Infiltration BMP Design and Maintenance Study

FINAL TECHNICAL REPORT
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Developed by:

2NDNATURE, LLC
www.2ndnaturellc.com

Northwest Hydraulic Consultants
www.NHCweb.com

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TAHOE
REGIONAL
PLANNING
AGENCY

GLOSSARY

A consistent terminology was created for this research to simplify discussions in the text. In some instances these terms may not be universal, but for the purposes of this research were extremely useful.

BMP condition is a visual estimate of the amount of material accumulation at the media surface, and at 6-12 inches depth within an infiltration BMP in the field. BMP condition is quantified using a 1-5 scoring rubric where 1 = severe clogging, 3 = moderate clogging, and 5 = clean.

BMP drainage surface is the contributing surface, typically impervious, from which the water generated is intended to be retained and/or infiltrated by a downslope infiltration BMP.

BMP impairment is determined by the results of the 1L Infiltration Performance test which is completed according to the protocols defined in the BMP RAM v. 1 (2NDNATURE et al 2009). For this research the threshold for indicating impairment was 60 seconds.

BMP infiltration performance is measured of as the time (seconds) required to infiltrate 1L of water poured onto the surface of a BMP in the field. This was a slightly improved version of the BMP RAM v 1 protocol for Infiltration Performance.

BMP media is the rock that an infiltration BMP is filled with, typically 3/4"- 1 ½" drain rock, pea gravel, or cobbles.

Coarse material is defined as any organic and inorganic material larger than fine sand or > 125 µm in diameter.

Dry basins are large engineered treatment BMPs designed to reduce regional stormwater volumes and pollutant loads via infiltration and particle settling. Stormwater runoff is detained within the basin and either infiltrated, evaporated or slowly released through one or more outlets.

Dry wells are a type of infiltration trench that are typically constructed with larger augers resulting in greater depth and relatively shorter length than infiltration trenches.

Fine sediment is defined for the purposes of this study as material the size of fine sand or smaller (<125 µm). The fine sediment definition used for this research includes the primary pollutant of concern for lake clarity, fine inorganic particles < 16 µm in diameter.

Infiltration capacity (Q) is the maximum rate at which an infiltration BMP can transfer water to the underlying soil over a specified duration of time. Infiltration capacity is quantified by the measured or calculated volumetric discharge in units of volume per time and is the sum the vertical (Q_v) and lateral ($Q_{l)}$) infiltration capacity.

Infiltration basins are large engineered structures designed to detain stormwater runoff and infiltrate the detained runoff over a period of days. Infiltration basins, while similar in design to a dry basin, do not include an outlet structure that is designed to slowly draw down the water quality storage volume of the basin but may include a high-flow bypass or emergency spillway.

Infiltration surface is the interface at the base and sides of an infiltration BMP where water passes from storage into the surrounding native soil.

Infiltration trenches are gravel filled holding areas that receive and store stormwater runoff from impervious surfaces such as roofs, driveways, and parking lots. Detained stormwater slowly infiltrates through the bottom and sides of the trench into the surrounding sub-soil. Trenches are typically filled with clean, washed angular gravel that is ¾ to 1½ inches in diameter.

In Situ is the term used to identify the 1ft^3 experimental infiltration BMP configuration installed directly into the ground either in Tahoe King's Beach soil or Santa Cruz beach sand.

Long is the term used to identify the laboratory infiltration BMP configuration within the custom enclosure that did not include any sides and thus was used to quantify vertical infiltration capacity dynamics as a function of fine sediment loading.

Media surface is the upper boundary of drain rock or other material where stormwater typically enters an infiltration BMP. In most cases, the media surface is level with the surrounding ground surface.

Mini is the term used to identify the laboratory infiltration BMP configuration within the custom enclosure that included both lateral and vertical infiltration.

Pervious pavement is any system comprised of a load bearing surface that allows for movement of water through the load bearing surface into an underlying storage layer that can infiltrate or attenuate stormwater runoff. Pervious pavements are most applicable to locations with light vehicle loading. The load bearing surface can be made of porous concrete, or unit pavers or turf blocks separated by spaces and joints, through which water can drain.

Storage capacity (C_s) is the maximum volume of stormwater an infiltration BMP can detain.

Stormwater conveyance refers to the transport of runoff from an impervious surface to another destination, such as an infiltration BMP. Permanent runoff collection and conveyance practices are linear structures designed to intercept stormwater runoff and convey it downstream in a non-erosive manner to an appropriate treatment and/or infiltration system.

Subsurface infiltration systems are underground holding structures that receive and store stormwater. Detained stormwater slowly infiltrates through the bottom and sides of the system into the surrounding sub-soil. These systems are typically filled with clean, angular gravel that is ¾ to 1½ inches in diameter, a prefabricated product, or corrugated pipe.

Treatment capacity (C_t) is the volume of stormwater runoff that an infiltration BMP can physically detain and infiltrate to the underlying soil layer during a 20 year 1 hour storm event. Treatment capacity is the sum of the BMP storage capacity and infiltration capacity.

LIST OF VARIABLES

Variable	Definition	Units
Experimental variables		
ΔH	Change in water position from the initial to final height (H_i-H_f)	in
H_i	Initial height of water surface level	In
H_f	Final height of water surface level	in
t	Time	sec
Q	Infiltration capacity measured as volumetric discharge rate out of a BMP	ft^3/hr
Q_i	Initial infiltration capacity measured as volumetric discharge before sediment loading	ft^3/hr
Q_f	Final infiltration capacity measured as volumetric discharge for a given amount of sediment loading	ft^3/hr
FS_c	Cumulative mass of fine sediment (< 125 um) loaded into BMP	g
BMP characteristics		
L_{BMP}	BMP length	ft or in
W_{BMP}	BMP width	
D_{BMP}	BMP depth	
N_{ss}	Number of BMP short sides	#
N_{ls}	Number of BMP long sides	
A_{inf}	Total BMP infiltration surface area	ft^2
A_{base}	Vertical BMP infiltration surface area	
A_{sides}	Lateral BMP infiltration surface area	
V_w	Volume of stormwater	ft^3
V_v	Void space, fraction of BMP volume that can store water	%
K_{sat}	Saturated hydraulic conductivity of native soil	in/hr
Calculated variables		
Q_l	Estimated lateral volumetric discharge rate as a function of FS_a	in/ft^3
Q_v	Estimated volumetric discharge rate as a function of FS_a	in/ft^3
FS_a	Cumulative mass of fine sediment loaded to BMP per unit infiltration surface area	g/ft^2
R	Infiltration capacity reduction coefficient = Q_f/Q_i	%
R_l	Lateral infiltration capacity reduction coefficient	%
R_v	Vertical infiltration capacity reduction coefficient	%
C_s	Storage capacity for 1 hr as estimated in the BMP Calculation Spreadsheet (NRCS 2011)	ft^3
C_t	Treatment capacity is the volume of water retained and infiltrated during the 20yr / 1 hr storm at the respective location as estimated in the BMP Calculation Spreadsheet (NRCS 2011)	ft^3

1 EXECUTIVE SUMMARY

Infiltration BMPs are installed throughout the Tahoe Basin to meet regulatory requirements to retain and infiltrate the runoff volume generated by a 20-year, 1-hour storm from all impervious surfaces on a parcel. When this regulation is successfully applied, the hydrologic impacts of impervious surfaces and pollutant loading via stormwater runoff can be significantly reduced. However, sustaining the hydrologic and water quality benefits of infiltration BMP implementation requires regular maintenance. Previous studies have identified a lack of BMP maintenance in the Tahoe Basin as a common occurrence, resulting in infiltration BMP performance declines and failures (DRI 2004, 2NDNATURE 2006, 2009, and 2010a). Funded by the Tahoe Regional Planning Agency (TRPA), this research relies upon field surveys and laboratory experiments to improve our understanding regarding the timing and mechanics of infiltration BMP performance declines. The findings from this research are intended to guide a series of recommended improvements to infiltration BMP design and maintenance guidelines, including those within the TRPA BMP Handbook (TRPA 2012).

Infiltration BMPs appear to be an effective and sustainable strategy for infiltrating runoff generated from roofs with minimal maintenance needs. However, notable and potentially frequent maintenance needs were identified for infiltration BMPs receiving runoff from surfaces that tend to accumulate heavy amounts of fine sediment (< 125um); such as parking lots, driveways, and roads. A field survey of 75 infiltration BMPs in the Tahoe Basin suggests that the majority of infiltration BMPs draining surfaces other than roofs had impaired performance. Comparisons of BMPs treating roof runoff verses surfaces that accumulate pulverized road abrasive material (e.g. roads, driveways, parking lots) suggest severe loss of performance due to material accumulation. The presence of fine sediment in infiltration BMPs contributed to a persistent clogging layer that reduced infiltration rates or in extreme cases caused water to simply pool on the surface of a BMP with no observable infiltration whatsoever. BMPs treating roof runoff did appear to accumulate significant amounts of pine needles and other course material but the observed infiltration rates using simple field tests often approximate performance at installation.

A series of controlled simulation experiments using constructed BMP enclosures showed that loading fine sediment (< 125um) laden stormwater rapidly reduced the performance of infiltration BMPs over time. Visual inspections of the laboratory BMP enclosures indicated that fine sediment accumulation is greatest at the base of the infiltration BMP, creating a clogging layer with very low permeability. The range of experiments conducted showed a consistent pattern with considerable losses in infiltration capacity measured during initial stormwater loading. BMP configurations with more lateral (side) infiltration surface area experienced a somewhat slower decline in measured infiltration capacity since less fine sediment accumulated at the sides of the BMP relative to the base. The results indicate that BMPs with a greater proportion of lateral infiltration surface area may provide longer lasting benefits before maintenance is needed. This finding suggests deeper infiltration BMP designs could be used to prolong performance between maintenance intervals, but in locations where the groundwater table is seasonally high (Appendix A; Figure 4.3), deeper infiltration BMP designs would not be appropriate. Given the notable performance reductions observed, reducing sources of fine sediment from impervious surfaces may be the most cost effective way to improve performance and lessen maintenance needs for thousands of distributed infiltration BMPs installed in the Tahoe Basin.

The laboratory and in-situ results were used to develop empirical equations that estimate the vertical and lateral declines in infiltration capacity independently as a function of fine sediment loading and infiltration BMP surface area. Measured infiltration declines were predicted with very good accuracy regardless of the initial soil permeability for these in-situ BMPs, providing a limited validation the infiltration capacity decay equations. Additional validation experiments would improve confidence and allow formal integration of infiltration decline rates and maintenance benefits into critical Tahoe stormwater tools (e.g., the BMP Designer Tool, PLRM, LRPT, etc.) to provide more realistic estimates of pollutant load reductions over time.

The empirical equations of vertical and lateral infiltration decline were practically applied by making modifications to the existing BMP Calculation Spreadsheet, which is used to size many infiltration BMPs in the Tahoe Basin. A number of modeling scenarios were conducted using the modified BMP Calculation Spreadsheet to predict the effect of fine sediment loading on infiltration capacity of BMPs many years following installation. Key findings of this analysis include:

- Fine sediment loading rates estimated for roof runoff did not significantly affect infiltration capacity on decadal time scales.
- Fine sediment loading rates estimated for untreated driveway and parking lot runoff substantially affected infiltration capacity within a few years. Within a simulated period of two to four years, infiltration capacity markedly declined if an infiltration BMP was loaded with untreated driveway or parking lot runoff.
- Surface infiltration BMPs may be the most appropriate selection for driveway and parking lot runoff (because maintenance actions to restore infiltration capacity are practical to conduct).
- As the proportion of lateral infiltration surface area increased relative to total infiltration surface area, the infiltration capacity of the infiltration BMP increased (i.e., deeper infiltration BMP designs could be used to prolong performance between maintenance intervals).

This analysis highlights the importance of BMPs with accessible maintenance and suggests that the effectiveness of infiltration BMPs for driveways, parking lots, and roads could be greatly improved by reducing the sources of fine sediment from impervious surfaces, increasing the frequency of maintenance, and including stormwater pre-treatment devices. The choices between these options would depend on site specific characteristics, installation costs, and opportunities.

Based on the research findings, recommendations include:

1. Current infiltration BMP sizing and maintenance practices are adequate for infiltration BMP receiving roof runoff, or runoff of similar quality. The lack of fine sediment in roof runoff reduces clogging compared to other drainage surfaces, extending the time adequate performance before maintenance is required.
2. BMP plans with infiltration BMPs sited to receive drainage from surfaces with substantial fine sediment sources should be required to demonstrate how infiltration performance will be sustained. The suite of strategies employed may include: a) controlling and reducing the sources of fine sediment from impervious surfaces; b) BMP maintenance; and c) installation of pre-treatment devices.
3. Revise the technical basis of algorithms used to calculate BMP treatment capacity to estimate declines in side and base infiltration capacity based on fine sediment loading rates.

4. Consider refinements to the BMP handbook to strengthen maintenance, pre-treatment, and source control requirements based on expected fine sediment loading from the associated drainage surfaces.
5. The current version of PLRM does not link estimated fine sediment loading rates to infiltration capacity reductions or required maintenance intervals. The PLRM could incorporate the empirical decay equations developed from this research to predict maintenance needs based on estimated fine sediment loading rates using current PLRM output.
6. Identify a test catchment for evaluating trade-offs between maintaining distributed infiltration BMPs, developing regional treatment systems, and improving source control efforts.

BMP design and long-term performance may be improved by development of an integrated user friendly web -based platform to track and assess BMP design, installation and maintenance requirements over time. Currently, an ad-hoc approach using a disparate set of tools is required for BMP sizing, site retrofit design and TRPA certification tracking for both single family residences and commercial projects. A great opportunity exists to integrate the technical knowledge gained from this research regarding infiltration performance changes over time with BMP Calculation Spreadsheet for BMP sizing, the graphic BMP Designer Tool (currently under development by TRPA) and Load Reduction Planning Tool (LRPT) that informs parcel scale retrofit design and provides an estimate of the pollutant load reductions achieved. Such a platform could include parcel as built BMP records and greatly simplify the design and certification process. Not only would the complete parcel scale BMP design, maintenance and tracking process be standardized, but it would make site-level information available for ongoing performance tracking, pollution reduction estimate reporting, and automated maintenance requirements alerts. Using the recently developed Stormwater Integrated Tracking Tool that supports the Tahoe TMDL and Lake Clarity Crediting Program as a model, a Tahoe BMP Inventory and Design tool could greatly increase the citing, design and effectiveness of infiltration BMPs to provide the intended water quality benefits Basin-wide.

2 INTRODUCTION

The Tahoe Regional Planning Agency (TRPA) initiated and managed this research effort to assess and improve current guidance for best management practices that rely upon infiltration (infiltration BMPs) to control stormwater runoff and reduce pollutant loading in the Tahoe Basin. Funding was provided by federal grants from the United States Environmental Protection Agency (USEPA) to the California Regional Water Quality Control Board - Lahontan Region (Lahontan) to implement California's Nonpoint Source Program pursuant to CWA Section 319(h). The research effort was led by 2NDNATURE and Northwest Hydraulic Consultants (NHC).

This report communicates the results of a BMP field survey, laboratory experiments, and in situ experiments conducted to improve understanding of BMP condition and performance declines over time. The research included an initial information synthesis to advise managers on the implementation and risks of infiltrating stormwater via infiltration BMPs in the Tahoe Basin (2NDNATURE and NHC 2011; Appendix A). The synthesis provides the scientific basis to support pollutant-specific assessment of the stormwater discharge to groundwater regulations; evaluate soil characteristics with the potential to affect subsurface pollutant transport; and identify key factors influencing decline and failure of stormwater infiltration BMPs.

This report is organized into six sections including an executive summary (Chapter 1). This introduction (Chapter 2) summarizes the functions of infiltration BMPs, existing Tahoe Basin standards of practice, research goals and objectives, and the research approach. Chapters 3 and 4 document the methods and findings for the field survey and stormwater loading simulations, respectively. Chapter 5 presents the recommended modifications to the current infiltration BMP design tool (USDA NRCS 2011), incorporating the applied knowledge of how infiltration BMP siting, design and maintenance practices can be improved to better achieve longer performing BMPs. The conclusions and recommendations are synthesized in Chapter 6.

2.1 INFILTRATION BMP FUNCTION AND TERMINOLOGY

Stormwater runoff from urbanized areas is recognized nationally as a major source of non-point source pollution and is identified by the Lake Tahoe TMDL (LRWQCB and NDEP 2010) as the largest source of pollution impairing Lake Tahoe's transparency. Urbanization alters the natural hydrologic response of a watershed to a runoff event, producing stormwater runoff with greater pollutant transport potential and erosive force. Rates and volumes of stormwater runoff are affected through several mechanisms, but the most important of these are: 1) conversion of pervious surfaces to impervious surfaces such as roofs and pavement; and 2) development of more efficient drainage systems that connect impervious surfaces to streams and other water bodies. These changes increase the rate and volume of stormwater runoff by reducing infiltration of precipitation as well as decreasing the storage and infiltration of runoff along natural drainage paths.

A key method for mitigating the hydrologic impacts of existing and allowable development in the Tahoe Basin is the implementation of infiltration BMPs. While different types of infiltration BMPs are used depending on the requirements of a particular project site, they all rely on same basic physical principles to control, detain, and infiltrate stormwater runoff to the underlying soil. Types of infiltration BMPs range in size and complexity from infiltration trenches under roof eaves and decks for a residential home, to subsurface infiltration systems installed in commercial parking lots, to large-scale infiltration basins that collect and detain runoff from a network of roads and storm drainage infrastructure. For the purposes of this report the following definitions are used when discussing the functions and components of an infiltration BMP (Figure 2.1):

- *Infiltration surface* is the interface where water passes from storage within the BMP to the surrounding soil. For example, the infiltration surface of an infiltration basin is the surface of the soil comprising the basin bottom, whereas the infiltration surfaces of an infiltration trench are the bottom and side walls of the trench.
- *Media surface* is the upper boundary of drain rock or other material where stormwater typically enters the infiltration BMP. In most cases, the media surface is the same height as the surrounding ground surface. Media used in infiltration BMPs are typically composed of drain rock of various sizes (usually ¾ to 1½ in), pea gravel, or cobbles.
- *Treatment capacity* is the volume of stormwater runoff that an infiltration BMP can physically detain and infiltrate to the underlying soil layer in an hour. Treatment capacity is the sum of the BMP storage capacity and infiltration capacity.
- *Storage capacity* is the maximum volume of stormwater an infiltration BMP can detain.
- *Infiltration capacity* (Q) is the rate at which an infiltration BMP can pass a water to the underlying soil over a specified duration of time, expressed herein as the volume per hour.

Infiltration BMPs can be a highly effective method for reducing annual stormwater volumes and associated pollutant loads. When stormwater is infiltrated, many pollutants are filtered or adsorbed by the soil particles in the subsurface, which severely limits any further transport of the pollutants. Infiltration can be highly effective at removing pollutants in stormwater such as fine sediment particles (FSP; <16µm), trace metals, particulate forms of nitrogen and phosphorus, dissolved forms of phosphorus, and oil and grease (see Appendix A). The Lake Tahoe TMDL established that fine inorganic particles are immobile in the subsurface (LRWQCB and NDEP 2010), and may in fact be mostly retained within the first few centimeter of soil beneath an infiltration feature and attenuate rapidly with depth (e.g., Barraud et al., 1999).

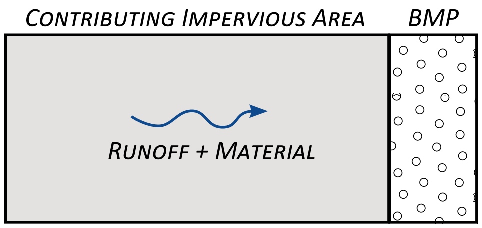
2.2 EXISTING STANDARDS OF PRACTICE

Chapter 60.4 of the TRPA Code of Ordinances (2012b) stipulates BMP requirements for development on public and private land, as well as BMP retrofit of existing development. Among the water quality protection measures is a requirement to control and infiltrate the runoff volume generated by a 20-year, 1-hour storm from all impervious surfaces on a parcel. The regulation provides that a precipitation intensity of 1 inch per hour be used to calculate the runoff volume and refers to the TRPA BMP Handbook (2012a) for guidelines on the design of infiltration BMPs. To demonstrate compliance with regulatory requirements, infiltration BMPs must have adequate treatment capacity to store and infiltrate the required runoff volume. For smaller residential and commercial projects, the design and sizing of infiltration BMPs to meet regulatory requirements is typically accomplished using the BMP Calculation Spreadsheet developed by the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS 2011). For larger private projects and public water quality improvement projects, compliance with regulatory requirements is typically demonstrated using a broad range of engineering and stormwater analysis tools, with one example being the Pollutant Load Reduction Model (PLRM; NHC et al. 2009).

Schematic of Typical Infiltration BMP

Infiltration BMPs are required to capture and infiltrate the runoff generated from an an adjacent impervious surface for a 1 inch, 1 hour storm event. BMPs are constructed within the native soil and BMP media is typically ³/₄" to 1-¹/₂" drain rock with a void space (V_v) of approximately 40%.

