	33.7	0.2	177.6	16%
		Spring WY11	01-Mar-11	31-May-11	92	662.5	69.0	4.5	588.9	11%	141.1	27.5	0.1	113.5	20%
		Summer WY11	01-Jun-11	30-Sep-11	122	200.0	45.0	5.9	150.0	25%	20.1	6.7	0.1	13.3	34%
	PA1	Fall/Winter WY09	03-Dec-08	28-Jan-09	57	9.6	5.6	0.9	3.0	67%	8.7	7.9	0.1	0.7	92%
		Spring WY09	01-Mar-09	31-May-09	92	15.0	13.3	1.6	0.5	98%	13.9	13.1	0.2	0.6	96%
		Summer WY09	01-Jun-09	30-Sep-09	122	9.0	6.5	2.1	0.4	93%	1.9	1.9	0.0	0.0	100%
		Fall/Winter WY10	01-Oct-09	28-Feb-10	151	14.3	9.9	2.0	2.5	82%	23.2	17.3	0.8	5.1	78%
		Spring WY10	01-Mar-10	31-May-10	92	16.6	15.1	1.6	0.0	99%	8.5	8.4	0.1	0.0	100%
		Summer WY10	01-Jun-10	30-Sep-10	122	2.3	0.4	2.0	0.0	94%	0.7	0.7	0.0	0.0	100%
		Fall/Winter WY11	01-Oct-10	28-Feb-11	151	50.2	20.0	2.5	27.5	44%	36.6	20.5	0.4	15.6	57%
		Spring WY11	01-Mar-11	31-May-11	92	95.3	15.5	2.0	77.8	18%	20.4	14.7	0.2	5.4	74%
		Summer WY11	1-Jun-11	30-Sep-11	122	25.0	13.3	2.5	9.6	60%	3.3	2.7	0.1	0.5	85%

- Upper Park Avenue Basin (PA1): As documented by previous monitoring of the Park Avenue Basins (2NDNATURE 2008), the constructed elevation of the inlet junction box that routes flows from the Rocky Point drainage to PA1 (see Rocky Point inlet in Figure 3.7B) allows water to bypass the PA1 wet basin when water levels are elevated in PA1. During these conditions, the research team has observed backwatering of the inlet junction box from PA1, which results in (1) water draining from the PA1 wet basin through the inlet pipe and into the bypass pipe connected to the junction box and (2) diversion of Rocky Point catchment inflows to the bypass channel. This variable conveyance adds uncertainty to the analysis of water level data and the modeled representations of performance in PLRM.
- Lower Park Avenue Basin (PA2): 2NDNATURE (2008) documented the poor hydraulic connection at the Park Avenue Basins between the upper wet basin (PA1) and the lower dry basin (PA2). Over the course of monitoring (WY05-WY07; WY09-WY11), outflow at PA1 was frequently observed (70% of the year on average) while inflow at PA2 was observed only 15% of the year on average. NHC (2007) studied the causes for the observed losses in the storm drain pipe connecting PA1 discharge to PA2, which uses an inverted siphon design at a profile conflict with the Stateline Creek storm drain system. The results of the NHC study concluded that the losses were caused by gaps between the joints in the storm drain pipe connecting the two basins which allowed exfiltration into: 1) the Stateline Creek storm drain system, which discharges to the North Ditch; and 2) the soils surrounding the storm drain pipe. In 2010 the City of South Lake Tahoe attempted repairs to the storm drain system to eliminate the observed hydraulic connection to the Stateline Creek storm drain system. The repairs appear to have improved the connection between the two basins based on water level data recorded in water year 2011. However, losses are still occurring in the storm drain system that would require direct PLRM calibration to observed data. Therefore, comparisons of observed PA2 data to PLRM estimates of hydrologic performance would not be meaningful and are not used for this purpose.
- Osgood Basin: The drainage area to the wet basin includes a notable amount of forested uplands, which includes a large stream environment zone (Keller Creek Drainage). During periods of spring snowmelt runoff, especially in above average water years, the tributary forested uplands input a significant baseflow to Osgood Basin. PLRMv1 was designed to model surface runoff from developed lands and does not attempt to model runoff generated from forested areas during saturated conditions that generated baseflow. The baseflow component of the basin complicates the comparison and analysis of water level data and the modeled representations of performance in PLRM. In addition to this complication, a bypass pipe located near the inlet of the Osgood pretreatment settling basin can be opened to bypass the SWT and directly discharge runoff to the outlet. Anecdotal evidence suggests that the gate to the bypass pipe was intermittently open during monitoring; however researchers were unable to obtain documentation of the frequency and duration of bypass flow adding uncertainty to water budget estimates.
- Eloise Basin: Similar to the situation at Osgood Basin, Eloise Basin includes a significant baseflow component, complicating the comparison of water level data and PLRM modeled performance. The catchment area (281 acres) presented in Table 3.4 includes only the urban area modeled in PLRM, while the total catchment area is over 560 acres and includes a significant forested upland component (NHC 2007). This area likely contributes baseflow regularly to Eloise Basin, even during below average water years. Furthermore Eloise Basin was not constructed with a low flow treated orifice(s) in the outlet structure. However, over the course of the last 25 years the outlet structure, which is a corrugated metal pipe, has gradually corroded and currently allows water to leak out the structure. This outflow is difficult to measure in the field and adds uncertainty to water budget estimates.

In addition to the site specific complications noted above, little to no maintenance has occurred in these SWTs over the past several years (see Table 3.5). Furthermore, if/when maintenance activities are performed there is typically no documentation of the actions taken. Lack of maintenance can result in the gradual decrease in volume capacity, reduced infiltration rates, and lowering of treatment outflow rates due to blocked orifices. The lack of consistent maintenance, and documentation of maintenance actions when they do occur, leads to variable hydrologic performance that is difficult to quantify and accurately track. In addition, it is extremely challenging to quantify the pollutant load reduction benefit of a SWT that is not in desired operational condition. This variability adds uncertainty to the analysis of water level data and the modeled representations of performance in PLRM.

INFLOW, TREATED AND BYPASS VOLUMES

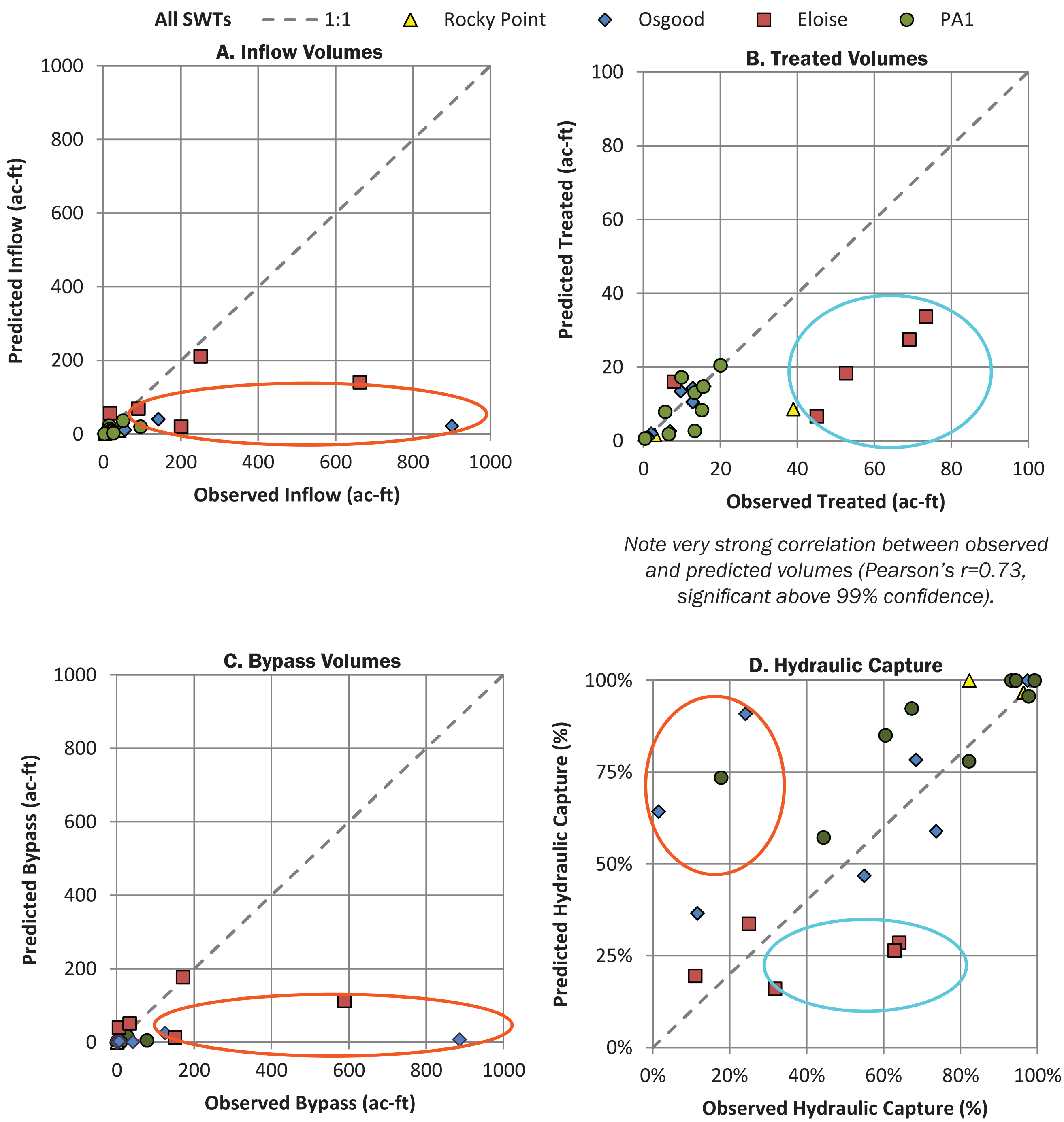
Figure 6.2 presents correlation plots of observed versus predicted values for inflow volume, treated volume, bypass volume, and hydraulic capture for all seasons (n=23) shown in Table 6.2 for Rocky Point, Osgood, Eloise, and PA1.

The inflow, bypass, and hydraulic capture data indicate a number of the observed values are significantly higher than the corresponding PLRM estimates (see Figures 6.2A, C-D). The higher observed values occurred during the extremely wet seasons of Spring 2010, Fall/Winter 2011, Spring WY11, and Summer WY11, when a significant baseflow component was present at the monitored wet basins. As discussed in Chapter 4.1, during the 3 water years of research, each year was successively wetter than the last. Table 6.3 shows the increasing trend in total precipitation, along with the concurrent increasing trend in observed inflow volumes to each SWT. Time series of observed storage supports this finding, as all basins were at or above the maximum water quality storage capacity more frequently in WY2011 than in previous years (see summary tables in Figures 6.1A-E). PLRM does not model baseflow within the current hydrology module, and therefore PLRM algorithms do not estimate increased inflows due to elevated groundwater during wet seasons, explaining the significant outliers shown in Figures 6.2A. Increased inflow also causes higher bypassed volumes and reduced hydraulic capture (see EQ 6.1 & 6.2), explaining the discrepancies in Figure 6.2C-D as well.

Review of Figure 6.2B indicates a very strong correlation between the observed and predicted treated outflow volumes (Pearson's r of 0.73, significant above 99% confidence). Treated outflow volumes are a critical metric with regards to PLRM modeling of pollutant load reductions and the general alignment between observed and predicted values suggest PLRM models the treatment volumes of SWTs reasonably well. The treated outflow outliers in Figure 6.2B are Eloise Basin and Rocky Point, where observed values are higher than predicted. The differences for Eloise can be attributed to the continual increase in baseflow contributions from forested upland area above catchment modeled by PLRM. Observed seasonal average baseflow inputs are estimated to range from 0.1 to 0.5 cfs in WY2010 for the fall/winter and spring, respectively, and 0.9 to 3.0 cfs in WY2011. As mentioned above, PLRM does not attempt to model baseflow generated from forested areas during saturated conditions and therefore the PLRM predictions are lower than the observed volumes, which include this contribution. At Rocky Point, the use of the north basin for snow storage during winter months may artificially raise the recorded water levels when the basin is inundated, resulting in a higher observed frequency of treated outflow (and therefore higher observed treated outflow volumes) than is actually occurring.

SWT Seasonal Hydrologic Comparisons

All seasons presented in Table 6.2



Note very strong correlation between observed and predicted volumes (Pearson's r=0.73, significant above 99% confidence).

Circled points indicate wet seasons (Spring WY10, All Seasons in WY11) in locations known to have high seasonal groundwater elevations (e.g., Osgood and Eloise Basins). The significant baseflow signal increases observed inflow volumes, resulting in higher bypass volumes and decreased hydraulic capture performance (red circles). In Eloise Basin, the baseflow inflow rates are roughly equivalent to the treated outflow rates, resulting in higher treated volumes and therefore higher than predicted hydraulic capture (light blue circles).

Inflow Volume = Treated +Bypass + Infiltration + Evapotranspiration

Hydraulic Capture = (Inflow - Bypass) / Inflow

Table 6.3. WY09-WY11 comparison of total precipitation and observed SWT inflow volumes.

