Tahoe Stormwater Treatment BMPs in a Changing Climate

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Executive Summary

Natural resource management plays an essential role in preserving and protecting the unique environmental characteristics and ecosystem processes of Lake Tahoe, which is world renowned for its remarkable clarity and striking blue color. Located in the Sierra Nevada mountains on the border of California and Nevada, this lake and the surrounding Tahoe Basin have drawn increased tourism and development over the years. Due to long-term lake clarity loss, however, the lake has been designated an impaired water body under the Clean Water Act. This ultimately resulted in development of the Tahoe Total Maximum Daily Load (TMDL) program, a management and regulatory framework focused on minimizing the input of pollutants such as sediment and nutrients to the lake to achieve numeric standards for open-water transparency (lake clarity).

Research to inform development of the Tahoe TMDL indicated that fine sediment particles (FSP) have a greater impact on lake clarity than nutrients, so FSP load reductions have been the primary target of stormwater best management practices (BMPs) for the TMDL. The results of ongoing lake monitoring show that annual average clarity appears to have stabilized. However, the winter clarity does not yet show a persistent pattern of improvement and summer clarity continues to deteriorate. Nonpoint source nutrient pollution and climate change are likely to contribute toward further declines in summer clarity. Also, as hydrologic conditions at Tahoe change with climate, the performance of stormwater infrastructure and pollutant loading rates will likely be affected. While stormwater BMPs have been aggressively implemented in Tahoe’s urban areas, additional reductions in FSP and nutrient loading will be needed to achieve the long-term target of 100 feet of annual average lake clarity by 2076.

The overall goal of this project was to assess and inform stormwater management about changing conditions expected for urban hydrology in the Tahoe Basin, based on climate change projections, and to identify new treatment BMP options with enhanced pollutant removal performance potential applicable to cold weather environments. Mountain ecosystems are particularly sensitive to impacts from climate change, due to changes in atmospheric circulation patterns that will alter the timing, amount, and type of precipitation, as well as the frequency, intensity, and duration of extreme events like droughts or atmospheric rivers. Warmer temperatures are causing snow levels to shift upslope and more winter precipitation to fall as rain rather than snow, leading to changes in the timing and amount of spring and summer runoff. Also, as climate warms, the atmosphere holds more moisture, which leads to larger precipitation events. With more land surface exposed by earlier snowmelt, and for longer periods each year due to warming temperatures, the shift in landscape solar adsorption (albedo) is causing overall changes to heat balance in surrounding areas. Thus, mountain regions within the snowline are warming faster than lower elevation areas and climate change impacts can be greater than elsewhere.

Several previous climate studies for the Tahoe Basin suggest an approaching regime of higher flow extremes and greater event volumes over shorter runoff periods, likely increasing soil erosion and sediment and nutrient loading into Lake Tahoe. Moreover, urbanized areas at lower elevations will be subject to hydrologic impacts from changing conditions in their upper catchments. Anticipating changes in the hydrology of these urban areas will be particularly important for urban stormwater management, as stormwater is still considered the main source of fine sediment particles loading into Lake Tahoe. Unfortunately, the data sets from previous studies were not well suited to a comparative evaluation of changes in BMP capture efficiency caused by changing climate. The most expedient and directly relevant approach for a comparative analysis of BMP performance in this project was to apply climate change projections from locally downscaled global climate models to an existing stormwater planning tool used by jurisdictional planners to estimate the pollutant load reductions derived from capital improvements in stormwater infrastructure at Tahoe. Specifically, we analyzed output from the Pollutant Load Reduction Model (PLRM), which was developed and is prescribed for pollutant load reduction accounting and reporting to the Tahoe TMDL. By using this approach, the changes in the hydrologic response of urban watersheds to future climate projections (2030-2060) were directly compared to their estimated performance characteristics under existing PLRM conditions (1988–2006).

The projected temperature and precipitation changes through 2060 were evaluated in the context of hydrologic impacts on three existing urban catchments within different areas of the Tahoe Basin: (Bijou Commercial Core [south], Lake Forest Highlands [northwest], and East Incline Village [northeast]). For standardized comparative purposes, climate change effects were also tested on hypothetical catchments at these same three locations within the Tahoe Basin, but where all three were modeled with equivalent drainage area, imperviousness, runoff coefficient, and BMP implementation. The results of PLRM runs for future climate conditions versus existing PLRM conditions showed that annual inflow volumes increase at all locations, accompanied by a reduction in BMP capture efficiency (i.e., total volume of treated water, including volume infiltrated, as a percentage of total volume routed to the BMP). For Bijou, the percent capture is expected to stay above 80% in the future if the design storm stays at 1 inch. However, East Incline Village and Lake Forest are both expected to see percent capture efficiency drop below 80% in the future. Percentage increase of inflow volume for the hypothetical model scenarios range from 33–38%, and although their median inflow rates are not significantly changed in the future, more extreme values become more frequent in the future at all locations, with those extreme values contributing to the reduction in percent capture. With the increase in inflow volumes and reduction in percent capture, the volume of untreated stormwater is expected to increase substantially. Urban areas with stormwater BMPs sized to the 1-inch design storm, may see an average annual increase of untreated bypass volumes of 98-337% during future conditions (2030-2060).

Urban hydrology projections also revealed that the number of days with snow cover will be drastically reduced at all locations. Although the number of days with rain-on-snow events doesn’t significantly change between historical and future scenarios, this is likely due to the reduction in number of days with snow cover (i.e., since there are fewer days with snow on the ground, there are fewer opportunities for rain-on-snow events), which is consistent with previous studies in stream watersheds that showed the rain-on-snow events are expected to increase initially but frequency will decline in the latter half of the century due to reduced snow cover.

Although not modeled directly in this study, the pollutant loadings are expected to follow climate change patterns in hydrology, simply because as runoff increases the total loading tends to increase as well. Specifically, runoff volumes at Tahoe typically range over several orders of magnitude, depending on the geographic location and size of drainage area, but pollutant concentrations usually range within about one order of magnitude. So, hydrology tends to drive loads in general, as well as the BMP load reduction calculations.

The decreased hydraulic capture efficiency of BMPs are largely a consequence of increasing outflows through overflow or bypass features when event volumes exceed the capacity of treatment basins. Although infiltration has been identified as an important TMDL practice for reducing stormwater runoff loads, the maximum rates of BMP infiltration are generally limited by the saturated hydraulic conductivity of underlying soils. This infiltration capacity limitation is reflected in the relatively modest increased infiltration (15-31%) estimated for the Lake Forest Highlands and East Incline Village stormwater basins.

Finally, we discuss the implications of these results for stormwater management at Tahoe and review a set of BMPs that may help improve hydrologic management and pollutant load reductions. Improved pollutant removal can likely be achieved through refinement of current practices as well as through implementation of new BMP technologies, of which several examples are identified and discussed in the text. Of potential use in the Tahoe Basin are bioinfiltration systems (or raingardens); biofiltration systems (such as phosphorus optimized stormwater treatment); regenerative stormwater conveyance; biochar amendments; and new wetland practices, including modular wetlands, subsurface wetlands, floating wetlands, and floating media bed reactors; and several proprietary filtration systems.

Of particular utility for improved performance would be a treatment train approach for stormwater BMPs, similar to wastewater treatment in which separate (unit) processes are implemented in sequence to optimize the conditions for removal of specific targeted pollutants. Several of the new and innovative BMPs discussed could be used in this way, along with selected types of treatment media amendments, such as biochars. Designs that incorporate forebays to accommodate snow and sediment storage will be more resilient and will improve performance of downstream basins and filters. Retrofits for more active hydraulic management that add peak flow control into designs would also be useful, such that higher flows with lower concentrations are treated separately from the more concentrated initial runoff volumes. Biofilters could be built into these practices, using tailored media designed to capture specific nutrients and particle sizes.

Next steps will include working with jurisdictional partners to identify one or more specific innovative practices of particular interest that may be suitable for testing in the Tahoe Basin and then to assess the specifications needed for potential implementation and associated performance monitoring. Further, based on the work conducted for this study, an update to the PLRM is highly recommended. It is important to support a process of continual improvement of the methods and critical tools that we rely on in the Lake Tahoe Basin for management and performance assessment. The PLRM was developed in the early 2000s, and the meteorological data that drive that model are from 1988–2006. An update would provide the opportunity to include a longer period representing contemporary conditions through 2020 or longer, as well as a module representing future precipitation and temperature conditions. This update could support the planning and design of more climate resilient BMPs in the Tahoe Basin. Equally important, a PLRM update should include adjustments that would allow the model to be run with user input of precipitation and temperature data, thus providing the opportunity to validate model results against local data and support confidence in TMDL estimates of pollutant reductions. New global climate models have recently become available and localized downscaled products will be released in the near future, potentially supporting further work at better resolution and with improved confidence.

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Introduction

Lake Tahoe is a subalpine lake in the Sierra Nevada that is world renowned for its remarkable clarity and striking blue color. Both the federal government and California have designated Lake Tahoe an “Outstanding National Resource Water,” which confers the highest level of protection with no degradation allowed under the Clean Water Act (CWA) of 1972. In Nevada it has been designated a “Water of Extraordinary Aesthetic or Ecologic Value.” Due to lake clarity loss over the preceding decades, Lake Tahoe qualified as an impaired water body under CWA section 303(d), which initiated the development of a Total Maximum Daily Load (TMDL) for clarity. The Lake Tahoe TMDL was developed and adopted by California and Nevada (LRWQCB and NDEP, 2011) to address pollutant load reductions needed to achieve numeric standards for open-water transparency (lake clarity).

The Lake Tahoe TMDL program was established in 2011 to guide efforts toward restoring historic lake clarity conditions over the subsequent 65 years. This program identified load reduction targets (from a baseline year of 2004) for fine sediment particles (FSP), total nitrogen, and total phosphorus. Research to inform development of the TMDL indicated that FSP exerts a greater impact on lake clarity than nutrients, so FSP load reductions are the primary target of TMDL implementation and nutrient reductions are secondary targets (LRWQCB and NDEP, 2011). Thus, implementation of Tahoe Basin stormwater best management practices (BMPs) has focused on capturing FSP to achieve targeted lake clarity improvements. The results of ongoing lake monitoring have shown that annual average clarity appears to have stabilized (TSAC, 2022; TERC, 2022). Winter clarity does not yet show a persistent pattern of improvement, however, and the summer clarity continues to deteriorate with nonpoint source nutrient pollution and climate change likely to contribute toward further decline. As hydrologic conditions at Tahoe change with climate, the performance of stormwater infrastructure and pollutant loading rates will likely be affected. At the same time, additional reductions in FSP and nutrient loading will be harder to achieve but will be needed to meet the long-term target of 100 feet of annual average lake clarity by 2076. The overall goal of this project was to assess and inform stormwater management based on the most up-to-date climate change projections in urban hydrology for the Tahoe Basin and to evaluate new treatment BMP options with enhanced pollutant removal performance and suitable for cold weather application within the Lake Tahoe Basin.

This report begins with a brief background on climate change effects anticipated for montane regions, including a synopsis of results from prior studies in the Lake Tahoe Basin. It then presents the results from climate data analyses conducted specifically for Tahoe urban hydrology by this team, based on our review of existing Global Climate Models (GCMs) and associated downscaled projections for relative applicability to this work. The projected temperature and precipitation changes through 2060 were evaluated in the context of hydrologic impacts on three existing urban catchments within the Tahoe Basin. For standardized comparative purposes, climate change effects were also tested on hypothetical catchments at these three same locations within the Basin, but where all three were modeled with equivalent drainage area, imperviousness, runoff coefficient, and BMP implementation. Finally, we discuss the implications of these results for stormwater management at Tahoe and review a set of BMPs that may help improve hydrologic management and pollutant load reductions.

Background

Mountain ecosystems are particularly sensitive to impacts from climate change (IPCC, 2022; Knight, 2022) due, in part, to changes in atmospheric circulation patterns that will alter the timing, amount, and type of precipitation, as well as the frequency, intensity, and duration of extreme events like droughts or atmospheric rivers. Warmer temperatures are causing snow levels to shift upslope and more winter precipitation to fall as rain rather than snow, leading to changes in the timing and amount of spring and summer runoff. Also, as climate warms, the atmosphere holds more moisture, which leads to larger precipitation events. As more land surface is exposed by earlier snowmelt, and for longer periods each year due to warming temperatures, the shift in albedo is causing overall changes to heat balance in surrounding areas. Thus, mountain regions within the snowline are warming faster than lower elevation areas and the climate change impacts can be greater than elsewhere (Knight, 2022).

Several previous studies for the Tahoe Basin have anticipated these types of changes. A 2010 climate change study (Reuter et al., 2010) evaluated the potential impacts to Lake Tahoe associated with two greenhouse-gas emissions scenarios, A2 and B1, of the Geophysical Fluid Dynamics Laboratory Model (GFDL), including how the magnitude and frequency of runoff may change and how this may affect BMP treatment performance estimated by the PLRM. The study found that BMPs designed to treat the 20-year, 1-hour design storm (1 inch of rain in 1 hour) would see a general decline in total annual runoff volume captured and treated, however the reduction in performance was small compared to historical performance and over 80 percent of the annual runoff volume would still be captured by the end of the century for both scenarios. The overall conclusion from this study was that SWT BMPs designed to the existing design standard would still be sufficiently effective under a changing climate.