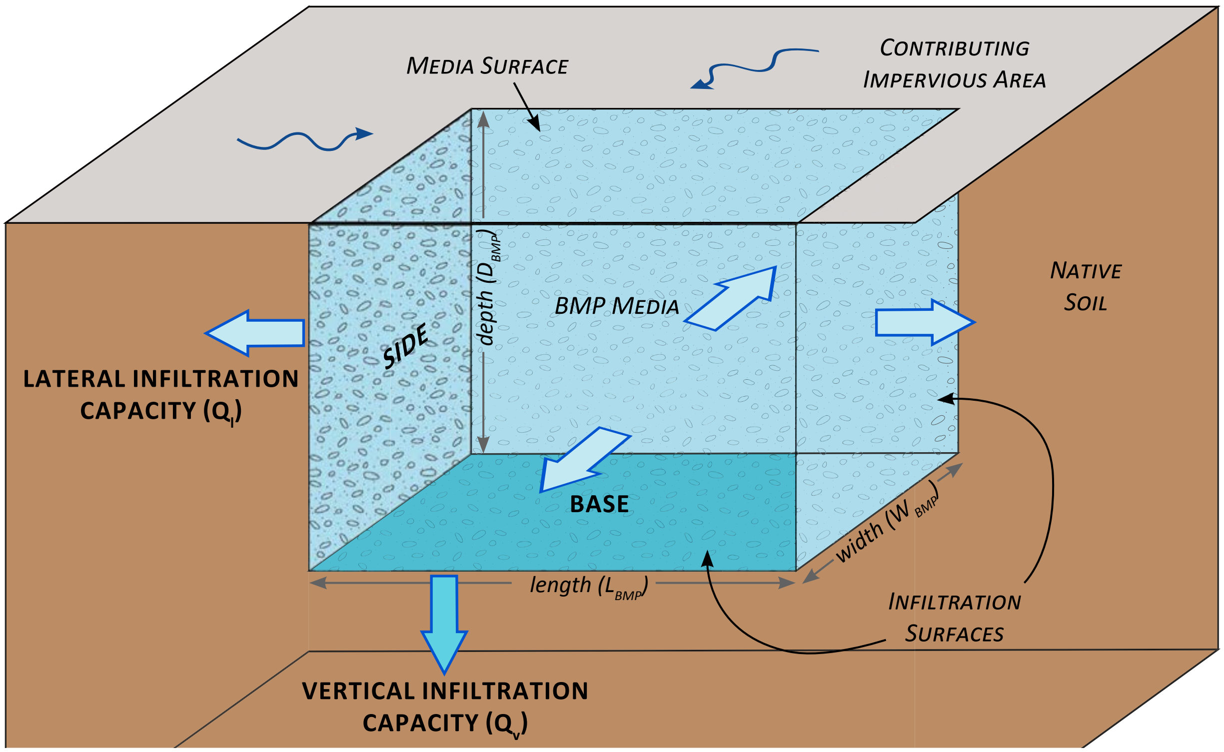
Planview



LEGEND

- ☐ Contributing Impervious Area
- 🟫 Native Soil
- ▨ BMP Media
- ⤳ Runoff + Material
- ⇨ Lateral Infiltration Capacity
- ⇩ Vertical Infiltration Capacity

Cross Section



Treatment Capacity ($\mathbf{C_t}$) =
Storage Capacity ($\mathbf{C_s}$) + Total Infiltration Capacity ($\mathbf{Q}$)

AND

Total Infiltration Capacity ($\mathbf{Q}$) =
Vertical Infiltration Capacity ($\mathbf{Q_v}$) + Lateral Infiltration Capacity ($\mathbf{Q_l}$)

DESIGNED BY
2NDNATURE | LLC
TEL: 831.426.9119 FAX: 831.426.7092
www.2ndnaturellc.com

BMP FUNCTIONAL FEATURES DIAGRAM

Figure 2.1

TRPA BMP Handbook

The TRPA BMP Handbook (2012a) is a general guidance document intended to aid Tahoe Basin property owners, BMP practitioners, and engineers with site analysis, BMP design, and identification of maintenance needs for stormwater quality control measures. The BMP Handbook provides information for the appropriate application of a number of infiltration BMPs, including: 1) pervious pavement; 2) infiltration basins; 3) infiltration trenches; 4) subsurface infiltration systems; 5) rain barrels and cisterns; 6) rain gardens; and 7) filter strips. Chapter 4 of the BMP Handbook summarizes the general applicability and functions of each of these infiltration BMPs and offers guidance for appropriate siting, design, installation, and necessary maintenance.

BMP Calculation Spreadsheet

The NRCS developed the BMP Calculation Spreadsheet to provide a simple method to size infiltration BMPs to meet TRPA regulations by comparing runoff volumes to designed treatment capacities (available at http://www.tahoebmp.org/BMPResources.aspx). The calculation of runoff volume in the BMP Calculation Spreadsheet is made by multiplying the intensity of the 20-yr/1-hr design storm by the area of each impervious surface on a parcel. The calculation of treatment capacity is made by summing the storage capacity and infiltration capacity of an infiltration BMP. Storage capacity is calculated based on the dimensions of the infiltration BMP, which includes a calculation of available void space for cases where a material such as drain rock is used within the infiltration BMP. Infiltration capacity is calculated based on the dimensions of the infiltration BMP, which are used to estimate the area of the infiltration surfaces, and the estimated saturated hydraulic conductivity (K_{sat}) of the soil on the subject parcel. See Figure 2.1 for a simple schematic of an infiltration BMP with terms displayed.

Pollutant Load Reduction Model

The PLRM was developed specifically for the Lake Tahoe Region to compute pollutant load estimates at spatial scales typical of public water quality improvement projects. The PLRM uses long-term continuous simulations of hydrology and Tahoe Basin stormwater quality data to compare project alternatives based on quantitative comparisons of pollutant loads and runoff volumes. Modeled scenarios in the PLRM may vary based on user specified inputs that affect pollutant load generation and reduction, which can include: land use types and land use conditions, pollutant source controls, hydrologic source controls (infiltration BMPs), and centralized stormwater treatment BMPs. The PLRM allows for comparison of various alternatives against a baseline scenario to evaluate potential load reductions.

2.3 PROBLEM STATEMENT

The long-term effectiveness of an infiltration BMP is dependent upon maintaining adequate treatment capacity, which as described above is a function of available storage capacity and infiltration capacity. Stormwater runoff in the Tahoe Basin can transport relatively high amounts of suspended sediment and particulate matter (LRWQCB and NDEP 2010, 2NDNATURE and NHC 2012). Accumulation of sediment and debris within an infiltration BMP can reduce storage capacity by filling available void spaces with material. Additionally, sediment can clog infiltration surfaces within a BMP, effectively reducing the infiltration capacity at the infiltration surface and rendering the saturated hydraulic conductivity of the underlying soil less important in the realized treatment capacity of the BMP.

While BMP maintenance is recognized in the TRPA Code of Ordinances and TRPA BMP Handbook as an essential action to achieve pollution reduction benefits over time, very little information is available to understand the specific mechanisms for how infiltration BMPs clog, or the relationship between pollutant loading rates and clogging rates. The lack of information limits the development of effective and reasonable maintenance schedules or the identification of an expected lifespan for a specific infiltration BMP. Consequently, current guidance, such as that included in the BMP Handbook, provides very general recommendations for necessary maintenance actions, and the recommended frequency of maintenance action does not include consideration of how anticipated loading to an infiltration BMP may affect its maintenance needs. Furthermore, existing tools such as the BMP Calculation Spreadsheet and PLRM do not provide mechanisms to evaluate the effect that declines in storage capacity and infiltration capacity may have on water quality performance over time.

A more tailored approach is needed to predict the trajectory of reduced infiltration capacity over time and identify appropriate maintenance needs for specific infiltration BMPs. This approach should be informed by an understanding of how infiltration BMP design and clogging affects performance over time based on field investigations and laboratory experiments.

2.4 RESEARCH GOAL AND OBJECTIVES

The research goal and objectives reflect priority knowledge needs related to infiltration BMP implementation in the Tahoe Basin. The overarching goal of this research is to:

Develop infiltration BMP performance decline understanding to support improvement of TRPA BMP Handbook guidance and Tahoe Basin stormwater tools.

Installation and maintenance of BMPs is costly and it is imperative to optimize their benefits after installation. By improving our understanding of the causes, rates, and magnitude of performance declines, we can improve policy recommendations to ensure that BMPs continue to function properly. With integration of new understanding to existing Tahoe stormwater guidance and tools, we hope to make the research outcomes readily usable for policy makers and practitioners. Three specific study objectives were defined to guide field observations and experimental designs:

1. ***Improve understanding of BMP clogging dynamics and factors contributing to performance decline***
2. ***Identify siting and design issues that contribute to failure or poor BMP performance***
3. ***Recommend a method to combine infiltration BMP design and drainage information to estimate BMP performance over and appropriate maintenance intervals.***

2.5 RESEARCH APPROACH

This effort included a series of information and data gathering steps to inform recommendations for updating the technical guidance available for infiltration BMP design, implementation and subsequent maintenance. The research included three components: 1) a synthesis of existing information (2NDNATURE and NHC 2011; Appendix A); 2) field surveys of infiltration BMP condition and performance; and 3) simulated stormwater loading experiments. The research focused on smaller scale infiltration BMPs such as infiltration trenches and dry wells since these types of improvements are quite common and a relatively large sample size was available for study through field surveys where results could be compared across many sites. The research activities were guided with input from a technical advisory committee (TAC) comprised of regulatory agency staff (Table 2.1).

Table 2.1. List of the technical advisory committee members for the study

TAC Member	Association
Robert Larsen	Lahontan Regional Water Quality Control Board
Jack Landy	U.S. Environmental Protection Agency
Shay Navarro	Tahoe Regional Planning Agency
Shane Romsos	Tahoe Regional Planning Agency

The simulated stormwater loading experiments and field surveys were designed to collectively fulfill the research objectives. Field observations provided useful information to assess how drainage conditions and specific siting and design factors for an infiltration BMP might influence performance declines. Information garnered from field surveys had a number of practical limitations since precise installation dates for an individual BMP, maintenance records, and estimates of pollutant loading rates were difficult to obtain. The simulated stormwater loading experiments allowed for direct observation of clogging mechanisms and the controlled introduction of sediment to assess performance using pollutant loading metrics that were not possible to predict with actual infiltration BMPs assessed during the field surveys. Analysis of the experimental data was performed to generalize the findings for application to the BMP stormwater tools and a specific example is provided using the BMP Calculation Spreadsheet (Chapter 5). Interpretation of the research findings resulted in specific recommendations for revisions to the BMP Handbook (Chapter 6).

3 FIELD SURVEY

The field survey was developed as a cost-effective approach to rapidly collect data sufficient to identify performance issues from a sample of infiltration BMPs located in various drainages within the Tahoe Basin. The survey was designed to address the following research questions:

1. What are the most common causes of infiltration BMP impairment?
2. Is there a typical depth or location at which material accumulates in infiltration BMPs that leads to clogging?
3. How do drainage characteristics affect BMP clogging and infiltration performance?

3.1 SITE SELECTION

Field surveys were conducted as three two-day campaigns from March to October of 2012. The survey design and the observations were coordinated with the TAC to ensure that the data collected would adequately address the research questions listed above (see Chapter 2.4). After several exploratory site visits, a targeted site selection process was used to ensure that our sample would capture an adequate range of BMP conditions and drainage characteristics (size, surface types, age, etc.). While a targeted sample design (opposed to a probabilistic sample) does not allow inference from our sample to the entire infiltration BMP population in the Tahoe Basin, it is more suited to directly address the research questions.

The majority of infiltration BMPs surveyed were located within the City of South Lake Tahoe with additional sites on the northwest shore of the Lake (Figure 3.1). Properties were primarily selected from the TRPA BMP certification database and TRPA staff coordinated with landowners to obtain property access. A total of45 sites were assessed with a mix of land use types: commercial (20), single family residential (12), multi-family residential (8), and public utilities (5). Sites were located in different urban catchments with different size drainage areas, surface types, and sediment and debris sources. At each site, 1-4 individual infiltration BMPs and associated drainage areas were assessed, resulting in a total of 75 BMPs surveyed. Often, there were more infiltration BMPs on a property than were surveyed as many of them had similar characteristics. Little information, other than the TRPA BMP certification date, was available on individual designs for most properties. Infiltration BMPs were categorized by type using the TRPA BMP Handbook nomenclature (TRPA 2012a): infiltration trenches, infiltration basins, dry wells, dry basins, pervious pavement, and subsurface infiltration systems (Figure 3.2). Of the BMPs surveyed, infiltration trenches (including roof drip lines) were considerably the largest group (Figure 3.3), with one or more installed on most properties visited. The most common media for all BMP types where media is used was ¾ to 1½ in drain rock (see Figure 3.3), which was used in 34 of the 45 Infiltration trenches surveyed.

3.2 METHODS

For each BMP, a set of observations and measurements were conducted to address the research questions. Observations included BMP characteristics such as dimensions and media type, as well as drainage area characteristics such as surface type, surface sediment accumulation, and area routed to each infiltration BMP (see Appendix B). We examined the conveyance systems for functionality and clogging to determine whether or not the intended drainage flow would reach the BMP. Visual estimates of sediment and debris accumulation

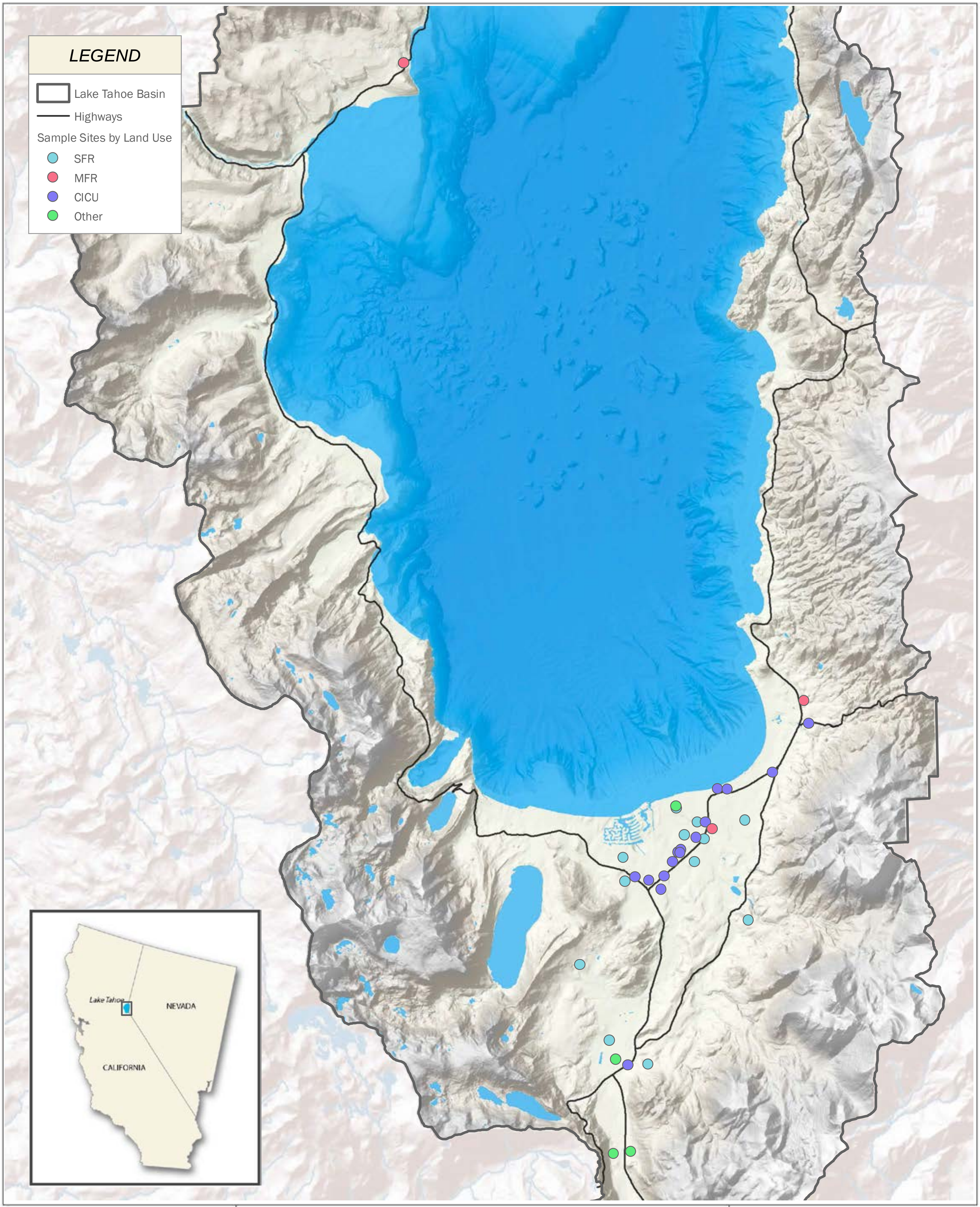


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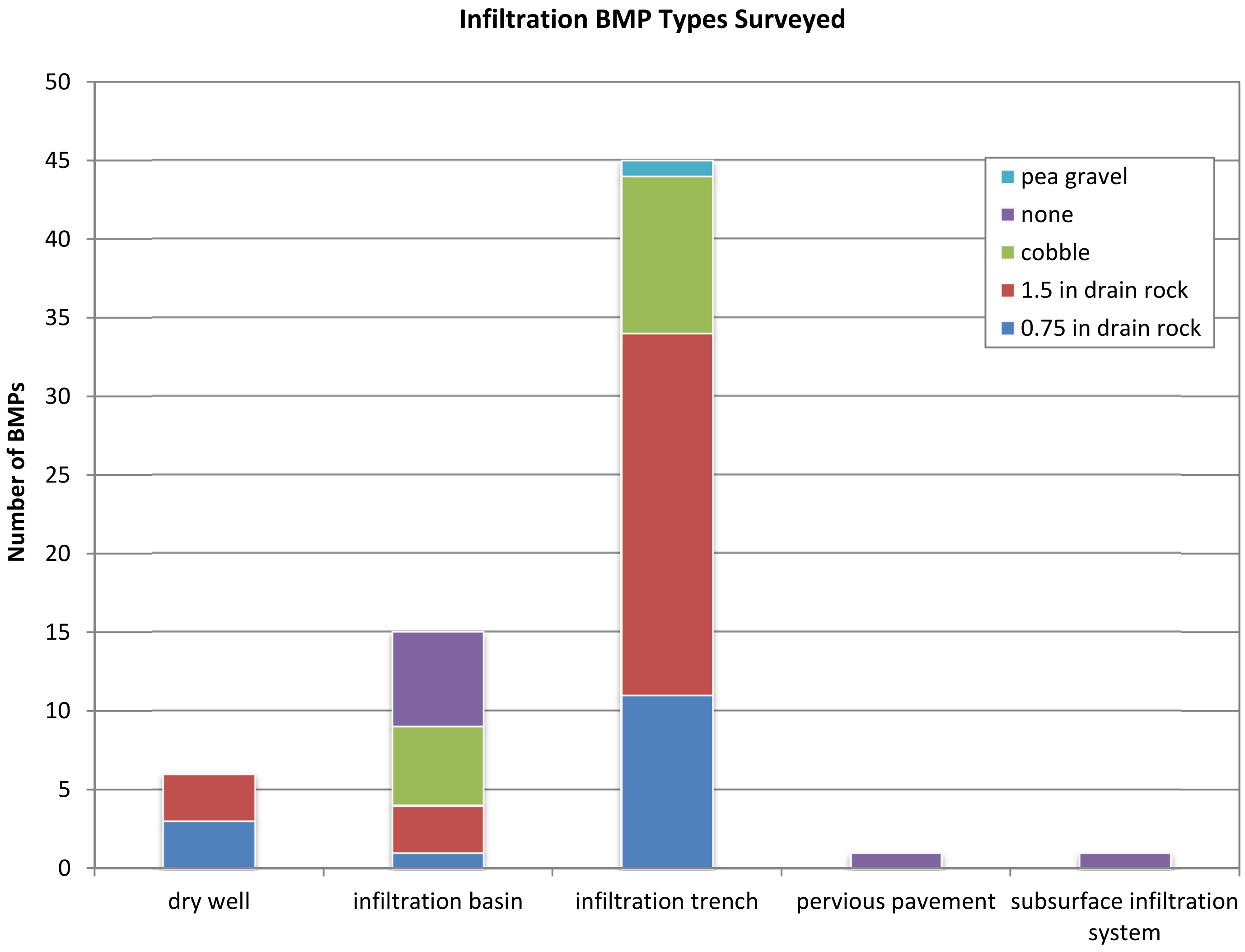
Figure 3.1: Infiltration BMP site locations surveyed by land use type.

EXAMPLES OF BMP TYPES SURVEYED

Figure 3.2



INFILTRATION BMPS SURVEYED BY TYPE

Figure 3.3

at the media surface, within the BMP media, and at the infiltration surface (see Figure 2.1) were used to estimate the relative degree of BMP clogging using the scoring rubric presented in Table 3.1. Typically condition was assessed at 1-3 locations within the BMP depending on the range of material evident at the surface. BMPs that fell between defined scores were assigned an intervening score of either 2 or 4.

Table 3.1. Scoring rubric used for BMP field surveys to denote degree of clogging

Score	Definition
5	**Clean**. Less than 20% of void space filled with accumulated sediment and debris. BMP condition appears close to what it would have been at time of original installation.
3	**Moderately clogged**. BMP media partially covered by sediment and other debris accumulation that fills approximately 40-60% of void space.
1	**Severely clogged**. BMP media nearly completely covered by sediment and debris accumulation that fills more than approximately 80% of void space.

BMP infiltration performance was measured using BMP RAM runoff test protocols (2NDNATURE et al. 2009) to provide a quantitative measure to compare with the visual estimates of the degree of clogging. One liter of water is poured onto the surface of the BMP media and the time for the water to infiltrate completely is measured. The test was performed at each location where condition was assessed. Using only 1L of water, infiltration time is not generally affected by sediment accumulation at the infiltration surface or mid-level depths within the BMP. Therefore the 1L pour test primarily allows us to differentiate severely clogged BMPs that have filled media void spaces nearly up to the media surface from clean and moderately clogged BMPs and does not indicate whether or not performance is adequate in absolute terms. Any evidence of siting and design issues was also noted, such as inappropriate BMP locations or elevations, or whether it appeared that the BMP received runoff not intended in the design.

Data were entered from field sheets into an MS Access database through custom built forms with a set of standardized lookup lists to reduce errors and facilitate efficient data analysis. QA/QC was performed on the digital data and validated by re-examining the field sheets. Queries were created to summarize the data collected and export from the database for analysis and graphing. Formal hypothesis testing to address the research questions was done using the Minitab statistical package (version 16). Since many of the observations and measurements collected did not have normal distributions, non-parametric tests were typically employed. For each statistical test, the influence of outlier data points was examined and either a 90% or 95% confidence interval was used as the threshold for rejection of the null hypothesis when formal hypothesis testing was employed.

3.3 FINDINGS

The findings presented focus on the identification of key factors that appear to cause the majority of performance impairments identified through the field surveys. They do not identify absolute relationships between BMP performance and specific design characteristics or maintenance actions, since this data were either unavailable or too difficult to obtain within the scope of this field survey. The findings are divided into a qualitative description of stormwater conveyance issues and quantitative observations of BMP condition and performance. Observations of BMP conveyance issues were augmented with those made in an independent study by the Natural Resource Conservation Service research (USDA NRCS – Tahoe Basin branch) to improve interpretation of the findings (USDA NRCS 2013).

3.3.1 STORMWATER CONVEYANCE ISSUES

Conveyance of stormwater to infiltration BMPs on residential and commercial parcels are commonly accomplished through the use of swales, channels, slotted channel drains, and drainage pipes. Constrictions in these features due to the accumulation of coarse material (e.g., pine needles, coarse sediment) and other debris was the most common reason observed for water not reaching infiltration BMPs. For cases where stormwater runoff is concentrated, the BMP Handbook (TRPA 2012a) recommends the use of sediment traps to treat stormwater runoff and collect coarse sediment and debris prior to discharging runoff to an infiltration BMP. Observations from this field survey, as well as the NRCS (USDA NRCS 2013), document that the quantity of coarse material and debris entrained in stormwater runoff can dramatically affect the ability of stormwater collection, conveyance, and pre-treatment systems to deliver runoff to an infiltration BMP. Clogging often occurs either within the slotted drain or at the piped connection between the drain and a pre-treatment device or the infiltration BMP.

A secondary or superimposed conveyance issue can be incorrect siting and design of an infiltration BMP relative to drainage surfaces; however, this was rarely identified in the field surveys. At two sites, BMPs were located at a higher elevation than some of the clearly intended drainage. This may have been due to design or installation errors, or perhaps, site conditions have changed since the installation of the BMP. In general, observations of design and implementation issues were much less frequent than observations of conveyance issues associated with debris accumulation. Based on visual observations of sediment and debris accumulation, as well as anecdotal information occasionally obtained from property owners, many of the infiltration BMPs surveyed had not been maintained for several years. While these issues may have been exacerbated by siting or design flaws, accumulation of material usually appeared to the final cause of intended drainage not reaching the BMP.