		Water Year	**WY2009**	**WY2010**	**WY2011**
		Water Year Type	Average	Wet	Wet
		Total Precipitation (in) (% increase over previous year)	27.2	37.9	45.0
SWT Type	**SWT**	**Catchment Area (acres)**	**Inflow Volume (ac-ft) (% increase over previous year)**		
Dry Basin	PA2	n/a	0.1	6.6	63.8
Wet Basin	Osgood	341.6	30.3	78.2	1070
	Eloise	280.8[1]	n/a	163	1550
	PA1	224.6	31.9	31.2	168

[1] This is the total urban area of the catchment modeled in PLRM. The actual area draining to Eloise Basin is significantly higher (560 acres; NHC 2007) and has a significant forested upland component.

Previous groundwater monitoring at Eloise Basin (2NDNATURE 2006) has measured nearly a 7 ft increase in the local groundwater elevation from fall to the spring peak of snowmelt runoff, which places the groundwater table above the bottom of the Eloise Basin. That research (2NDNATURE 2006) was conducted during WY04 and WY05, which were a dry year following 2 average years and a wet year, respectively (see Figure 4.1). Other local groundwater monitoring in the Park Avenue Basins (2NDNATURE 2008) in WY06 (a wet year) and WY07 (a dry year) show increases in the groundwater elevation on the order of 4 ft with a 1.5 to 2 ft separation between the basin bottom and the highest groundwater elevation. The differences in fluctuations in groundwater levels for these two basins, in combination with the much higher forested upland area in the Eloise and Osgood catchments compared to Park Avenue (see Table 3.4, and footnote in Table 6.3) likely explains why observed inflow volumes at Eloise and Osgood Basins were much higher relative to PA1 (see Table 6.3) in WY10 and WY11.

Figure 6.3 presents data for the periods of time when baseflow inputs are suspected to be negligible to compare PLRM and measured hydrology metrics. While the number of data points used in the correlation plots is limited (n=9), the alignment between observed and predicted inflow and bypass volumes and hydraulic capture greatly improves. All data show very strong correlations between observed and predicted volumes significant above 95% confidence (see Figure 6.3). Future efforts to compare PLRM and measured hydrology must consider potential baseflow inputs that will not be included in PLRM predictions.

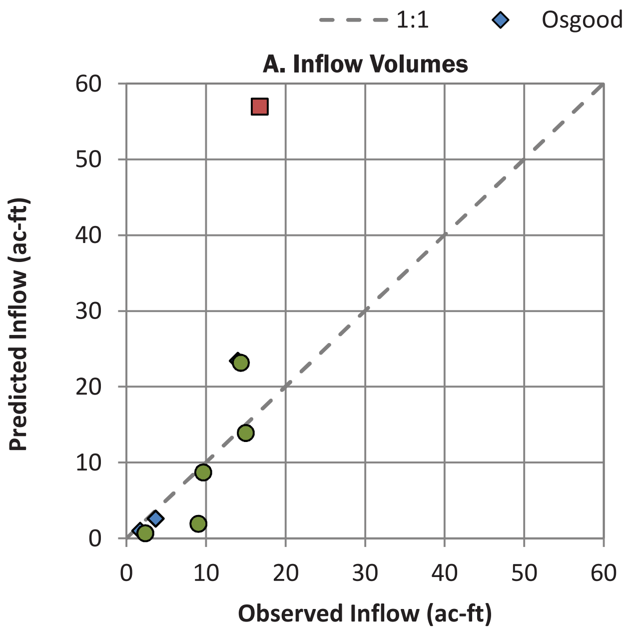
EVAPOTRANSPIRATION AND INFILTRATION VOLUMES

Figure 6.4 compares observed to predicted infiltration + evapotranspiration seasonal volumes in Table 6.2. Evapotranspiration is estimated using the surface area of the detained water, which varies with water surface area predicted from depth-area relationships, and standard monthly evapotranspiration rates for areas in the vicinity of the Tahoe Basin (www.cimis.water.ca.gov). Estimated evaporation volumes are a necessary variable to compare to PLRM performance estimates for wet basins, but in comparison to other loss terms, evapotranspiration volumes on a seasonal scale are negligible. Therefore, the differences between observed and predicted values shown in Figure 6.4 are assumed to be primarily due to differences in infiltration volume estimates. PLRM v1 does not estimate infiltration from wet basins. However, calculations of observed infiltration suggest that wet basins do infiltrate water volumes on a seasonal time scale, and future PLRM modifications may need to consider this factor. A previous water budget analysis on Eloise Basin suggested that infiltration occurred through the sides of the basin, rather than the basin bottom (2NDNATURE 2006).

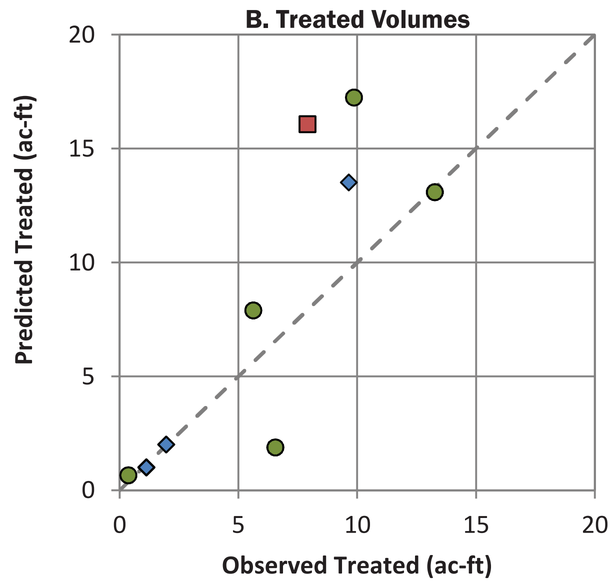
The observed time series of storage was used to calculate seasonal infiltration rates for each of the five SWTs with reliable water level data using the methodology described in Chapter 3.2.1. For each SWT, there was a strong

SWT Seasonal Hydrologic Comparisons

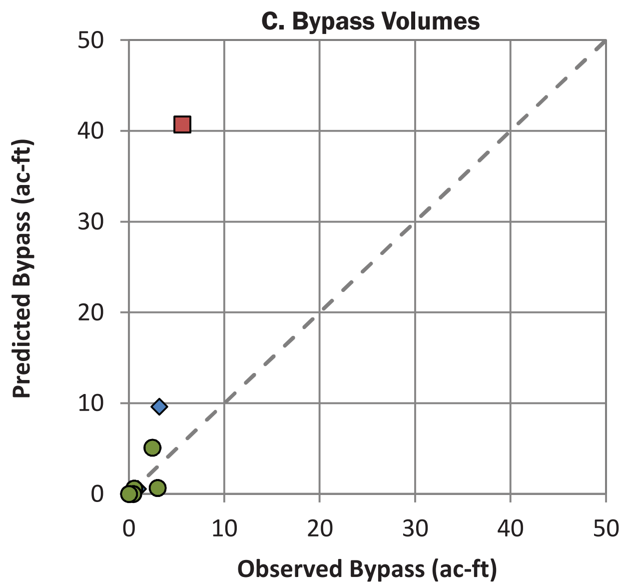
Seasons when baseflow is negligable



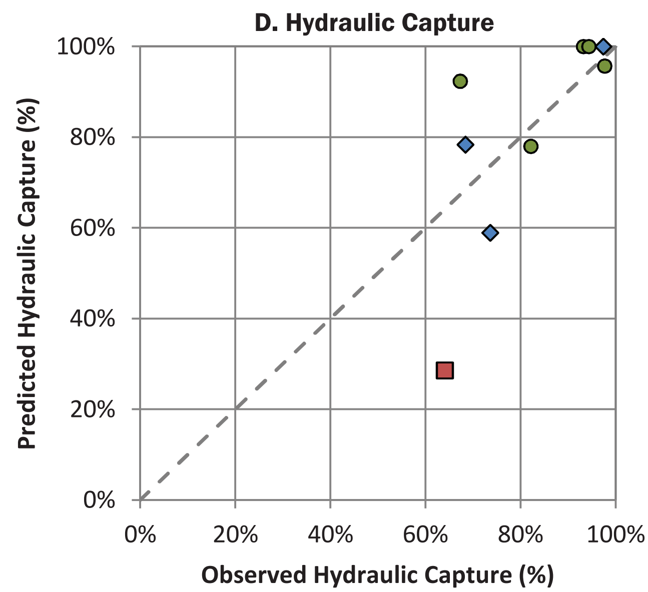
Very strong correlation between observed and predicted volumes (Pearson's r=0.78, significant above 98% confidence).



Very strong correlation between observed and predicted volumes (Pearson's r=0.83, significant above 99% confidence).

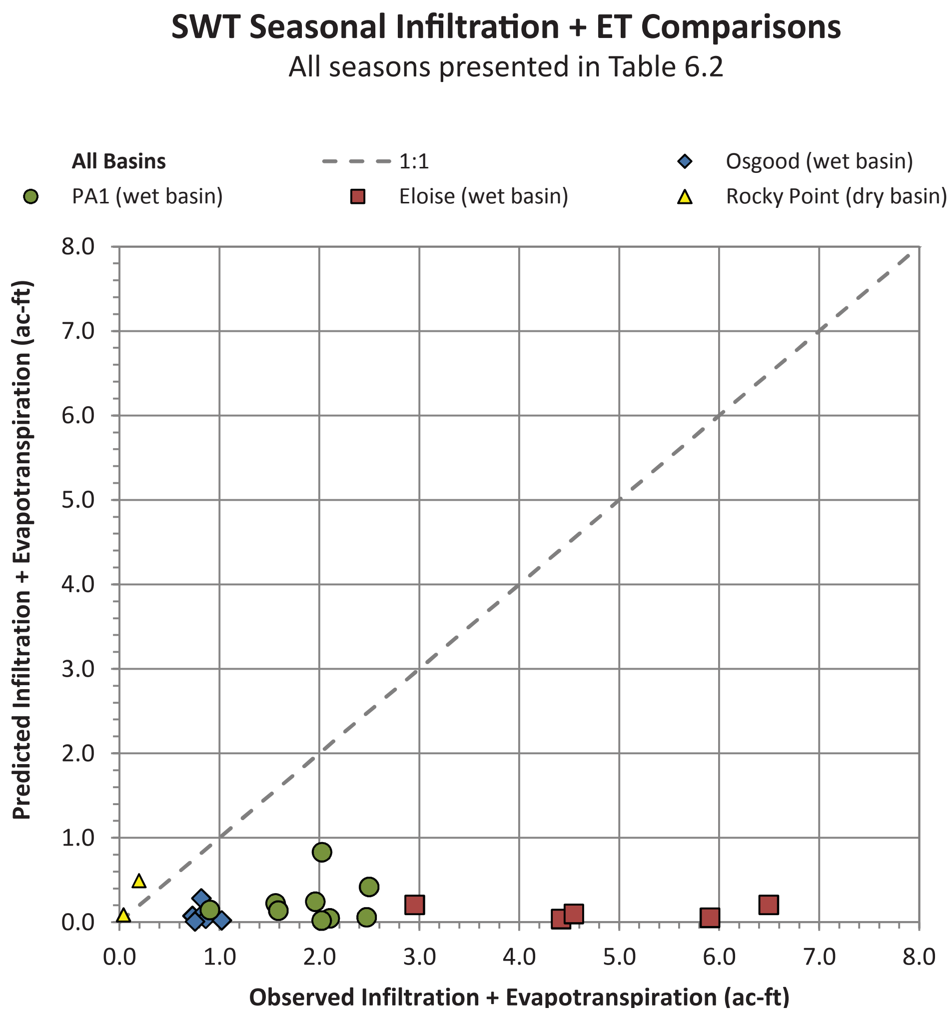


Very strong correlation between observed and predicted volumes (Pearson's r=0.85, significant above 99% confidence).



Very strong correlation between observed and predicted volumes (Pearson's r=0.73, significant above 95% confidence).

Seasons included are
Fall/Winter WY09
Spring WY09
Summer WY09
Fall/Winter WY10
Summer WY10
see Table 6.2



Observed and predicted seasonal infiltration and evapotranspiration volumes based on data shown in Table 6.2. Evapotranspiration volumes are negligible in comparison to infiltration volumes on seasonal time scales. Limited dry basin data (yellow triangles) show general agreement, while wet basin data show higher observed values relative to PLRM predictions. PLRM assumes infiltration does not occur in wet basins; however observations during WY09-WY11 suggest otherwise.

seasonal difference in the observed infiltration rates with spring/early summer typically at least 50% lower than the late summer/ fall rates (Table 6.4). This difference is expected as result of soil saturation, increased shallow groundwater table elevations in the spring, and the concurrent reduction in the amount of separation between the bottom of a basin the groundwater elevation. The seasonal rates estimated in Table 6.4 were averaged to determine the average annual infiltration rate for each SWT. Note that winter infiltration rates were difficult to calculate using the water budget analysis given the flashy hydrology of winter rain and rain on snow events, and the frequency of basin water depths above the treated outflow elevation.

Table 6.4. Average seasonal and annual infiltration rates calculated using the water budget analysis. For purposes of this analysis, spring/early summer is defined as April-July, and late summer/early fall is August-November.

SWT Type	SWT	# of data points		Observed infiltration rate (in/hr)		Observed average annual infiltration rate(in/hr)	Range of PLRM Recommended Infiltration Rates (in/hr)
		Spring/ Early Summer	Late Summer/ Fall	Spring/ Early Summer	Spring/ Early Summer		
Dry Basins	PA2	3	16	0.19	0.26	0.23	0.05 – 0.50
	Rocky Point	4	8	0.07	0.20	0.14	
Wet Basins	Osgood	2	4	0.01	0.02	0.02	n/a
	PA1	5	11	0.05	0.15	0.10	
	Eloise	1	11	0.05	0.10	0.08	

Observations indicate that the dry basins monitored had average annual infiltration rates on the order of 0.14 to 0.23 in/hr and seasonal rates ranging from 0.07 to 0.26 in/hr (see Table 6.4). PLRMv1 recommends a range of 0.05 - 0.50 in/hr for dry basins. While this research is limited to observations of two dry basins in South Lake Tahoe, CA over a period of roughly three water years, the available data suggest the range of infiltration rates recommended by PLRMv1 for dry basins is reasonable.