Since the 2010 climate study was completed, however, there have been updates to climate change predictions that reflect additional data and improvements to global circulation models. The Integrated Vulnerability Assessment (California Tahoe Conservancy, 2020) evaluated two greenhouse gas (GHG) concentration scenarios, RCP 4.5 and 8.5, that were developed by the Intergovernmental Panel on Climate Change (IPCC). The RCP 4.5 assumes GHG concentrations rise until 2040 and then decline. The RCP 8.5 scenario assumes GHG concentrations continue to rise throughout the century and represents the new “business as usual” scenario. Therefore, RCP 8.5 can be considered an update to scenario A2 and RCP 4.5 can be considered an update to scenario B1. RCP 8.5 agrees most closely with cumulative CO2 emissions from 2005 to 2020 and is arguably the more realistic scenario for policy-relevant planning horizons (Schwalm et al., 2020).

The Tahoe Climate Adaptation Action Portfolio (CAAP, 2021) summarizes how temperature and precipitation patterns will change in the Tahoe Basin, and how these changes affect the vulnerability of natural resources, infrastructure, and cultural factors including public health and safety. Projections through year 2100 show temperatures in the Basin rising by 3.6 to 9 degrees Fahrenheit, along with greater variability in year-to-year precipitation, and with rainfall from the largest storms increasing by up to 30 percent. Analyses conducted by Coats et al. (2021) focused on trends in extreme events through 2100, including trends in the annual maximum daily stream discharges. Their results indicated a 65–117 percent increase in the 20-year flood frequency for modeled Tahoe streams. More recently, Dettinger and Rajagopal (2022) evaluated a range of factors from precipitation-runoff modeling simulations at a finer resolution than used in previous assessments. Looking at ensemble results from eight different GCMs and two different greenhouse-gas emissions scenarios, they projected the 3-day maxima precipitation extremes would increase by 10–25%, depending upon subbasin, and that greater flow volumes would be delivered over shorter intervals of time. These higher spatial-resolution hydrosimulations showed considerable runoff variability among the sixty subbasins around Lake Tahoe, with flood flows in some subbasins almost tripling by 2100. Although rain-on-snow events are expected to increase initially, their frequency will decline in the latter half of the century due to reduced snow cover as snowline elevations increase.

Taken together, these studies suggest an approaching regime of higher flow extremes and greater event volumes over shorter runoff periods, likely increasing soil erosion and sediment and nutrient loading into Lake Tahoe. Moreover, urbanized areas at lower elevations will be subject to hydrologic impacts from changing conditions in their upper catchments. Anticipating changes in the hydrology of these urban areas will be particularly important for urban stormwater management, as stormwater is still considered the main source of fine sediment loading into Lake Tahoe (TSAC, 2022). Unfortunately, the data sets produced by these previous studies are not well suited to a comparative evaluation of changes in BMP capture efficiency with changing climate.

The most expedient and directly relevant approach for a comparative analysis of BMP performance in this project was to apply climate change projections to an existing stormwater planning tool used by jurisdictional planners to estimate the pollutant load reductions derived from capital improvements in stormwater infrastructure at Tahoe. Specifically, we analyzed output from the Tahoe Pollutant Load Reduction Model, which was developed and is prescribed for pollutant load reduction accounting and reporting to the Tahoe TMDL. By using this approach, changes in the hydrologic response of urban watersheds to future climate projections could be directly compared to their estimated performance characteristics under existing historic conditions (1988–2006).

Background on PLRM

The Pollutant Load Reduction Model (PLRM) is a planning tool used to quantify pollutant load reductions achieved through implementation of stormwater BMPs on urban lands within the Tahoe Basin. Pollutant load reductions are based on modeled runoff volumes and pollutant concentrations from tributary land uses, with hydrologic or pollutant source controls and treatment BMPs installed in the catchment, as compared to baseline loads from 2004. Treatment performance is a function of the average annual runoff volume captured, infiltrated, and/or treated by a structural BMP. Average annual percent capture is based on long-term continuous simulation of hydrology using the EPA Storm Water Management Model (SWMM) engine. The forcing data for hydrologic simulation is hourly precipitation and temperature data derived from extrapolation of local meteorological datasets available from October 1988 through September 2006. Details on how the PLRM meteorological data were developed can be found in the PLRM Model Development Document (NHC et al., 2009).

Runoff volume estimated at each time step in the PLRM is a function of the precipitation type (rain or snow), precipitation depth, snow accumulation and melt, infiltration, and evapotranspiration. These variables are influenced by the meteorological input data and user-defined catchment parameters. The total runoff volume routed to stormwater treatment is either captured or bypassed.

The percent capture is a function of inflow volume and rate, as well as the BMP type, size, and design configuration. If climate change ultimately generates increased runoff volumes and rates, there is concern that the current water quality design standards in the Tahoe Basin for treatment BMPs may be insufficient to capture and treat the same percentage of runoff as historically possible. With larger runoff volumes and lower volumetric percent captures, the mass of fine sediment and nutrients discharging to the lake may increase. Following selection and analysis of climate model data, the potential impacts of changing precipitation and temperature on volumetric percent captures were assessed with the PLRM for select locations in the Tahoe Basin, as presented below.

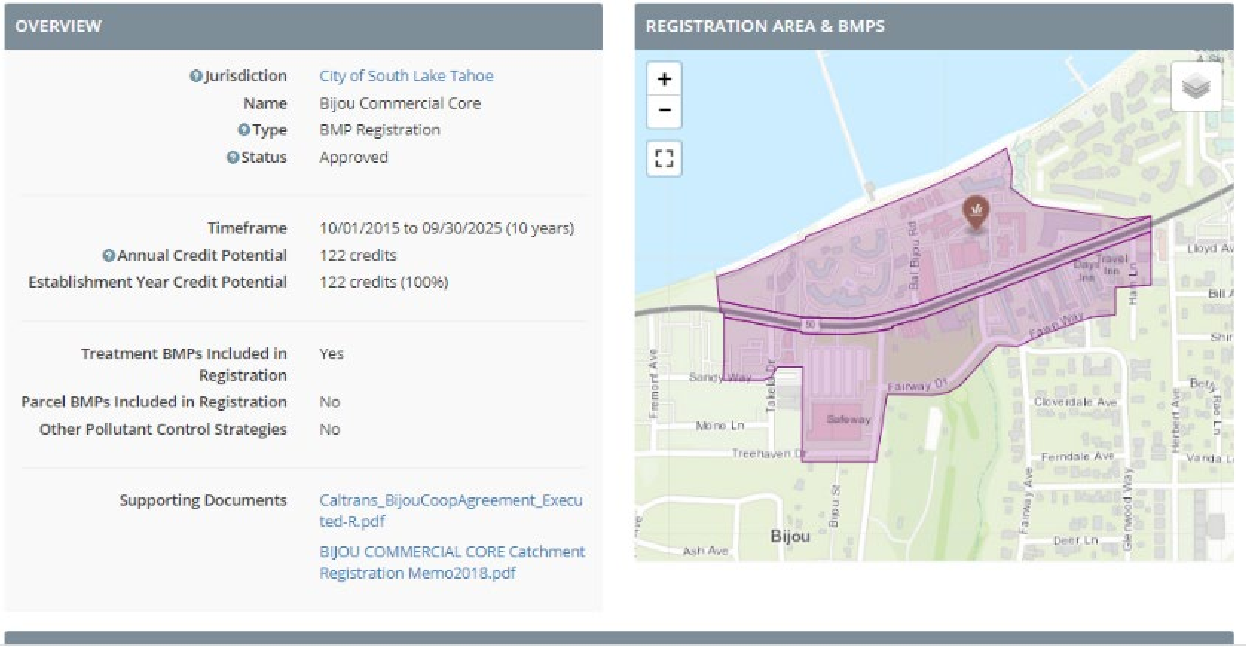
Selection of BMP Projects for Simulation

In combination with criteria proposed in the scope of work for the project and discussions with SWQIC at the March 16, 2022 meeting, the following criteria for catchment selection were assembled.

1. Registered catchment with PLRM model already built and vetted to reduce the effort needed to develop catchment characteristics and prepare models,
2. Geographical distribution of sites across the Tahoe Basin to capture the spatial variability in climate model predictions,
3. Local rain gage data available to compare precipitation statistics with both the SNOTEL-adjusted precipitation record in PLRM and the downscaled climate predictions,
4. High Directly Connected Impervious Area (DCIA) draining to treatment BMPs to reduce the potential for internal catchment hydrological processes to confound or mask the effects of a changing climate,
5. Limited structural BMPs or just one regional BMP at downstream end of catchment that is sized for the 20-year, 1-inch design storm (or close to that specification).

Following recommendations from SWQIC and subsequent discussions with the project team and funders, the following three urban catchments were selected: Bijou Commercial Core in the City of South Lake Tahoe (Figure 1), East Incline Village Phase I in Washoe County (Figure 2), and Lake Forest Highlands in Placer County (Figure 3). An overview of each project is provided below. Additional details are provided in Appendix C.

1. City of SLT – Bijou Commercial Core
   https://stormwater.laketahoeinfo.org/BMPRegistration/Detail/18

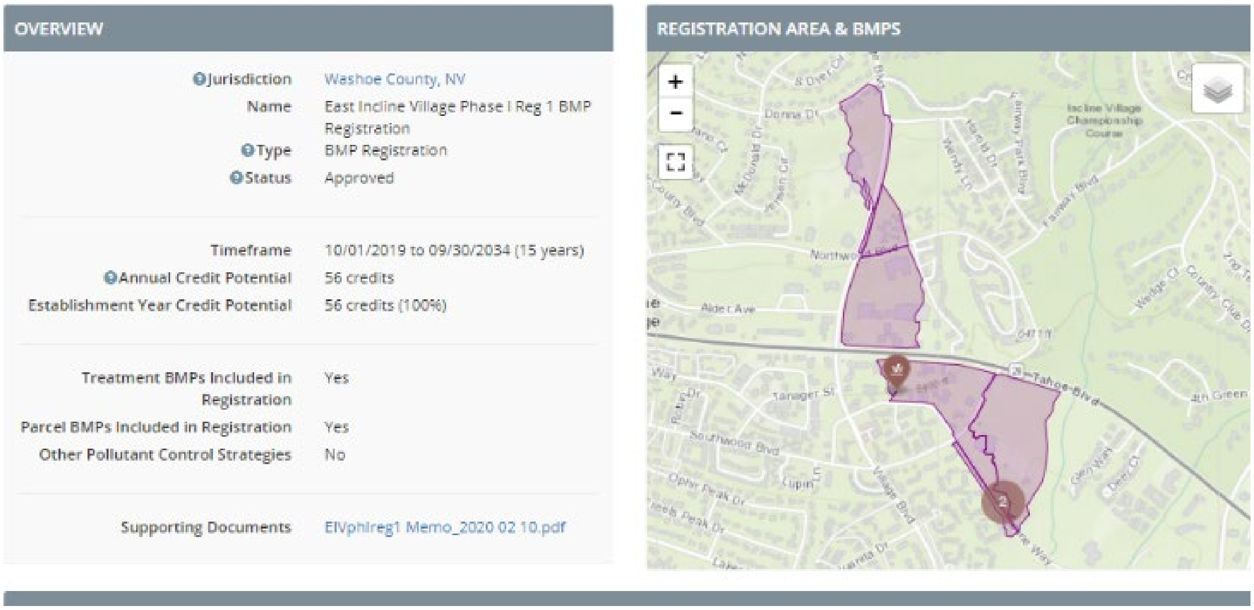


OVERVIEW

Jurisdiction	City of South Lake Tahoe
Name	Bijou Commercial Core
Type	BMP Registration
Status	Approved
Timeframe	10/01/2015 to 09/30/2025 (10 years)
Annual Credit Potential	122 credits
Establishment Year Credit Potential	122 credits (100%)
Treatment BMPs Included in Registration	Yes
Parcel BMPs Included in Registration	No
Other Pollutant Control Strategies	No
Supporting Documents	Caltrans_BijouCoopAgreement_Executed-R.pdf BIJOU COMMERCIAL CORE Catchment Registration Memo2018.pdf

Figure 1. Overview of Bijou Commercial Core from Lake Tahoe Info.