3.3.2 BMP CONDITION AND PERFORMANCE

Infiltration BMPs surveyed represented a range of clogging conditions from clean to severely clogged (1-5; see Table 3.1). Figure 3.4A shows the distribution of clogging scores (averages for each BMP) for applicable BMPs. Note that the mean value of the scores is approximately equal to a moderate degree of clogging with a numeric score of 3 indicating that the scoring rubric is well designed for this sample of BMPs. Moderately and severely clogged BMPs often showed material accumulation throughout the media (see photos at top of Figure 3.4) without any clear preferential accumulation at the media surface, within the media, or at the infiltration surface. This means that we are not able to identify a clear vertical ordering from the initiation of material accumulation and subsequent clogging over time. Accumulation of finer material (e.g., smaller than fine sand, <125 µm) could not always be identified visually where it had accumulated at the infiltration surfaces or if it was in small amounts at mid-depths within the media. However, fine material was evident where it had accumulated in substantial amounts at the surface of the BMP.

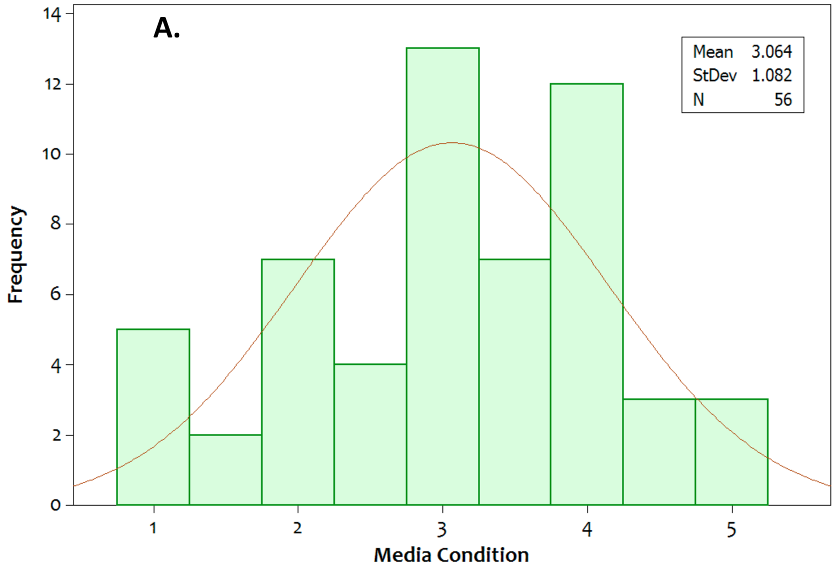
BMP Condition Examples

1. Severely clogged

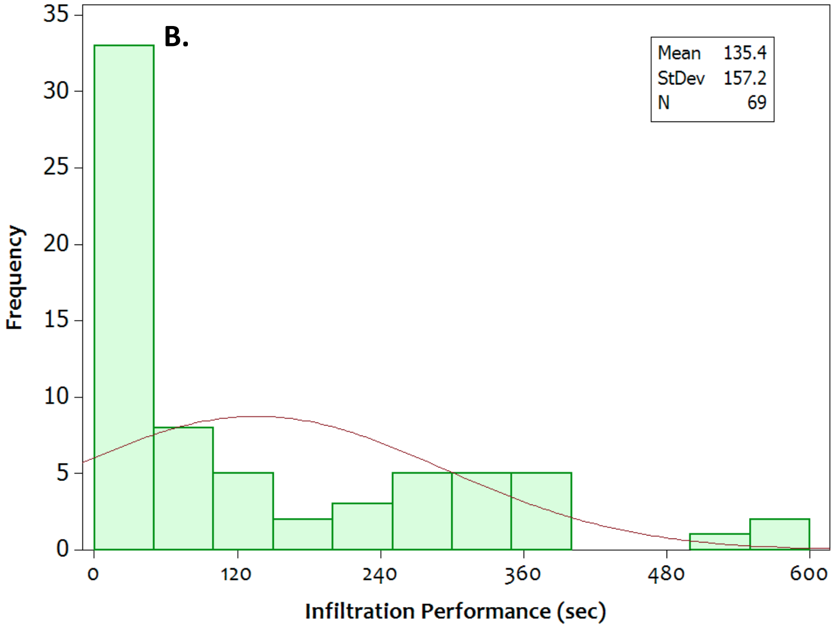
3. Moderately clogged

5.Clean

Media Condition



1L Infiltration Performance



Frequency distributions, with normal curves included for reference. While the media condition data have an approximately normal shape, the infiltration performance data have a strong positive skew.

MEDIA CONDITION AND INFILTRATION PERFORMANCE DISTRIBUTIONS

Figure 3.4

Severely clogged BMPs often had a source of debris readily observable directly upslope from the BMP such as an eroding slope, overhanging pine trees, or significant sediment accumulation that appeared to originate from a road or parking lot. Figure 3.5 illustrates two examples of small cobble lined infiltration basins with nearby sources contributing a notable amount of sediment to the infiltration BMP. Images on the left of Figure 3.5 show sediment sources to the BMPs (images on the right). The infiltration basin shown in the upper right of Figure 3.5 receives runoff from thousands of square feet of roadway in addition to the parking lot and roof that appeared to be its intended drainage area. The result is a BMP that is severely clogged with fine material delivered from the upslope roadway, which generates a chronic source of pulverized traction abrasives. These examples dramatically illustrate some of the most identifiable instances of drainage characteristic impacts on BMP condition. However, many other BMPs surveyed had similar, though less severe issues, which were more difficult to identify during a single observation period.

Fifty-two percent of the BMPs surveyed showed substantial performance impairment, defined as requiring more than 1 minute to infiltrate 1L of water. Infiltration performance results ranged from 4 seconds to more than 10 minutes (see Figure 3.4B). While the clogging condition scores showed an approximately normal distribution (see Figure 3.4A), infiltration performance shows a strong positive skew since the clean or moderately clogged BMPs typically took less than 4 seconds to infiltrate 1 liter of water, leading to many observations in this range. In the worst performing BMPs, water would simply pool and not infiltrate observably during the 10 minute test (Figure 3.6C).

We investigated the relationship between our visual estimate of clogging condition and BMP infiltration performance to understand the importance of material accumulation to BMP function over time. Figure 3.7A shows the association between clogging condition scores (depth averaged) and infiltration performance (area averaged); the R-squared value indicates that clogging condition explains approximately 45% of the variance in infiltration performance. The interpretation of this plot is that clogging condition was a significant determinant on the infiltration performance, but not a highly accurate predictor. So while the amount of clogging visually apparent is important, it is not sufficient on its own as a rapid method for estimating expected BMP performance. The residual scatter in the relationship is likely due to several factors such as BMP design, contributing drainage size, and clogging material type.

3.3.3 BMP CLOGGING MATERIAL AND DRAINAGE SURFACES

The dataset suggests that different surfaces contribute different types and size of material to an infiltration BMP. The material observed clogging infiltration BMPs ranged from coarse sand-sized material (0.5 -1 mm) with high organic content (e.g., decomposing pine needles) to fine material (<125 µm). The dominant material collected within the BMP appeared dependent upon the upslope drainage surfaces and the condition of the surfaces discharging stormwater to the subject BMP (see Figure 3.6). BMPs that primarily drained roads and parking lots were often filled with finer material than those draining other surfaces, such as roofs. BMPs primarily clogged with fine material (estimated <125 µm) created a very effective, even hydrophobic, layer that caused water to pool at the surface as seen in the Figure 3.6C). In contrast, the BMPs clogged with coarse material (from erosional sources) and pine needle accumulation did not substantially impede BMP infiltration capacity (see Figure 3.6A-B).

The scatter in the relationship shown in Figure 3.7A suggests other factors also contribute to infiltration performance beyond the visual appearance of accumulated material. We explored the influence of surface

Left-hand images show material sources for runoff draining to the two BMPs shown on right. The top right-hand BMP shows severe clogging and the bottom right-hand BMP shows moderate clogging.

BMP MATERIAL SOURCES

Figure 3.5

Clogging Material Types

Predominantly Coarse Material

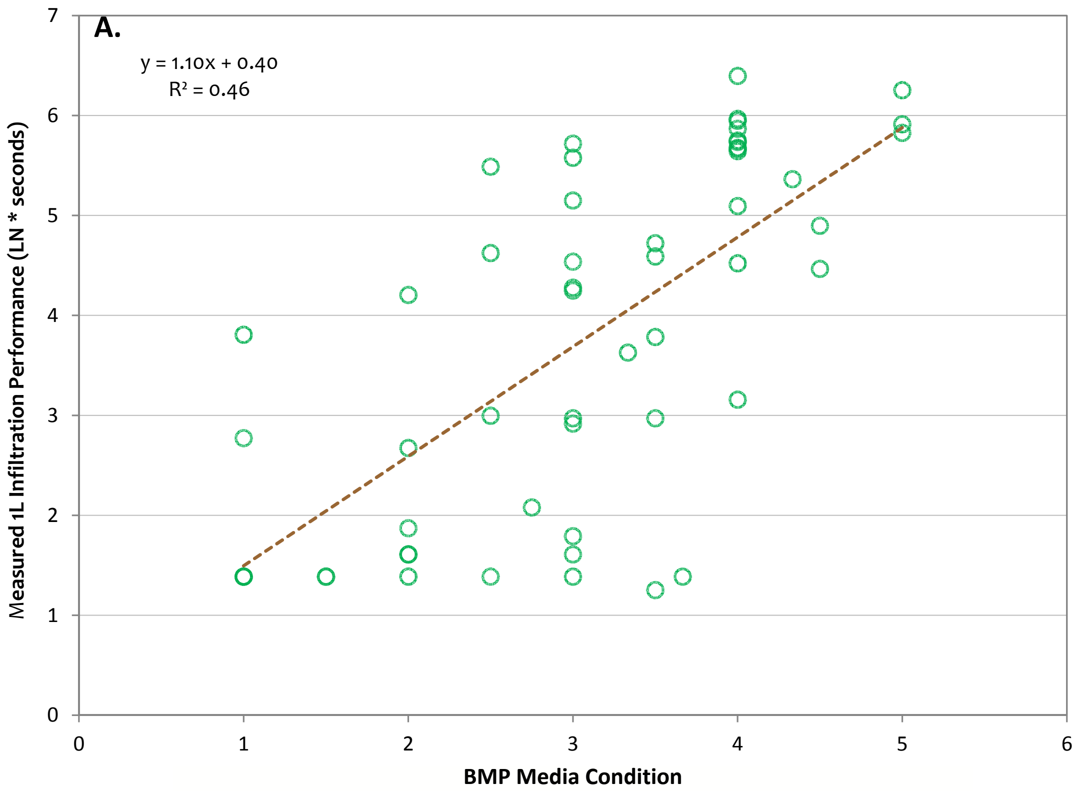
High Degree of Fine Sediment

Images to illustrate clogging material types observed in infiltration BMPs. Top images are examples of relatively large material composed primarily of coarse sand, silt, and organic material. Bottom images show a BMP with a high degree of fine sediment material (fine sand, silt, clay)

INFILTRATION BMP CLOGGING EXAMPLES

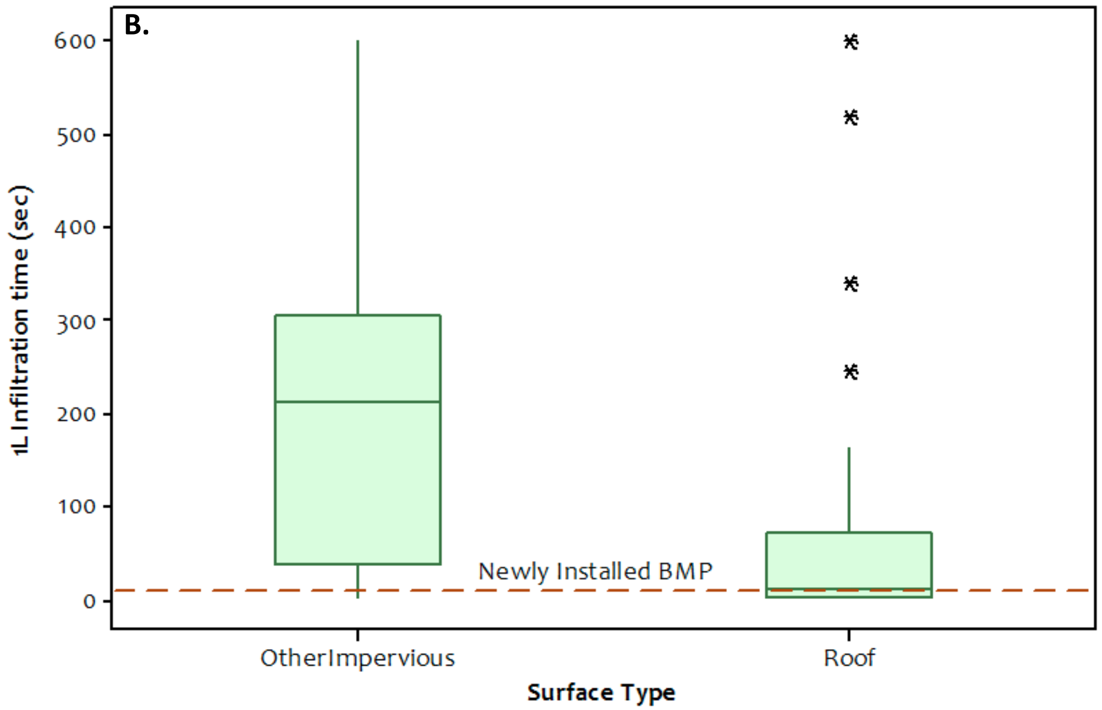
Figure 3.6

BMP Media Condition v. 1L Infiltration Performance



The plot illustrates moderate degree of variance of infiltration performance can be explained by the clogging condition with substantial redidual scatter. Note that the vertical axis is the natural log of infiltration time.

Infiltration Time by Surface Type



Box plots show differences in the data distributions for BMPs that recive runoff primarily from roofs compared to those that receive runoff primarily from other impervious surfaces (roads, parking lots, driveways, etc.). Box center line is the median, box ends are the 25th and 75th percentile values, ends of whiskers are the 10th and 90th percentiles, and stars are statistical outliers. The non-parametric Mann-Whitney U test verified that the two data sets differ with a 99.99% level of confidence.

1L INFILTRATION TIME BOXPLOTS BY SURFACE TYPES

Figure 3.7

drainage types by stratifying the dataset by primary drainage surface type (>50% of total drainage area) and testing for differences between the two. BMPs which drained other impervious surfaces (roads, parking lots, driveways) had significantly greater 1L infiltration times compared to those that primarily drained roofs (see Figure 3.7B). The results of the statistical analysis indicate that we can be highly confident that the two data sets differ from one another, with the median infiltration time of BMPs that receive runoff from roofs 22 times lower than those draining other surfaces (Table 3.2). Since the visual estimation protocol used to specify BMP clogging condition did not account for the type or size of material observed in the BMP, and the roofs tend to deliver coarser material than other surfaces, the different surface drainage types are likely an important contributor to the scatter in the relationship between BMP clogging condition and BMP performance (see Figure 3.7A). The results indicate that BMPs receiving primarily roof runoff nearly always showed adequate infiltration performance. The implication of this result is that BMPs draining roofs require far less frequent maintenance actions to maintain adequate performance, compared to those BMPs draining other impervious surfaces due to the fact that the coarser material the roofs deliver to the BMP has a lesser impact on infiltration performance.

Table 3.2. Results of the Mann-Whitney U test (non-parametric alternative to a t-test) to test for differences between BMP drainage surfaces. The two data sets show a significant difference of infiltration performance between drainage surface types at 99.99% (p-value <0.001) confidence level.

Surface Type	N	Median 1L Infiltration Time (s)	Mann-Whitney U test p-value
Roofs	26	12	<0.001
Other Impervious	31	265	

The field surveys indicate surface drainage types are important determinants on the infiltration performance decline of BMPs via the type and size of material that is generated. Smaller particles (e.g., silt or clay) are able to more efficiently fill pore spaces between soil particles compared to coarser particles as conceptually illustrated in Figure 3.8. While larger particles may maintain similar porosity at the media-soil interface as the native soil, the smaller particles reduce porosity of the uppermost soil layer by more efficiently filling void spaces (see Figure 3.8). Thus, fine sediments can form a more effective clogging agent in comparison to sand and larger sized sediments.

3.3.4 SUMMARY OF FINDINGS FOR THE FIELD SURVEY

Key findings from the field survey include:

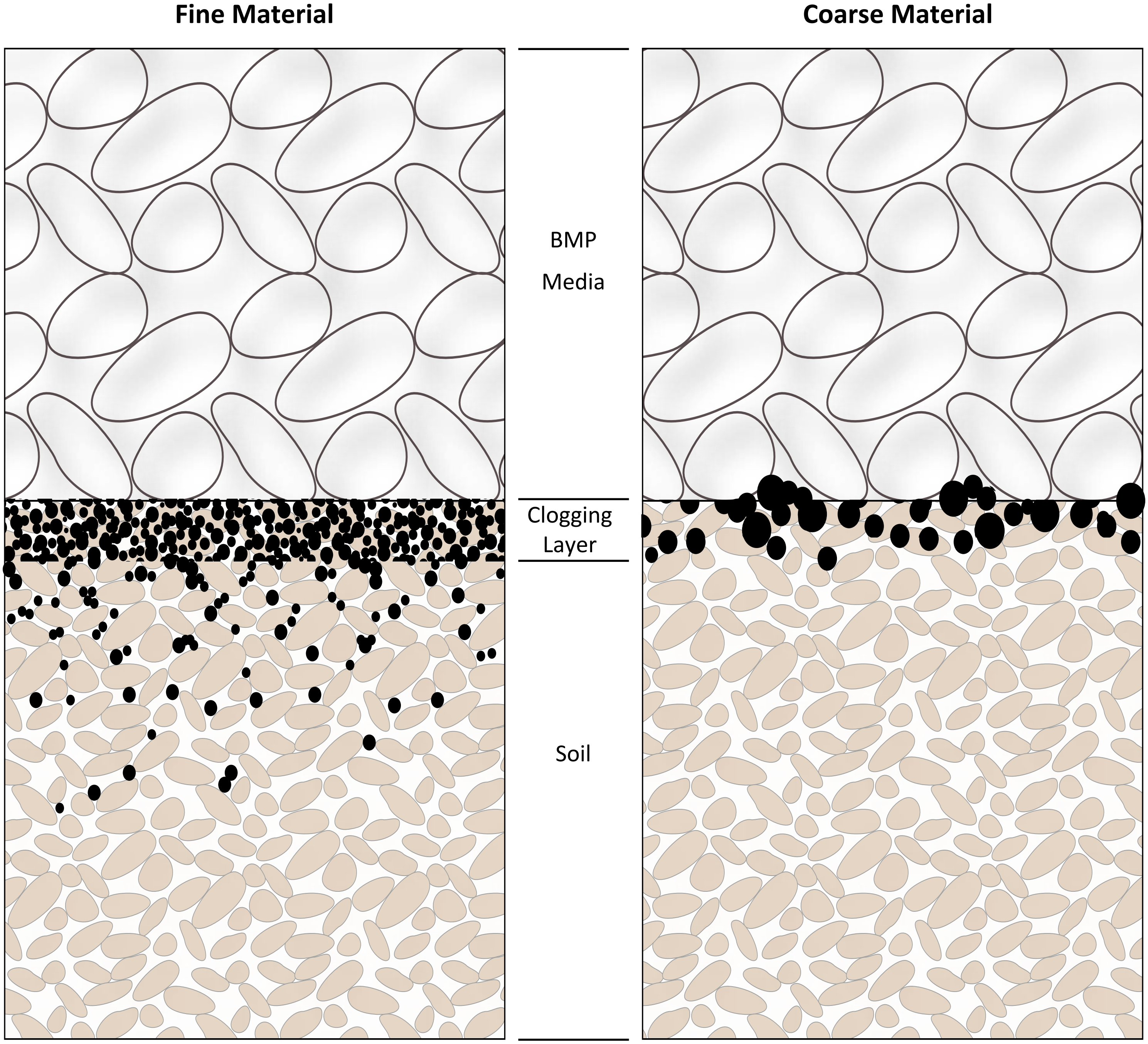
- **A general lack of maintenance conducted on infiltration BMPs was prevalent.** While precise installation or maintenance dates were not available, the degree of material accumulation observed and anecdotal information acquired during the field surveys indicated that maintenance was rarely performed.
- **Infiltration trenches that received primarily roof runoff generally did not show performance issues regardless of the amount of material accumulated.** This is attributable to the relatively low degree of fine sediment typically contained in roof runoff, which appears to be a more effective clogging agent compared to coarse sediment and organic material.

- **Clogging in conveyance or pre-treatment systems was the most common stormwater conveyance issue.** This finding is supported by visual observations from this survey and those by the NRCS.

- **Approximately half of the BMPs surveyed showed impaired infiltration performance, most of which primarily received runoff from driveways, parking lots, and roads**. While the infiltration performance test employed is not adequate in itself for determining BMP performance relative to regulatory standards, the results provide strong evidence that the majority of BMPs that drain driveways, parking lots, and roads may have severely reduced treatment capacities relative to when they were installed.

- **Estimation of infiltration performance from visual observations of BMP condition may be improved by specifying the proportion of fine material (e.g., <125 µm) in addition to the total material accumulated**. The analysis results indicate that this would account for some of the unexplained variance in the relationship between clogging condition and infiltration performance.

The field survey did not allow complete understanding of BMP clogging mechanisms and locations. Incomplete design, maintenance and material loading rate information for the BMPs surveyed was a substantial obstacle for applying the data collected to determine infiltration performance decline rates. These limitations informed the design and objectives of subsequent laboratory experiments.



CLOGGING PARTICLE SIZE DIAGRAM

Figure 3.8

4 STORMWATER LOADING EXPERIMENTS

Building upon the lessons learned and remaining questions from the field surveys, two types of stormwater loading experiments were performed: 1) lab-based experiments that used custom-built BMP enclosures and 2) in situ experiments where small-scale test BMPs were constructed by placing drain rock directly into in the ground. Research questions addressed by these experiments were:

1. Where does sediment accumulate within BMPs and where does it cause the greatest impact on infiltration capacity?
2. How does infiltration capacity decline as a function of sediment loading?
3. How does the use of woven filter fabric affect sediment accumulation and infiltration rate decline?
4. How does native soil permeability affect infiltration capacity decline as a function of sediment loading?
5. What role does lateral infiltration play in the decline of infiltration capacity as sediment accumulates in the BMP?

All of the loading experiments involved pouring synthetic stormwater into a series of BMPs with different geometric configurations. Infiltration capacity was quantified by measuring draw down times at increments of stormwater loading with a known mass of fine-grained sediment (very fine sand (125 µm) and finer). Experiments were typically run in triplicate to quantify measurement precision. Both types of experiments used similar stormwater mixing, loading, and infiltration measurement procedures as described below.

4.1 STORMWATER LOADING AND INFILTRATION MEASUREMENT PROCEDURES

Synthetic stormwater was created by mixing tap water with material collected from a Washoe County high efficiency vacuum-assisted street sweeper to focus the experiments on the impact of fine material on BMP performance. Our stormwater was created using a known mass per unit volume of fine material collected from the sweeper cartridge filters. Aside from its availability, the use of only fine material allowed us to focus the loading simulations on the effects on a clogging element that the field observations indicated was especially problematic. Sieving of this material indicated that all was smaller than fine sand (<125 µm) with approximately 50% composed of silt or clay-sized particles or finer (<63 µm).