Observations indicate that the wet basins monitored had average annual infiltration rates ranging from 0.02 to 0.10 in/hr and seasonal rates ranging from 0.01 to 0.15 in/ hr (see Table 6.4). These estimated infiltration volumes contributed as much as 5-10% of the annual water loss from a wet basin (see Table 6.2). While this research is limited to observations of three wet basins in South Lake Tahoe, CA over a period of roughly three water years, the available data suggests that future improvements to PLRM should consider incorporating an algorithm that simulates infiltration in wet basins, at least on a seasonal time scale.

6.1.2 USING DISCRETE MEASUREMENTS TO INFORM INFILTRATION RATE INPUT TO PLRM

In addition to the comparison of observed and predicted volume estimates, this research included a series of discrete infiltration rate measurements using a constant head permeameter (CHP) (NRCS 2010; 2NDNATURE et al. 2010) to inform recommendations on how discrete CHP measurements could be used to infer appropriate PLRM inputs for average annual infiltration rates in SWTs. Despite calculated observations of infiltration in wet basins from the water level data, CHP measurements were not conducted in wet basins due to the sustained inundation of these SWTs, and therefore only dry basin data is available.

The CHP data are compared to the seasonal and annual infiltration rates calculated from the water budgets for each dry basin (see Table 6.4). As expected, CHP measurements varied spatially and seasonally within each SWT. Therefore, each SWT evaluation included multiple CHP measurements that collectively represented the different surface types and relative inundation frequencies of different infiltration surfaces within the SWT and at different times of year. Figure 6.5 presents these CHP values for each SWT compared to the measured seasonal infiltration rates for the respective SWT using the data in Table 6.4.

While the data is limited, it does provide a preliminary numerical relationship to convert CHP measurements to a seasonal infiltration rate for dry basins. Given both the seasonal variability of the CHP measurements and the seasonal differences in observed infiltration rates, it is recommended that multiple measurements are made across different seasons for the dry basin of interest to determine the appropriate average annual infiltration rates required for input to PLRM. One approach may be 4 discrete CHP observations (consisting of multiple CHP measurements that collectively spatially represent the SWT infiltration conditions that are then averaged) conducted every 3 months for one year. The rating curve equation in Figure 6.5 would be used convert to 4 seasonal infiltration rates that are averaged to obtain an average annual infiltration rate estimate for PLRM. This approach would provide an estimate of the average annual infiltration rate for the observed year only. The caveat of this approach is that the infiltration rate of an SWT that accepts urban stormwater in the Tahoe Basin will decline over time without maintenance (see Chapter 6.1.3 below). We recommend that the user consider the both the time since last maintenance prior to the discrete CHP measurements and the anticipated frequency of maintenance within the SWT when determining a representative average annual infiltration rate over the 18-year PLRM simulation. As discussed below, observations from this research suggest dry basin SWT infiltration rates might notably decline within a few years of treating typical Tahoe Basin urban stormwater.

6.1.3 OBSERVED DECLINE IN SWT INFILTRATION RATE

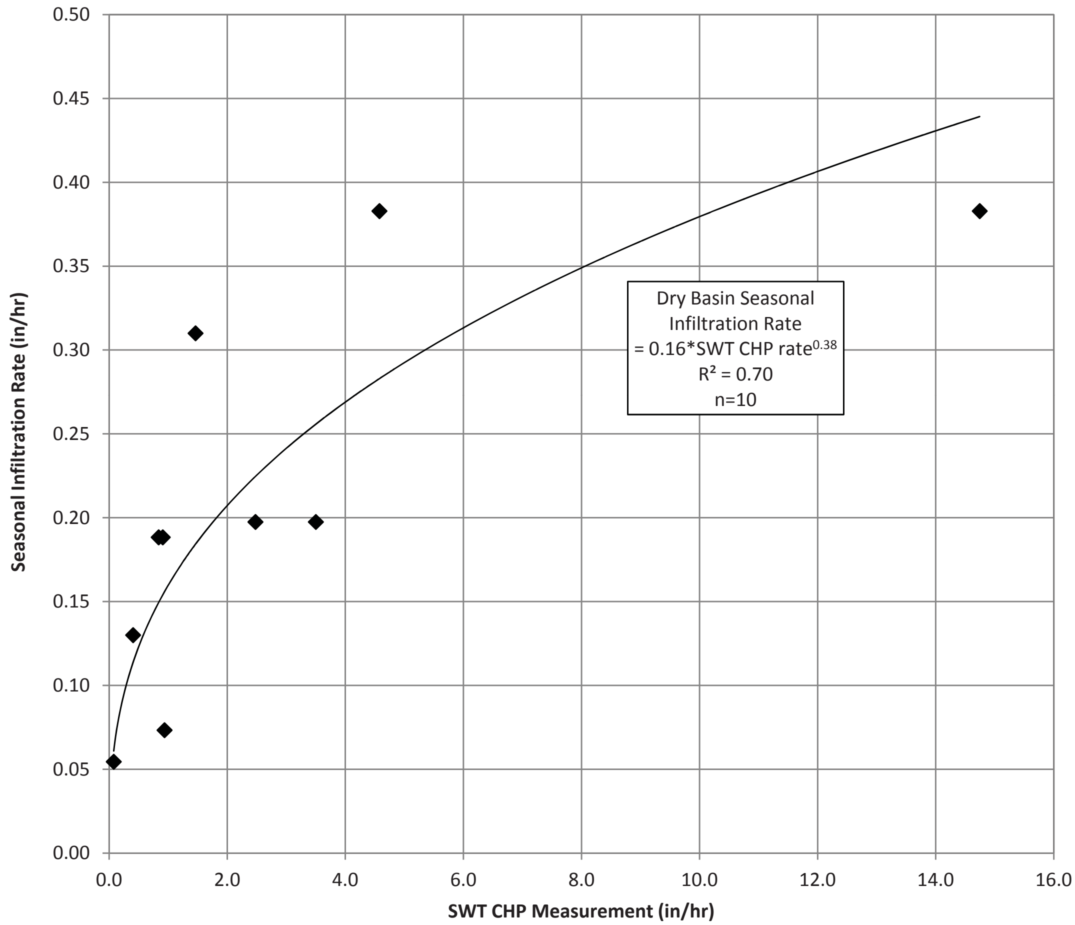
PLRM user guidance suggests the selection of an infiltration rate for a dry basin or infiltration basin that represents the average condition of the SWT facility over the long-term. In reality the infiltration rate of an SWT facility will vary over time based on the amount of pollutant loading and maintenance performed.

Layer of fine material accumulation in upper cell of PA2 following sustained inundation in Spring WY11.

Observations of the lower Park Avenue Basin (PA2) over the past 5 water years suggest that the decline in infiltration rate can occur fairly rapidly. Prior to Spring 2011, sustained inundation in PA2 had not been observed (see Figure 6.1C and 2N 2008) and any events that did inundate the dry basin were rapidly infiltrated. Modifications by the City of South Lake Tahoe to improve conveyance from PA1 to PA2 and the above normal 2011 water year notably increased the amount of observed stormwater routed to PA2 in the WY2011. The design of PA2 includes a rock weir that creates separate detention cells in the basin (see Figure 3.7C). Site observations and water level data suggested that the upper cell of the dry basin was inundated 57% of the time in WY2011, which is a significant increase relative to prior years monitored (Table 6.5). Following sustained inundation in the spring of 2011, field personnel observed a layer of fine material caking the basin surface in the upper cell of the dry basin (see photo at right). Coincidently, calculated observation of seasonal infiltration rates declined by 45% from WY10 to WY11 in the upper cell of the dry basin (see Table 6.5). The rapid decline in infiltration rates from a single water year, albeit one with a notable volume of stormwater discharged to the dry basin, was an unexpected result. This finding likely further highlights the need for frequent SWT maintenance to preserve desired infiltration rates.

Discrete CHP and seasonal infiltration rate comparisons

Dry Basins



SWT CHP measurement values are a spatially weighted series of discrete measurements taken throughout the dry basin, which collectively represent the different surface types and relative inundation frequencies of different infiltration surfaces within the SWT. SWT seasonal infiltration rates are shown in Table 6.4. Seasons are defined as Spring/Early Summer (April - July) and Late Summer/Early Fall (August - November).

While the above data is limited, it does provide a preliminary numerical relationship to convert CHP measurements to a seasonal infiltration rate for dry basins. Given both the seasonal variability of the CHP measurements and the seasonal differences in observed infiltration rates, it is recommended that multiple measurements are made over an annual time period for the dry basin of interest to determine the appropriate average annual infiltration rates required for input to PLRM. A potential approach could include 4 discrete SWT CHP observations conducted every 3 months for one year, which are converted to 4 seasonal infiltration rates and averaged to obtain an average annual infiltration rate. This approach would provide an estimate of the average annual infiltration rate for the observed year only and would potentially need to be adjusted to inform the long-term PLRM input of the SWT average annual infiltration rate.

Table 6.5. PA2 changes in measured infiltration rates from the water budget analysis compared to frequency of inundation within the basin based on the water level time series data. WY06 and WY07 data from previous 2NDNATURE (2008) research.

Water Year	Frequency of Inundation (% WY)	Average Annual Infiltration Rate (in/hr)
WY2006	4%	0.65
WY2007	0%	0.48
WY2009	0%	0.31
WY2010	0%	0.31
WY2011	57%	0.14

In Table 6.6 the CHP measurement time series is presented for the upper and lower cells of PA2. Prior to 2011, there is little difference in the observations made in the two cells. However, following sustained inundation of the first cell in 2011 there is a marked deviation between the measured CHP values. CHP measurements in the upper cell significantly decline while measurements made in the lower cell remain high. These results are consistent with the differences in infiltration rates measured using the water budget analysis (see Table 6.5).

Table 6.6. Comparison of CHP measurements in upper and lower cells of PA2.

Water Year	PA2 Upper Cell CHP Measurement (in/hr)		PA2 Lower Cell CHP Measurements (in/hr)	
	Summer	Fall	Summer	Fall
WY2009	-	14.74	-	11.53
WY2010	1.62	3.69	3.69	-
WY2011	1.98	3.50	>20	9.93

While similar datasets are not available to evaluate the potential decline in infiltration rates in wet basins, anecdotal evidence suggests that these basins were previously capable infiltrating greater volumes than they can currently. The photos below provide a visual time series of the progression of wetland vegetation development in PA1 from April 2005 to August 2011. This increasing presence of wetland vegetation suggests a higher percentage of organic material and fine-grained sediment at the basin bottom, which will likely decrease the infiltration capacity of the soil. Similar to PA1, Osgood and Eloise Basins are currently dominated by wetland vegetation. Using a simple assumption that each wet basin had an initial benchmark infiltration rate at time of construction of 0.25 in/hr, we estimate the potential reduction of the initial infiltration rate to those observed during this research (Table 6.7). We suspect the 0.25 in/hr benchmark infiltration rate is within the range of newly constructed basins in Tahoe soils with no developed wetland vegetation community. However, discrete measurements taken directly following construction or maintenance actions to restore basin infiltration are needed to improve this estimate.

Progression of wetland vegetation development in the Upper Park Avenue Basin (PA1) over the years: April 2005; September 2005, and August 2011.

Table 6.7. Simple assumptions of potential SWT infiltration rate decline.