2. Washoe – East Incline Village Phase I Reg1
   https://stormwater.laketahoeinfo.org/BMPRegistration/Detail/150

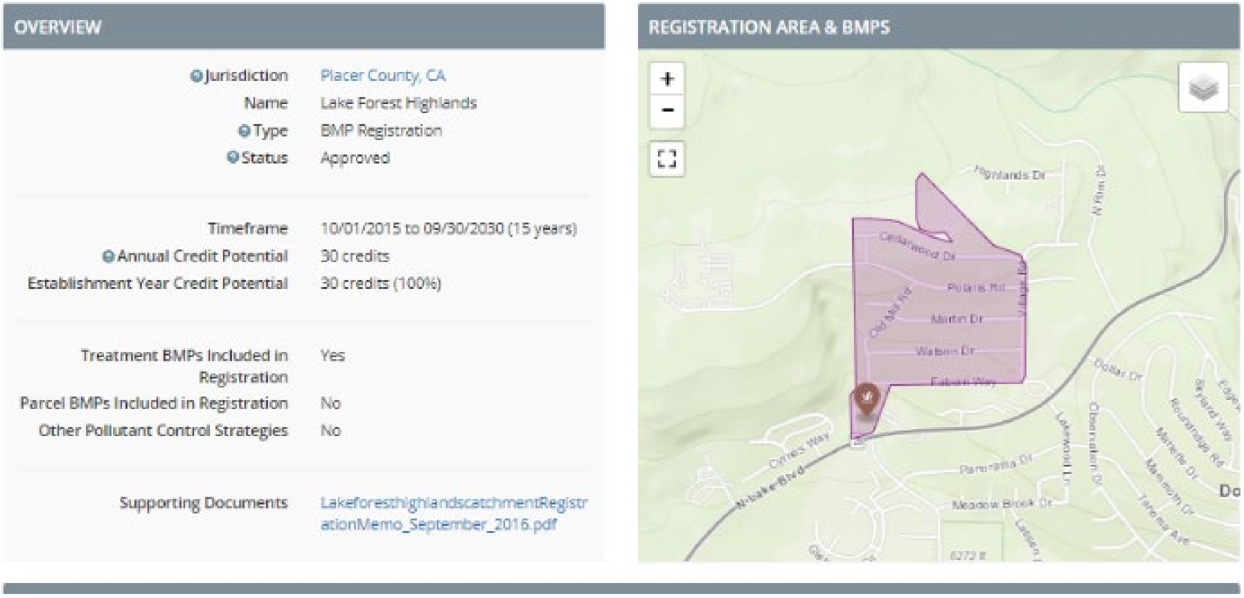


OVERVIEW

Jurisdiction	Washoe County, NV
Name	East Incline Village Phase I Reg 1 BMP Registration
Type	BMP Registration
Status	Approved
Timeframe	10/01/2019 to 09/30/2034 (15 years)
Annual Credit Potential	56 credits
Establishment Year Credit Potential	56 credits (100%)
Treatment BMPs Included in Registration	Yes
Parcel BMPs Included in Registration	Yes
Other Pollutant Control Strategies	No
Supporting Documents	EIVphIreg1 Memo_2020 02 10.pdf

Figure 2. Overview of East Incline Village from Lake Tahoe Info.

3. Placer – Lake Forest Highlands
   https://stormwater.laketahoeinfo.org/BMPRegistration/Detail/27



Jurisdiction	Placer County, CA
Name	Lake Forest Highlands
Type	BMP Registration
Status	Approved
Timeframe	10/01/2015 to 09/30/2030 (15 years)
Annual Credit Potential	30 credits
Establishment Year Credit Potential	30 credits (100%)
Treatment BMPs Included in Registration	Yes
Parcel BMPs Included in Registration	No
Other Pollutant Control Strategies	No
Supporting Documents	LakeforesthighlandscatchmentRegistrationMemo_September_2016.pdf

Figure 3. Overview of Lake Forest Highlands from Lake Tahoe Info.

All three of these BMP projects are registered under the TMDL Program and have PLRM models built. The three catchments are geographically distributed around Lake Tahoe: Bijou Commercial Core catchment is located on the south side of the lake, the East Incline Village catchment is located on the northeast side of the lake, and the Lake Forest Highlands catchment is located on the northwest side of the lake. The Bijou Commercial Core catchment is located near the Lake Tahoe Regional Stormwater Monitoring Program (RSWMP) Bellevue precipitation gauge, the East Incline Village catchment is located near the RSWMP Tahoe Environmental Research Center precipitation gauge, and the Lake Forest Highlands catchment is located near the RSWMP Hatchery precipitation gauge.

For the purposes of this study, directly connected impervious area (DCIA) greater than 50% were considered high DCIA. The Bijou Commercial Core catchment was estimated to have 76% DCIA. The subcatchments that make up East Incline Village range from 0% to 71% DCIA with an area weighted average of 43% DCIA. Though this is under the threshold for high DCIA, it was determined to be close enough for this study. The Lake Forest Highlands catchment was estimated to be 55% DCIA. Each of these three catchments has one treatment basin at the downstream end of the catchment.

In summary, all the selected sites fit the selection criteria well and serve as examples for analysis of how climate change will affect hydrology and BMP efficacy. The scenarios modeled for each of the selected sites are described in the “Model Scenarios” section.

Climate Data Analysis

The primary datasets leveraged to produce the climate scenario models were from Cal-Adapt's database of 32 Localized Constructed Analogs (LOCA) downscaled Global Climate Models (GCMs) from the RCP 8.5 CO_2 concentration scenario for select grid cells (Cal-Adapt, n.d.[a]). LOCA downscaling is a statistical method that correlates daily model estimates to daily measured observations (analog days) to produce a downscaled grid at a finer spatial scale than the original GCM (UCSD, n.d.). Each GCM is from the Coupled Model Intercomparison Project, version 5 (CMIP5). The GCMs from CMIP5 provide long term continuous modeling of several atmospheric parameters, including daily precipitation and daily temperature maximum and minimums. Since these models cover nearly the entire planet, the spatial scale of the CMIP5 data is on the order of 1.5°–3° (~60 miles equivalent near Lake Tahoe). The LOCA downscaling processes take these large spatial coverages of climate data and bring the spatial domain down to a 1/16° (3.7 miles) grid covering the US. The LOCA downscaling process includes data from local gauges as part of its bias correction to better account for small-scale spatial variability.

Despite the high quality of the data analysis used for the LOCA spatial downscaling, spatial and temporal averaging still influences the daily weather patterns of the LOCA downscaled climate models. These limitations are reasonable, even de minimis, for assessing long-term trends in climate, but they pose some specific challenges for use in stormwater modeling and BMP performance assessment.

First, global climate models exhibit what's known as the 'drizzle problem' in which precipitation patterns are characterized by high frequency and low-intensity events (Maraun, 2013; Navarro-Racines et. al, 2020). This is a well-known issue with GCMs and some data-processing techniques are used by researchers to correct for this bias with statistics, further modeling, neural networks, and other means. Climate researchers are often looking to correct for this in the most extreme cases (e.g., drought or flood magnitude) or in long-term averages. The result is that improved and bias-corrected models, like those available from LOCA, are bias corrected for long timescales 'climate' but may still exhibit more drizzle than would be expected in daily 'weather' data.

The second challenge is that the CMIP5 global GCMs and the LOCA downscaled models are at daily time increments. Using daily precipitation data when modeling the long-term stormwater capture of a BMP sized for a design storm would tend to lead to a dramatic overestimation of stormwater capture performance for the facility. To illustrate, consider 3" of precipitation in a 24-hour period. With a daily precipitation dataset, this volume would load a BMP at a rate of 0.125" per hour for 24 hours, well below the design standard and would lead to a full-capture outcome. However, if an hourly dataset is used and the same event occurs over the course of three hours as 0.5", 2.25", 0.25", then the BMP is likely to bypass over an inch of the total event runoff volume. For stormwater BMP capture performance analysis, daily precipitation time steps are too coarse.

To address these issues, the team took the following approach to prepare the climate data for BMP modeling:

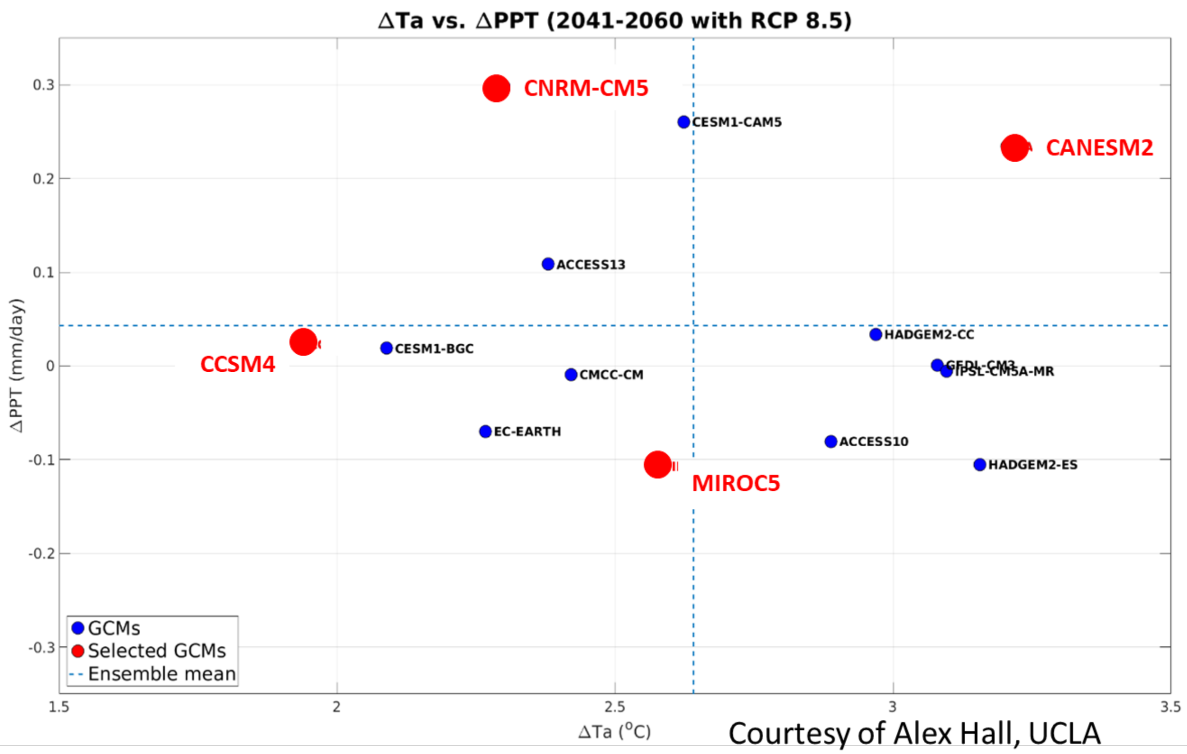
- Selected four representative GCMs for the Lake Tahoe region.
- Assessed long term statistics for each climate model at each study site in the region.

- Converted each GCMs historic and future precipitation datasets from daily to hourly timesteps (i.e., upsample) using a pattern matching algorithm that applies representative days of hourly data from an observed historical dataset (e.g., the existing PLRM precipitation data).
- Upsampled (converted) each of the GCMs daily min/max temperature data to hourly data
- Combined the temperature and precipitation datasets and performed synoptic event analysis to identify which GCM represents the best candidate for moving forward with the BMP performance study.

Each of these steps are described below.

GCM Evaluation

Four GCMs from Cal-Adapt's database of 10 GCMs from the CMIP5 project are recommended for use in California (Cal-Adapt, n.d.[b]): CanESM2, CCSM4, CNRM-CM5, and MIROC5. These were selected to bracket the influence of climate variability on future precipitation and temperature, as shown in Figure 4. Three of the four selected GCMs (CanESM2, CNRM-CM5, and MIROC5) have also been identified by Cal-Adapt as being among the best GCMs to use to represent a broad range of potential future climate conditions in California (Cal-Adapt, n.d.[b]). As such, these four GCMs were also selected for further analysis in this study. As indicated in Figure 4, CCSM4 indicates a low estimated change in temperature (ΔTa) and an average estimated change in precipitation (ΔPPT). CNRM-CM5 shows a mild change in temperature and a high change in precipitation. CanESM2 has the upper extremes for both temperature and precipitation, which represents a warm and wet climate scenario. MIROC2 shows average changes in temperature and a reduction in daily precipitation.



Courtesy of Alex Hall, UCLA

Figure 4. Selected GCMs based on relative change in precipitation (ΔPPT) and temperature (ΔTa) compared to full ensemble.

Additionally of note, each of these GCMs is a preferred model according to the historical absolute modeling error analysis performed by UCLA (Pierce, 2021). Based on the results of this study, each of the four GCMs recommended by Cal Adapt and UCLA simulate historical climate patterns better than most of the other GCMs analyzed. In sum, the four GCMs: CanESM2, CCSM4, CNRM-CM5, and MIROC5 were selected based on standards from Cal-Adapt, UCLA, UCSD, and best professional judgement to simulate extreme future conditions for the purposes of this climate change analysis. The team then analyzed these four GCMs and selected one to utilize for hydrologic and hydraulic modeling as described in the following sections.

Precipitation and Temperature Data Preparation

Precipitation

The LOCA downscaled CMIP5 GCMs are available in daily timesteps, but this time increment is too large to provide a reasonable and conservative estimate of long-term capture performance. To prepare a dataset that would allow for future simulations of BMP performance with reasonable hourly precipitation sequences, the team utilized a matching algorithm that leverages historically observed precipitation events. This matching exercise has several key requirements for the historical dataset:

- The historical datasets should be as long as possible, preferably greater than 30 years to provide enough event variability to be representative.