All drain rock incorporated as the BMP media was rinsed prior to use to remove residual material that may have been adhered to the gravel and increase our confidence that all sediment loaded into the BMPs was generated from the synthetic stormwater. At initiation of each experiment, the enclosure was saturated with clean water until a steady-state draw down rate within the BMP was observed. Once saturation was achieved, initial infiltration capacity was measured, prior to any sediment-laden stormwater being applied.

Synthetic stormwater was poured into the middle of the BMP media in 5 gallon increments with fine sediment concentrations that varied with experiment (ranging from 100 to 2000 mg/L) depending on BMP size and observed infiltration capacity declines. Synthetic stormwater application did not always occur over continuous days, such that some enclosures had the opportunity to dry between applications. Following application of each 5 gallon bucket, the draw down time (Δt) was measured as the time it took for the water surface level to move from an initial height (H_i) to a final height (H_f). Measurements were recorded on field data sheets, entered into MS Excel spreadsheet templates and results plotted to identify data entry errors and potential outliers. Where data issues occurred, field data sheets and photo documentation were consulted to assess whether corrections were necessary.

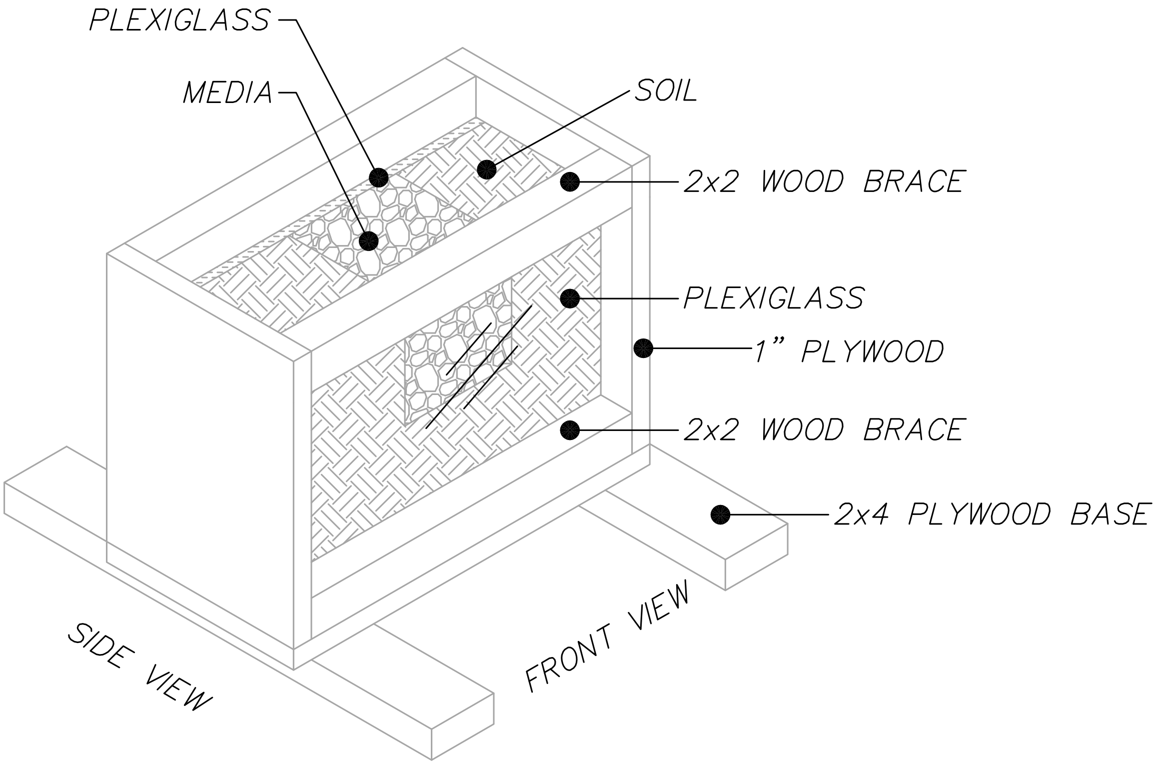
4.1.1 LAB METHODS

Three identical enclosures were built from wood and quarter inch plexiglass to the specifications shown in Figure 4.1 and filled with three-quarter inch drain rock as the BMP media. Holes were drilled at the base of the enclosures to allow synthetic stormwater to drain into a collection bucket below. Two different configurations were tested using the enclosures, termed *Long* and *Mini* as illustrated in Figure 4.2. For each experiment, construction of the replicate BMPs were identical and the underlying sand was installed and packed according to a standard procedure. Each laboratory configuration was designed to address the specific research questions. The *Long* configuration (see top schematic in Figure 4.2) was designed to detect differences in infiltration performance decline associated with installation of woven filter fabric at the base of the media and to isolate the vertical infiltration capacity decline (see Figure 2.1). Filter fabric is commonly installed in infiltration BMPs to assist with maintenance procedures. The experiment was designed to assess if filter fabric can actually speed up the rate of clogging and associated decline in infiltration capacity. During the field surveys of BMPs, visual observations were made of notable amounts of accumulated material on the filter fabric, which led to the generation of this hypothesis. The *Mini* configuration (see bottom schematic in Figure 4.2) was designed with both vertical and lateral infiltration surface area to assess the importance of lateral infiltration on infiltration capacity as sediment accumulated in the BMP.

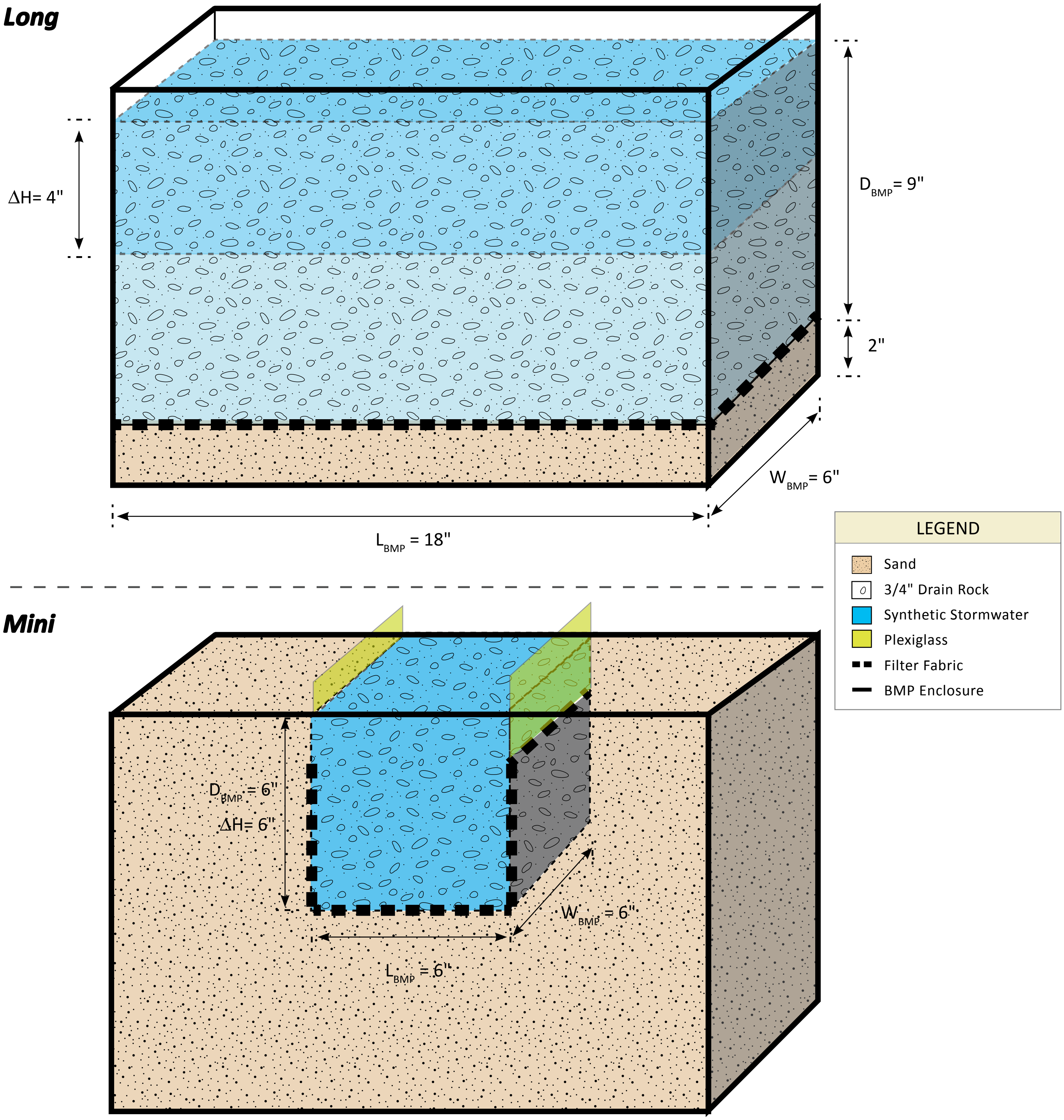
A series of trials were conducted to determine design integrity, feasible stormwater loading rates, and precision adequacy. For each trial, a target precision for the replicate measurements was a standard deviation ratio (SDR) of less than 1. The SDR is the percent of the standard deviation that each measurement's difference from the mean represents. The higher the degree of precision, the more confidence we had that the measured differences across experimental configurations were not due to sampling error or variations in the construction of each experiment. A number of different designs were tested prior to the selection of the *Long* and *Mini* enclosure specifications, but were not viable due to either feasibility or design integrity issues. Preliminary testing using soils extracted from the Tahoe Basin (Christopher-Gefo series) did not allow for acceptable precision across the triplicate experiments due to heterogeneity of the structure, composition, and compaction of the soil samples. However, we were able to create triplicate enclosures with high initial infiltration capacity precision using beach sand. Since measurement variability would have confounded our ability to distinguish infiltration performance differences between configurations, we utilized beach sand as a substitute for the underlying soil. In addition, the higher permeability of the sand substantially increased the rate at which stormwater could be loaded to the enclosures, reducing lab time.

The plexiglass sides of the enclosures (see Figure 4.1) allowed visual examinations of sediment accumulation within the BMP media. The location and relative amount of sediment accumulated within the drain rock and at the infiltration surfaces were recorded and photographed. Additionally, at the completion of each experiment the drain rock was carefully extracted from the enclosure to inspect and document the patterns and locations of sediment accumulation.

Enclosure Experiment Design



Top image shows the design specifications of the BMP enclosures and bottom image shows the finished construction along with the tool used for uniform compaction of sand prior to media placement.



$$V_w = \Delta H \times L_{BMP} \times W_{BMP} \times V_v$$

$$Q = V_w/t$$

Outer boundary is BMP enclosure (see Figure 4.1). Images show dimensions of the *Long* and *Mini* experiment configurations constructed within enclosure.

MINI & LONG ENCLOSURE CONFIGURATIONS

Figure 4.2

4.1.2 IN SITU METHODS

The *In Situ* experiments were completed to estimate infiltration capacity declines using controlled experiments more comparable to actual BMP performance, since the *In Situ* setup preserved key characteristics such as soil structure, compaction variability within the surrounding soil, and development of a more natural wetting front during stormwater loading. Some of these characteristics could not be adequately represented by the laboratory experiments using the BMP enclosures. *In Situ* experiments were conducted in Tahoe soil and Santa Cruz beach sand to identify if the rate of infiltration decline was dependent upon the initial saturated hydraulic conductivity of the surrounding soil. The *In Situ* design consisted of extracting one cubic foot of the native soil (either Tahoe soil or Santa Cruz beach sand) and filling the hole with washed three-quarter inch drain rock. A 4 inch diameter perforated pipe was installed in the center of each BMP to measure the draw down rate over time (Figure 4.3). One of the soil experiments was conducted in an area mapped by the USDA NRCS soil survey (USDA NRCS 2007) as Kings Beach soil series ($K_{sat} \approx 5.5$ in/hr) on the North Shore of the Tahoe Basin. Two configurations, with and without filter fabric placed at the infiltration surface (see Figure 4.3), were tested. The *In Situ* experiment completed in Santa Cruz beach sand (Ksat ≈ 15 in/hr) represented the upper bound of high permeability soil. These experiments were run in duplicates using filter fabric installed at the infiltration surface, primarily to prevent the sand from sloughing into the BMP media during the experiment.

4.2 CALCULATIONS

Measurements taken for each experiment recorded the time required to infiltrate a volume of synthetic stormwater by observing the draw down time of water within the BMP for a given cumulative mass of sediment. A number of calculations were employed to compare and integrate the data across the experiments. A number of variables utilized throughout the remainder of this report are defined in the List of Variables Table presented at the front of this document.

The total volumetric discharge rate (Q) through the BMP is the volume of water within the BMP media given BMP dimensions (L_{BMP}, WBMP); the media void space (V_v); and the change in water depth over time ($\Delta H/t$) (see Figure 4.2):

$$Q = (L_{BMP} * W_{BMP} * V_v) * (\Delta H / t) \qquad \text{(EQ1)}$$

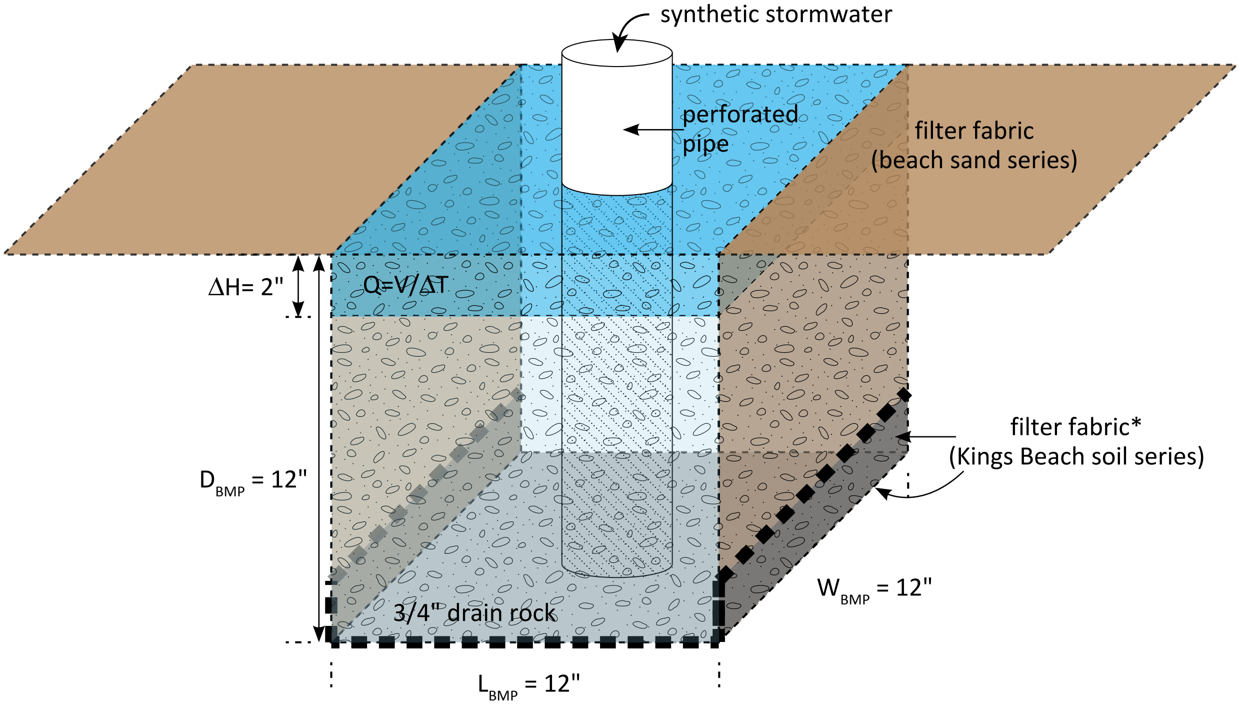
The total volumetric discharge rate (Q) through the BMP and into the surrounding soil is the sum of the vertical (Q_v) and the lateral (Q_l) infiltration components:

$$Q = Q_v + Q_l \qquad \text{(EQ2)}$$

Since the experiments were conducted in saturated conditions, Q can be considered equivalent to the infiltration capacity of the BMP, which may be expressed as either a length or a volume per time (Beven 2004). Thus, within the context of these experiments, volumetric discharge variables are hereafter referred to as 'infiltration capacity'. The relative infiltration capacity (R) of a BMP is defined as a dimensionless coefficient that is the remaining fraction of the infiltration capacity (Q_f) after loading of a known mass of sediment relative the initial (pre loading) infiltration capacity (Q_i):

$$R = Q_f / Q_i \qquad \text{(EQ3)}$$

In Situ Experiment Design and Setup



Top image shows configuration dimensions for *In Situ* experiments for both King's Beach soil series and beach sand. Bottom images show construction of an *In Situ* BMP in King's Beach soil with plexiglass cube to ensure uniform sizing (left image) and the planview of the constructed *In Situ* BMP (right image).

IN SITU EXPERIMENTAL SETUP

Figure 4.3

All experiments were continued until the final relative infiltration capacity had declined 75% of the initial value or $R < 0.25$.

The relative infiltration capacity (R) was evaluated as a function of the total mass of sediment per unit infiltration surface area available (A_{inf}) for each BMP configuration. The infiltration surface area for the experimental BMPs is:

$$A_{inf} = A_{base} + A_{sides} \qquad \text{(EQ4)}$$

where:

$$A_{base} = L_{BMP} * W_{BMP} \qquad \text{(EQ5)}$$

$$A_{sides} = (W_{BMP} * D_{BMP} * N_{ss}) + (L_{BMP} * D_{BMP} * N_{ls}) \qquad \text{(EQ6)}$$

In order to compare the amount of sediment loaded across a range of experimental configurations, the cumulative fine sediment loaded to each test BMP (FS_c) was adjusted to reflect the amount of sediment loaded per square foot of available infiltration surface area for the test BMP (FS_a):

$$FS_a = FS_c / A_{inf} \qquad \text{(EQ7)}$$

Plots of the relative infiltration capacity (R) as a function of the cumulative mass of fine sediment loaded per square foot of infiltration surface (FS_a) are used to compare the experimental data and assess infiltration capacity declines.

4.2.1 RELEVANCE TO BMP CALCULATION SPREADSHEET

As presented in Chapter 2, the calculation of infiltration capacity in the BMP Calculation Spreadsheet is controlled by the mapped or measured saturated hydraulic connectivity (K_{sat}) of the native soil and the dimensions of the BMP. The relative infiltration capacity declines (R) measured by these experiments are essentially a result of reducing the permeability of the interface between the BMP media and the uppermost layer of the underlying soil or sand due to accumulation of sediment. The infiltration capacity declines may therefore be used to scale the K_{sat} parameter used in the BMP Calculation Spreadsheet which specifies the rate of water movement from the BMP into the surrounding native soil. The current version of the BMP Calculation Spreadsheet does not incorporate potential reductions in the infiltration capacity over time as a function of material loading to the BMP. Application of stormwater loading experiment results to estimate treatment capacity declines as a function of sediment loading to BMPs are provided below and the specifics of potential modifications to the BMP Calculation Spreadsheet are presented in Chapter 5.

4.3 FINDINGS

The following sections report the results of the stormwater loading experiments as they relate to the research questions stated on page 4-1.

4.3.1 SEDIMENT ACCUMULATION PATTERNS

Visual inspections indicated the majority of fine sediment introduced to the BMPs under the lab tests accumulated at the base of the enclosures as illustrated in Figure 4.4. Evidence of the preferential fine sediment accumulation on the vertical infiltration surface (i.e., bottom of the BMP) was observed in both the *Long* (with and without filter fabric) and *Mini* configurations. Examination of the enclosures and media at the conclusion of the experiments, after > 200 grams of fine sediment had been loaded for each experiment, showed that minimal amounts of fine sediment had accumulated at the surface of the drain rock or within the pore spaces of the drain rock. The fine sediment formed a layer approximately 2-8 mm thick at the base of the enclosures (see top and middle images of Figure 4.4) or on top of the filter fabric when it was installed. In the *Mini* configuration, upon removal of the filter fabric, the majority of accumulated material was found along the base with very little material accumulated on the sides.

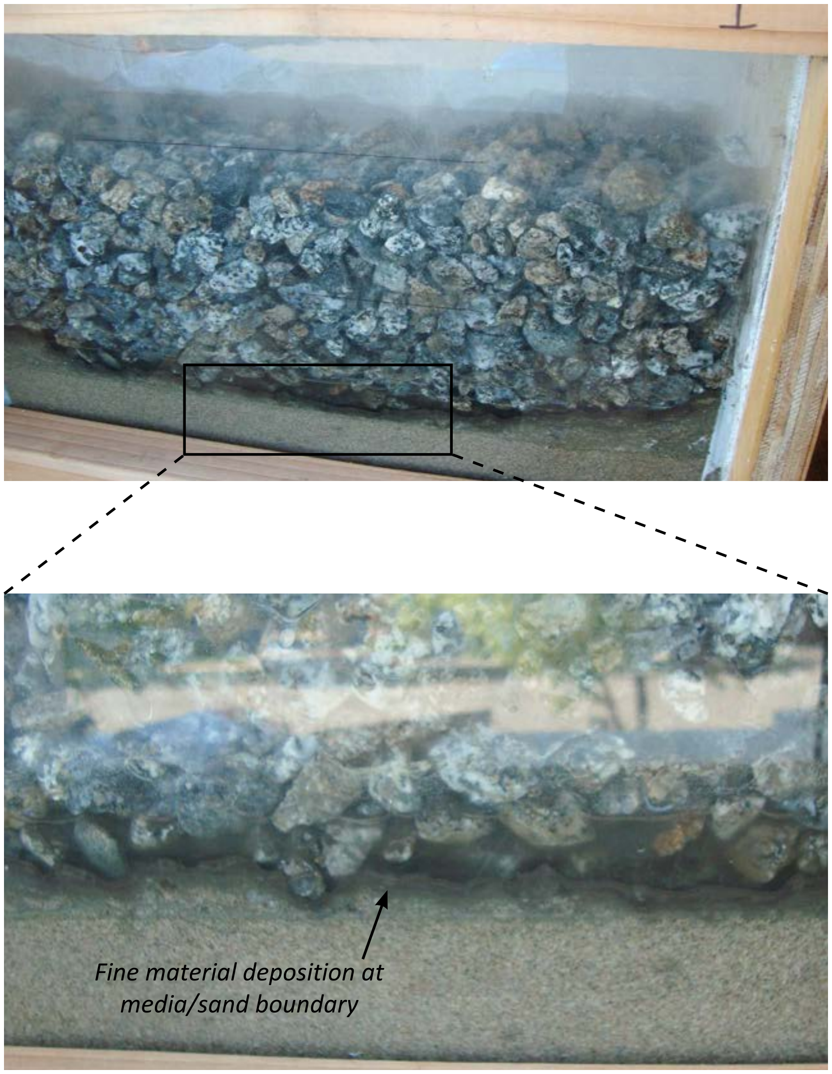
Experimental variations, including different concentrations of stormwater and longer intervals between applications, were tested to assess if the experimental setup could potentially bias the location of material accumulation. However, there was no evidence that sediment accumulation locations varied based on the introduced stormwater concentration or with the timing of stormwater applications. While field observations often showed severe clogging at the surface of BMPs, this was not repeated in laboratory experiments. We attribute the lack of fine sediment accumulation within the void spaces of the drain rock to the fact that the synthetic stormwater was composed entirely of fine sand and smaller material (<125 µm). We suspect that in the field the introduction of pine needles, pollen and coarser grained sediment to the BMP will cause more accumulation of material, including finer sediment, at the surface of the BMP media and within the void spaces of the BMP media (see Figure 2.1).