SWT	Year Constructed	Assumed Infiltration Rate at Construction (in/hr)	WY2011 Observed Infiltration Rate (in/hr)	Total Rate Loss (in/hr)	% Performance Decline
Eloise	1990	0.25	0.08	0.22	74%
Osgood	1997	0.25	0.02	0.28	94%
PA1	2001	0.25	0.10	0.21	68%

6.1.4 SWT HYDROLOGY FINDINGS AND RECOMMENDATIONS

- A comparison of 23 seasonal estimates generated from 3 water years of SWT hydrology data collection to PLRM predictions indicate a very strong correlation (significant above 99% confidence) between measured and modeled treated outflow volumes across a range of hydrologic conditions experienced by dry and wet basins (see Figure 6.2B). Given that treated outflow is the most critical hydrology metric used to adjust pollutant loads as a result of SWT construction, this is a very valuable finding.
- Calculations from observed water level data confirms that baseflow can significantly influence the hydrologic performance of SWTs in the Tahoe Basin during wetter water years and runoff periods, and this influence is strongest in wet basins with large forested tributary areas. The current PLRM hydrology module was not developed to simulate baseflow, and during times of high seasonal groundwater the model will likely underestimate actual inflow and therefore overestimate the hydraulic capture performance of the SWT. PLRM was designed to be a relatively simple tool to predict potential pollutant load reductions from stormwater quality improvement projects in the Tahoe Basin over a long-term continuous simulation. The inclusion of additional algorithms that would accurately model seasonal baseflow on a site-specific basis would greatly increase the complexity of the model for the PLRM user, and therefore this potential improvement is not recommended. Furthermore, SWT designs that include large amounts of commingled forested runoff with urban stormwater runoff are discouraged, as the increased input of forested runoff to an SWT likely affects the hydraulic capture performance of an SWT.
- Future improvement to PLRM should consider allowing a user to define a baseflow component for a modeled SWT facility. To avoid significantly increasing the modeling complexity of PLRM, the recommended approach would allow a user to specify in the SWT editor the average monthly baseflow to the SWT facility. An internal PLRM refinement to this user input could then vary the monthly average baseflow during the long-term continuous simulation based on a statistical analysis of total precipitation for the water year being simulated. The PLRM algorithm would reduce average monthly baseflow when simulating below normal water years and would increase average monthly baseflow when simulating above normal water years.
- Despite the baseflow issue described above, the comparison of SWT hydrology data generated from three water years of data collection to PLRM predictions of performance illustrates reasonable agreement between measured and modeled performance across a range of hydrologic conditions (see Figure 6.2B). When the modeled to measured hydrologic comparisons are limited to seasons when baseflow is negligible, the alignment between measured and modeled hydrologic performance greatly improves (Figure 6.3). Given that PLRM estimates of treated flow and hydraulic capture are critical metrics used to estimate pollutant load reductions resulting from SWT implementation, this is an encouraging finding.
- PLRM algorithms include static rates of infiltration and flow through treatment outlets over the long-term continuous simulation. These static rates assume that SWTs are maintained over time to ensure

continued function at some standard level of performance. However, as noted in this research, consistent maintenance of SWTs in the Tahoe Basin is lacking (see Chapter 3.1.4 and Table 3.5). This research team has been monitoring SWTs in the Tahoe Basin for over a decade and to date maintenance of SWTs to restore function and preserve condition over time is not generally occurring. There is limited evidence from this research of rapid declines (up to 50%) in infiltration rates due to trapping of particulates at the basin surface in as little as 1-2 years. Furthermore, frequent clogging of low-flow treatment outlets for SWTs with heavy pollutant loads was observed during this research, which notably altered the hydrologic performance of the SWT relative to predicted performance. In order for SWTs to consistently achieve the pollutant load reductions predicted by PLRM, inspections and maintenance actions appear to be necessary on a frequent basis.

- Available data has been used to convert discrete CHP measurements to a seasonal SWT infiltration rate in dry basins. More data collection is necessary to refine this relationship. However, based on limited set of observations, the suggested range of average annual infiltration rates (0.05-0.50 in/hr) in PLRMv1 for dry basins appears reasonable.
- PLRMv1 does not allow for the simulation of infiltration in wet basins. Based on the results of this research, seasonal infiltration in wet basins may be an important factor in the overall water balance for wet basins. Should future versions of PLRM include infiltration in wet basins, a range of 0.01 to 0.10 in/hr is recommended.
- To ensure that modeled estimates of performance are reasonable, user inputs for PLRM should reflect a strong understanding of the hydrologic function of an SWT based on actual observations and measurements taken after construction of the SWT and not rely upon design specifications. SWT design and function is frequently more complicated than can be readily modeled in PLRM. Therefore, users of the PLRM will typically need a strong understanding of actual SWT function and the PLRM algorithms to develop a reasonable model representation. Future improvements to PLRM should consider allowing a PLRM user to input customized stage-discharge relationships for SWTs and potentially include more than one treatment or bypass outlet structure.

6.2 CHARACTERISTIC EFFLUENT CONCENTRATIONS (CEC)

The SWT sampling effort included inlet and outlet comparisons across a range of events to inform our understanding of pollutant treatment capabilities, particularly for FSP. Water quality data to inform PLRMv1 CECs are constrained to the quality of treated outflow from each SWT (see schematic on page 2.6). Resource limitations and data collection challenges result in a prioritization of SWTs for instrumentation and sampling to inform the CECs. Please refer to the SWT sampling methods section (Chapter 3.1.4) for details, but the majority of effluent samples have been obtained from a series of dry and wet basins over the past three water years. The figures and tables below include the results for all 4 pollutants evaluated (FSP, TSS, TP and SRP), but in an effort to keep the results section concise, we focus discussions on FSP due to the minimal amount of previous stormwater data available for this priority pollutant of concern.

6.2.1 EVENT CONCENTRATION REDUCTIONS

Passive samplers were installed in each dry and wet basin as inlet and outlet pairs set at the same elevations to sample the same time period of rising water in an SWT. The experimental design is based on the assumption that during a specific runoff event, the inlet/outlet pairs of passive samples will collect pre and post treatment water quality samples (see Figures 3.9A-B). Figures 6.6A-E present the pollutant concentrations obtained for each inlet and outlet pair for three dry basins and three wet basins. Samples that fall below the 1:1 line suggest pollutant concentration reductions as a result of treatment. It must be noted that some of the outlet samplers were installed above the treated outlet elevation in an SWT, and therefore Figure 6.6A-E includes both samples inferred to represent both treated and bypass flows. No grab sample data, which is discussed later, are included in the inlet and outlet data comparisons presented in Figure 6.6A-E.

Of the 85 inlet/outlet pairs analyzed for FSP, 68 or 80% of the samples collected at the outlet indicated an FSP concentration reduction. The frequency of FSP concentration reductions was more common in wet basins than dry basins. These simple concentration comparisons indicate that in addition to volume reductions, wet and dry basins do provide some removal of the mass of FSP in stormwater, which is likely attributable to particle settling and adherence onto vegetation. FSP concentration reductions as a result of treatment appear to be much more reliable when inlet concentrations are less than 300mg/L, which is particularly evident at PA1 (Figure 6.6D).

Given the available data, the average urban mixed catchment concentration (inflow to SWTs sampled) was 128 mg/L FSP and the average SWT effluent was 41.5 mg/L FSP (Table 6.8). Since PLRM assigns a static effluent concentration to treated volumes, a comparison of the effluent concentrations as a function of inflowing water quality suggests that the treatment capability of wet and dry basins is influenced by the FSP incoming concentrations. The average effluent SWT FSP concentration is 26 mg/L and treatment is more reliable when the inflowing stormwater is below 100 mg/L FSP, but the effluent is over 200 mg/L when the inflowing FSP concentration is > 300 mg/L (see Table 6.8). These findings support the assumption that effective pollutant source control actions in the catchment will reduce the concentrations and loads of pollutants delivered to public stormwater treatment systems, thereby increasing their effectiveness and duration of adequate performance prior to maintenance needs. The implications of these findings to inform future PLRM modeling of SWT treatment capabilities is addressed in the recommendation sections below.

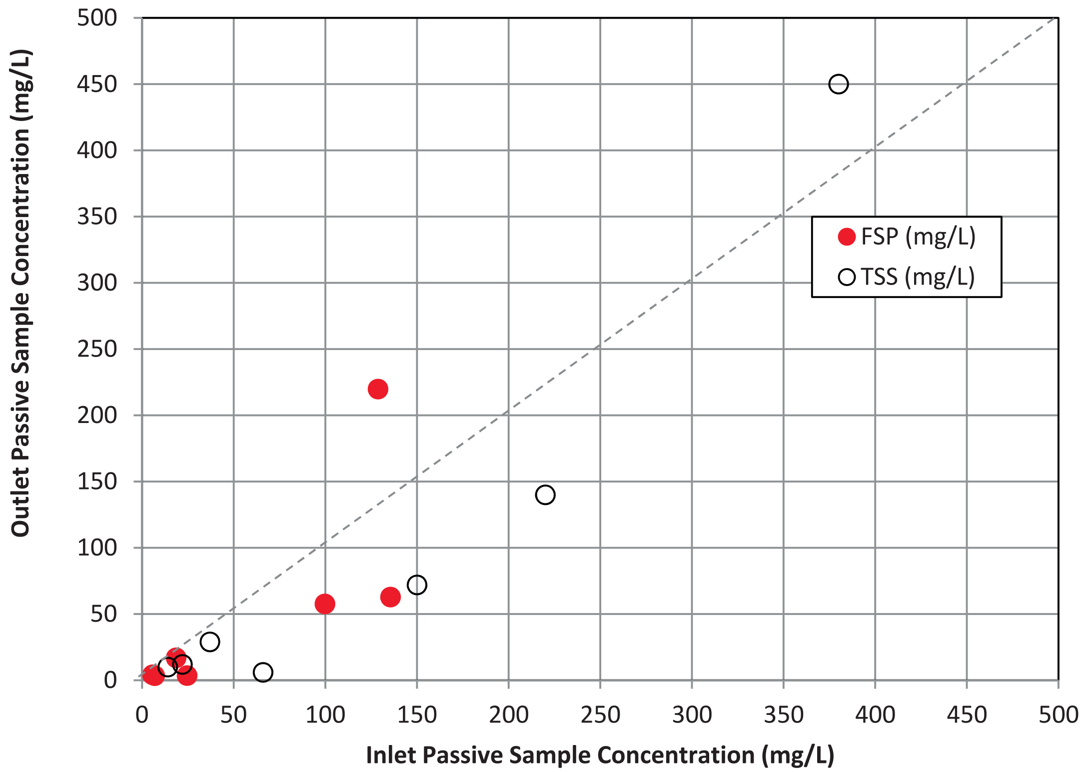
Table 6.8. Mean, standard deviation and n values for metrics of interest generated from the SWT water quality dataset. Values include samples collected from wet and dry basins as well as treated and bypass volumes as presented in Figures 6.6A-E.

	Mean	St Dev	*n*
Catchment (SWT inflow) FSP (mg/L)	129	156	*95*
SWT effluent FSP (mg/L)	41.5	76.0	*153*
SWT effluent FSP when inflow FSP < 100 mg/L	26.3	30.2	*55*
SWT effluent FSP when inflow FSP > 300 mg/L	204	177	*14*

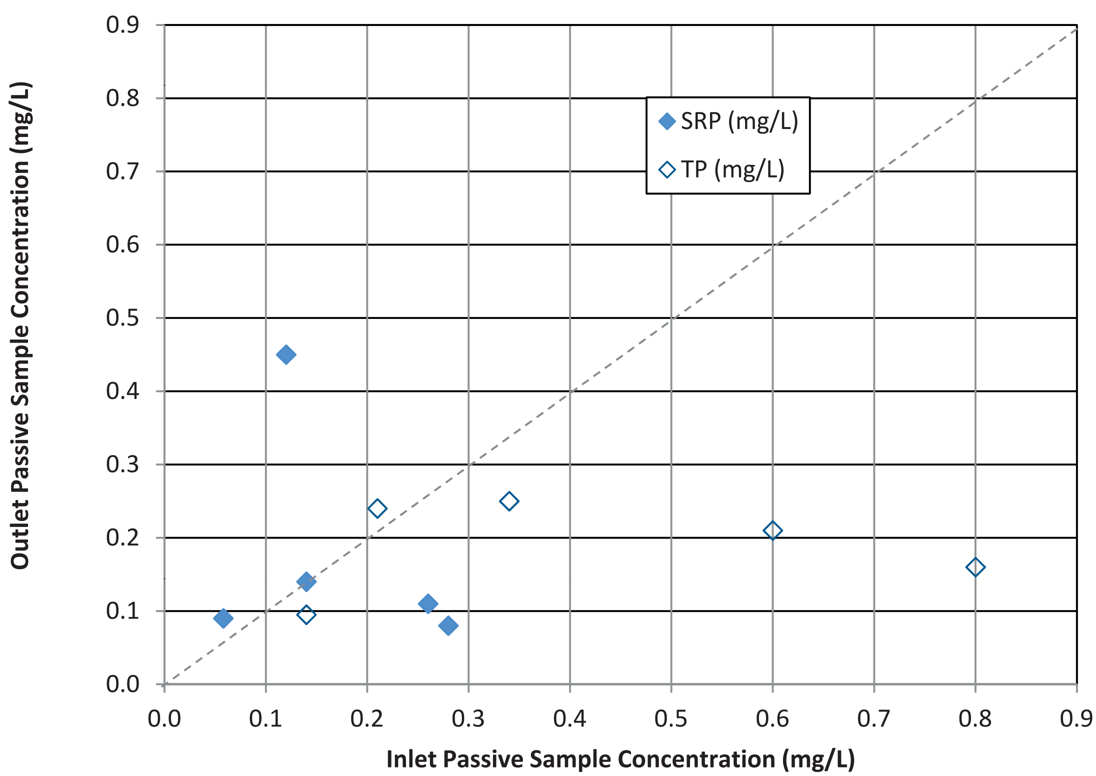
6.2.2 SEASONAL SWT OUTFLOW CONCENTRATIONS

Figure 6.7 illustrates the treated and bypassed FSP sample concentrations for dry and wet basins by collection month. The data show relatively elevated outflow concentrations (> 150 mg/L FSP) during high intensity summer and winter rain events compared to the winter and spring events. These findings are consistent with an array of other stormwater research findings that document relatively higher pollutant concentrations measured during intense summer and fall rains compared to snowmelt runoff or other low intensity rain events that do not have the same pollutant transport capacity. While higher intensity summer and winter rain events will produce larger peak flows in stormwater runoff that can influence treatment performance, the data appear to suggest that achievable effluent FSP concentrations for dry and wet basins may be linked to the inflowing concentrations of FSP.