- The historical datasets should at least cover the same time period as the existing PLRM models (1988-2006) so that BMP capture results for historical periods are comparable to prior modeling. If possible, the historical datasets should extend this period through to 2020.
- The historical datasets should be available at multiple locations and elevations around Lake Tahoe to help account for the wide variation of precipitation patterns across this large region.

The team investigated several potential data sources for hourly precipitation data in the Lake Tahoe area, including local precipitation stations maintained by Tahoe RCD, the airport gauge in South Lake Tahoe, and SNOTEL sites.

The local precipitation stations have data available from 2014 to 2022. These stations are positioned primarily at low elevations. The team investigated use of these data to amend or inform an updated historical period dataset to extend the PLRM data from 2006 through to 2020 but found that the data suffered from quality assurance (QA) issues, sensor intermittency issues, and do not fully cover the required period at enough locations to warrant direct use by the team for this modeling effort. These stations are still excellent data sources for supporting their intended purpose of assessing individual storm events at key locations around the lake but were not suitable for use as a reliable regionally continuous dataset for the period 2006-2020.

The team also assessed the precipitation data from the South Lake Tahoe Airport (KTVL). These data were also deemed unsuitable due in part to missing or incomplete data, and because this dataset from South Lake Tahoe is not representative of rainfall conditions along the west or north shores of the lake.

The SNOTEL dataset was the most likely candidate for a regionally complete and well-maintained record of regional precipitation. The team retrieved and reviewed the data but after noticing several severe issues with using these data for hourly simulations and discussing these issues with researchers at NRCS, it became clear that the SNOTEL monitoring equipment and QA process are configured to be accurate for daily precipitation accumulation, not for hourly records of the storm event. This is caused by the unique challenge of recording precipitation that falls heavily as snow or is situated in locations where the instrument is likely to freeze. Significant data artifacts are caused by snow plugging the gage and then getting recorded as a large pulse when melted. Issues with the SNOTEL dataset and the additional avenues explored by the team to make use of these data are provided in more detail in Appendix B.

The consultant team was ultimately forced to proceed with the analysis using the best available existing historical precipitation dataset for the region: i.e., the PLRM dataset derived from the SNOTEL data for the period 1988–2006, as there was neither time nor budget to conduct the same analysis on the 2006-2020 SNOTEL dataset as was conducted by Tetra Tech on the 1988–2006 SNOTEL dataset.

These historical data were used as reference hourly datasets to upsample the GCM daily precipitation datasets. The upsampling algorithm assesses each day of precipitation in the GCM dataset and finds a best matching day in the historical reference dataset based on several factors, including the precipitation occurring two days prior and two days after (to help favor matches with a similar multi-day pattern of rainfall), and also to prefer matches occurring in a similar season. The details of this algorithm and the matching process are provided in more detail in Appendix B. The resulting timeseries includes hourly precipitation records that were observed in the PLRM dataset, while preserving the exact same daily total summary statistics as the original GCM for every day in the modeled dataset. Figure 5 below illustrates how the daily GCM data are transformed by this process into something more representative at the hourly level.

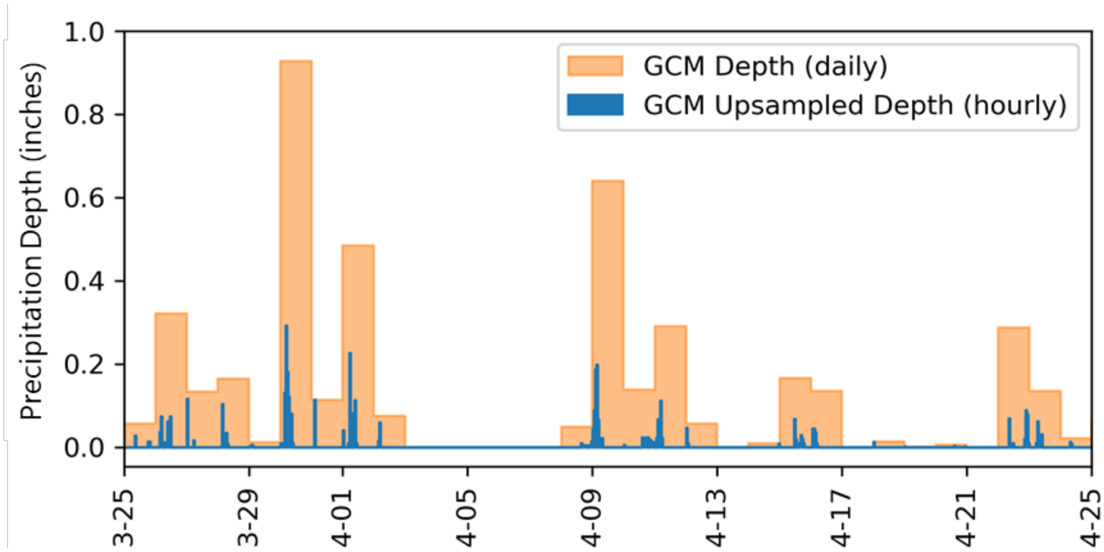


Figure 5. Example of daily GCM precipitation data from LOCA dataset (orange) and hourly data (blue) after upsampling.

In this figure, the daily total precipitation given by the GCM are shown in orange, and the upsampled hourly precipitation is shown in blue. If the daily data were used in continuous BMP modeling, the maximum intensity of the highest rainfall day would still be less than 0.04 inches/hour (figured as 1 inch / 24 hours). The distribution of intensities of the upsampled data is much more similar to the hourly precipitation sequences that a stormwater BMP would need to be sized to deal with and are shown here to reach intensities of 0.2-0.3 inches per hour during this storm event sequence.

Temperature

Daily maximum and minimum temperature data were obtained for each GCM. To transform this daily data to hourly timesteps, a cubic interpolation function was applied. Using this methodology, the maximum daily temperature was assumed to occur at 12pm, the minimum daily temperature was assumed to occur at 12am, and the hours in between were interpolated using a cubic polynomial pattern. A section of the interpolated temperature timeseries for the CanESM2 GCM at an example project site is shown in Figure 6.

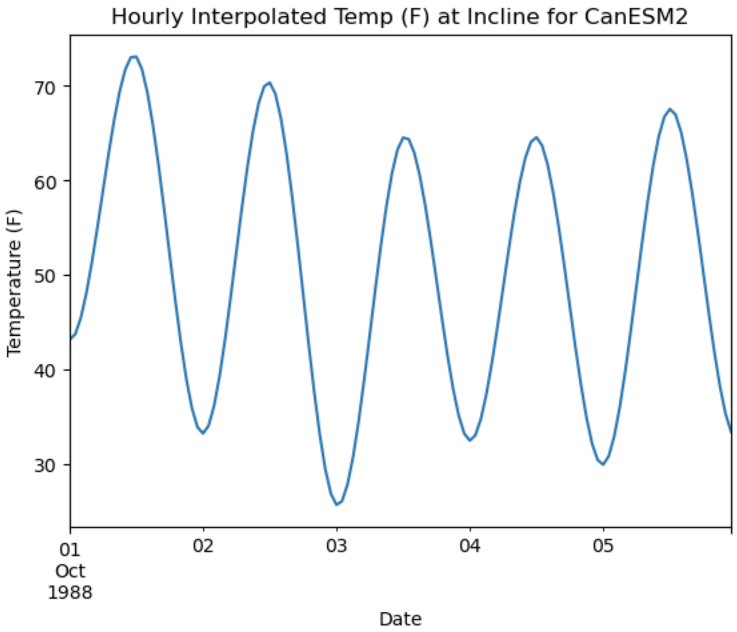


Figure 6. Cubic interpolation of hourly temperature from daily minimum and maximum temperatures.

Hourly interpolated temperature data can be used alongside the hourly upsampled precipitation data to determine periods of co-occurring precipitation and low temperatures for use as an estimate for precipitation falling as snow and/or as rain on snow. Statistical analyses comparing various precipitation and temperature conditions for each GCM at each site are summarized in the following section, and the complete set of comparison tables is provided in Appendix C.

Selection of single GCM

The team analyzed the four GCMs (CanESM2, CCSM4, CNRM-CM5, and MIROC5) and selected one to utilize for hydrologic and hydraulic modeling. Metrics evaluated for all four GCMs include mean annual precipitation (including snow) and mean annual rainfall as measures of precipitation volume, and hourly, daily, and event-based storm statistics as indicators of precipitation intensity. For each GCM, these metrics were calculated for both the historical (1988-2006) and future time periods (2030-2060). The historical GCM metrics were compared to those for the observed data to assess the historical accuracy of the GCM. The historical GCM metrics were also compared to those for the GCM during the future time period to determine the relative change in conditions. Note that both GCM and observed precipitation timeseries vary across the three project locations, which are discussed in the next section. Metrics were averaged across the locations to allow for an overall comparison between the observed and GCM data types and historic and future time periods.

The selected model, CanESM2, exhibited a large increase in precipitation volume and intensity in the future time period relative to the historic period, while matching the observed data during the historic period within a reasonable margin (Appendix C). A cumulative sum plot of total precipitation and rainfall only[1] for the Bijou project site is shown in Figure 7. The figure demonstrates that

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[1] Rainfall, or days with no snow, were estimated as days when the average temperature was above 32°F.

CanESM2 and CNRM-CM5 have similarly large precipitation volumes in the future time period compared to the other two GCMs in terms of both total precipitation and rainfall only (no snow) volume. The relative spread of the total precipitation and no-snow lines associated with each of the GCMs at the end of the time period is an indicator of the effects rising temperatures have on the form of precipitation that would be expected.

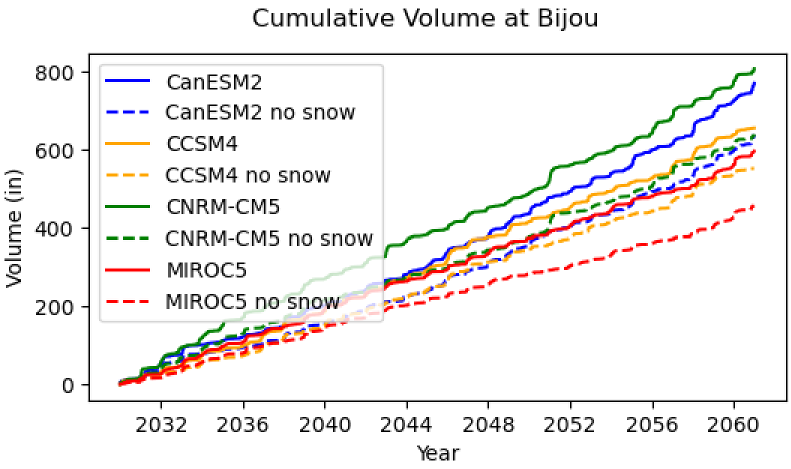

Figure 7. Comparison of GCM cumulative precipitation volume at Bijou with and without snow.

Both GCMs also have relatively large increases in precipitation intensity both in terms of the 20-year, 1 hour design storm depth and the 85th percentile, 24-hour storm depth (Table 1). Additional statistical tables and comparisons are included in Appendix C.

Table 1: GCM Comparison 2030-2060

Event	Site/Statistic	CanESM2	CCSM4	CNRM-CM5	MIROC5
20yr, 1hr design storm depth (inches):	Bijou	0.161	0.160	0.167	0.149
	Incline	0.154	0.143	0.153	0.140
	Highlands	0.204	0.194	0.205	0.190
	Mean	0.173	0.166	0.175	0.160
	% Diff from Historical	15.590	3.112	13.391	-0.828
85th percentile, 24hr storm depth (inches)	Bijou	0.745	0.719	0.733	0.674
	Incline	0.788	0.771	0.791	0.690
	Highlands	1.177	1.172	1.173	1.011
	Mean	0.903	0.887	0.899	0.792
	% Diff from Historical	21.263	13.546	14.931	0.588

Though CNRM-CM5 model is predicted to accumulate a greater total precipitation volume in the future period (Figure 7), CanESM2 exhibits the largest change in both the 20 year 1-hour event and in the 85th percentile event depths compared to the corresponding GCM metrics for the historical period (Table 1). For this reason, CanESM2 was selected for use as the GCM model that would be the best test of the Lake Tahoe stormwater BMP sizing criteria and for evaluating how climate change may impact the performance of existing BMPs.

Model Scenarios

At each of the three selected locations, two models were prepared for climate change analysis. The first was the original PLRM model with real catchments and the registered project BMPs. The parameters and configuration of these models were not modified. The second was the hypothetical model with 10-acre catchments and identically sized detention basins. The current PLRM meteorological data and the LOCA-modified meteorological data were input into both the real and hypothetical models at each location.

Registered Model Conditions

The first set of models prepared for the three locations were based on the original PLRM models. These models contain the real catchments draining to the project site and the registered BMPs. The purpose of these models was to explore the impact of climate change on real projects. The configuration of each project site in PLRM is described below.