The fact that in the laboratory BMP configurations fine sediment accumulated almost exclusively at the infiltration surfaces and preferentially on the vertical infiltration surface has some key implications for infiltration BMP performance declines. Because the infiltration surface is the interface where water stored within a BMP passes into the surrounding soil, the rate of clogging of an infiltration surface is the controlling factor to estimate infiltration capacity declines. This rate appears to be controlled by the amount of fine sediment introduced to the BMP. The greater accumulation of material *within* the BMP media observed in the field survey may have been due to greater cumulative fine sediment loading than was used in the lab, but also may be related to accumulation of coarse sediment and organic detritus higher up in the BMP media than occurred in the laboratory experiments. The accumulated layer at the infiltration surfaces effectively reduces the hydraulic conductivity of the boundary through which water must move to exit the BMP. Because much less fine sediment appears to accumulate on the sides of the BMP, the lateral infiltration surfaces likely retain a higher infiltration capacity relative to the vertical infiltration surface.

4.3.2 INFILTRATION CAPACITY DECLINES

Laboratory and in situ experimental data is presented in Figure 4.5 as the measured infiltration capacity (Q) as a function of the cumulative mass of fine sediment loaded to each experiment. These measurements consistently showed steep initial declines in infiltration capacity followed by a gradual reduction in the rate of decline, indicating an exponential decay in performance as the infiltration surfaces clogged with material. Absolute infiltration capacity varied as a function of infiltration surface area and initial K_{sat} (see Figure 4.5),

Visual Evidence of Clogging



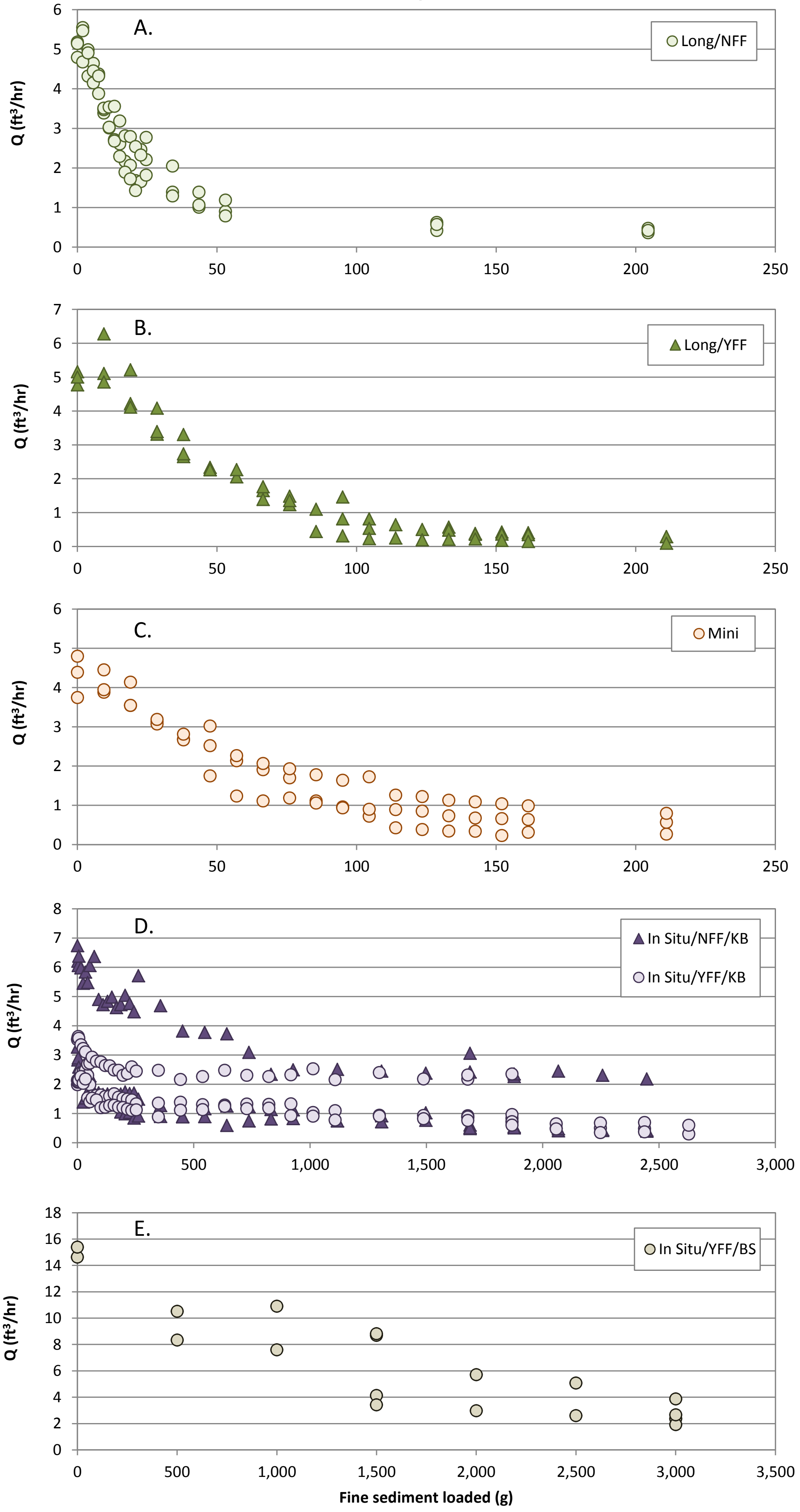
Fine material deposition at media/sand boundary

After significant sediment loading, surface of BMP media remain visibly clear

CLOGGING LOCATIONS OBSERVED

Figure 4.4

Stormwater Loading Simulation Results



Long

$A_{inf} = 0.75$ ft^2

$A_{base} = 0.75$ ft^2

$A_{sides} = 0$ ft^2

Mini

$A_{inf} = 0.5$ ft^2

$A_{base} = 0.25$ ft^2

$A_{sides} = 0.25$ ft^2

In Situ Kings Beach

$A_{inf} = 5.0$ ft^2

$A_{base} = 1.0$ ft^2

$A_{sides} = 4.0$ ft^2

$K_{sat} \approx 5.5$ in/hr

In Situ Beach Sand

$A_{inf} = 5.0$ ft^2

$A_{base} = 1.0$ ft^2

$A_{sides} = 4.0$ ft^2

$K_{sat} \approx 15$ in/hr

RESULTS OF ALL SIMULATION EXPERIMENTS

Figure 4.5

where experiments with greater infiltration surface area and higher starting K_{sat} values required a greater cumulated mass of fine sediment to create a comparable decline in infiltration capacity.

As explained in Section 4.2, relative infiltration capacity decline as a function of cumulative fine sediment loaded was normalized by the infiltration surface area of each experiment (see EQ7) (Figure 4.6).Nearly all of the experiments showed greater than 80% decline from the initial infiltration capacity and several showed greater than a 90% decline (Table 4.1). Notice that the total mass of fine sediment loaded per square foot of infiltration surface increased from the *Long* to the *Mini* to the *In Situ* configurations to achieve the same relative decline in infiltration capacity. This simple comparison illustrates that BMP geometry appears to play a role in the rate of infiltration capacity decline, where overall declines for the same loading rate tend to decrease as the proportion of lateral infiltration surface area increases. The laboratory enclosures (*Long* and *Mini*) had two side infiltration surfaces available while the *In Situ* experiments had four sides of infiltration surface, which also may have contributed to less abrupt initial declines shown in Figure 4.6. Differences in wetting front development in the underlying soil from the laboratory to the *In Situ* experiments also may have played a role in the decline trajectories.

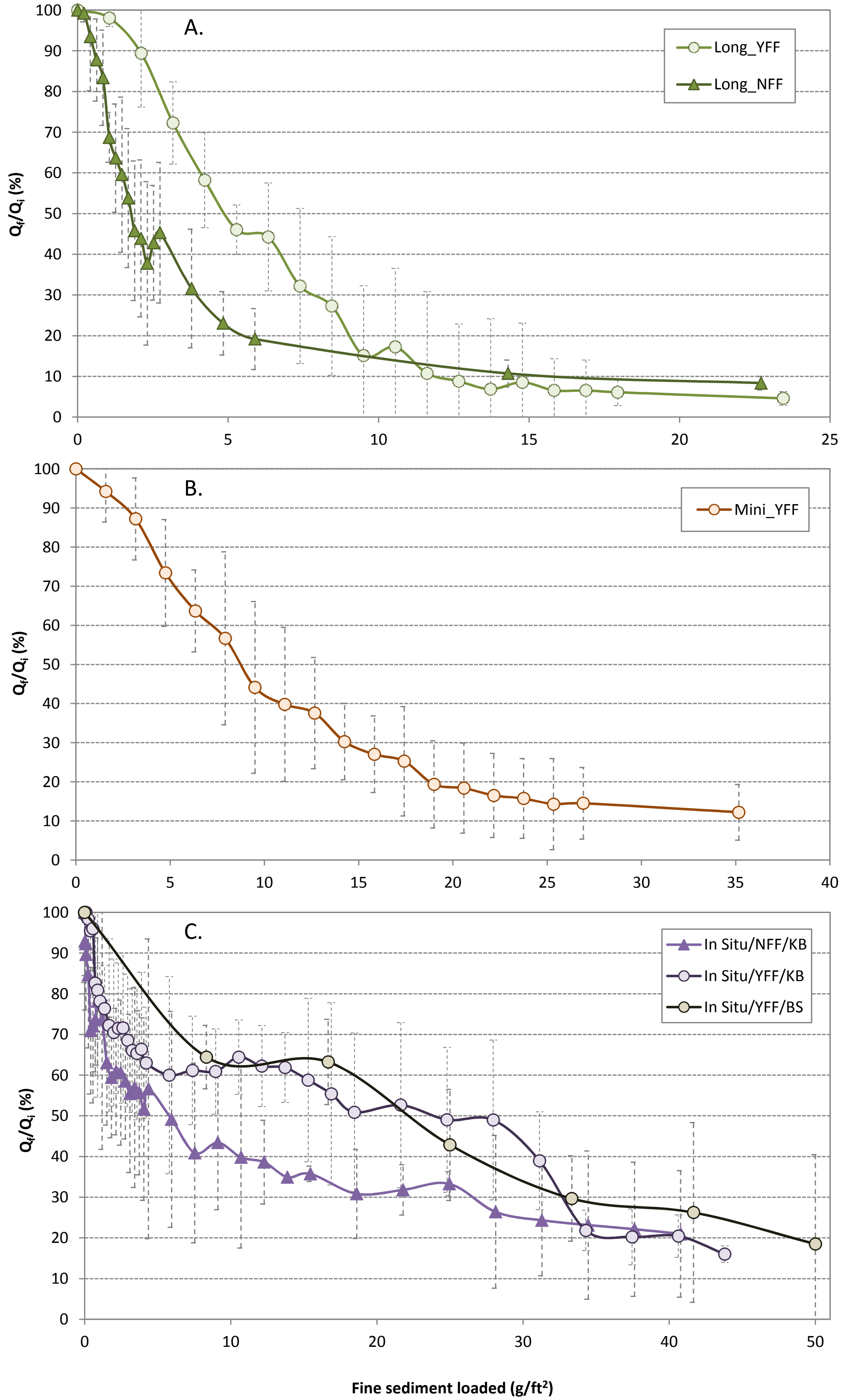
Table 4.1. Total infiltration performance decline for all the experiments performed in units of % decline of the volumetric discharge rate from the initial measurement prior to any sediment loading (100-Q_f/Q_i or 100-R. Experiments included those with filter fabric installed (YFF), without filter fabric installed (NFF), and *In Situ* experiments were conducted in Kings Beach soil series (KB) and beach sand (BS).

Measurement		Long		Mini	In situ		
		NFF	YFF	YFF	NFF/KB	YFF/KB	YFF/BS
100-R (%)	Trial 1	93.9	90.8	92.8	67.6	84.9	86.6
	Trial 2	94.3	92.9	87.1	87.8	83.1	81.8
	Trial 3	98.0	91.2	83.4	81.5	82.6	-
	Trials Avg.	95.4	91.6	87.8	79.0	83.5	84.2
	Configuration Avg.	94.0		87.8	82.2		
A_{inf} (ft^2)		0.75		0.5	4		
FS_a (g/ft^2)		23		35	50		
A_{side}/ A_{base}		0		1	4		

4.3.3 ROLE OF FILTER FABRIC

The *Long* configuration was used to investigate the role that filter fabric, which is a recommended design component to many infiltration BMPs and is intended to reduce maintenance efforts when cleaning a BMP, has on infiltration performance decline. Aside from the installation of filter fabric, all experimental differences between the *Long/YFF and Long/NFF* trials were held constant. Relative infiltration capacity declines are shown in Figure 4.6A, plotted as averages for each triplicate experiment with error bars that show 1.65 standard deviations (approximate 90% confidence interval). Final relative infiltration capacity declines measured with or without filter fabric are similar, with declines of 95.4 % with filter fabric and 91.6% without filter fabric given the same cumulative mass of fine sediment loaded. However, earlier in the experiment the rate of infiltration capacity decline was slower when filter fabric was installed, as noted where the error bars do not overlap (i.e., we can be 90% confident that the two configurations are significantly different from one another). After

Stormwater Loading Simulation Results by Configuration Type



$$R = Q_f / Q_i$$

EXPERIMENTAL RESULTS FOR ALL CONFIGURATIONS

Figure 4.6

approximately 8 g/ft^2 of fine sediment are loaded, the difference between the two configurations is not discernible (see points with overlapping error bars in Figure 4.6) and both trials result in over an 80% decline from the initial infiltration capacity within this period. While the use of filter fabric appears to have some effect on maintaining infiltration capacity as the BMP is loaded with fine sediment, the relative and final rates of performance declines were only marginally influenced by its presence or absence.

Comparisons of the *In Situ* configuration in Kings Beach soil also included trials with and without filter fabric and the mean values with error are provide in Figure 4.6C. The findings are similar to the laboratory experiment, suggesting that at least initially the use of filter fabric decreases the rate of infiltration capacity decline as the BMP is loaded with fine sediment.

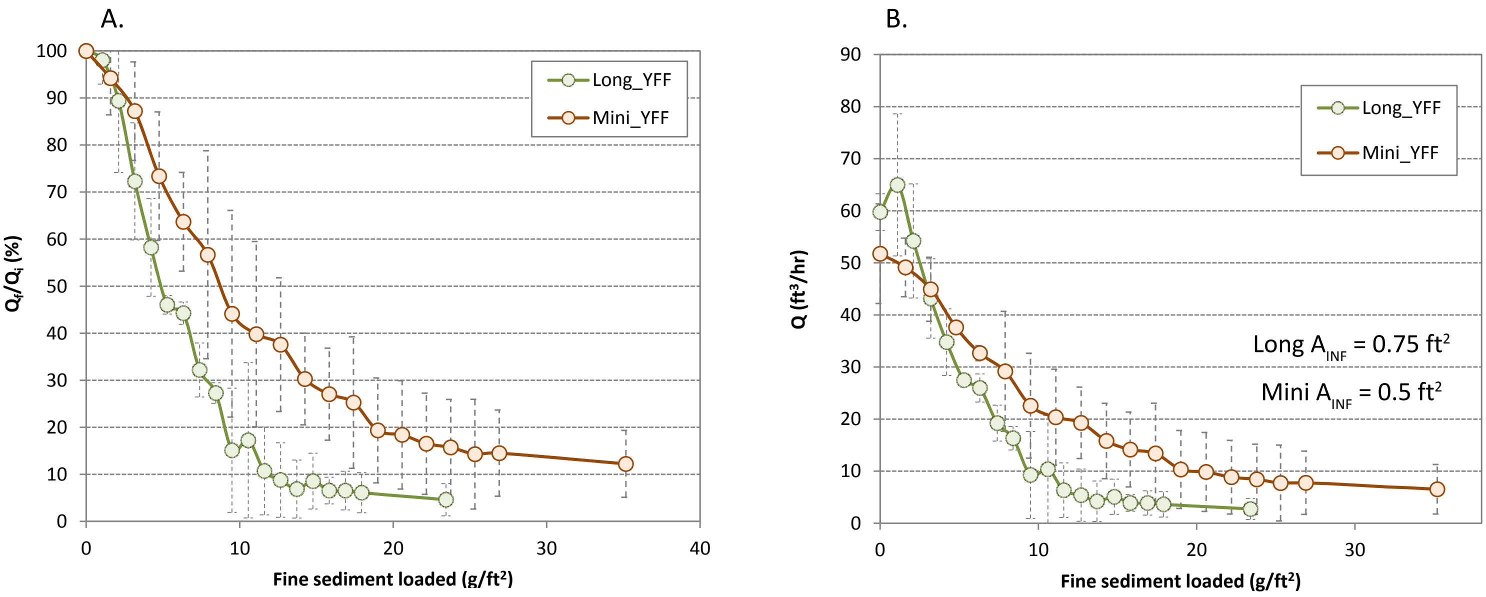
4.3.4 INFLUENCE OF NATIVE SOIL TYPES

A comparison of the two *In Situ* experiments allows inspection of the influence of native soil permeability on infiltration capacity declines. The Kings Beach soil series and beach sand (both with woven filter fabric installed) show very similar infiltration capacity declines (e.g., the overlap of the error bars in Figure 4.6C) even though the K_{sat} of the native soils are very different: approximately 5.5 in/hr for the Kings Beach soil (USDA NRCS 2007) and a 15 in/hr rate measured using a constant head permeameter in Santa Cruz beach sand. These results suggest that while the absolute infiltration capacity of a BMP installed in beach sand is much greater than the same BMP installed in the Kings Beach soil, the relative rate of infiltration capacity decline does not vary significantly as a function of the initial K_{sat} of the native soil. Interpretation of these results is limited, since they are only based on two soil types, both with relatively high K_{sat} values. However, the range of K_{sat} values that they represent (5.5-15 in/hr) encompasses K_{sat} for native soil types that cover approximately 42% of urbanized areas in the Tahoe Basin (see 2NDNATURE and NHC 2010, p. 17).

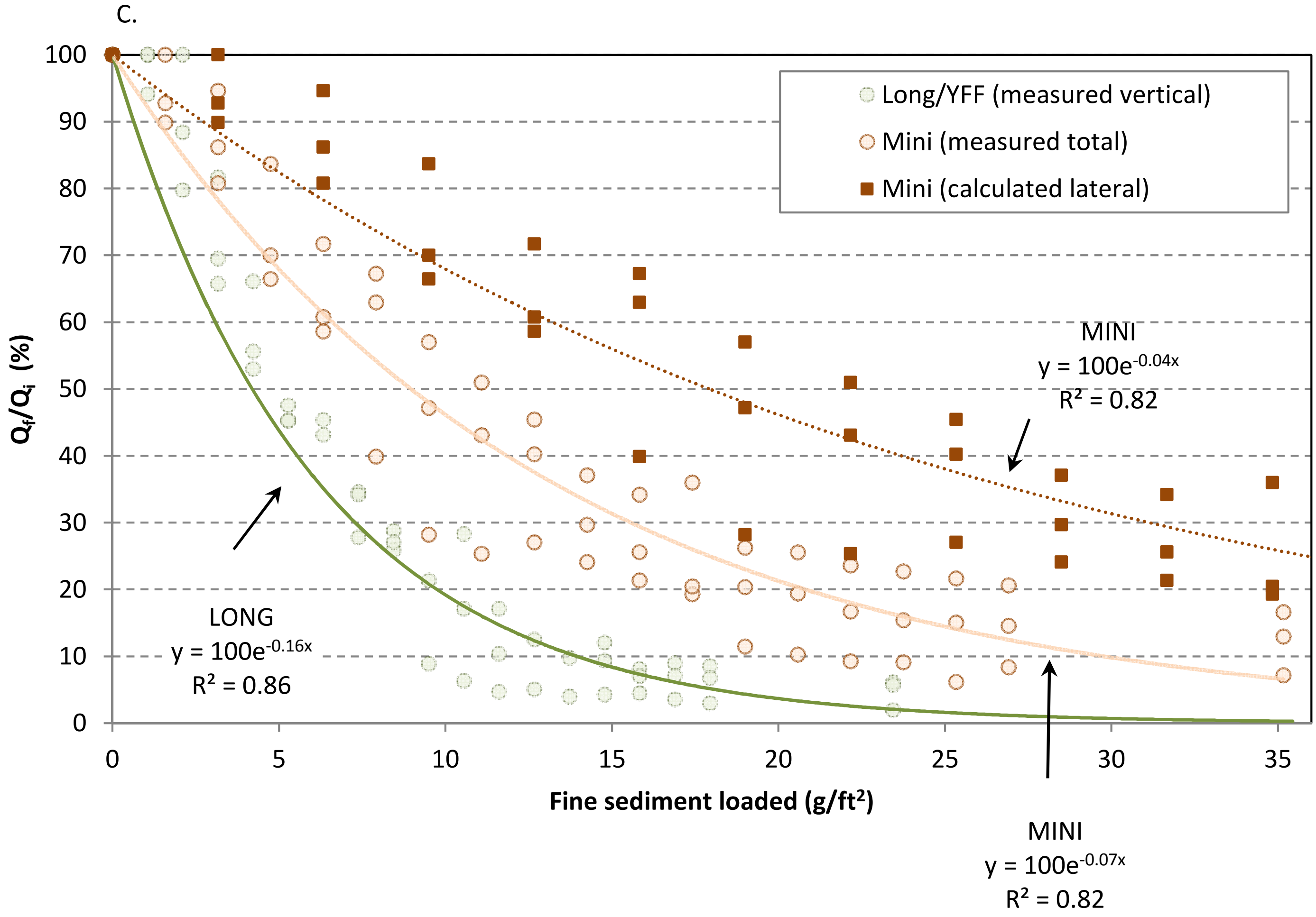
4.3.5 LATERAL INFILTRATION

A comparison of the data obtained from the *Mini* and *Long* configurations allows an evaluation of the relative importance of lateral infiltration on infiltration capacity decline. While the use of 2/3 of one of the long BMP sides is a standard method for estimating the area available for lateral infiltration (as in the BMP Calculation Spreadsheet), we were interested in the role of lateral infiltration as the observations from the laboratory experiments indicated that the base of the BMP accumulates the majority of fine sediment loading to the BMP. In the *Mini* configuration the vertical infiltration surface area is roughly 1/3 of the total infiltration surface area (see Figure 4.2). Because the *Mini* had filter fabric between the media and sand, comparisons of performance decline are made with the *Long* configuration that included filter fabric (*Long/YFF*).