Blue Lakes; Dry Basin



Treated n = 7
Bypass n = 0



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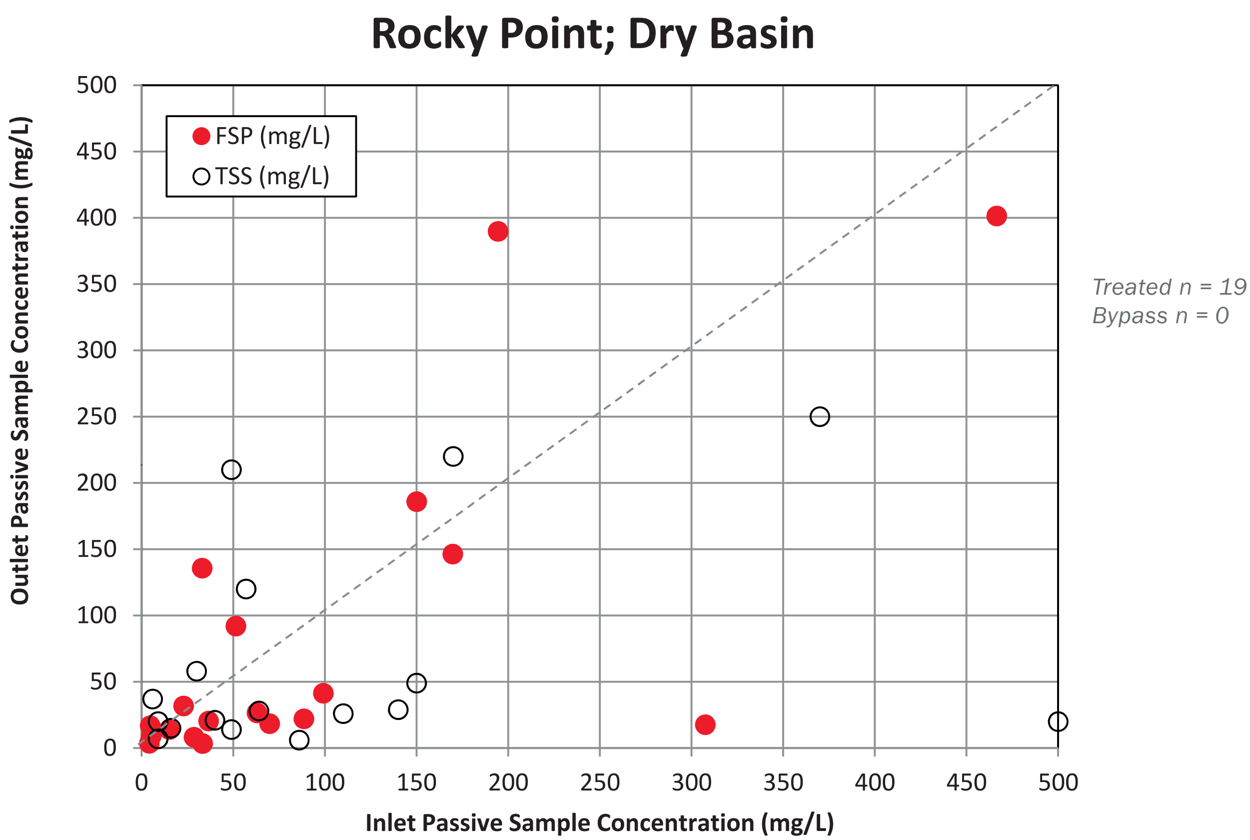
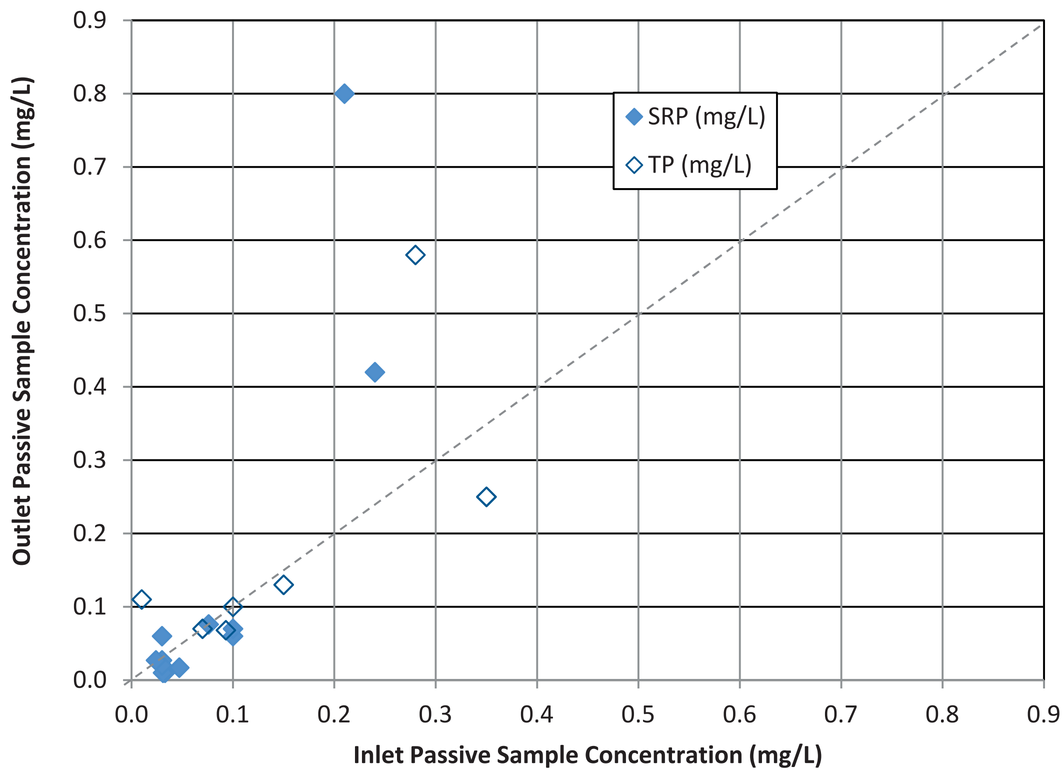
INLET/OUTLET CONCENTRATION COMPARISON: BLUE LAKES

FIGURE 6.6A





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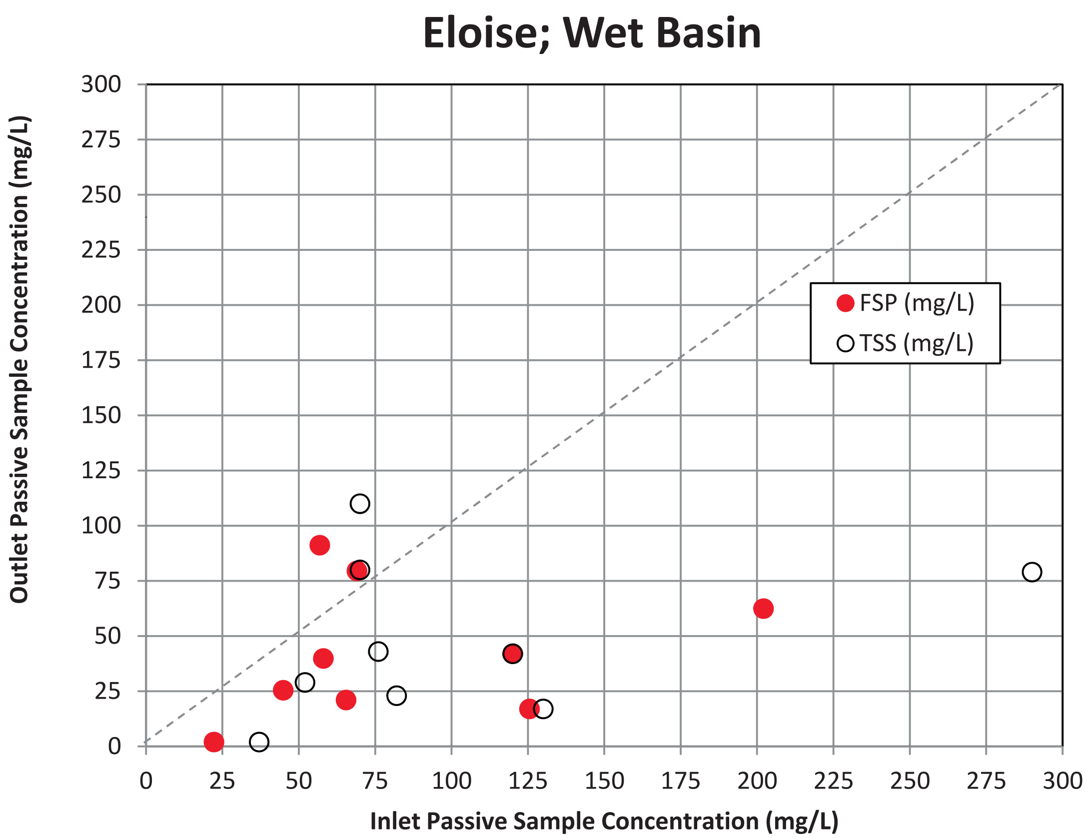
INLET/OUTLET CONCENTRATION COMPARISON: ROCKY POINT

FIGURE 6.6B



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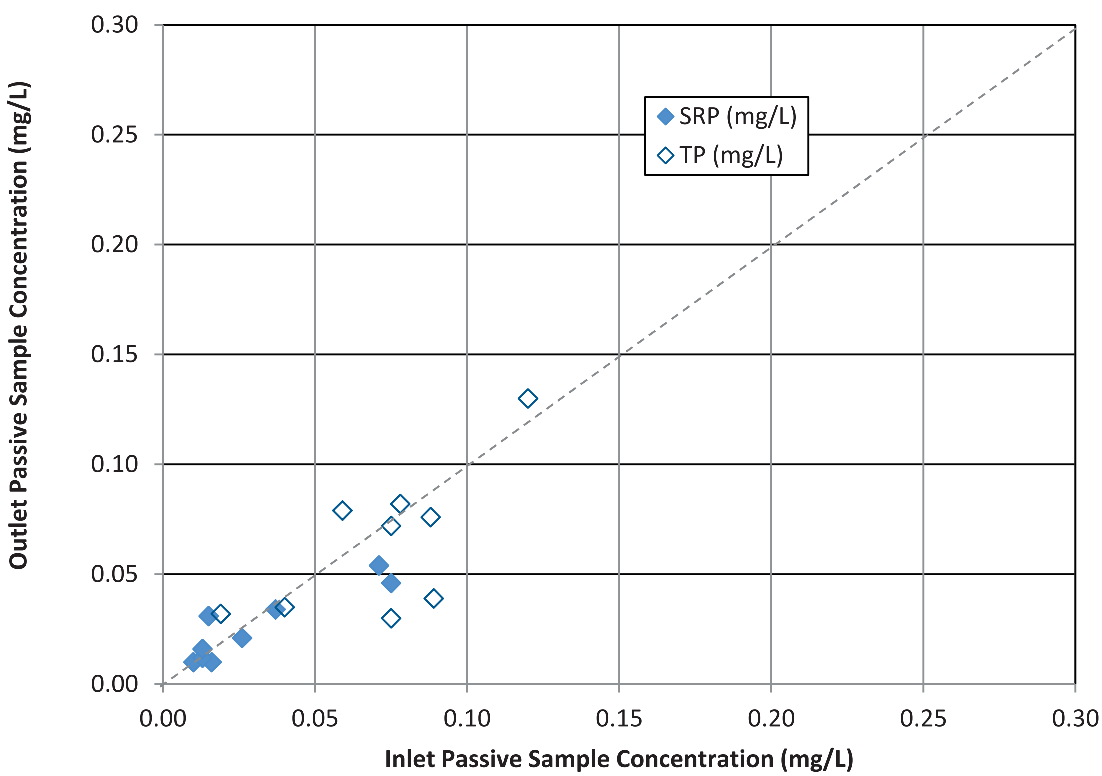
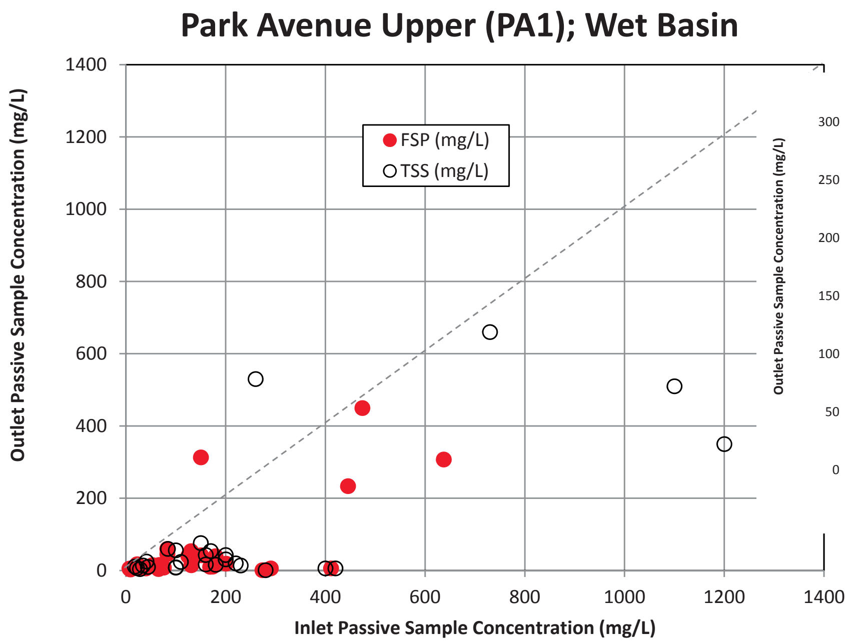
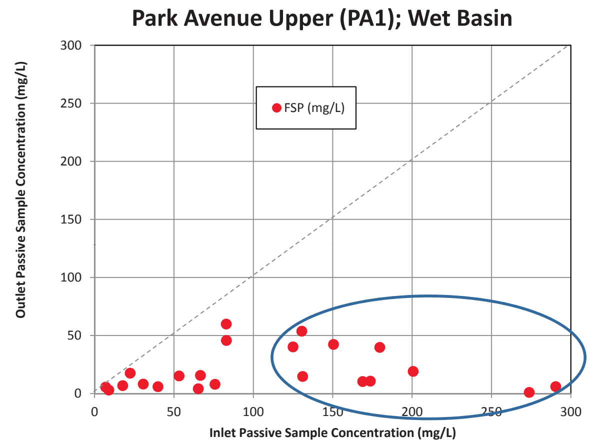
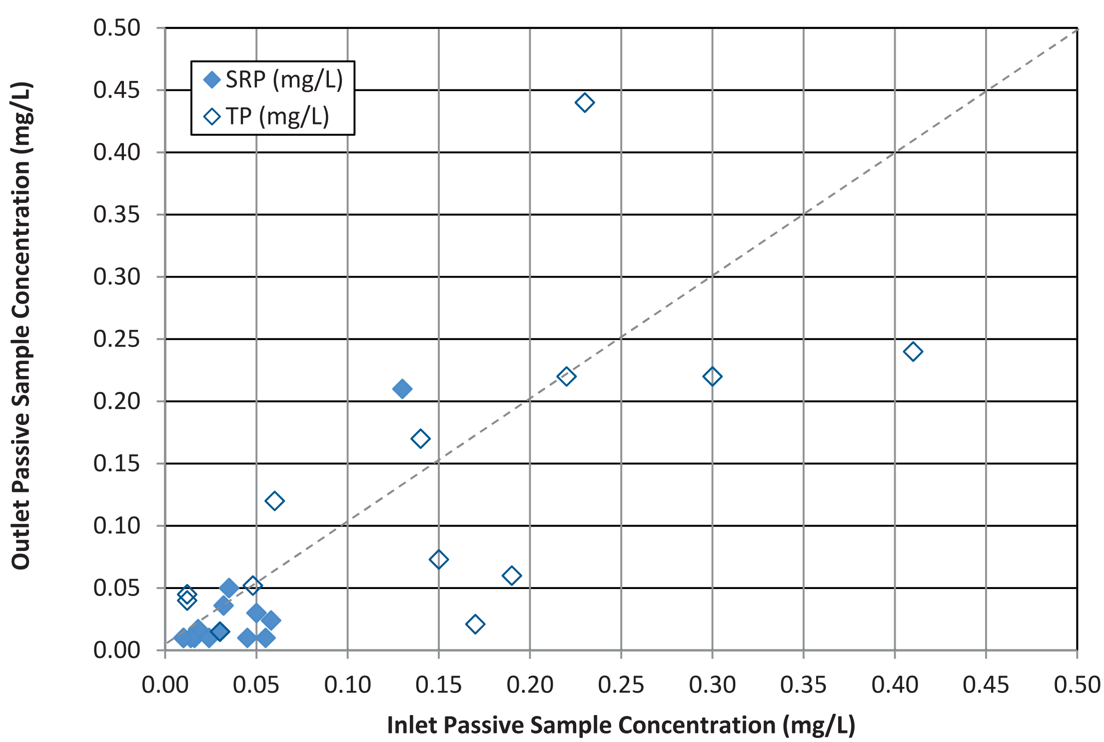
Bypass n = 9