At Bijou Commercial Core, several catchments drain to the project and first enter a vault, wherein a flow splitter (named a pump in PLRM) diverts a portion of inflow to the USFS Basin and causes the rest to bypass the infiltration basin (Figure 8). The flow that enters the vault was considered to be the total inflow to the BMP for the purposes of the climate change analysis. Flow that is not infiltrated by the USFS Basin overflows, resulting in a secondary pathway for untreated flow during events larger than the basin's design capacity.

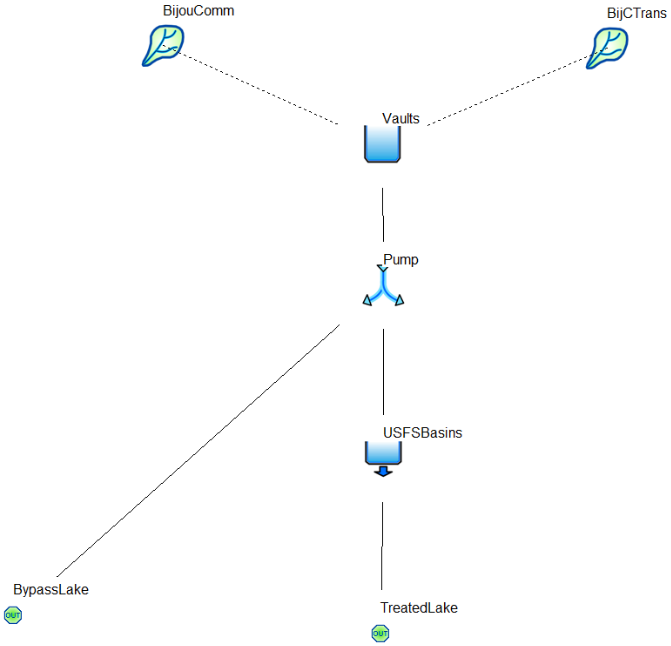

Figure 8. Bijou Commercial Core PLRM Model

At East Incline Village, multiple catchments drain to WCDB0033, which is an unlined dry basin (Figure 9). While there are several other BMPs downstream, only WCDB0033 was analyzed for the climate change analysis to isolate the effect of climate change on the BMP via runoff from the land surface. Untreated bypass was assumed to occur when the inflow volume to WCDB0033 exceeded its storage capacity.

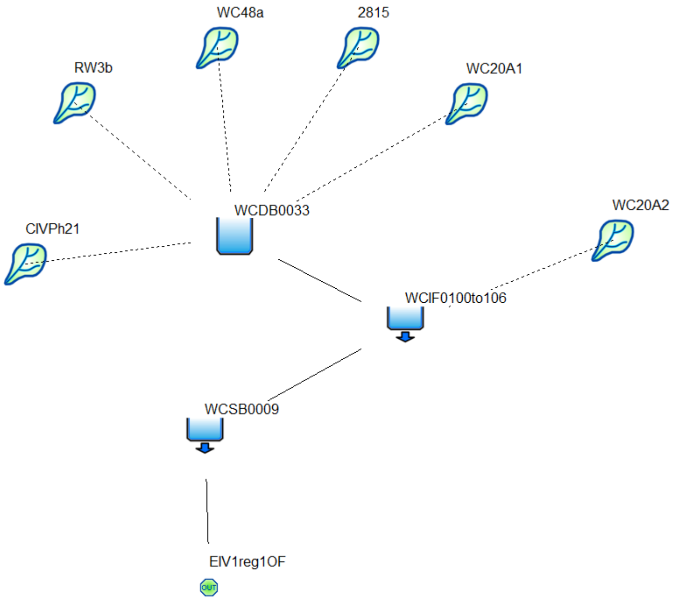

Figure 9. East Incline Village Phase I Reg 1 PLRM Model

At Lake Forest Highlands, a single catchment drains to LF2_DB02, which is an unlined dry basin (Figure 10).

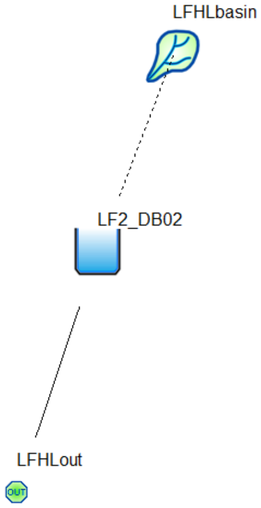

Figure 10. Lake Forest Highlands PLRM Model

Hypothetical Conditions for Standardized Comparisons

The other set of models prepared for the three locations represented identical hypothetical catchments and detention basins at each location, sized to meet current design criteria. The models were derived from the original PLRM model files, but the catchment size, percent imperviousness and structural facilities were replaced with consistent inputs. The purpose of these models was to isolate the spatial variability of climate change impacts by analyzing a standardized project layout representative of current design criteria across multiple locations.

The hypothetical catchment was 10 acres in size with an imperviousness of 100%, to maximize the signal of climate change in the runoff to the BMP. The estimated runoff coefficient for this catchment is 0.89 based on the recommended imperviousness-based formula in Urban Runoff Quality Management Manual of Practice No. 23 (Urbonas, 1998). These characteristics are summarized in Table 2.

Table 2: Hypothetical catchment characteristics

Catchment Characteristic	Value
Drainage Area (ac)	10
Imperviousness (%)	100%
Runoff Coefficient	0.89

The hypothetical dry basin was sized assuming a 1-inch design storm depth incident on the hypothetical catchment, resulting in a storage volume of 32,380 cu ft. Assuming a maximum ponding depth of 2.5 ft, a footprint of 12,952 sq ft was assigned. The basin is assumed to be lined with an outlet sized to draw down the full basin in 60 hours. These characteristics are summarized in Table 3.

Table 3: Hypothetical BMP characteristics

BMP Characteristic	Value
Design Storm Depth (in)	1
Storage Volume (cu ft)	32380
Depth (ft)	2.5
Area (sq ft)	12952
Brimful Drawdown Time (hr)	60
Infiltration Rate (in/hr)	0

Climate Scenarios

For each of the two model sets, registered and hypothetical, three scenarios were evaluated using different climate records. The first scenario uses the PLRM precipitation and temperature data for the registered model during the historical period 1988-2006. The second scenario simulates the same model period using precipitation and temperature from the GCM record. The third scenario simulates the future period 2030-2060 using the GCM precipitation and temperature record. These scenarios allow for assessment of the baseline representativeness of the GCM data and the relative change between the historical and future periods. These scenarios are summarized in Table 4. Note that, regarding the start and end of years, the model simulations begin on October 1st of the start year and end on September 30th of the end year to model complete water years.

Table 4: Climate scenario time periods and data sources

Simulation Period	Start – End Year	Data Source
Historical – Observed	1988-2006	PLRM Observed
Historical – Global Climate Model	1988-2006	LOCA GCM CanESM2
Future – Global Climate Model	2030-2060	LOCA GCM CanESM2

Scenario Matrix

At each of the three project locations, two different hydraulic settings were modeled (registered PLRM and hypothetical). For each of those models, three climate scenarios were evaluated (historical observed, historical GCM, and future GCM). This resulted in a total of 18 scenarios, identified by the scenario codes listed in Table 5.

Table 5: Complete set of 18 scenarios and configurations

Project Location	Hydraulic Setting	Analysis Period	Met Data Source	Scenario Code
Bijou Commercial Core	Real PLRM catchment and BMP	1988-2006	PLRM Observed	BIJ_R_Hist_PLRM
Bijou Commercial Core	Real PLRM catchment and BMP	1988-2006	LOCA GCM CanESM2	BIJ_R_Hist_LOCA
Bijou Commercial Core	Real PLRM catchment and BMP	2030-2060	LOCA GCM CanESM2	BIJ_R_Futr_LOCA
Bijou Commercial Core	Hypothetical catchment and BMP	1988-2006	PLRM Observed	BIJ_H_Hist_PLRM
Bijou Commercial Core	Hypothetical catchment and BMP	1988-2006	LOCA GCM CanESM2	BIJ_H_Hist_LOCA
Bijou Commercial Core	Hypothetical catchment and BMP	2030-2060	LOCA GCM CanESM2	BIJ_H_Futr_LOCA
East Incline Village	Real PLRM catchment and BMP	1988-2006	PLRM Observed	EIV_R_Hist_PLRM
East Incline Village	Real PLRM catchment and BMP	1988-2006	LOCA GCM CanESM2	EIV_R_Hist_LOCA
East Incline Village	Real PLRM catchment and BMP	2030-2060	LOCA GCM CanESM2	EIV_R_Futr_LOCA
East Incline Village	Hypothetical catchment and BMP	1988-2006	PLRM Observed	EIV_H_Hist_PLRM
East Incline Village	Hypothetical catchment and BMP	1988-2006	LOCA GCM CanESM2	EIV_H_Hist_LOCA
East Incline Village	Hypothetical catchment and BMP	2030-2060	LOCA GCM CanESM2	EIV_H_Futr_LOCA
Lake Forest Highlands	Real PLRM catchment and BMP	1988-2006	PLRM Observed	LKF_R_Hist_PLRM
Lake Forest Highlands	Real PLRM catchment and BMP	1988-2006	LOCA GCM CanESM2	LKF_R_Hist_LOCA
Lake Forest Highlands	Real PLRM catchment and BMP	2030-2060	LOCA GCM CanESM2	LKF_R_Futr_LOCA
Lake Forest Highlands	Hypothetical catchment and BMP	1988-2006	PLRM Observed	LKF_H_Hist_PLRM
Lake Forest Highlands	Hypothetical catchment and BMP	1988-2006	LOCA GCM CanESM2	LKF_H_Hist_LOCA
Lake Forest Highlands	Hypothetical catchment and BMP	2030-2060	LOCA GCM CanESM2	LKF_H_Futr_LOCA

Analysis of Results

Assessing BMP Performance

The primary metric of interest for BMP performance in this study was long-term capture efficiency. The capture efficiency is the total volume of treated water (including volume infiltrated) as a percentage of the total volume that is routed to the BMP. Table 6 summarizes the average annual inflow volume, treated discharge, infiltrated volume, bypassed volume, and capture efficiency for each of the model scenarios. Inflow is the total inflow volume to the BMP. Treated discharge is the volume treated and discharged. Infiltrated is the volume infiltrated and not discharged. Bypass is the volume bypassed without treatment. Outflow is the treated discharge plus bypass volume. Capture efficiency is calculated as (Inflow-Bypass)/Inflow. The Bijou site (BIJ_R) is an infiltration basin where all stormwater is either infiltrated or bypassed/overflowed. For this reason, the treated discharge is zero. Note that in PLRM, volumes that overflow a BMP are not considered treated even though some treatment may occur.

Table 6: Long-term capture (all volumes are annual average volumes)

Scenario	Inflow (acre-ft/yr)	Treated Discharge (acre-ft/yr)	Infiltrated (acre-ft/yr)	Bypass (acre-ft/yr)	Outflow (acre-ft/yr)	Capture Efficiency (%)
BIJ_R_Hist_PLRM	40.42	0.00	39.19	1.23	1.23	97.0
BIJ_R_Hist_LOCA	36.64	0.00	35.72	0.92	0.95	97.5
BIJ_R_Futr_LOCA	53.40	0.00	46.65	6.75	6.75	87.4
BIJ_H_Hist_PLRM	15.13	14.13	0.00	1.00	15.13	93.4
BIJ_H_Hist_LOCA	12.98	12.16	0.00	0.82	12.98	93.7
BIJ_H_Futr_LOCA	17.89	14.31	0.00	3.58	17.89	80.0
EIV_R_Hist_PLRM	9.15	7.30	1.42	0.43	7.73	95.3
EIV_R_Hist_LOCA	9.57	7.53	1.47	0.57	8.10	94.0
EIV_R_Futr_LOCA	15.65	10.16	1.93	3.56	13.72	77.3
EIV_H_Hist_PLRM	16.54	15.16	0.00	1.38	16.54	91.7
EIV_H_Hist_LOCA	15.41	14.00	0.00	1.41	15.41	90.9
EIV_H_Futr_LOCA	21.08	16.78	0.00	4.30	21.08	79.6
LKF_R_Hist_PLRM	22.16	10.52	6.02	5.62	16.14	74.6
LKF_R_Hist_LOCA	22.34	10.61	6.14	5.59	16.20	75.0
LKF_R_Futr_LOCA	35.08	12.28	7.06	15.74	28.02	55.1
LKF_H_Hist_PLRM	26.61	21.32	0.00	5.29	26.61	80.1
LKF_H_Hist_LOCA	26.94	21.32	0.00	5.62	26.94	79.1
LKF_H_Futr_LOCA	35.81	24.67	0.00	11.14	35.81	68.9

As indicated in the table, the differences in total inflow volume and percent capture for the historical period (1988-2006) when using the original PLRM meteorological data and LOCA meteorological data for all models is very small, indicating that the LOCA data accurately represents historical weather patterns. The capture efficiency results from Table 6 are represented visually in Figure 11 and Figure 12 to facilitate comparison across locations for the registered and hypothetical models, respectively.