Figure 4.7A presents the performance decline differences between the two configurations, with error bars that approximate a 90% confidence interval of the mean. For the same loading rate, the rate of decline for infiltration capacity with the *Mini* configuration is more gradual than the *Long* configuration. While the overlapping error bars along some of the decline trajectory indicate that it is often difficult to distinguish between the two with a high level of confidence, statistically valid differences exist where the two diverge from one another (see Figure 4.7A). Because the data have been normalized by the infiltration surface area available, it is reasonable to infer that the difference between the two curves is largely due to the geometry of the BMP configurations with the lateral infiltration surfaces appearing to become proportionally more



Results of *Long* and *Mini* configurations for relative infiltration capacity [$R=Q_f/Q_i$] (on left) and absolute infiltration capacity (on right).



Measured relative infiltration capacity reductions ($R=Q_f/Q_i$) from the 3 *Mini* experiments are presented with a best fit curve (orange). The measured reductions from the *Long* experiments with filter fabric are presented with a best fit curve (green) that represent comparable vertical declines for the *Mini*. Given that $Q = Q_V + Q_L$, Q_L for the *Mini* is calculated for each data point and Q_f/Q_i plotted (red).

important for overall infiltration capacity as the BMP becomes clogged with fine sediment. The *Mini* configuration appears to outperform the *Long* configuration by sustaining a higher relative infiltration capacity for a longer period of stormwater loading. Also the *Mini* configuration appears to sustain a higher absolute infiltration capacity even with a smaller total infiltration surface area (see Figure 4.7B). These findings suggest that BMPs with a greater proportion of lateral infiltration surface area will maintain a higher amount of their infiltration capacity as the BMP is loaded with fine sediment.

We utilized the *Long* and *Mini* experimental data to estimate infiltration capacity decline of the base and the sides of an infiltration BMP. The measured data from the *Long* configuration isolated estimated infiltration capacity decline due to clogging at the base in the vertical direction. The *Mini* (and *In Situ*) experimental data measured total infiltration capacity decline as the sum of the vertical and lateral components as a function of total fine sediment loading. Figure 4.7C presents the best fit curves of all of the experimental data. Assuming that the decline in relative infiltration capacity measured in the *Long* experiment is similar in response to the vertical component for *Mini*, we can estimate the lateral component of *Mini* by subtracting the *Long* measurements from the total infiltration capacity declines observed in the *Mini*. The resulting calculations of lateral infiltration capacity declines for the *Mini* are presented as red boxes in Figure 4.7C. This analysis yields the following equations for the vertical (R_v) and lateral (R_l) infiltration capacity reduction coefficients empirically estimated as a function of the amount of fine sediment loaded to the BMP per square foot of infiltration area (FS_a):

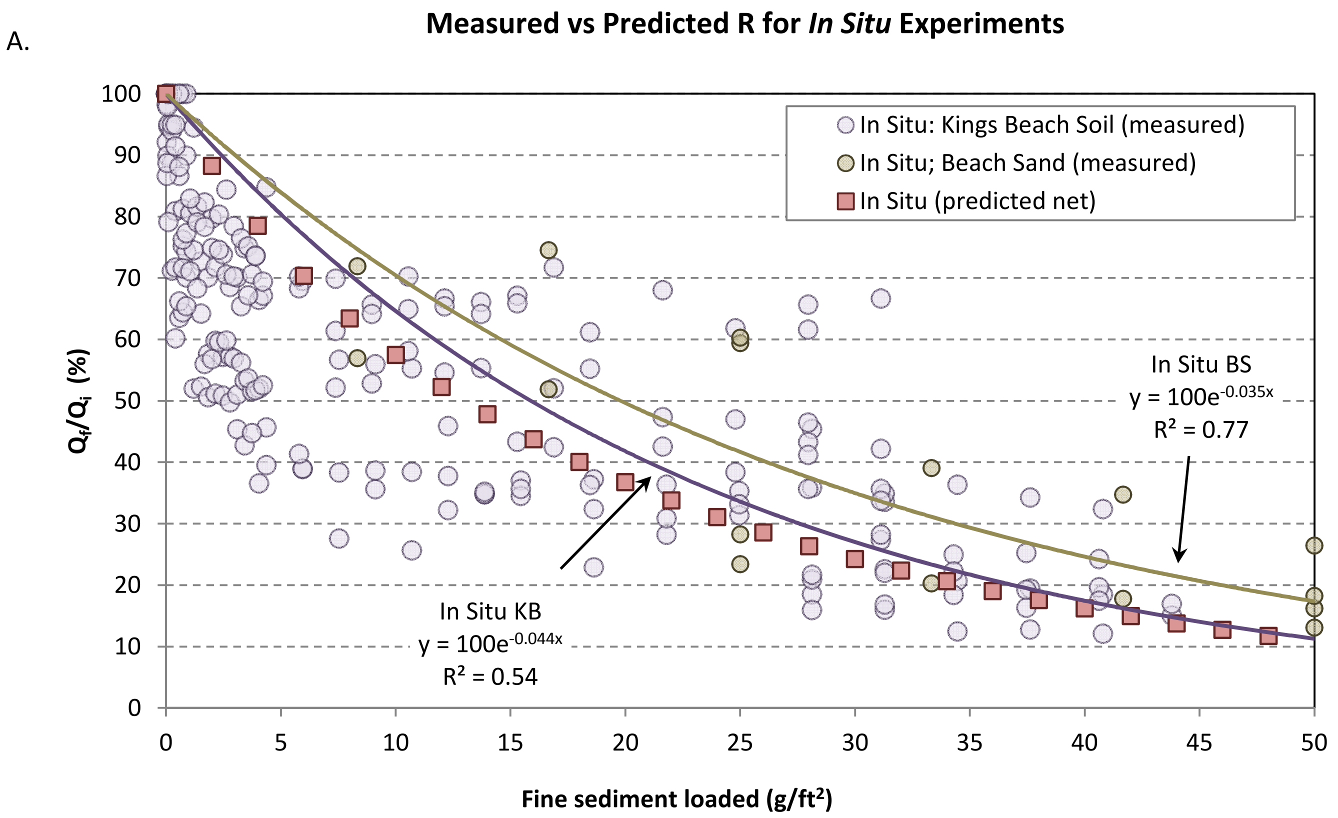
$$R_v = e^{-0.16 * FSa} \tag{EQ8}$$

$$R_l = e^{-0.04 * FSa} \tag{EQ9}$$

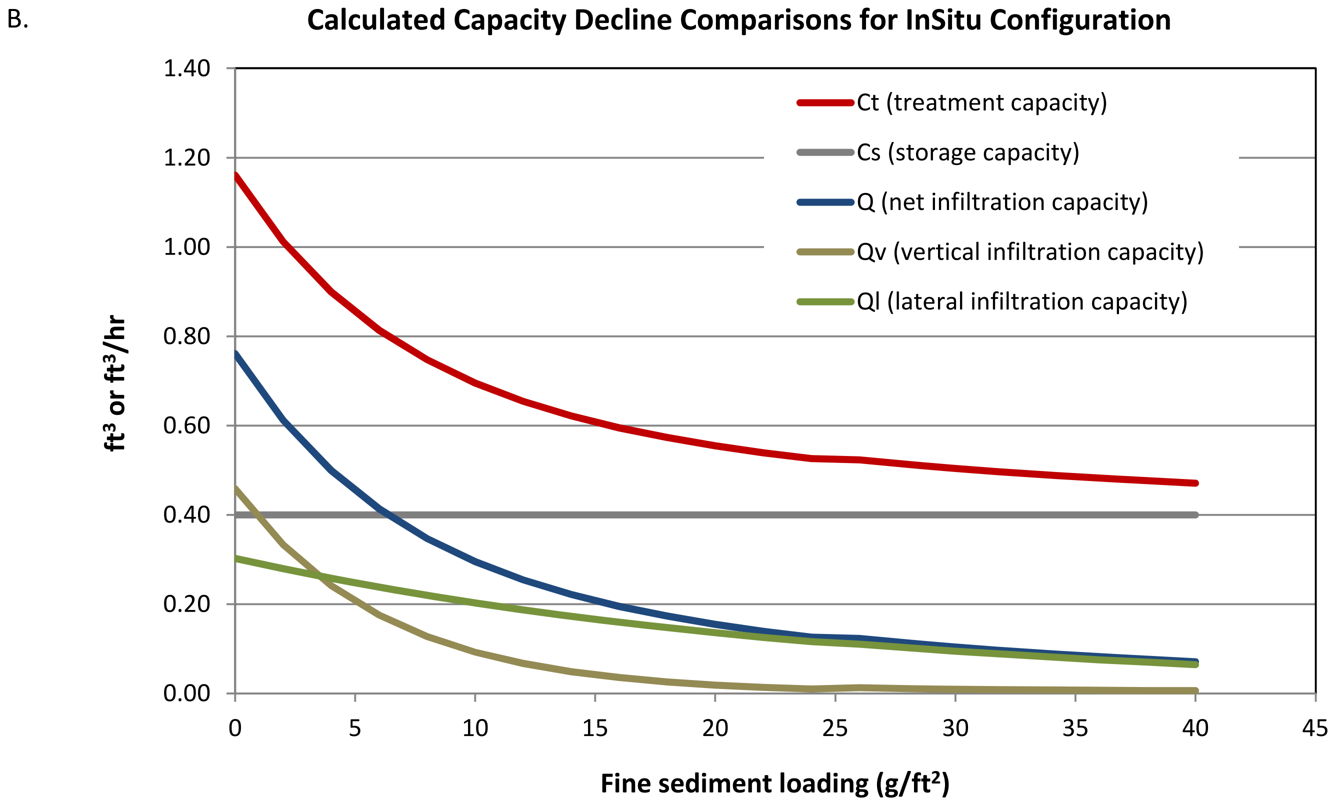
We validated the above equations by using them to predict the measured infiltration capacity decline as a function of fine sediment loading rate of the *In Situ* experiments. We used the measured vertical and calculated lateral exponential equations above (EQ8 and EQ9; see Figure 4.7C) to predict the relative infiltration capacity decline (R) as a function of fine sediment loading for the *In Situ* configuration. These predictions are presented as red squares in Figure 4.8A. The close alignment between the predicted values and the best fit exponential curves of the measured *In Situ* data suggests that the empirical method used to separate and predict the vertical and lateral component of infiltration capacity produces reasonable results. This validation, however, is limited to one small-scale BMP configuration (1 ft^3) and a limited number of measurements. Confidence in the equations could be greatly improved if the model were applied to other infiltration BMP configurations that varied the ratio of vertical and lateral infiltration surface area.

4.3.6 IMPLICATIONS FOR TREATMENT CAPACITY

We can estimate the treatment capacity decline of our *In Situ* BMP using the decline rate derived from the *In Situ* measurements, the empirically derived vertical/lateral decay equations (EQ 8 and 9), and the BMP Calculation Spreadsheet (see Figure 4.8B). Recall that treatment capacity (C_t) in the BMP Calculation Spreadsheet is scaled to the 20 year, 1 hour storm with an intensity of 1 in/hr and calculated as the sum of storage capacity (C_s) and infiltration capacity (Q). Note the treatment capacity decline is directly proportional to that of the total infiltration capacity and that divergence between the two is largely because the change in storage capacity is negligible. Beyond approximately 4 g/ft^2 of loading, the lateral infiltration capacity surpasses the vertical infiltration capacity due to the steeper decline of the vertical component and high proportion of



In Situ measured net relative infiltration capacity decline (Q_f/Q_i) (sum of lateral and vertical declines) values presented for all experiments conducted in Kings Beach soil (purple) and Beach Sand (brown). Using the exponential coefficients in Figure 4.7 for lateral and vertical infiltration rate decline, the net decline for the *In Situ* BMP is predicted (red).



Treatment capacity (as predicted using the BMP Calculation Spreadsheet) compared to the change in lateral, vertical and net infiltration capacity (ft^3/hr) as a function of fine sediment loading per unit infiltration surface area.

side infiltration surfaces available in the *In Situ* configuration (see Table 4.1). After 10 g/ft^2 of loading, treatment capacity declines to approximately 60% of its initial capacity and after 40 g/ft^2 it retains only 23% of the initial capacity. The rate of treatment capacity decline over time for a BMP installed in the Tahoe Basin will depend on the sediment loading that results from the contributing drainage area and surface types (see Chapter 5 for a discussion of these topics).

4.3.7 SUMMARY OF FINDINGS FOR STORMWATER LODING EXPERIMENTS

- **Sediment preferentially accumulates at the base of infiltration BMPs.** Visual inspections of the BMP enclosures indicate that the majority of accumulated fine material was found along the base of the BMP with very little material accumulated on the sides. Infiltration capacity decline of the base appears to be the controlling factor of observed BMP infiltration capacity declines, particularly when total sediment loading is < 10g/ft^2 of the total BMP infiltration area.
- **BMP infiltration capacity declines exponentially.** A rapid initial decline in infiltration capacity was observed followed by a more gradual decline after roughly 10 to 15 g/ft^2 of fine sediment per infiltration surface area had been loaded to the BMP.
- **Filter fabric somewhat preserves infiltration capacity somewhat during initial loading.** Installation of filter fabric appears to cause a slower loss in initial infiltration capacity as the BMP is loaded with fine sediment (< 5 g/ft^2). However, the presence or absence of filter fabric does not appear to be a significant factor influencing the rate of infiltration capacity decline once loading exceeds 10 - 15 g/ft^2 of fine sediment.
- **Initial permeability of the native soil doesn't appear to affect relative infiltration capacity decline**. A comparison of infiltration capacity decline was conducted in test BMPs that had initial soil K_{sat} values of 5.5 and 15 in/hr, yet no discernible difference was observed in the relative decline as a function of fine sediment loading. However, absolute infiltration capacity appears to be influenced by initial K_{sat} in the two relatively high K_{sat} soils that were tested
- **The infiltration capacity of the base of a BMP declines significantly faster than the sides.** Measurements of infiltration capacity supports the visual observation that the base of a BMP will clog more rapidly than the sides as fine material is introduced, leading to a more rapid decline in infiltration capacity for the base of a BMP relative to the sides.
- **Empirical equations to estimate the vertical and lateral infiltration capacity as function of fine sediment loading appear to reasonably estimate infiltration capacity changes over time.** Given the available data and experimental design, coefficients have been identified (and preliminarily validated) to predict the vertical and lateral components of infiltration capacity decline of an infiltration BMP as function of fine sediment loading per square foot of infiltration area.

While the research findings appear to reasonably predict the influence of fine sediment loading on infiltration BMP performance over time, there were a number of key limitations to note with the research:

1. Creating an infiltration BMP in the laboratory that mimics real world conditions is challenging due to the nature of soil dynamics and heterogeneities that exist in soil surrounding a real BMP. *In Situ*

experiments inherently include factors that contribute variability to experimental results that can confound the ability to rigorously test hypotheses about BMP performance declines.

2. We assumed that the observed declines from the *Long* configuration adequately represent the vertical component of the *Mini* enclosure. This assumption could be further validated with enclosures that allowed the independent measurement of infiltration out of the base and the sides of a BMP.
3. Validation of the empirical equations to calculate lateral and vertical infiltration capacity decline was conducted on only one BMP configuration in only two native soil types. Because there may be some scale dependence of these equations, validation on other BMP geometries would be helpful to improve confidence and refine the coefficients. Similar studies on BMPs with a range of base to side infiltration surface area ratios conducted in other soil types would improve and/or further validate these values.
4. The synthetic stormwater used for the experiments contained only fine sediment <125 µm. Actual stormwater would also contain coarse sediment and organic material, and we do not know what the differences in clogging dynamics or infiltration capacity declines may have been with the addition of coarser material. The combination of course sediment, organic debris, pollen and fine material may result in the creation of impermeable layers at locations well above the base of the BMP as observed in the field surveys. Future laboratory experiments could include simulations with a mixture of material in ample supply to accumulate in Tahoe Basin infiltration BMPs to better understand performance implications and the effectiveness of different maintenance strategies.

5 APPLICATION OF RESEARCH

Using the observations and results of the field surveys and stormwater loading simulations, Chapter 5 explores an approach for applying the findings to inform the selection, siting, sizing, and maintenance of infiltration BMPs by considering declines in infiltration capacity as a function of anticipated fine sediment loading.

5.1 MODIFICATIONS TO BMP SIZING AND SELECTION METHODOLOGY

The current version of the BMP Calculation Spreadsheet was modified to estimate declines in infiltration capacity resulting from stormwater loading and subsequent clogging of infiltration surfaces by fine sediment. The BMP Calculation Spreadsheet is the primary tool used to site and design residential BMPs and some commercial BMPs in the Tahoe Basin to achieve regulatory requirements. The modifications described below resulted in a tool that can assess declines in infiltration capacity over time for a range of BMP types, designs, and fine sediment loading rates. The specific modifications to the BMP Calculation Spreadsheet described below are intended to be general concepts that could be applied to any stormwater tool used in the Tahoe Basin to size and design Infiltration BMPs. Figure 2.1 illustrates and describes the key terms used in the discussion below (e.g., treatment capacity, infiltration capacity, infiltration surface area, etc.).

1. **Estimate average annual fine sediment loading to an infiltration BMP.** Fine sediment loading was estimated by adding a new field in the BMP Calculation Spreadsheet that allows assignment of the dominant impervious surface type that drains to the infiltration BMP. The impervious surface type, combined with the presence or absence of stormwater treatment, was then used to estimate the loading rate of fine sediment on an annual basis to the infiltration BMP. Table 5.1 presents the loading rates used in the evaluation. The approach targets fine sediment loading, and potential variations in fine sediment loading, for the following reasons:

    - Field observations indicated that fine sediment loading to an infiltration BMP was an important factor affecting the infiltration performance of BMPs.
    - Stormwater loading experiments indicated that infiltration capacity can markedly decline as an infiltration BMP is loaded with fine sediment and the infiltration surfaces clog.
    - Different types of impervious surfaces, and different conditions for each surface, can generate notably different amounts of fine sediment in stormwater runoff.
    - The presence of a stormwater treatment device, or pre-treatment device, upstream from an infiltration BMP can reduce the amount of fine sediment loaded to the BMP.

    The values in Table 5.1 were developed by examining information from a number of sources including: stormwater data presented in the Lake Tahoe TMDL; compilations of Road RAM observations (2NDNATURE et al. 2010); and information provided from the NRCS regarding their ongoing and unpublished research investigating residential driveway BMP performance (Chuck Taylor, pers. comm. December 2012). The reader should note that the estimates in Table 5.1 are based on the best available data available to the research team, and the values are not intended to be applied beyond this research without further critical assessment or supplemental land use specific sampling using available techniques (2NDNATURE et al. 2010). For example, for each surface type the presence of a stormwater treatment device is assumed to be 60% effective at removing fine sediment relative to the loading rate for the same surface type without stormwater treatment. However, the effectiveness of stormwater treatment could markedly vary depending on the type of treatment facility selected and the design and maintenance of the facility. In most instances, these estimates are conservative when compared to the poorest condition surfaces observed in the Basin (2NDNATURE et al. 2010). Furthermore, stormwater data characterizing roof runoff in the Tahoe Basin was not located. The loading rate shown in Table 5.1 for roof runoff is based on data gathered during the field surveys, as well as anecdotal observations that roof runoff is generally quite clean and free of substantial amounts of fine sediment.

Table 5.1. Estimates of fine sediment loading rates by surface type for use in calculations

Surface Type and Condition	Fine Sediment (<125 µm) Characteristic Runoff Concentration (mg/L)	Fine sediment loading rate (grams/ft^2/year)
Roof	2	0.1
Single Family Driveway (with treatment)	16	0.4
Single Family Driveway (without treatment)	40	0.9
Multi-Family Driveway (with treatment)	30	0.7
Multi-Family Driveway (without treatment)	75	1.8
Parking Lot (with treatment)	80	1.9
Parking Lot (without treatment)	200	4.7

By incorporating the loading rates from Table 5.1 into the BMP Calculation Spreadsheet, an estimate of total annual loading of fine sediment is made by multiplying the drainage area of the impervious surface by the associated loading rate. For example, a standard 20 ft x 20 ft driveway without a stormwater treatment system is estimated to generate 360 grams of fine sediment per year (400 ft^2 x 0.9 g/ ft^2/yr = 360 g/yr).

2. **Modify the current infiltration capacity equation to allow additional lateral infiltration surface area.** The current method used in the BMP Calculation Spreadsheet estimates the lateral infiltration surface area by multiplying 2/3 the depth of the BMP by the length of the BMP. Effectively, this equation gives credit for lateral infiltration to a portion of a single long side of the infiltration BMP. In some cases this restriction on lateral infiltration may be a reasonable assumption, such as when an infiltration BMP is installed adjacent to the foundation of structure. However, in other cases a BMP may be sited in a location with no restrictions on lateral infiltration and the current approach will likely underestimate the lateral infiltration capacity of the BMP.

   To incorporate a more flexible approach to estimating lateral infiltration surface area, a new field was added to the BMP Calculation Spreadsheet that requires the user to define the BMP type and the siting factors that might cause restrictions to the number of sides available for lateral infiltration. Table 5.2 was used to identify the number of sides to credit an infiltration BMP with lateral infiltration. Using the values in Table 5.2, the current infiltration capacity equation was modified to calculate lateral infiltration surface area based on the defined BMP type and proximity to potential infiltration restrictions. The current assumption in the BMP Calculation Spreadsheet that uses 2/3 the depth of the BMP to calculate lateral infiltration surface area was retained.

Table 5.2. Number of Sides Used in Lateral Infiltration Surface Area Calculation

BMP Type and Siting	Number of Sides Used to Calculate Lateral Infiltration Surface Area
Infiltration Trench (no restrictions)	4
Infiltration Trench (adjacent to foundation or driveway)	1
Dry Well (no restrictions)	4
Dry Well (adjacent to foundation or driveway)	2
Infiltration Basin	4
Subsurface Infiltration System	4
Sheet Flow / Land Application	0

3. **Apply decay equations developed from the stormwater loading experiments to estimate declines in infiltration capacity.** The stormwater loading experiments described in Chapter 4 produced equations to estimate the relative declines from the initial vertical (R_V) and lateral (R_l) infiltration capacity based on cumulative fine sediment loading per square foot of total infiltration surface area (FS_a) within a BMP. The exponents of the decay equations are the empirically derived coefficients (see Chapter 4) used to estimate the relative decline in infiltration capacity for the base and sides of an infiltration BMPs as a function of fine sediment loading per square foot of total infiltration surface area. The equations are as follows:

$$R_V = e^{-0.16 * FSa} \qquad \text{(EQ8)}$$

$$R_l = e^{-0.04 * FSa} \qquad \text{(EQ9)}$$

New fields were added to the BMP Calculation Spreadsheet to separately calculate lateral and vertical infiltration surface area of a BMP using inputs specified for: 1) BMP dimensions; and 2) BMP type, which was used to identify restrictions to lateral infiltration (see Table 5.2). With this modification and the previous modifications described above, the majority of information necessary to estimate infiltration capacity decline for a BMP is available within the tool. With the assistance of user inputs to the BMP Calculation Spreadsheet, the following variables within the decay equations are available:

- Fine sediment loaded to the infiltration BMP on an annual basis
- Infiltration surface areas of the BMP (total, lateral, and vertical)
- Lateral and vertical decay coefficients (if modified from current values)

The remaining step to inform the decay equations was to estimate cumulative fine sediment loading to predict declines in infiltration capacity over specific intervals of time. The selected method to incorporate an interval of time into the decay equations is described next.