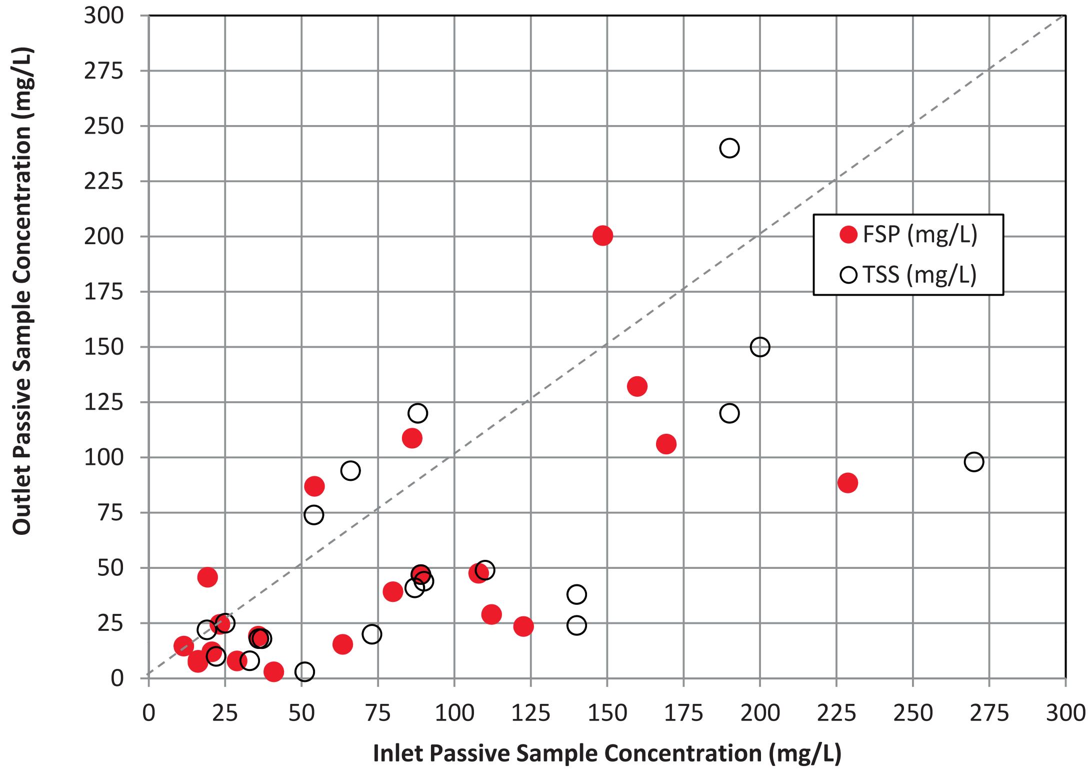




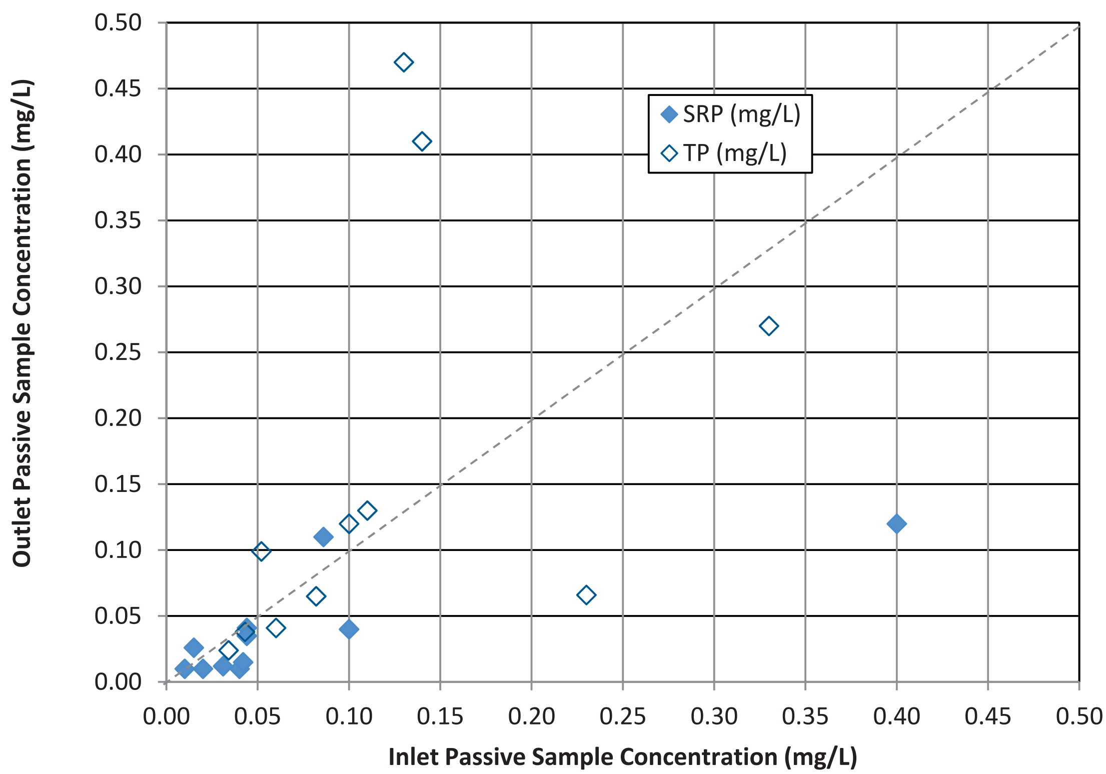
Treated n = 23
Bypass n = 4

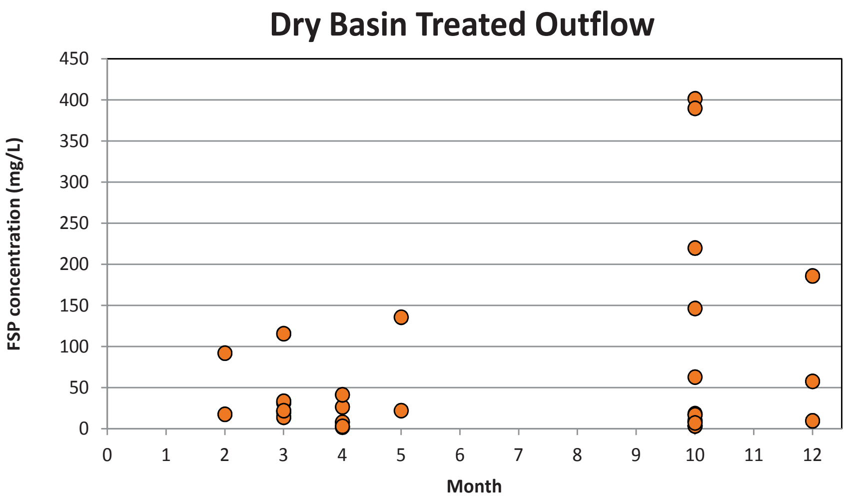


Osgood; Wet Basin

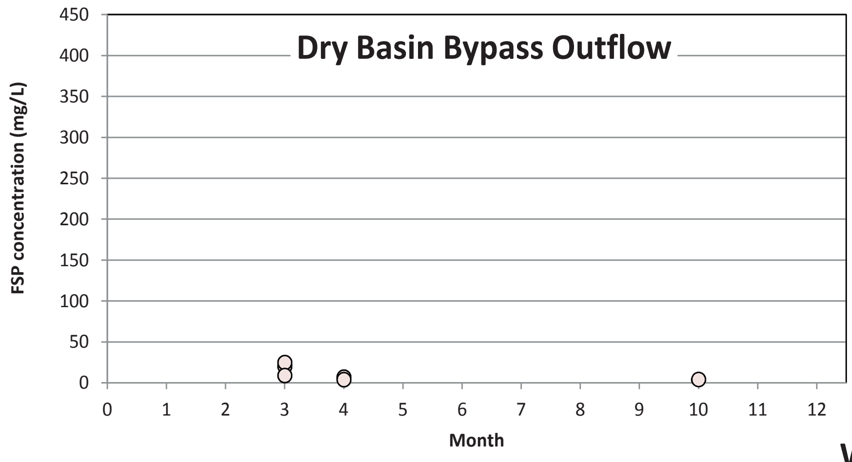


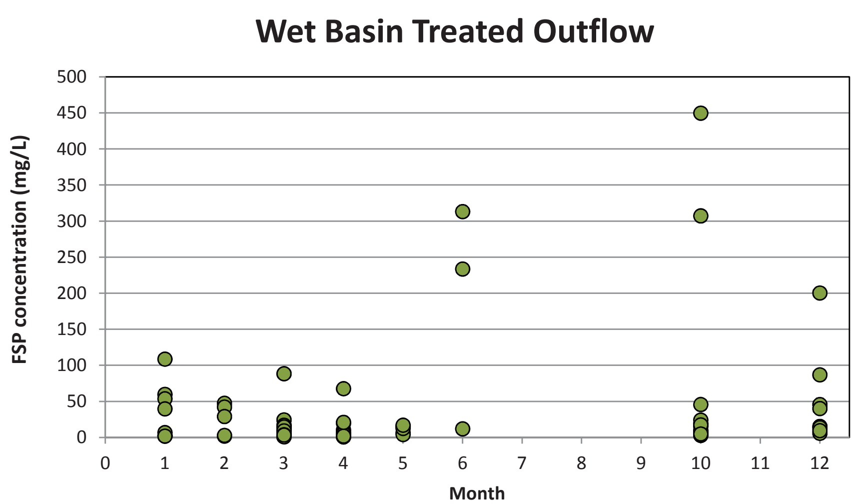
Treated n = 13
Bypass n = 13



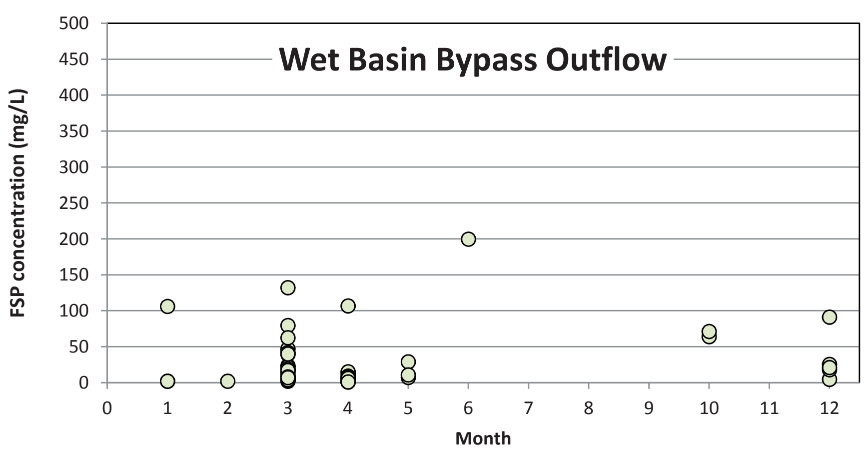


Of the 34 treated samples collected from dry basins, 15 were obtained via grab.