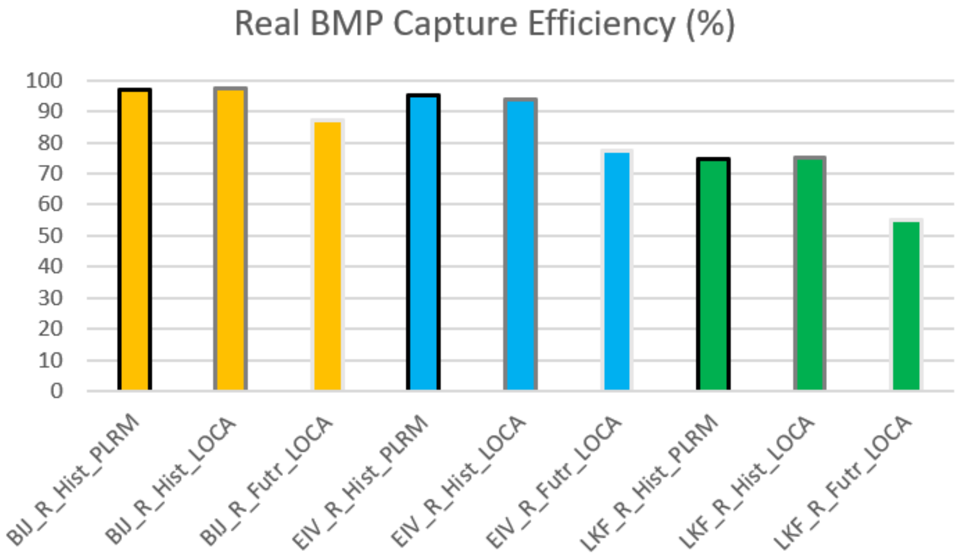

Figure 11. BMP capture efficiencies from historical PLRM, historical LOCA, and future LOCA scenarios for the PLRM registered models at all three locations

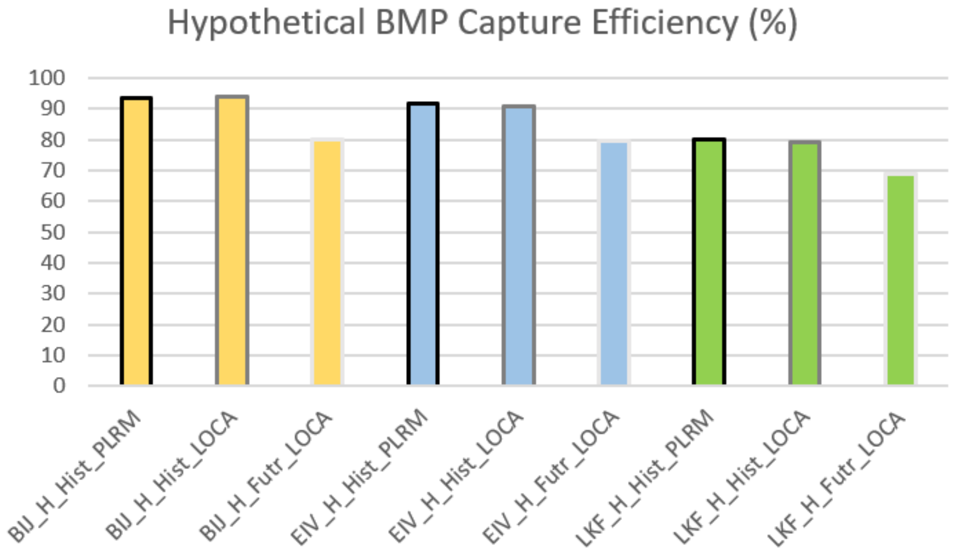

Figure 12. BMP capture efficiencies from historical PLRM, historical LOCA, and future LOCA scenarios for the hypothetical models at all three locations

Table 7 summarizes the difference between the historical and future LOCA climate scenarios at each location, where the change in volume is expressed as the percent difference relative to the historical scenario and the change in capture efficiency is the percent difference between the historical and future capture efficiencies.

Table 7: Percent change in capture volumes and difference in capture efficiency between historical and future LOCA simulations

Scenario	Inflow Percent Change	Treated Discharge Percent Change	Infiltrated Percent Change	Bypass Percent Change	Outflow Percent Change	Percent Difference in Capture Efficiency
BIJ_R	46	n/a	31	634	611	-10
BIJ_H	38	18	n/a	337	38	-15
EIV_R	64	35	31	525	69	-18
EIV_H	37	20	n/a	205	37	-12
LKF_R	57	16	15	182	73	-27
LKF_H	33	16	n/a	98	33	-13

n/a – not applicable.

Bijou and EIV have similar levels of performance with baseline (historical) percent captures of 97% and 94%, respectively, for their registered models and 94% and 91%, respectively, for their hypothetical models. Lake Forest has a baseline of 75% for its registered model and 79% for its hypothetical model. For the future conditions (2030-2060), all locations are expected to see an increase in runoff volume and a drop in the percent capture. For Bijou, the percent capture is expected to stay above 80% in the future if the design storm stays at 1 inch. However, EIV and Lake Forest are both expected to see the percent capture drop below 80% in the future. With all things being equal, BMPs installed in the Lake Forest area have lower percent captures than BMPs of the same size installed elsewhere.

Summary of Hydrologic Results

Statistical analyses of hydrologic model results included inflow to the BMP and precipitation events. Statistics describing inflow to the BMP are of interest as they are expected to directly affect the long-term capture efficiency of the BMPs presented in the previous section. Statistics for precipitation events, especially related to snowpack, are of interest as they may reveal whether changing temperatures impact snow build-up and melt-off, which may in turn affect runoff to the BMP. Non-parametric statistics for these variables were expressed as median, interquartile range (IQR), 1.5x the IQR, and outlier data points on box plots comparing the three simulation periods for each modeled location and hydraulic configuration. These statistics are used to explore differences between modeled time periods and across locations, so only the results from the hypothetical model scenarios are discussed in this section.

Total inflow volume per water year was calculated by summing the flow received by the BMP on a water year basis and converting the volume to units of acre-feet. These statistics are presented in the left-most subplots in Figure 13, for which the boxplots are blue. Peak inflow was summarized for the entire simulation period by calculating the maximum hourly inflow on a daily basis, only considering days during which at least 1 inch of rainfall occurred (note that rainfall is defined by an hourly timestep with positive precipitation and air temperature greater than 32 degrees

Fahrenheit).These statistics are presented in the right-most subplots in Figure 13, for which the boxplots are yellow.

Precipitation metrics of interest included the occurrence of snow cover and rain falling on snow per water year. The number of days per water year with snow cover were defined as the sum of days with at least one hourly timestep reporting greater than 0.1 inch of snow depth. These statistics are presented in the center-left subplots in Figure 13, for which the boxplots are light pink. The number of rain-on-snow days per water year were calculated by tallying the days during which at least 0.1 inch of rain was incident on at least 0.1 inch of snow on the ground. These statistics are presented in the center-right subplots in Figure 13, for which the boxplots are dark pink.

The plots of annual inflow volumes show that these volumes increase in the future for all locations. This can also be observed in the average annual increases in inflow volume from Table 7, which shows that the percent increase in inflow volume for the hypothetical model scenarios ranges from 33-38%. The plots of peak inflow rate in Figure 13 indicate that, while the median inflow rates are not significantly changed in the future, more extreme values are more frequent in the future at all locations as indicated by the outlier data points. It can be concluded that these extreme values contribute to a reduction in percent capture and an increase in bypass volumes.

Figure 13 also reveals that the number of days with snow cover is drastically reduced at all locations. This is apparent by the absence of any overlap in the interquartile ranges between the historical and future scenarios. It should be noted, however, that only Lake Forest has a historical period where the PLRM and LOCA match well, which indicates the temperature data in PLRM and LOCA may not correlate well. This may be due to the coarse scale of the LOCA grid cell, while PLRM uses a lapse rate to adjust the temperature at higher-resolution locations based on elevation. Additionally, Figure 13 shows that the median number of days with rain on snow doesn't significantly change between historical and future scenarios. This is likely due to the reduction in the number of days with snow cover (i.e., if there are fewer days with snow on the ground, there are few opportunities for rain-on-snow events). This finding is consistent with Dettinger and Rajagopal (2022) who found that rain-on-snow events are expected to increase initially but their frequency will decline in the latter half of the century due to reduced snow cover.

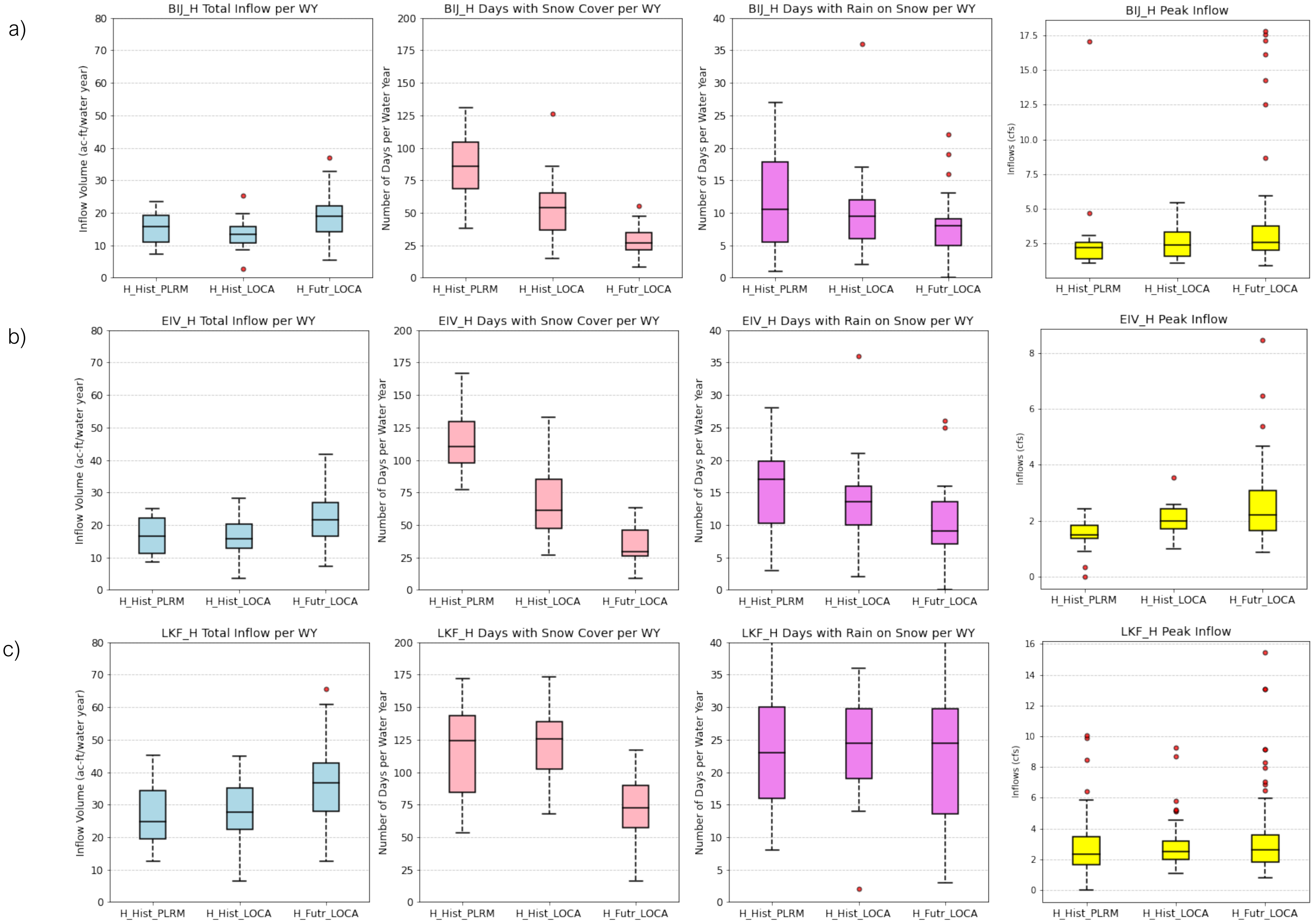

Figure 13. Inflow and precipitation statistics for hypothetical model scenarios at a) Bijou, b) East Incline, and c) Lake Forest. Statistics for these variables expressed as median lines, interquartile range (IQR) boxes, 1.5x the IQR for whiskers, and outlier data points.

Implications of Results for BMPs in the Tahoe Basin

The focus of this discussion has been on urban hydrologic modeling, rather than on pollutant load modeling. As a first estimate, it is reasonable to expect that pollutant loadings will follow climate change patterns in hydrology, because as runoff increases the total loading tends to increase as well. Furthermore, reductions in pollutant loads modeled by the PLRM are calculated as a function of the runoff proportion treated (hydraulic capture), characteristic runoff concentrations (CRCs) assigned to each land use type, and the characteristic effluent concentration (CEC) assigned to each BMP type. Although runoff volumes at Tahoe typically range over several orders of magnitude depending on the geographic location and size of drainage area, the pollutant concentrations usually range within about one order of magnitude. Thus, hydrology tends to drive loads in general, as well as the BMP load reduction equation, which is simply the product of volume captured and discrete BMP-specific CECs plus the volume bypassed and the composite land use CRC.