4. **Define and apply the concept of a Restoration Interval to the calculation of infiltration capacity.** A Restoration Interval is defined as the duration of time before maintenance activities are needed to restore the infiltration surfaces of an infiltration BMP to ensure the long-term treatment capacity of a BMP is sustained at an acceptable level. Depending upon the type of BMP and the ease of access to its infiltration surfaces, restoration activities will require different levels of effort. For example, restoring the infiltration surfaces of a vegetated infiltration basin may simply involve raking, tilling, or aerating the exposed soil surfaces of the basin. Conversely, restoring the infiltration surfaces of a dry well may require complete reconstruction of the BMP as the infiltration surfaces are covered by drain rock. Restoration Intervals are intended to identify reasonable durations of time between activities necessary to regenerate the infiltration capacity of a BMP based the type of BMP and the associated level of effort to complete the restoration activities. Table 5.3 presents the intervals selected for this research application by BMP type. If the concept of standardized Restoration Intervals is adopted into BMP design guidelines or Tahoe Basin policies, the values presented in Table 5.3 should be revisited.

Table 5.3. Restoration Intervals used to calculate infiltration capacity decline

BMP Type	Restoration Interval (years)
Infiltration Trench	10
Dry Well	10
Infiltration Basin	2
Subsurface Infiltration System	5
Sheet Flow / Land Application	2

5. **Calculate infiltration capacity and the associated treatment capacity at the Restoration Interval.** Within the modified BMP Calculation Spreadsheet, cumulative fine sediment loading to an infiltration BMP is estimated by multiplying the annual loading rate of fine sediment by the number of years associated with the Restoration Interval of the selected BMP type. This estimate of cumulative fine sediment loading is divided by the total infiltration surface area of the BMP to estimate cumulative fine sediment loading per square foot of infiltration surface area when a Restoration Interval is reached. Next, the decay equations are used to estimate the remaining lateral and vertical infiltration capacity at the Restoration Interval. Finally, the remaining infiltration capacity was summed with storage capacity to estimate treatment capacity credited to the BMP at the Restoration Interval.

6. **Calculate draw down time of the infiltration BMP at the Restoration Interval.** Using the storage capacity of the BMP and the infiltration capacity at the Restoration Interval, a new check was added to the BMP Calculation Spreadsheet to estimate the draw down time of the BMP at the Restoration Interval. The check was set up to flag situations where the draw down time exceeded 24 hours at the Restoration Interval. The intent of this modification is to prohibit infiltration BMPs from meeting treatment capacity requirements solely through the use of storage capacity. In other words, a reasonable rate of infiltration should be maintained so that storage capacity within an infiltration BMP is regenerated and available for subsequent runoff events.

The modifications described above produced a functional tool that allowed the research team to explore and assess multiple BMP configurations and stormwater loading scenarios to analyze impacts to infiltration capacity of infiltration BMPs. Potential benefits from using the concept of a standardized Restoration Interval by BMP type combined with estimates of infiltration capacity declines based on stormwater loading are as follows:

1. Standardizing the time period for conducting the key maintenance activity for an infiltration BMP (restoration of the infiltration surface area) would provide a clear and more manageable system for both TRPA and properties owners to track and conduct infiltration BMP maintenance.
2. Infiltration BMPs could be sited, designed, and sized to maintain a treatment capacity estimated to meet regulatory requirements for a specified period of time.

While the modifications described have resulted in a functional tool that can be used to assess the implications of the key findings from this research, the tool was not developed to a level of technical sophistication, usability, or quality assurance that would facilitate the distribution of the modified BMP Calculation Spreadsheet. However, the modified BMP Calculation Spreadsheet has been provided digitally in Appendix C in case further exploration and analysis by TRPA is desired.

5.2 EXAMPLE SCENARIOS AND RESULTS

The modified BMP Calculation Spreadsheet was used to assess how estimated declines in infiltration capacity at a defined Restoration Interval might affect BMP sizing. The scenarios tested varied the type of infiltration BMP, fine sediment loading rate to a BMP, and BMP configuration. This section presents a brief summary of the approach used to test the various scenarios and the results of the assessment. The reader should note that the results are highly sensitive to the following data and assumptions: 1) decay coefficients used to predict declines in lateral and vertical infiltration capacity; 2) unit loading rates of fine sediment by surface type; and 3) Restoration Intervals defined for each BMP type.

To limit the number of variables and permutations used during the exercise, the following standard assumptions and inputs were applied across all scenarios:

- The impervious surface area draining to an infiltration BMP was set to have dimensions of 20 ft x 20 ft, which equates to 400 ft^2 of impervious area or the typical size of a standard driveway in the Tahoe Basin.
    - The 20-year 1-hour storm volume generated from the impervious area is 33.3 ft^3 = 400 ft^2 / (1 in precipitation / 12 in).
    - 33.3 ft^3 of stormwater runoff was the targeted treatment capacity for each infiltration BMP at its defined Restoration Interval.
- Initial saturated hydraulic conductivity (K_{sat}) was set to 3 in/hr.
- The average void space of drain rock within an infiltration BMP was set to 40 %.

<u>Scenario 1 – Variations in Infiltration Capacity Based on Fine Sediment Loading Rates (Figure 5.1)</u>

Scenario 1 evaluates how estimated infiltration capacity for an infiltration BMP would vary between the current algorithms in the BMP Calculation Spreadsheet and the modified algorithms described above in Section 5.1. The following steps explain the assumptions and parameters used in Scenario 1.

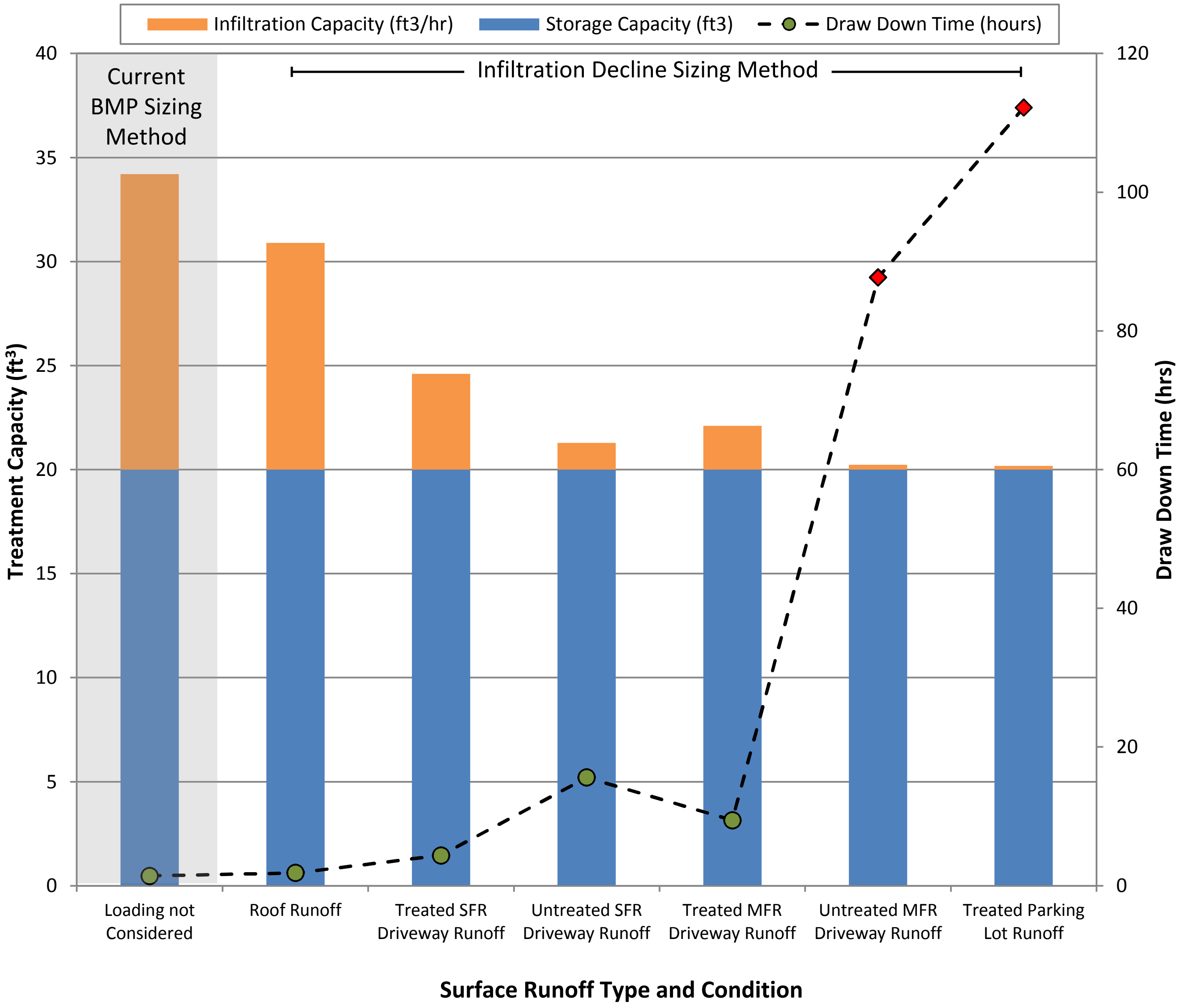
Step 1 – Using the current BMP Calculation Spreadsheet, an infiltration trench was sized to retain the targeted treatment capacity of 33.3 ft^3. The trench was sized to be 20 ft long by 2 ft wide by 15 in deep. Assuming the average void space of the drain rock within the infiltration trench is 40 percent, the dimensions for infiltration trench yield a storage capacity of 20 ft^3. The infiltration capacity of the infiltration trench is estimated to be 14 ft^3/hr. Note that the current BMP Calculation Spreadsheet approach credits lateral infiltration as 2/3 the depth of one long side of an infiltration trench.

Step 2 – To test how variations in fine sediment loading rates might affect calculated infiltration capacity using methods proposed by this research, the dimensions of the infiltration trench described in Step 1 were input into the modified BMP Calculation Spreadsheet. Next, fine sediment loading to the infiltration trench was varied by changing the surface runoff type and condition, which ranged from roof runoff to treated parking lot runoff. For the calculations using the modified BMP Calculation Spreadsheet, lateral infiltration was credited as 2/3 the depth of all sides of an infiltration trench.

The results of the analysis are presented in Figure 5.1 for varying rates of fine sediment loading to the infiltration trench. On the graph shown in Figure 5.1 the primary Y-axis displays the proportion of treatment capacity credited to storage capacity and infiltration capacity at the Restoration Interval, which is defined as 10 years for an infiltration trench. Since the dimensions of the infiltration trench were held static, the storage capacity across the permutations remained at 20 cubic feet. A second performance metric was added to the secondary Y-axis that displays the estimated draw down time of the infiltration trench. When the draw down time exceeds 24 hours it is flagged as unacceptable in Figure 5.1. The results shown in Figure 5.1 support the following points:

- **Fine sediment loading rates estimated for roof runoff did not significantly affect infiltration capacity.** Based on the small amount of cumulative fine sediment loaded to an infiltration BMP receiving roof runoff, roughly 80% of the initial infiltration capacity calculated using the current BMP Calculation Spreadsheet method was retained when modified approach that incorporates fine sediment loading was applied.
- **Fine sediment loading rates estimated for untreated driveway runoff and treated parking lot runoff substantially affected infiltration capacity**. For fine sediment loading rates estimated for untreated driveway runoff and treated parking lot runoff, the remaining infiltration capacity using the modified approach was less than 10% of the infiltration capacity predicted with the current BMP Calculation Spreadsheet method at the define Restoration Interval of 10 years for the infiltration trench. Additionally, the draw down time reached unacceptable levels on the order of 3-4 days.

An implication of these results is that pollutant source controls, which reduce fine sediment loading rates to infiltration BMPs, may substantially reduce infiltration capacity declines**.** The current estimates of fine sediment loading rates used for this analysis (see Table 5.1) do not estimate how pollutant source controls could reduce cumulative fine sediment loads to infiltration BMPs. For example, sweeping a driveway in the spring to recover and remove fine sediment that has accumulated on a driveway over the winter may be a very effective approach for reducing fine sediment delivery to an infiltration BMP.



Treatment capacity is equal to the storage capacity (ft^3) plus the infiltration capacity (ft^3/hour). As infiltration capacity declines, storage capacity would need to be increased to provide the same total treatment capacity. Draw down times greater than 24 hours are flagged as unacceptable and shown in red.

Parameters used in analysis:

- Surface drainage area: 20ft x 20ft = 400 ft^2
- 20-year 1-hour storm criterion: 33.3 ft^3 of runoff
- Surface type and condition: Varies in analysis
- Surface loading estimate to infiltration BMP at restoration interval: Varies in analysis
- Infiltration BMP type: Infiltration trench
- Infiltration BMP dimensions: 20ft long x 2ft wide x 15in deep
- Restoration interval for infiltration decline sizing method: 10 years
- Initial Ksat: 3.0 in/hr

SCENARIO 1: VARIATIONS IN INFILTRATION CAPACITY FROM VARIABLE FINE SEDIMENT LOADING RATES

FIGURE 5.1

Scenario 2 – Variations in Infiltration Capacity Based on the Concept of Restoration Intervals (Figure 5.2)

To test how fine sediment loading rates affect infiltration capacity over time, a time series analysis was created using the dimensions of the infiltration trench described in Scenario 1 while varying fine sediment loading rates from roof runoff to treated parking lot runoff. Figure 5.2 shows the estimated proportion of remaining infiltration capacity as a function of time as the infiltration BMP accumulates with fine sediment and indicates:

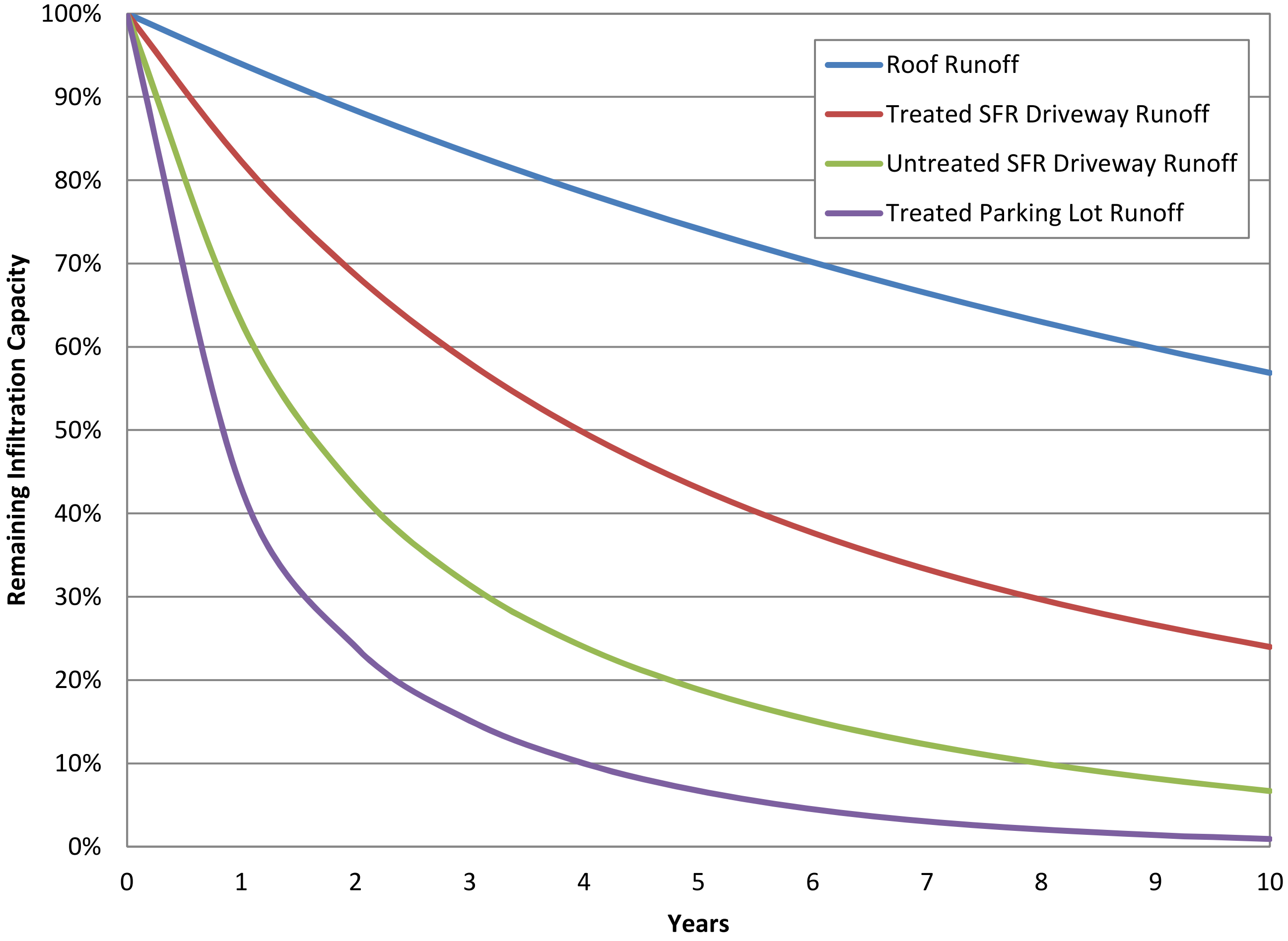
- **Within two to four years, infiltration capacity appears to markedly decline if an infiltration BMP is loaded with untreated driveway runoff or treated parking lot runoff.** For example, within four years untreated driveway runoff and treated parking lot runoff were estimated to decrease infiltration capacity by 75 % and 90 %, respectively.
- **Surface infiltration BMPs may be the most appropriate selection for driveway and parking lot runoff.** The concept behind a Restoration Interval is that requiring more frequent maintenance periods is only reasonable if maintenance activities that restore infiltration surfaces are practical and convenient to complete. Infiltration BMPs with shorter Restoration Intervals could receive more credit for infiltration capacity because cumulative fine sediment loading between Restoration Intervals is less. Surface infiltration systems typically have more frequent but more practical maintenance requirements and thus shorter Restoration Intervals. Consequently, these types of BMPs may be the best selection for targeting infiltration of stormwater with relatively high fine sediment loading rates (defined by this research to be untreated driveway runoff or worse quality).

Scenario 3– Variations in Infiltration Capacity Based on Lateral Infiltration Surface Area (Figure 5.3)

To test how variations in the amount of lateral infiltration surface area might affect infiltration capacity, an infiltration trench was simulated with a Restoration Interval of 10 years. For this test, all four sides of the infiltration trench were used to calculate the available lateral infiltration surface area. Lateral infiltration surface area was increased under each permutation of this scenario by progressively decreasing the width of the BMP while increasing the depth and maintaining a static storage capacity of 20 ft^3. Fine sediment loading to the infiltration trench was simulated for treated driveway runoff, which equated to 1,500 g of cumulate fine sediment loaded to the BMP at the Restoration Interval defined as 10 years.

On the graph shown in Figure 5.3 the primary Y-axis displays the proportion of treatment capacity credited to storage capacity and infiltration capacity at the Restoration Interval. A second performance metric was added to the secondary Y-axis that displays the estimated draw down time of the infiltration trench. When the draw down time exceeds 24 hours it is flagged as unacceptable in Figure 5.3. Figure 5.3 indicates:

- **As the proportion of lateral infiltration surface area increased relative to total infiltration surface area, the infiltration capacity of the infiltration BMP increased.** As lateral infiltration surface area increased from 50 percent to 80 percent of the total infiltration surface area of the BMP, the resulting infiltration capacity was approximately doubled. This result appears to indicate that narrower and deeper infiltration BMPs may sustain higher rates of infiltration as the BMP is loaded with fine sediment, provided that a deeper infiltration BMP does not intersect seasonally high groundwater or soil layers that are restrictive to infiltration.
- **As the proportion of lateral infiltration surface area increased relative to total infiltration surface area, the draw down time of the infiltration BMP decreased.**

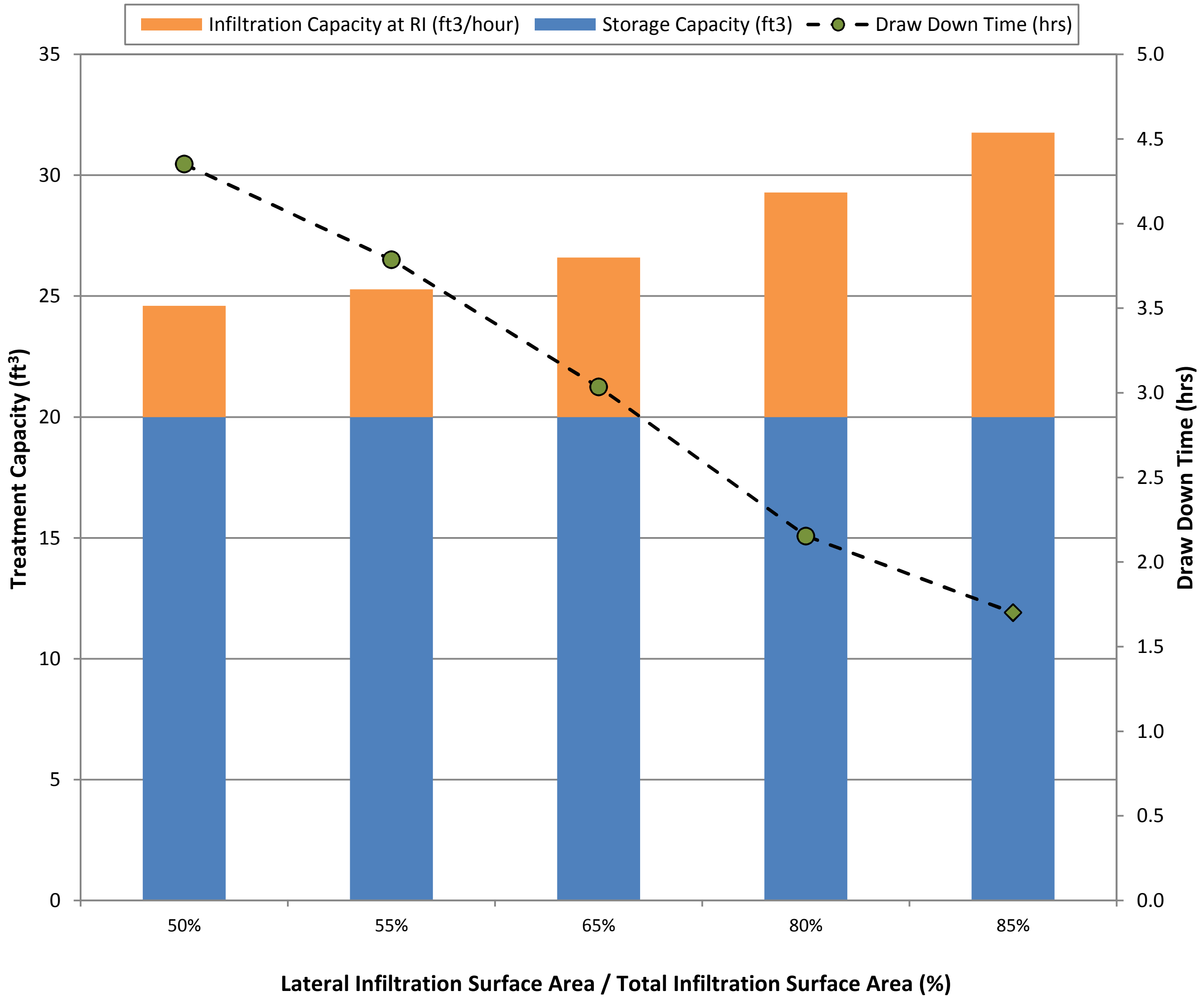


Parameters used in analysis:

- Surface drainage area: 20ft x 20ft = 400 ft^2
- Surface type and condition: Varies in analysis
- Surface loading estimate to infiltration BMP: Varies in analysis
- Infiltration BMP type: Infiltration trench
- Infiltration BMP dimensions: 20ft long x 2ft wide x 15in deep
- Initial Ksat: 3.0 in/hr

SCENARIO 2: VARIATIONS IN INFILTRATION CAPACITY OVER TIME
BASED ON FINE SEDIMENT LOADING RATE

Figure 5.2



Parameters used in analysis:

- Surface drainage area: 20ft x 20ft = 400 ft^2
- 20-year 1-hour storm criterion: 33.3 ft^3 of runoff
- Surface type and condition: Treated SFR driveway
- Surface loading estimate to infiltration BMP at restoration interval: 1,500 grams of fine sediment
- Infiltration BMP type: Infiltration trench
- Infiltration BMP dimensions: 20ft long x 2ft wide x 15in deep
- Restoration interval: 10 years
- Initial Ksat: 3.0 in/hr

SCENARIO 3: VARIATIONS IN INFILTRATION CAPACITY BASED ON
LATERAL INFILTRATION SURFACE AREA

FIGURE 5.3

6 RECOMMENDATIONS

BMPs are a cornerstone practice for reducing pollutant transport to restore the clarity of Lake Tahoe and the outcomes of this research are a step towards improving their effectiveness. The research conducted has greatly improved our understanding of infiltration BMP performance declines in a way that can be applied to tools used to estimate BMP effectiveness for pollution load reduction and BMP design. There is no doubt that additional applied research could strategically build upon these findings and continue to fill remaining data gaps critical to the future management priorities and directions extracted from the recommendations below.