Of the 64 treated samples collected from wet basins, 34 were obtained via grab.



FSP TREATED AND BYPASS MONTHLY CONCENTRATIONS

FIGURE 6.7

6.2.3 COMPARISON OF MEASURED CONCENTRATIONS WITH PLRMV1 CEC VALUES

PLRMv1 currently assigns a static CEC value to all treated effluent volumes for each pollutant modeled based on the type of SWT facility modeled. This research obtained the largest dataset to date of dry basin and wet basin performance estimates for reducing pollutant concentration in stormwater runoff in the Tahoe Basin to compare with PLRMv1 CEC values. The overall sampling approach was designed to cost-effectively produce a dataset that captures the range of treated effluent pollutant concentrations across SWT sites and event types (i.e., summer thunderstorms, winter rain, rain on snow, and snowmelt) in order to infer the most representative CECs for wet and dry basins. While automatic sampling techniques may have produced a dataset with greater resolution and diversity of possible effluent concentrations, these techniques are extremely costly, and had they been implemented under this research, high resolution data collection would have been limited to a single SWT for two water years. The more cost-effective passive sampling technique combined with limited grab sampling was chosen in order to increase the spatial and temporal range of the dataset resulting in over 30 sampled events at three different wet basins and over 20 events at two dry basins.

It is worth noting that monitoring of flow-based cartridge filters with the same cost-effective passive sampling techniques used for dry and wet basins was not feasible, and therefore automated instrumentation had to be used to estimate treatment performance. The one cartridge filter included in the study proved to be extremely challenging to instrument properly due to backwater and high moisture content in the subsurface vault and the monitoring effort produced a very limited dataset. Data from the monitored cartridge filter is presented in Table 6.9, but additional effluent data from cartridge filters is necessary prior to evaluating the representativeness of the PLRMv1 CEC values for this type of SWT facility.

Over the three year period, treated outflow was sampled using both the passive samplers and grab sampling to capture concentrations during the rising limb, falling limb and peak of the event hydrographs and we believe the wet and dry basin dataset in hand provides a representative range of hydrograph characteristics across sites and event types. Evaluations of the grab sample timing indicate that that the majority of the grab samples were collected on the falling limb of the respective event hydrograph. The treated outflow samples are nearly an even split with 43% collected via grab sampling for the dry basins and 53% collected via grab from the wet basins (see Figure 6.7). Grab samples are an opportunistic sampling approach, which require site visits by field personnel during an event, and can result in sample collection anywhere on the storm hydrograph. In comparison, a passive sampler reliably collects a discrete sample on the rising limb of a storm at the same water level of SWT inundation across all events. The first flush phenomena that results in higher pollutant concentrations during the rising limb of an event hydrograph has been well documented in streams (Stubblefield et al. 2006) and urban stormwater (Bertand-Krajewski et al. 1998, CWP 2005). Thus, we expect sample concentrations collected from passive samplers on the rising limbs to be higher on a relative basis when compared to grab samples collected on the falling limbs of an event hydrograph. Quantitative comparison of passive and grab samples from all sites (using the non-parametric Mann-Whitney U statistic) shows that passive sample means are significantly higher (95% confidence) in the dry basins, while the same difference cannot be distinguished in the wet basins. These results were greatly influenced by the summer thunderstorms that infrequently resulted in treated outflow from wet basins during the study period, but rarely resulted in treated outflow (and thus were not sampled) at the subject dry basins (see Figure 6.7).

Given the potential sampling biases associated with the sampling design and our desire to determine a single average annual treated outflow concentration for dry and wet basins from the measured data to compare with PLRMv1 CEC estimates, the following approach was implemented and results verified using an objective statistical technique. All of the treated samples (grab and passive) were integrated by season and key statistical metrics for

WET BASIN TREATED OUTFLOW

	SRP (mg/L)	DP (mg/L)	TP (mg/L)	TSS (mg/L)	FSP (mg/L)
	Fall/Winter (Oct 1- Feb 28)				
mean	0.04	0.04	0.16	59.5	48.8
median	0.02	0.04	0.12	28.0	16.5
stdev	0.05	0.03	0.13	103.2	91.4
n	26	26	26	36	36
	Spring (Mar 1- May 31)				
mean	0.01	0.02	0.03	17.4	15.0
median	0.01	0.01	0.03	14.0	10.6
stdev	0.01	0.01	0.01	20.9	19.2
n	13	4	4	28	28
	Summer (June 1- Sept 30)				
mean	-	-	-	403	186
median	-	-	-	530	234
stdev	-	-	-	339	156
n	0	0	0	3	3

DRY BASIN TREATED OUTFLOW

	SRP (mg/L)	DP (mg/L)	TP (mg/L)	TSS (mg/L)	FSP (mg/L)
	Fall/Winter (Oct 1- Feb 28)				
mean	0.18	0.20	0.19	125	80.2
median	0.09	0.11	0.17	26.0	17.0
stdev	0.22	0.26	0.13	187	122
n	14	14	14	21	21
	Spring (Mar 1- May 31)				
mean	0.02	0.03	0.08	51.0	36.6
median	0.02	0.02	0.07	28.0	22.1
stdev	0.24	0.28	0.13	210	136
n	11	11	11	16	16
	Summer (June 1- Sept 30)				
mean	-	-	-	-	-
median	-	-	-	-	-
stdev	-	-	-	-	-
n	0	0	0	0	0

CARTRIDGE FILTER TREATED OUTFLOW

	SRP (mg/L)	DP (mg/L)	TP (mg/L)	TSS (mg/L)	FSP (mg/L)
	Fall/Winter (Oct 1- Feb 28)				
mean	0.02	0.02	0.06	40.3	22.3
median	0.02	0.02	0.06	28.0	21.4
stdev	-	-	-	27.6	15.4
n	1	1	1	3	3
	Spring (Mar 1- May 31)				
mean	0.01	0.02	0.06	43.8	34.9
median	0.01	0.02	0.05	48.0	17.0
stdev	0.001	0.01	0.01	28.6	31.7
n	3	3	3	5	5
	Summer (June 1- Sept 30)				
mean	-	-	-	65.0	54.1
median	-	-	-	-	-
stdev	-	-	-	-	-
n	0	0	0	1	1

wet basins, dry basins and cartridge filter samples and are provided in Table 6.9. The PLRM long-term simulation was used to determine the relative seasonal contribution of the average annual total urban runoff (Table 6.10). The seasonal runoff volume contributions were used to calculate a weighted mean and median for each pollutant of concern (Table 6.11) and compared to PLRMv1 CEC values by SWT type. EQ 6.3 summarizes how the seasonal FSP concentration values were integrated to calculate volume weighted average FSP concentration for wet and dry basins:

$$[FSP]average = [FSP]_{f/w} fRV_{f/w} + [FSP]_{spr} fRV_{spr} + [FSP]_{sum} fRV_{sum} \qquad \text{EQ (6.3)}$$

where [FSP] average is assumed to be our best representation of a flow-weighted annual average FSP concentration given the available dataset, $[FSP]_i$ is the average FSP concentration of all observations made within the respective seasons (see Table 6.9), and fRV_i is the fraction of the total average annual urban runoff volumes for each season indicated in Table 6.10.

Table 6.10. Average annual seasonal contribution to total urban runoff volumes as simulated by PLRM. These season designations are consistent with the NPDES permit stormwater monitoring reporting requirements (LRWQCB 2011).

Season	% of WY
Fall/Winter (Oct 1- Feb 28)	53%
Spring (Mar 1- May 31)	40%
Summer (June 1- Sept 30)	7%

By definition, a CEC is the long-term flow weighted concentration of all treated outflow discharged from a specific SWT type maintained in acceptable condition over an 18 year period. While the dataset used to estimate the values in Table 6.11 is limited, we do believe the dataset captures the range of potential event types, seasons, and pollutant loading conditions for the water years sampled. However, given the higher frequency of occurrence and relative ease of sampling snowmelt runoff event types, we believe the timing of the sample collection is likely to bias the existing dataset towards a higher number of low flow and low concentrations samples. While episodic high intensity rain events can transport substantially greater pollutant loads, they are more infrequent and therefore more challenging to sample, particularly using grab sampling techniques. Therefore, the flow weighted mean obtained from a representative dataset is assumed to be the most representative value to compare to PLRM CECs, rather than the median that can disproportionately reduce the influence of the higher concentration events on estimates of CECs during the monitoring period. The seasonal flow weighting approach incorporates greater importance of fall and spring seasonal concentrations on the annual stormwater loads. Thus, we recommend the most representative measured concentrations are the volume weighted seasonal means; highlighted in red in Table 6.11.

In order to assess the reasonableness of the volume weighted mean concentrations measured during this research (see Table 6.11), we employed a bootstrap resampling method. Since it is infeasible to sample the event mean concentration of all runoff events, we must obtain a subset of the population of possible events. The bootstrap analysis provides a measure of the variability of the mean we have computed from our sample by constructing a number of sample populations of the observed dataset (and of equal size to the observed dataset), each of which is obtained by random sampling with replacement from the original dataset. We resampled the wet and dry basin datasets 10,000 times for each pollutant to create a distribution of mean values from which we can estimate a confidence interval of the mean. The output of the bootstrap analysis is expressed as the range of the 95% confidence interval of the mean concentration. As presented in Table 6.11, all of the flow weighted means fall

WET BASIN

	SRP (mg/L)	TP (mg/L)	DIN (mg/L)	TN (mg/L)	TSS (mg/L)	FSP (mg/L)
	PLRM v1 CEC					
	0.04	0.10	0.10	0.10	10	10
	WY09-11 data					
volume weighted mean	**0.03**	**0.10**	NA	NA	**67**	**45**
volume weighted median	0.01	0.08	NA	NA	58	29
n	*39*	*30*	*NA*	*NA*	*67*	*67*
	Bootstrap Results					
bootstrap mean	0.03	0.14	NA	NA	57	41
95% confidence interval	0.02 - 0.05	0.10 - 0.20	NA	NA	33 - 115	25 - 75
bootstrap simulations	10,000	10,000	NA	NA	10,000	10,000

DRY BASIN

	SRP (mg/L)	TP (mg/L)	DIN (mg/L)	TN (mg/L)	TSS (mg/L)	FSP (mg/L)
	PLRM v 1 CEC					
	0.05	0.16	0.10	0.10	25	25
	WY09-11 data					
volume weighted mean	**0.10**	**0.13**	NA	NA	**87**	**57**
volume weighted median	0.06	0.12	NA	NA	25	18
n	*24*	*20*	*NA*	*NA*	*34*	*34*
	Bootstrap Results					
bootstrap mean	0.11	0.16	NA	NA	96	63
95% confidence interval	0.06 - 0.43	0.12 - 0.25	NA	NA	54 - 190	36 - 125
bootstrap simulations	10,000	10,000	NA	NA	10,000	10,000

within the bootstrapped 95% confidence intervals. These results indicate that we are 95% sure that the actual volume weighted mean is within the range of possible means that would be calculated for the entire event population, given the distributional characteristics of our dataset. In addition, the seasonal weighted average annual means for TSS and FSP are within 15% of the bootstrap means for TSS and FSP, which given the information available confirms these are the best estimations of the CECs using the measured datasets.

Comparing to PLRMv1 values, both the wet basin and dry basin TP and SRP CEC values currently fall within the 95% confidence range and are very similar to the volume weighted means generated with this dataset. In contrast, the PLRMv1 TSS and FSP CEC values for both wet and dry basins are lower than the minimum values of the 95% confidence interval (see Table 6.11). Given that this is the best available data on wet and dry basin treated outflow quality in the Tahoe Basin, it suggests that the TSS and FSP PLRMv1 CEC values are potentially too low relative to Tahoe Basin stormwater conditions. However, any recommendations for refining PLRM CECs for wet and dry basins should consider the following limitations of the dataset.

- The data was obtained from three increasingly wet water years. The winters were characterized by above average snowfall, which as explained in Chapter 5 could have potentially resulted in greater delivery of FSP from increased road abrasive use relative to normal or below normal water years. Additionally, greater annual volumes of runoff were sampled during the study relative to what would be expected during an average water year, which can reduce SWT treatment performance for TSS and FSP.
- As discussed in Chapter 6.1 when evaluating the limitations of SWT hydrology observations, there was a general lack of maintenance performed on the SWTs monitored for this study. Therefore, it is likely that each of the SWTs monitored was not performing at its highest achievable treatment condition and thus the observed treated water quality might be better if regular maintenance was implemented. Regardless of this point, we believe the data is representative of the general performance of most current SWTs in the Tahoe Basin, which typically receive infrequent water quality maintenance.
- The flow weighted mean for dry basins does not include any summer samples from high intensity and short duration rain events that typically have relatively high concentrations, thus biasing the dry basin population to the more frequent event types with lower pollutant concentrations.