Clearly, most future climate scenarios indicate higher flow extremes and increased event volumes at Tahoe. The analyses for BMP performance discussed above show decreased hydraulic capture efficiency. To a large extent this is due to increasing outflows through bypass features as the event volumes exceed the capacity of treatment basins (Table 6). Although infiltration has been identified as an important TMDL practice for reducing stormwater runoff loads, the maximum rates of BMP infiltration are generally limited by the saturated hydraulic conductivity of underlying soils (e.g., Heyvaert et al., 2008) or, in some cases, depth to bedrock or the water table. This infiltration capacity limitation is reflected in the relatively modest increases seen for future infiltration volumes compared to bypass outflows of modeled catchments in the current study.

Reduced hydraulic capture efficiency suggests that loading of pollutants to the Lake will likely increase over time with climate change, unless we implement larger and/or more effective treatment systems. As mentioned above, this study only evaluated potential hydraulic performance impacts and did not assess potential water quality performance impacts that may be affected by changes in influent quality, first-flush characteristics, hydraulic residence times, or other BMP design features. Expanding stormwater infrastructure designs to include a treatment train approach may be particularly useful to offset increased hydraulic loadings and improve pollutant reductions in outflows. There is no single process that is equally effective at removing fine sediments along with both phosphorus and nitrogen. Nutrient removal will become more important with warmer climate as algal growth in both the nearshore and the mid-lake will increase due to higher water temperature and nutrient availability. This increased organic production in the lake, along with delivery of more organic material from the watershed, could also contribute to more decomposition and increased consumption of dissolved oxygen in the water column, which would have serious longer-term impacts on lake clarity and health.

Fortunately, improved pollutant removal probably can be achieved through refinement of current practices as well as through implementation of new BMP technologies, which will be addressed in the next section. This may require, for example, retrofits with more active hydraulic management to add peak flow control into designs, such that higher flows with lower concentrations are treated separately from the more concentrated initial runoff volumes. Biofilters could be built into these practices, using tailored media designed to capture specific nutrients and particle sizes. Also, comparing the capture efficiencies of hypothetical catchments with BMPs (Figure 12) suggests that a single basin-wide design-storm specification may not be the most efficient practice for stormwater treatment systems if the larger volume capture systems are not necessary in some locations. However, there is also concern that a reduction below 80% capture efficiency, which is the current design standard, would provide no further buffer against even a modest decrease in percentage capture efficiency. Notably, the PLRM simulations showed a 10–20% decrease in capture efficiency and a relatively large increase in bypass volumes (90–600%) at sites studied (Table 7). Not all sites would be amenable to increased runoff capacity, but where fiscally and geographically feasible, an upsizing of stormwater facilities with greater capacity and increased capture efficiency could help to compensate for the changing conditions. Increased urban runoff and bypass volumes could also increase erosion potential and associated hydromodification impacts on receiving streams.

Limitations of the Current Study and Next Steps

It is worth noting that the climate model chosen for this study (CanESM2) represents one of the more extreme future conditions. Typically, in climate change analyses, several GCM models are applied to bracket the variability in forecasted climate simulation. That was not possible given the number of PLRM scenarios developed and limited available resources. While this study made efforts to select a GCM that provides a plausible upper demarcation for potential effects on BMP performance, it is not a decisive target at this time. A more complete and thorough investigation is warranted given the risks posed to the Lake Tahoe Basin and its communities by climate change and the difficult decisions faced by water resource managers and planners in the region.

Fortunately, climate science continues to advance our knowledge and provide better information. Recent advancements in climate models are represented in CMIP6, which was released while this project was in progress. These models will support the next generation of climate projections and the LOCA downscaled products expected next year as part of the upcoming California Fifth Climate Change Assessment. Projected warming may increase modestly in these new products (Dettinger and Rajagopal, 2022) and LOCA downscaling may include finer spatial and temporal resolutions, which would be very useful for future investigations along the line of this current study.

Reliable hourly precipitation and temperature data are particularly important for updates to the current study. As discussed above, this study was forced to apply existing PLRM precipitation timeseries for the period 1988–2006 as the source of historical rainfall records for use in the statistical approach that converted daily GCM precipitation to hourly time steps. The PLRM records are likely reasonable, but they themselves are the result of a statistical estimation process performed by Tetra Tech in the early 2000’s on Tahoe SNOTEL data. This would tend to propagate any statistical bias that exists in the PLRM dataset into this study’s results. Although the methods applied in this study represent a reasonably robust approach, given the limitations of existing data and project resources, it is not ideal. Since we do not have sub-hourly data, we could not evaluate changes in sub-hourly intensities, which means runoff capture efficiency could be worse than projected, particularly for treatment systems that rely on pumping, flow diversion, or flow-based treatment such as swales and media filters. If hourly LOCA downscaled data become available, these could be upsampled to produce much better estimates of precipitation intensity, assuming a reliable source of sub-hourly precipitation observations is also available to use as reference for the upsampling process.

This study revealed several key opportunities to invest in the PLRM tool to make it more reliable and more flexible as a planning tool. A few priority features and improvements are listed below:

> **Update reference datasets** – The PLRM is an excellent place to centralize reference data that supports stormwater performance quantification analyses throughout the region. Updating this dataset to include a longer period of rainfall and temperature data that includes recent observations should be a priority. Organizing a region-wide network of meteorological sites producing high-quality data, particularly for precipitation, should be a priority.
>
> **Climate change module** – Water managers in the Tahoe Basin need tools to support planning of new capital investments in their stormwater infrastructure and in planning retrofit activities that would make existing stormwater infrastructure more resilient. A built-in climate change module with future precipitation and temperature datasets drawn from a standard suite of hourly GCM model results could help PLRM address this need.
>
> **User-provided datasets** – The PLRM tool could be improved to allow users to load their own precipitation and temperature datasets. This feature would allow an advanced user to perform site-based investigations of specific precipitation events, a sequence of events, or seasonal and annual observed data. This could be used to validate model results against local runoff quality and BMP performance data, which would help improve confidence in estimates of pollutant load reductions and overall progress in achieving TMDL targets.

Each of these suggested improvements to PLRM represents an investment that would greatly improve the ability of this tool to support planners, decision makers and researchers in the Lake Tahoe Region.

BMPs for the Tahoe Basin

Conventional BMPs

There are many types of BMPs recommended for use in the Tahoe Basin, as described in the Tahoe Regional Planning Agency's Best Management Practices Handbook (TRPA, 2014). The BMPs most frequently utilized by jurisdictions responsible for implementing the Total Maximum Daily Load (TMDL) are listed and described in the Pollutant Load Reduction Model User Manual (NHC et al., 2021). These are the ones that jurisdictions must model to get credit under the Lake Clarity Crediting Program. There are six primary categories of BMPs: dry basins, infiltration basins, wet basins, bed filters, cartridge filters, and treatment vaults (or a user defined stormwater treatment facility).

Dry basins are volume-based and allow particle and associated pollutant settling by detaining runoff for an extended period of time. Pollutant load reductions come from improvements in effluent quality relative to influent quality due to particle settling, as well as from some volume reduction due to infiltration. They are designed to drain completely between runoff events, leaving no permanent pool of water. Infiltration basins are similar in that they are volume based and designed to detain and infiltrate stormwater runoff, which retains particles, but the difference is that infiltration basins do not include a water quality outlet that discharges treated effluent as surface flow. Likewise, wet basins are volume based, but they require perennial or seasonal base flow and have an outlet designed to maintain a permanent or seasonal pool of water. They can be designed to store stormwater for an extended period of time. Pollutant load reductions come from volume reduction via evaporation of the wet pool and improvements in effluent quality relative to influent quality by settling of sediment particles and/or nutrient uptake by vegetation supported by the permanent pool. Due to the additional treatment processes present, wet basins generally have lower CECs than dry basins.

Bed filters are flow-based and utilize vertical filtration of stormwater through a porous medium like sand, compost, biochar, zeolite, or other natural and engineered substrates for pollutant removal. Pollutant load reductions come from physically removing particulates and associated pollutants through straining and adsorption. Cartridge filters are also flow based, and they are typically made up of numerous proprietary cartridges filled with engineered filtration media housed in a subsurface vault. Pollutant load reductions come from physically removing particulates and associated pollutants through straining and adsorption. Large vaults can provide some storage volume, but typically don’t allow for infiltration to underlying soils. Treatment vaults are defined as generic flow-based stormwater treatment facilities where treatment may occur by one or more distinct processes built into the system. This is also a catch-all category generally used for proprietary vaults or other treatment approaches not currently defined within the PLRM.

All six categories of BMPs have historically been constructed by the implementing jurisdictions, to varying degrees of success. Basins generally provide the best treatment, especially infiltration basins where it is assumed that 100% of the captured volume is infiltrated and all pollutants except for those associated with the bypass volume are removed and retained in the basin and underlying soils. These basins can be very sensitive to clogging from excessive sediment and must be maintained on a schedule sufficient to support adequate infiltration rates for the typical stormwater volumes experienced at the site. Both dry basins and wet basins, while generally effective, can have periods of pollutant retention and periods of pollutant release, so do not provide 100% treatment efficiency for the capture volume in the way that infiltration basins might. For example, wet basins support and depend on vegetation for pollutant removal. However, in the fall, when plants are dying and decomposing, nutrients are released and higher nutrient levels may be measured in the effluent as compared to the influent. Likewise, if a dry basin hasn’t been maintained to remove accumulated fine sediment particles (FSP), a large pulse of incoming stormwater runoff can resuspend the FSP, resulting in higher effluent FSP concentrations as compared to influent concentrations. Excessive heat and prolonged periods of drought may also impact plant health and the associated benefits that plants can provide to the performance of vegetated BMPs.

Bed filters can be quite effective, trapping sediment and nutrients in their porous medium. However, these straining and adsorption media have limited lifespans and must be replaced to restore pollutant removal efficiency. This can be costly if influent pollutant concentrations are high and the pollutant adsorption capacity of the engineered media is frequently reached or the media quickly becomes clogged with accumulated sediment. Sediment tends to accumulate on the surface and can form an almost impenetrable crust, barring further infiltration of incoming runoff volumes. This causes the system to bypass (if it is designed to allow for this) and thus no pollutant removal is achieved. Cartridge filters are similar to bed filters in that they contain engineered media designed to adsorb pollutants, but they may be easier to maintain than bed filters. This is because the cartridges can more easily be cleaned or replaced in some installations. However, the cartridges are generally proprietary and can be more costly to replace than the sand, compost, zeolite or other media used in a bed filter. Also, because cartridge filters have less media and are typically used with higher design flow rates, media-stormwater contact times can be very short (minutes), which can impact the treatment performance, especially for fine sediment and dissolved pollutants that rely on sorption.

Each BMP functions differently and has varying degrees of efficiency depending on where it is installed. In-situ conditions are the most important factor affecting pollutant removal efficiencies because they determine influent concentrations and loading rates to the given BMP. In-situ conditions include size of tributary catchment, land use in the catchment, roadway operation and maintenance practices, existence or absence of upstream BMPs or conveyance infrastructure, annual precipitation totals and event types, and many other factors. Secondary to catchment conditions are BMP maintenance intervals, which vary widely between different jurisdictions and within jurisdictions annually. It is therefore exceedingly difficult to estimate the efficiency of any given BMP without some reasonable period of in-situ monitoring data. Removal efficiencies associated with proprietary BMPs are generally estimated from lab or pilot studies, where the condition of the BMP is pristine and maximum removal efficiencies can be achieved. However, this is rarely the case in the field. While reliable estimates of achievable effluent concentrations for new or retrofit designs may not be available, an assessment of the potential performance improvement over traditional BMPs is possible based on understanding of comparable treatment processes. For example, the typical soil in a raingarden may be expected to provide some pollutant removal, but if amended with a natural or engineered media specifically designed to improve removal of a target pollutant, it can be reasonably expected that the raingarden will have an increased pollutant removal efficiency. Thus, implementing innovative BMPs may provide the needed “boost” required to achieve the stormwater treatment necessary to continue working toward TMDL goals in the face of climate change.

Innovative BMPs

Climate change is expected to bring more extremes, both in terms of increased storm intensity and total rainfall, as well as from periods of prolonged drought. During periods of high rainfall, it will be important to have increased volume capture and treatment capacity. It will also be important to shorten maintenance intervals to keep up with the increased sediment accumulation likely during large, intense storms that dislodge and transport more sediment. More aggressive maintenance may also be needed immediately after the spring snowmelt and before the fall wet season. The settling of FSP may be hindered if large volumes of runoff are not allowed an adequate retention time in a basin before more runoff enters the BMP. Designs that promote settling include extended drawdown times (e.g., >48 hours), shallow depths, laminar flows, and circuitous and vegetated flow paths. A hypothetical 48–60 hour drawdown time for dry basin or infiltration basin may not be sufficient to settle fine particles if the energy of inflow is not sufficiently dissipated or the surface overflow rate (flow/surface area) is too low. Frequent maintenance will be especially important to remove accumulated FSP that can be resuspended and transported to Lake Tahoe. During periods of drought, it will be important for BMPs that depend on vegetation for nutrient uptake to have soil amendments that support increased moisture retention. Temporary or seasonal irrigation may be also be needed.