The remainder of this chapter applies the research findings to a series of recommendations to local and regional practices, the TRPA BMP Handbook, and potential improvements to other Tahoe stormwater tools.

6.1 POTENTIAL BMP HANDBOOK REFINEMENTS

A number or refinements and updates to the BMP Handbook (TRPA 2012a) could be made to incorporate the findings of this research on the topics of infiltration BMP performance and maintenance:

- **Incorporate estimated loading rates based on surface types and requirements for stormwater treatment.** This will quantify current guidance describing acceptable loading rates to BMPs (i.e., what is meant by acceptably low loading rates vs. unacceptably high loading rates) and the rationale for requiring treatment of stormwater generated from driveways and parking lots prior to infiltration.
- **Incorporate the implications of fine sediment loading into guidelines/requirements in BMP Handbook for maintenance of infiltration BMPs.** Guidance recommendations could include more targeted maintenance recommendations tailored to specific BMPs and its estimated loading rates.
- **Incorporate the concept of Restoration Intervals by BMP type and identify specific maintenance activities necessary to restore infiltration surfaces by BMP type**. BMPs with similar contributing drainage surface types will generally have similar fine sediment loading rates and therefore similar estimated treatment capacity declines. Standardizing the time period for conducting the key maintenance activity for an infiltration BMP (restoration of the infiltration surface area) would provide a clear and more manageable system for both TRPA and properties owners to track and conduct key infiltration BMP maintenance.
- **Strengthen guidelines in the BMP Handbook to target selection of BMPs with accessible infiltration surfaces for treatment of driveway, parking lot, and road runoff.** Even when accessible clean-out ports are required, it may be much more difficult to restore the infiltration surfaces of a subsurface infiltration system relative to a surface infiltration system.
- **Strengthen guidelines/requirements in BMP Handbook for pollutant source control associated with fine sediment generation on impervious surfaces.** Requirements for pollutant source control on impervious surfaces could extend the treatment capacity life of an infiltration BMP and decrease maintenance needs within the BMP.

As part of this work effort the research team has provided an MS Word document including the suggested revisions as ‘tracked changes’ within the document for the relevant sections of the BMP Handbook to better incorporate the findings, concepts, and recommendations of this research. The suggested edits to the BMP

Handbook has been provided to TRPA staff for their consideration for inclusion in a future version of the BMP Handbook. Applicable sections the research team will review and make suggested edits shall include:

- Chapter 3 – Permanent BMP Planning and Selections
    - 3.7 – Inspection, Maintenance and Monitoring
    - 3.8 – Site Constraints and Limitations
- Chapter 4 – BMP Toolkit
    - 4.1 – Hydrologic Source Control
    - 4.3 – Stormwater Collection and Conveyance (only applicable BMPs such as slotted channel drains)
    - 4.4 – Stormwater Treatment (only applicable BMPs such as sediment traps)
- Chapter 6 - Inspection, Maintenance and Monitoring

6.2 APPLICATIONS TO OTHER TAHOE STORMWATER TOOLS

In addition to the BMP Handbook and the BMP Calculation Spreadsheet (discussed in Chapter 5), the improved technical understanding of infiltration capacity decline can be applied to the current suite of stormwater tools used in the Tahoe Basin to estimate pollution reduction benefits and maintenance needs.

- **The Pollutant Load Reduction Model (PLRM)** The PLRM (NHC et al. 2009) is used to compute pollutant load estimates at the spatial scale of public water quality improvement projects. Currently, infiltration capacity of BMPs is represented within the model using a constant rate over 18 years of simulation. Recognizing the limitations to this approach, the recommended range of acceptable infiltration rates within the PLRM is set well below expected initial design rates. This approach is somewhat conservative because it factors in performance reductions over time. However, it does not link estimated fine sediment loading rates to a stormwater treatment facility with infiltration capacity reductions or required maintenance intervals. Because the PLRM already predicts loading rates to stormwater treatment facilities, the model could be improved to incorporate the decay equations developed from this research with the concept of Restoration Intervals to predict maintenance needs using current PLRM output.
- **The Load Reduction Planning Tool (LRPT)** The LRPT (2NDNATURE and NHC 2011) is used to estimate the potential water quality pollutant load reductions associated with implementation of Best Management Practices (BMPs), including redevelopment projects and private parcel retrofits. LRPT estimates the average annual runoff generated from the site using a simple disaggregation of the surface and routing across the parcel. Like the PLRM, the LRPT's representation of BMP performance can be improved using the empirical performance decline curves generated from this research to provide more realistic estimates of treatment capacity over time and inform appropriate maintenance intervals.

  There would be substantial benefit to combining the functionality of the LRPT with that of the BMP Calculation Spreadsheet or the BMP Designer Tool (currently under development). The two could be integrated in a web-based, user-friendly platform that would provide a more cohesive way to design, assess, and manage BMPs at a site. The resulting tool would combine the surface specific BMP sizing guidance of the modified BMP Calculation Spreadsheet, the graphic design tools included in the BMP Designer Tool, and the flexible stormwater routing algorithms used in LRPT to inform the most effective parcel-scale configuration of a series of BMPs. A well-designed platform like this would provide a mechanism to capture and use data from individual BMPs that could be used for effectiveness assessment analysis and creating an automatic maintenance alerts. Outputs would include recommended maintenance intervals and provide an estimate of the average annual volume and pollutant load reduction achieved as a result of implementation.

- **BMP Rapid Assessment Method (BMP RAM)** Results from the field survey infiltration performance tests were used to refine the BMP RAM v1 protocols. BMP RAM v1 protocols called for a binary interpretation of the 1L infiltration performance test (pass or fail). The distribution of infiltration times obtained in this research made it clear that interpretation of results using a scoring continuum was more appropriate to capture the range of measurements that may have less than ideal but acceptable performance. The recently updated BMP RAM tool (2NDNATURE 2013) has incorporated the time required to infiltrate 1L of water to quantify the infiltration performance of infiltration features such as infiltration trenches or dry wells.
- **Road Rapid Assessment Method (Road RAM)** Road RAM (2NDNATURE et al. 2010) is a complete field assessment, data management and data reporting tool that has been developed to rapidly quantify the relative amount of fine sediment particles (< 16 μm) on an impervious road surface in the Tahoe Basin. The extensive land use specific sampling conducted to inform the Road RAM development indicated that the relative amount of fine sediment on a road is highly dependent upon road maintenance practices that influence the amount of abrasives applied and the effectiveness of recovery programs. Thus, it is now understood that road condition (the amount of fine sediment potentially generated from a road segment should runoff occur) on an average annual basis can be controlled by more effective practices. The same is true for driveways and parking lots, and cost-effective opportunities exist to create a module for Road RAM that allows comparable rapid assessments of parking lots and driveways. This could be a critical verification tool to inform the adequacy of any impervious surface to be reasonably treated by localized infiltration trenches or dry wells with feasible Restoration Intervals of >10 years.

6.2.1 REGIONAL OPPORTUNITIES

The concept of parcel-scale retention and infiltration of stormwater runoff is a desirable approach to restore natural hydrologic processes in an urbanized watershed. However, depending upon the loading rate of fine sediment within stormwater runoff, the water quality benefit provided by infiltration BMPs may only be sustainable through frequent maintenance. In some situations, regional solutions designed to retain and infiltrate stormwater runoff from entire neighborhoods or community centers may be a more practical and cost-effective approach. In all situations, effective source control actions will reduce the available mass of fine sediment in Tahoe stormwater which may contribute to Lake clarity improvement.

6.2.2 REGIONAL STORMWATER TREATMENT

Based on the observations and findings of this research, the performance of infiltration BMPs receiving roof runoff appears to require minimal maintenance to function effectively for long durations (e.g., >10 years). Conversely, elevated fine sediment loading rates typical of driveway and parking lot runoff results in additional and potentially more frequent maintenance requirements for infiltration BMPs and stormwater treatment systems. Given the time and effort necessary to rehabilitate infiltration surfaces for the most common parcel-scale infiltration BMPs deployed in the Tahoe Basin (e.g., infiltration trenches and dry wells), regional (neighborhood-scale) treatment systems may be a more viable option to address driveway and parking lot runoff when considering the trade-offs between overall maintenance costs and stormwater pollution reduction benefits. The feasibility of siting and designing regional treatment systems will strongly depend upon downstream land availability and drainage conditions of the catchment under consideration. It must be noted that recent detailed hydrologic studies on a series of regional stormwater treatment systems in South Lake Tahoe indicated substantial baseflow inputs due to elevated groundwater tables and minimal pollutant removal effectiveness during these seasonal spring snowmelt conditions (2NDNATURE and NHC 2012).

A potential approach to consider based on the findings of this research is to implement a hybrid strategy that: 1) continues current parcel-based BMP regulations to retain the 20-year 1-hour storm from the cleaner impervious surfaces on a parcel (i.e., roofs); while 2) routing surfaces with higher concentrations of fine sediment (driveways and parking lots) to regional treatment systems that are preferably a surface infiltration system. Maintenance of regional surface infiltration systems could simply constitute removal of accumulated material and tilling the surface soil to restore infiltration capacity, which would be a more cost-effective activity when compared to restoring the functions of many small distributed infiltration BMPs. This approach could also be used to develop a simple system for generating in-lieu stormwater assessment fees. A private parcel in compliance with pollutant source control and roof runoff storage requirements would pay an in-lieu stormwater assessment fee calculated based on the square footage of driveway area or parking lot area draining to a regional treatment system.

6.2.3 REGIONAL SOURCE CONTROL PROGRAMS

Each component of this research points strongly to the benefits realized from reducing the amount of fine sediment and material delivered to infiltration BMPs. The field surveys frequently identified significant accumulations of fine sediment at the infiltration surfaces of BMPs receiving driveway and parking lot runoff; the stormwater loading experiments identified exponential declines in infiltration capacity resulting from fine sediment loading; and the modifications to the BMP Calculation Spreadsheet and subsequent analyses illustrated the practical design and maintenance issues that arise from fine sediment loading over time. Recent observations from the USDA NRCS (2013) indicate that stormwater treatment systems and pre-treatment systems can require frequent maintenance and are susceptible to conveyance issues that can cause stormwater runoff to bypass infiltration BMPs. Short of filtration, many common treatment processes relied upon in the Tahoe Basin (i.e., particle settling) employed by treatment vaults may not be effective, as fine sediment can remain in suspension and continue downslope to an infiltration BMP.

For surfaces and land use types that typically exhibit elevated concentrations of fine sediment in runoff, enhancing source control efforts may be the most effective way to reduce loading to infiltration BMPs. Previous research efforts have identified that roads in the Tahoe Basin have the potential to generate the greatest amount of fine sediment per unit area (2NDNATURE et al. 2010), and this generation is strongly correlated to the ubiquitous application and subsequent pulverization of traction abrasives. Previous research and observations suggest that fine sediment generated on the road surfaces are effectively transported with vehicles and can accumulate on surfaces where abrasives are not actually applied in substantial amounts, such as parking lots and driveways. Expansion of a road sweeping programs to include parking lots and driveways has the potential to remove much of the sediment that would otherwise rapidly reduce the infiltration capacity of an infiltration BMP. A series of research projects suggest that strategic and frequent street sweeping programs can effectively reduce the amount of fine sediment from roads (2NDNATURE et al. 2010, 2NDNATURE and NHC 2012, and 2NDNATURE 2012), and these findings are likely applicable to driveways and parking lots. Similar to regional treatment system in-lieu fee system, a sweeping program could generate in-lieu stormwater assessment fees proportional to the area required for sweeping.

6.3 RECOMMENDATIONS

The findings detailed above provide a scientific basis to support some specific recommendations targeted at improving infiltration BMP effectiveness.

1. **Current infiltration BMP sizing and maintenance practices are adequate for infiltration BMP receiving roof runoff, or runoff of similar quality.** The lack of fine sediment in roof runoff reduces clogging compared to other drainage surfaces, extending the time adequate performance before maintenance is required.
2. **BMP plans with infiltration BMPs sited to receive drainage from surfaces with substantial fine sediment sources should be required to demonstrate how infiltration performance will be sustained.** The suite of strategies employed may include: a) controlling and reducing the sources of fine sediment from impervious surfaces; b) BMP maintenance; and c) installation of pre-treatment devices.
3. **Revise the technical basis of algorithms used to calculate BMP treatment capacity to estimate declines in side and base infiltration capacity based on fine sediment loading rates**. Preliminary modifications to the BMP Calculation Spreadsheet have been completed to illustrate one potential approach, but the technical basis of the changes is independent of the tool and could be applied to any tool used to design and size infiltration BMPs. The findings strongly support modifications regarding incorporation of infiltration capacity decline, lateral infiltration allocation, and surface-specific fine sediment loading rates to a BMP. The explicit incorporation of the need for, and treatment benefits of, regular maintenance actions into infiltration BMP sizing and design tools is recommended.
4. **Consider refinements to the BMP handbook to strengthen maintenance, pre-treatment, and source control requirements based on expected fine sediment loading from the associated drainage surfaces**. Recommendations for suggested revisions to the BMP Handbook will be provided externally from this report for the applicable sections of the BMP handbook (as commented versions of the MS Word documents with changes tracked). Suggested refinements will use the research findings and target development on enhanced guidelines to increase the implementation of effective and necessary maintenance actions to feasibly maximize both performance and lifespan of BMPs that rely upon infiltration to provide a water quality benefit. TRPA staff will decide on the feasibility and long-term implications of integrating proposed refinements in the Handbook.
5. **Validate empirical equations for incorporation to Tahoe stormwater tools.** The design of additional research should be focused on refining BMP infiltration capacity decay equations for use in stormwater tools that are used to estimate pollution load reductions over time, particularly PLRM. The current model assumes a conservative, but constant performance over time. In some instances, the

current approach may be over estimating the volume reduction benefits associated with infiltration BMPs. Additional research to expand the experimental design to a greater range of BMP configurations, conditions, maintenance intervals and soil types would improve confidence for refining the functionality of current tools. Further collaboration with the NRCS, as was accomplished late in this research, would add further value to those components of the research that depend on measurements of actual BMPs in the field such as loading rates from different surface types and performance adequacy verification.

6. **Identify a test catchment for evaluating trade-offs between maintaining distributed infiltration BMPs, developing regional treatment systems, and improving source control efforts for driveway and parking lot runoff.** An ideal test catchment would be one with substantial driveway and parking lot runoff, and with at least anecdotal evidence that past infiltration BMPs installed in the catchment require very frequent maintenance to function. An analysis would characterize the feasibility and cost of a regional treatment system or enhanced source control efforts, and compare those costs against the feasibility and cost for implementing and maintaining parcel-scale infiltration BMPs at an adequate performance level.
7. **Prioritize urban sediment source control actions to reduce the annual mass of fine sediment available for transport and accumulate within infiltration BMPs in the Tahoe Basin.** Given the strong dependence of infiltration capacity decline on fine sediment loading rates identified in this research, efforts to reduce the generation, accumulation and persistence of fine sediment on Tahoe Basin impervious surfaces is critical. Enhanced source control measures, such as sweeping to remove accumulated sediment in parking lots and driveways, may be a more feasible and cost effective alternative to pre-treatment requirements or the required maintenance schedule to preserve the intended treatment capacity of infiltration BMPs. The findings from this research suggest that fine sediment is significantly reducing the effectiveness of infiltration BMPs that provide one of the primary processes relied upon to reduce the annual loads of fine sediment to the Lake.
8. **Develop a complete site-based platform for BMP citing, design, maintenance management, and ongoing assessment that builds on previously developed tools and knowledge.** The current version of the BMP Calculation Spreadsheet has provided a valuable tool for BMP practitioners, homeowners, and regulators for many years now, but the tool has deficiencies inherent to its development platform as a desktop spreadsheet. While the tool may still be the best alternative for some users, transitioning the concepts and mechanics of the current spreadsheet, along with the newly acquired understanding of infiltration capacity decline from this research, to a new platform will provide a number of benefits. The integration of the web-based BMP Designer Tool (currently under development) with the parcel scale BMP design approach currently provided by the LRPTv2 would result in a single tool to cite, design and configure a complete parcel that would also provide required maintenance intervals and estimated pollutant load reductions. The graphic design tools used in the BMP Designer Tool together with the stormwater routing algorithms used in the LRPT can provide a complete platform for tracking BMP information and performance over time that will be closely tied to pollutant load reduction estimates. Such a platform would include a simple user-friendly interface, centralization and compilation of BMP implementation data and inventories, customizable outputs and reporting functions, and the ability to create a more automated system than could identify and potential notify property owners of required maintenance intervals and activities.

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APPENDIX A. SYNTHESIS OF EXISTING INFORMATION, INFILTRATION BMP DESIGN AND MAINTENANCE STUDY (2NDNATURE AND NHC 2011)

Available for download at
http://www.2ndnaturellc.com/wp-content/uploads/2011/09/BMPSynthesisFinal_reduced.pdf

APPENDIX B – DATA SHEETS

STORMWATER SIMULATIONS DATA SHEET

Media Type	Stormwater	Soil Type	
pea gravel	100 mg/L = 1.9 g/5gal	Christopher-Gefo	**Date:** **Personnel:** **Media Cube ID:** **Configuration: Long / Mini** **Plexiglas:**
0.75 inch drain rock	150 mg/L = 2.8 g/5gal	Inville	
1.5 inch drain rock	200 mg/L = 3.8 g/5gal	Jorje	
cobbles	500 mg/L = 9.5 g/5gal	Beach Sand	
	Other		

Bucket #	[FSP] (mg/L)	Distance (in)	Time (min)	Time (hr)	Infiltration Rate (in/hr)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Visual Observations:

BMP FIELD SURVEY DATA SHEET

Site ID		**Primary Land Use**	**SFR MFR CICU**
Address		**Photo #'s**	
Observations Date		**Observer**	
BMP ID		**Type of Media**[11]	

Surface Drainage Conditions

Surface #	**Impervious or Pervious**	**Surface Type**[1]	**Length (ft)**	**Width (ft)**	**Area (ft^2)**	**Avg. Slope (%)**	**Surface Condition Evaluation**[2] **(Circle One)**
1							**1 2 3 4 5**
2							**1 2 3 4 5**
3							**1 2 3 4 5**
4							**1 2 3 4 5**

[1] Impervious Surface = Roof; Driveway; Parking Lot; Secondary Road; Primary Road; Other (describe)

Pervious Surface = Stable; Moderate Erosion/Debris; Severe Erosion/Debris; Other (describe)

[2] Based on the following scale: 1 = Excessive Debris; 3 = Moderate Debris; 5 = Clean

[11] Pea-Gravel; ¾" Drain Rock; 6" Cobble; Native Soil; Other (describe)

Infiltration BMP Characteristics

Infiltration BMP Type[3]	**Infiltration BMP Location Description**[4]

Length (ft)	**Width (ft)**	**Surface Area (ft^2)**	**Notes (include apparent design issues)**

Type of Pre-Treatment Device[5]	**Estimated Storage Volume (ft^3)**	**Condition of Device**[6] **(Circle One)**	**Accessibility of Device for Cleaning**[7] **(Circle One)**
		1 2 3 4 5	**1 2 3 4 5**

[3] Dry Well (DW); Infiltration Trench (IT); Dry Basin (DB); Pervious Pavement (PP); Subsurface Infiltration System (SIT); Other (describe)

[4] Example: Infiltration trench located on north side of house

[5] Sediment Trap; Baffled Vault; Wet Basin; Drop Inlet Insert; Media Filter; Other (describe). If none, then enter: N/A

[6] Based on the following scale: 1 = Severely Clogged w/debris; 3 = Moderately Clogged w/debris; 5 = Clean

[7] Based on the following scale: 1 = Difficult; 3 = Moderately Difficult; 5 = Easy

Infiltration BMP Condition and Performance

Obs ID	Location Description[8]	Depth from Surface[9] (inches)	Depth Location[10] (circle one)	Media Condition[12] (Circle One)	1L Infil Time (sec)	Soil Texture [13]
			media surface mid depth Infiltration surface	1 2 3 4 5		
			media surface mid depth Infiltration surface	1 2 3 4 5		
			media surface mid depth Infiltration surface	1 2 3 4 5		
			media surface mid depth Infiltration surface	1 2 3 4 5		
			media surface mid depth Infiltration surface	1 2 3 4 5		

[8] Describe where test was taken within the BMP Example: Water test was conducted in the center of the BMP

[9] Depth where layer starts relative to top surface down of Infiltration BMP

[14] All water tests are based on the infiltration time for 1 Liter (1L) of water

[10] Relative depth of observation: Media Surface = top surface of media; Mid Depth = ½ the media depth; Infiltration Surface = location where water infiltrates into the native soil or into filter fabric

[12] Based on the following scale: 1 = Severely Clogged w/debris; 3 = Moderately Clogged w/debris; 5 = Clean

[13] For soil, include brief description of dominant soil texture in notes. Example: clay/loam soil

CHP Performance

Location ID	CHP Test #	Depth of CHP (inches)	Initial Reading	Final Reading	Time Elapsed (seconds)	Ksat (inch/hour)

APPENDIX C. MODIFIED BMP CALCULATION SPREADSHEET

Available for download at

http://www.2ndnaturellc.com/modified-bmp-calculation-spreadsheet/

Contact Gary Conley for login information at gary@2ndnaturellc.com