Assuming the PLRM SWT module is not modified and continues to assign a static CEC for all treated outflow by SWT type, and based on the limitations and considerations above, we present recommended revisions to the PLRM CEC values (Table 6.12) assuming minimal SWT maintenance for water quality is performed. Each value presented in Table 6.12 falls between the minimum value of the 95% confidence interval and the volume weighted mean measured and considers the fact that the majority of data was obtained from wet water years. The recommended CEC revisions are intended to reflect our current understanding of SWT function and commitment to maintenance in the Tahoe Basin.

Table 6.12. Recommended revisions to PLRM TSS and FSP CECs for wet basins and dry basins in the Tahoe Basin.

SWT Type	Current PLRM TSS CEC (mg/L)	Recommended TSS CEC (mg/L)	TSS Rationale	Current PLRM FSP CEC (mg/L)	Recommended FSP CEC (mg/L)	FSP Rationale
WET BASIN	10	40	Minimum of 95% interval: 33 mg/L Volume weighted mean: 67 mg/L	10	30	Minimum of 95% interval: 25 mg/L Volume weighted mean: 45 mg/L
DRY BASIN	25	60	Minimum of 95% interval: 54 mg/L Volume weighted mean: 87 mg/L	25	40	Minimum of 95% interval: 36 mg/L Volume weighted mean: 57 mg/L

6.2.4 CEC FINDINGS AND RECOMMENDATIONS

- PLRMv1 currently assigns a static CEC value to all treated effluent volumes for each pollutant modeled based on the type of SWT facility modeled. Results suggest the treatment capability to achieve effluent FSP concentrations similar to the recommended FSP CECs in Table 6.12 are limited when inflow concentrations are relatively elevated (> 300 mg/L). The results of the data analysis suggest that future revisions to PLRM should consider developing a linkage between achievable effluent concentrations, especially for FSP, to inflowing concentrations while maintaining limits on the maximum achievable quality of treatment runoff. It is likely that PLRMv1 is currently overestimating treatment performance for SWTs where influent pollutant concentration are consistently high (e.g., greater than 300 mg/L; see Table 6.8). Effective pollutant source control actions implemented in catchments tributary to an SWT will reduce influent pollutant concentrations and thereby improve the treatment performance of the SWT.
- Volume weighted means of treated outflow quality were calculated for comparison to current PLRM CEC values for TSS, FSP, TP and SRP. A bootstrapping statistical technique was conducted on the raw datasets to define the 95% confidence interval within which we expect the actual long-term volume weighted mean to exist. The TP and SRP results were similar to PLRM CEC values and do not appear to require modification. However, the TSS and FSP estimates of treated effluent quality derived from this research were 3 to 4 times higher than the PLRMv1 CEC values for both wet and dry basins. Recommended revisions to the current PLRM TSS and FSP CECs for wet and dry basins are provided in Table 6.12. These relatively higher CEC values for FSP and TSS may be more appropriate estimates of achievable effluent quality from wet basins and dry basins given typical Tahoe Basin maintenance practices. Anecdotal evidence obtained from this research (see Chapter 3.1.4 and Table 3.5) and previous research efforts suggests that SWTs in the Tahoe Basin are generally not maintained to the level of maintenance assumed over the 18 year time period of simulation in PLRMv1.
- The continuation of long-term monitoring and sampling of treated outflow would be extremely valuable to increase the population of data across water year types and hopefully characterize improvements in treated effluent water quality as SWT maintenance actions likely increase in the Tahoe Basin as part of the Lake Tahoe TMDL implementation process. The inclusion of other SWT types modeled in PLRM using defensible and consistent data collection techniques would be also address key data gaps. The re-evaluation of efforts similar to this research on 5 year intervals would provide Tahoe specific stormwater quality data that would continue to inform and improve PLRM estimates of pollutant load reductions.

REFERENCES

2NDNATURE. 2006a. Detention Basin Treatment of Hydrocarbon Compounds in Urban Stormwater. Final Report. Prepared for South Tahoe Public Utility District. March 17, 2006.

2NDNATURE. 2006b. Lake Tahoe BMP Monitoring Evaluation Process: Synthesis of Existing Research. Final Report. Prepared for USFS Lake Tahoe Basin Management Unit. October 2006.

2NDNATURE. 2007. Water Quality Evaluations of a Fertilized Turf Surface in the Lake Tahoe Basin (2002-2006), Village Green, Incline Village, NV. Final Report. Prepared for the Nevada Tahoe Conservation District and USFS Lake Tahoe Basin Management Unit. May 2007.

2NDNATURE. 2008. Water Quality Performance Evaluation of Park Avenue Detention Basins; South Lake Tahoe, CA. Final Technical Report. Prepared for City of South Lake Tahoe Engineering Division. August 15, 2008.

2NDNATURE, Northwest Hydraulic Consultants (NHC), and Environmental Incentives. 2009a. Best Management Practice Maintenance Rapid Assessment Methodology (BMP RAM) Technical Document, Tahoe Basin. Final Document. Prepared for Army Corps of Engineers, Sacramento District. September 2009.

2NDNATURE, Northwest Hydraulic Consultants (NHC), and Environmental Incentives. 2009b. Best Management Practice Maintenance Rapid Assessment Methodology (BMP RAM) User Manual, Tahoe Basin. Final Document. Prepared for Army Corps of Engineers, Sacramento District. September 2009.

2NDNATURE and NHC. 2009c. Lake Tahoe Pollutant Load Reduction Model (PLRM) Database Refinement Final Monitoring Plan. Prepared for Army Corps of Engineers, Sacramento District. May 2009.

2NDNATURE and NHC. 2010a. PLRM v1 Focused Stormwater Monitoring to Validate Water Quality Source Control and Treatment Assumptions Technical Report. Final Document. Prepared for Army Corps of Engineers, Sacramento District. March 2010.

2NDNATURE and NHC. 2010b. PLRM Refinement Monitoring, Phase II Monitoring Plan. Final Document. Prepared for USFS Pacific Southwest Research Station. July 2010.

2NDNATURE, NHC, and Environmental Incentives. 2010c. Road Rapid Assessment Methodology (Road RAM) Technical Document, Tahoe Basin. Final Document. Prepared for the California Tahoe Conservancy and Nevada Division of Environmental Protection. November 2010.

2NDNATURE, NHC, and Environmental Incentives. 2010d. Road Rapid Assessment Methodology (Road RAM) User Manual, Tahoe Basin. Final Document. Prepared for the California Tahoe Conservancy and Nevada Division of Environmental Protection. November 2010.

2NDNATURE and NHC. 2011a. Pilot Catchment Validation and Testing of Existing Tahoe Basin Stormwater Tools. Final Data Collection Plan. Prepared for Army Corps of Engineers, Sacramento District. April 2011.

2NDNATURE and NHC. 2011b. Placer County Stormwater TMDL Strategy. Final Technical Report. Prepared for Army Corps of Engineers, Sacramento District and Placer County. July 2011.

2NDNATURE and NHC. 2012a. Pilot Catchment Validation Study. Draft Technical Report. Prepared for Army Corps of Engineers, Sacramento District. April 2012.

2NDNATURE. 2012 *In progress.* Statistical analysis of data obtained from an Incline Village street sweeping effectiveness study. Progress Report. Prepared for Nevada Tahoe Conservation District (NTCD) and Nevada Division of State Lands (NDSL). April 2012.

Bertand-Krajewski, J., Chebbo, G., and Saget, A. 1998. Distribution of pollutant mass vs. volume in stormwater discharges and the first flush phenomenon. Water Resources, 32(8): 2341-2356.

Center for Watershed Protection (CWP). 2005."The National Stormwater Quality Database, Version 1.1: A Compilation and Analysis of NPDES Stormwater Monitoring Information." Report prepared for U.S. Environmental Protection Agency, Washington, DC. September 4, 2005.

Gunter, M.K. 2005. Characterization of Nutrient and Suspended Sediment Concentrations in Stormwater Runoff in the Lake Tahoe Basin. M.S. Thesis. University of Nevada, Reno. May 2005.

Heyvaert, A., D. Nover, T. Caldwell, W. Trowbridge, G. Schladow, and J. Reuter. 2010. Assessment of Particle Size Analysis in the Lake Tahoe Basin, Draft Final Report. Desert Research Institute, Reno, NV, and University of California, Davis, CA. August 6, 2010.

Kayhanian M., T.M. Young, and M. K. Stenstrom. 2005. Small Particles and the Associated Constituents in Highway Runoff: Methodology and Preliminary Results. Final draft report prepared for the California Department of Transportation, Report No. CTSW-RT-06-73-23.1. Sacramento, California.

Lahontan Regional Water Quality Control Board (LRWQCB) and Nevada Division of Environmental Protection (NDEP). 2008a. Integrated Water Quality Management Strategy Project Report v1.0. March 2008. http://www.swrcb.ca.gov/rwqcb6/water_issues/programs/tmdl/lake_tahoe/

Lahontan Regional Water Quality Control Board (LRWQCB) and Nevada Division of Environmental Protection (NDEP). 2008b. Lake Tahoe TMDL Pollutant Reduction Opportunity Report v2.0. March 2008. http://www.swrcb.ca.gov/rwqcb6/water_issues/programs/tmdl/lake_tahoe/

Lahontan Regional Water Quality Control Board (LRWQCB) and Nevada Division of Environmental Protection (NDEP). 2009. Lake Clarity Crediting Program Handbook: for Lake Tahoe TMDL Implementation v0.99. Prepared by Environmental Incentives, LLC. South Lake Tahoe, CA. September 2009. http://www.swrcb.ca.gov/rwqcb6/water_issues/programs/tmdl/lake_tahoe/

Lahontan Regional Water Quality Control Board (LRWQCB) and Nevada Division of Environmental Protection (NDEP). 2010. Final Lake Tahoe Total Maximum Daily Load. November 2010. http://www.swrcb.ca.gov/rwqcb6/water_issues/programs/tmdl/lake_tahoe/docs/tmdl_rpt_nov2010.pdf

Lahontan Regional Water Quality Control Board (LRWQCB). 2011. Lake Tahoe Municipal NPDES Permit. December 2011. http://www.swrcb.ca.gov/rwqcb6/water_issues/programs/tmdl/lake_tahoe/npdes.shtml

Natural Resources Conservation Service (NRCS). 2007. Soil survey of the Tahoe Basin Area, California and Nevada. Accessible online at: http://soils.usda.gov/survey/printed_surveys/

Natural Resources Conservation Service (NRCS) - U.S. Department of Agriculture. 2010. Constant Head Permeameter (CHP) Construction and Implementation Guide. U.S. Department of Agriculture, NRCS South Lake Tahoe field office, South Lake Tahoe, CA. June 2010.

Nevada Tahoe Conservation District (NTCD) and Desert Research Institute (DRI), 2011. Effectiveness of Street Sweeping in Incline Village, NV. Prepared for USDA Forest Service, Nevada Division State Lands. December, 2011.

Northwest Hydraulic Consultants (NHC). 2007Aa. Site Investigation and Recommended Improvements to Increase Conveyance to Lower Park Avenue Basin. Prepared for City of South Lake Tahoe. July 2007.

Northwest Hydraulic Consultants (NHC). 2007b. Site Investigation and Recommended Improvements to Seepage in Lake Tahoe Boulevard in the Vicinity of D Street. Prepared for City of South Lake Tahoe. August 2007.

Northwest Hydraulic Consultants (NHC), Geosyntec Consultants, and 2NDNATURE. 2009a. Pollutant Load Reduction Model (PLRM) Model Development Document. Prepared for Tahoe Basin Storm Water Quality Improvement Committee. South Tahoe Basin, CA. October 2009. Complete documentation, users manual and tool available for download at http://www.tiims.org/TIIMS-Sub-Sites/PLRM.aspx.

Northwest Hydraulic Consultants (NHC). 2009b. Pollutant Load Reduction Model (PLRM) User's Manual. Prepared for Tahoe Basin Storm Water Quality Improvement Committee. South Tahoe Basin, CA. December 2009. Complete documentation and tool available for download at http://www.tiims.org/TIIMS-Sub-Sites/PLRM.aspx.

NHC, Geosyntec Consultants, and 2NDNATURE. 2010. PLRM Applications Guide. Prepared for Lake Tahoe Basin Storm Water Quality Improvement Committee. South Lake Tahoe, CA. October 2009.

Sartor, J. and G. Boyd. 1972. Water Pollution Aspects of Street Surface Contaminants. USA EPA. Contract No. 14-12-921. EPA-R2-72-081. 236pp. Washington, D.C. November 1972.

Stubblefield, A.P., M. I. Escobar, and E.W. Larsen. 2006. Retention of suspended sediment and phosphorus on a freshwater delta, South Lake Tahoe, California. Wetlands Ecology and Management, v. 14, p. 287-302, doi:10.1007/s11273-005-1482-6.

Tahoe Regional Planning Agency (TRPA). 2007. 2006 Threshold Evaluation Report. Prepared by TRPA staff. September 2007. Available at: http://www.trpa.org/default.aspx?tabindex=1&tabid=174

TMDL GIS Land Use Layer. Available for download at: http://www.swrcb.ca.gov/rwqcb6/water_issues/programs/tmdl/lake_tahoe/index.shtml