The objective of considering new, innovative and retrofit BMPs is to identify options that increase storage capacity, pollutant removal, soil moisture retention and groundwater recharge in the face of larger precipitation events with greater runoff volumes and loading rates as well as prolonged periods of drought. These challenges could require adjustments to the standard sizing guidelines for BMPs, more frequent maintenance to maintain pollutant removal efficiency, additional design components in existing BMPs, and a new catalogue of BMPs for implementers to choose from that are better designed to capture and treat stormwater in the cold climate of the Tahoe Basin. Possible innovative or retrofit BMP options that would expand the inventory of current BMPs include: bioinfiltration systems/raingardens; biofiltration systems with underdrains, including phosphorus optimized stormwater treatment (POST); regenerative stormwater conveyance; biochar amendments; wetland practices, including modular wetlands, subsurface wetlands, floating wetlands, and floating media bed reactors; and proprietary filtration systems. A summary of these BMPs is provided below. However, please see Appendix A: Alternative BMPs for Urban Stormwater Treatment in the Tahoe Basin for fuller descriptions of these options.

Raingardens, also known as bioinfiltration systems or bioretention cells, are engineered landscape depressions that gather, store, infiltrate, evaporate, and treat stormwater. They are generally composed of several vertical layers, including an upper layer to support vegetation and a filter media layer to provide a substrate for physiochemical sorption and biological transformation of pollutants. They can be installed in medians, along road shoulders, in parks, etc. POST systems are an example of an enhanced biofiltration system. Biofilters are similar in that they contain several vertical media layers and may be contained in concrete vaults, retaining walls, or curbing and may be installed in parking lots and sidewalks. They typically have underdrains to allow complete drainage even when native soils have limited infiltration capacity or when the system is lined.

Regenerative stormwater conveyance (RSC) systems are designed to both convey runoff and provide an opportunity for infiltration and filtration. They may contain cascading step-pools with vertical layers of different media designed to increase infiltration and treat stormwater through a variety of mechanisms. For example, an organic carbon source, such as wood chips, can be included in an anoxic media layer to promote denitrification. RSCs are generally installed along road shoulders, below culverts, and in areas where large volumes of stormwater cannot infiltrate in place but must be conveyed downstream.

The filtration media associated with all the BMP examples above can be amended with biochar to improve adsorption and removal of pollutants. Biochar is created from pyrolysis of organic waste products and results in organic matter with larger pore size, greater surface area, and charged surface functional groups that increase pollutant removal capability. Biochar is receiving considerable attention as a renewable media applicable to various stormwater treatment practices (as discussed, for example, in the Minnesota Stormwater Manual[2]).

Modular wetlands and subsurface wetlands may be installed in urban locations to provide the benefits of larger wetland systems that are not possible in constrained settings. Baseflows are generally needed to sustain the wetland environment. Their design encourages anaerobic digestion of nitrate to nitrogen gas, but many other microbially mediated transformations as well as vegetative uptake are promoted in this system to enhance pollutant removal. Floating wetlands are designed to be used in wetlands or wet detention ponds to increase pollutant removal by providing additional root surface area covered in biofilm to uptake nutrients and adhere fine sediment and heavy metals. Floating media bed reactors can also be used in wetlands or wet detention ponds to enhance removal of nutrients by continuously pumping water from the pond, through filtration media and out an effluent pipe. The filtration media provides both biological transformation and physiochemical sorption of nutrients, much like other filter media mentioned.

Proprietary filtration systems refer to a wide variety of different types of filters designed to sieve out and adsorb sediment particles. They have been used in the Tahoe Basin in a few applications, but generally have not shown a lot of promise unless maintained frequently. In areas with high sediment loads, these systems can quickly become inundated by accumulated sediment and lose their ability to efficiently remove both coarse and fine sediment particles. The efficiency of these systems improves if a pre-treatment mechanism for settling out coarse sediment is installed upstream of the filter, like a hydrodynamic separator, baffle box, or settling basin. This is true for the majority of BMPs mentioned in this study. However, improved technology for filtering out very fine particles, coupled with increased funding to support maintenance of all BMPs in the Tahoe Basin, may result in proprietary filtration systems that provide sufficient filtration capability for fine sediment particles.

Importance of the Treatment Train Approach

The treatment train approach uses a series of separate BMPs (or “cells”) designed to target specific pollutants (or size of pollutants) through different removal mechanisms. Stormwater is treated by flowing through each of the cells in succession. This concept may prove instrumental in achieving the pollutant removal efficiencies necessary to continue making progress toward TMDL goals. It is unreasonable to expect that one BMP can sufficiently remove all pollutants in question

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[2] https://stormwater.pca.state.mn.us/index.php?title=Biochar_and_applications_of_biochar_in_stormwater_management

because pollutants differ in their physical, biological, and chemical properties and are therefore not all removed effectively by the same processes. For example, the pollutants of concern in Tahoe, sediments, nitrogen, and phosphorus, are all best removed by different mechanisms. Sediment is best removed by sedimentation (or settling) and filtration. Phosphorus is best removed by sorption and precipitation with metals or uptake by organic matter, and nitrogen is best removed through plant assimilation or from denitrification processes. If stormwater were to flow through a series of BMPs optimized for each of these processes, the resulting effluent would likely be much cleaner than if only one BMP process were depended upon to remove all three pollutants. Figure 14 shows a hypothetical treatment train example that could maximize removal of a host of pollutants if runoff flows successively through each cell of the system. Sedimentation and filtration can also be further broken down into coarse settling, extended detention sedimentation, coarse filtration, and fine filtration. This allows for successively smaller particles to be removed while reducing the clogging potential of downstream treatment processes. Also, since all unit treatment processes rely on sufficient hydraulic residence time, detention storage and flow control structures are important components of the treatment train. Flow duration control is also important to minimize downstream impacts from scour and hydromodification.

Figure 14. Example of the treatment train concept.

Selected High-value Opportunities (from Jurisdictional Feedback)

During meetings with the Stormwater Quality Improvement Committee (SWQIC) jurisdictions responsible for ensuring that pollutant load reductions are achieved in accordance with the TMDL expressed particular interest in raingardens/biofilters, biochar, filters that work better than ones they are already using, and the treatment train concept. They were also interested in a passive groundwater injection system that promotes lateral infiltration called the Parjana® Energy Passive Groundwater Recharge Product (EGRP®). Please see Appendix A for further discussion on high value opportunities for continued exploration (Alternative BMPs for Urban Stormwater Treatment). Next steps would include the selection of one or more specific new or innovative practices of particular interest to Tahoe Basin jurisdictions and then assessment of the additional information needed by planning and engineering staff to evaluate opportunities and specifications for potential implementation and associated performance monitoring.

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Appendix A.

Alternative BMPs for Urban Stormwater Treatment in the Tahoe Basin, Tahoe Stormwater Treatment BMPs in a Changing Climate Project

Alternative BMPs for Urban Stormwater Treatment in the Tahoe Basin

Tahoe RCD, Desert Research Institute, Geosyntec Consultants

Introduction

The goals of this project are to assess how climate change projections may affect urban hydrology in the Lake Tahoe Basin and to evaluate new treatment BMP options or retrofits for their potential to enhance pollutant removal and contribute to increased climate resilience.

A literature review was conducted to discover new treatments and retrofits that may have applicability in the Tahoe Basin. Literature identified from Web of Science and Google Scholar database searches were reviewed, an internet search of innovative BMPs was also conducted, and emerging stormwater treatment technologies reviewed and certified by the State of Washington TAPE (Technology Assessment Protocol – Ecology) were considered.

After a thorough review, ten BMP innovations, enhancements, or retrofits were selected for inclusion in a presentation to the Stormwater Quality Improvement Committee (SWQIC), a group of stormwater managers in the Basin responsible for reducing pollutant loading from the urban environment to Lake Tahoe.

The ten BMP options were chosen because they have strong potential to meet the following objectives:

1. adequate capture and retention
2. increased volume reduction
3. better pollutant removal efficiency
4. improved retention of 1–5 μm particles
5. increased carbon capture
6. better soil moisture retention
7. groundwater recharge and/or capture and reuse
8. reasonable installation, operations, and maintenance
9. suitability for use in cold climates

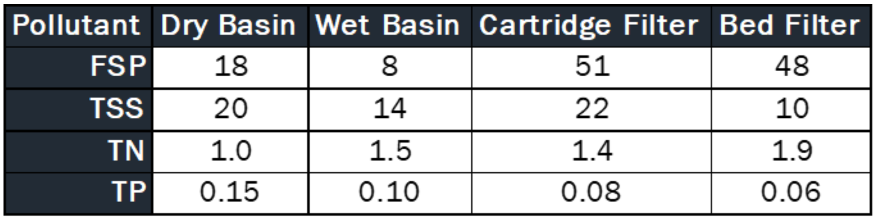
Cold climates require special considerations for BMP designs and maintenance. Snow management and the use of traction sands can impact BMP performance by blocking inflows, damaging vegetation, and clogging soils and media due to excessive sedimentation. Frost heaves have the potential to damage structural features of BMPs such as pipes or concrete infrastructure. This must be accounted for in any cold climate construction and practices known to alleviate issues can be applied to BMP installations. When freezing occurs, there is a reduction in treatment due to reduced biological activity, reduced particle settling velocities due to increased viscosity of colder water, and reduced infiltration due to freezing of soils and filter media. There are also access issues to deal with as access points may be frozen or difficult to locate under snow load. The BMP options presented in this memo will naturally have decreased treatment capacity in the winter months but are still likely to provide enhanced treatment on an average annual basis.

The default Characteristic Effluent Concentrations (CECs) used in the PLRM for Tahoe were developed through statistical analysis of event mean concentration data from treatment BMP performance studies in the Tahoe Basin and from the International Stormwater BMP Database (www.bmpdatabase.org). The PLRM Stormwater Treatment BMP Data Evaluation Project Compilation and Analysis Report updated the original default values (NHC, 2017). Most new, innovative BMP options have been tested in a lab or pilot installation under pristine, controlled conditions, with little real-world efficacy data available, and therefore often show artificially high pollutant removal efficiencies. It should be expected that in-situ installations of these new BMP options will have lower pollutant removal efficiencies and consequently higher CECs than the values available in the literature. CECs are heavily influenced by surrounding and tributary land use type, soils, seasonal conditions, temperature, inflow concentrations, and maintenance schedules and therefore are very site specific, making comparisons with lab results inappropriate The paucity of information on real-world CECs for new BMPs in the reviewed literature makes a comparison between available innovative treatment BMP efficiencies and those compiled in the PLRM Stormwater Treatment BMP Data Evaluation Project Compilation and Analysis Report unachievable. Instead, the ten BMPs innovations presented to SWQIC were chosen for their preliminary suitability for application in the Tahoe Basin based on their potential to meet the nine objectives for enhanced performance listed above.

Statistical analysis of monitoring data from enough in-situ installations of BMPs can predict minimum outflow concentrations attainable from the processes inherent to a specific BMP as “irreducible concentrations” (Larm et al 2019). Irreducible concentrations indicate lower limits on effluent pollutant concentrations below which it becomes increasingly difficult for a particular BMP to achieve in practice. Because inflow concentrations of pollutants in the Tahoe Basin are often relatively low, there may be runoff events where it can reasonably be expected that little to no pollutant reduction is achieved with a single BMP. This dilemma endorses the idea of using innovative BMPs, treatment trains, and improved maintenance to achieve higher pollutant removal efficiencies than could otherwise be attained with one traditional BMP.

In-situ BMPs that are continuously maintained to a high standard may be more effective, but a rigorous maintenance schedule can be costly and may not be feasible. However, at minimum, annual or bi-annual maintenance should be included in a cost-benefit analysis. Each of the ten BMP options presented in this technical memo will be associated with one of the four traditional categories of treatment BMPs presented in Table 2.6 of the PLRM Stormwater Treatment BMP Data Evaluation Project Compilation and Analysis Report (NHC 2017) excerpted below (Table A-1). Because the new BMP options discussed below purport to be improvements over these traditional BMPs, it can be reasonably assumed that the new options will reduce concentrations at least as well as their counterparts shown in Table A-1. However, these efficiencies should be used as guidelines only.

Table A-1. Excerpt from Table 2.6: Updated dataset median default CEC values in mg/L. (NHC 2017)



Pollutant	Dry Basin	Wet Basin	Cartridge Filter	Bed Filter
FSP	18	8	51	48
TSS	20	14	22	10
TN	1.0	1.5	1.4	1.9
TP	0.15	0.10	0.08	0.06

The CECs shown in Table A-1 align well with the 2020 median effluent concentrations summarized from the International Stormwater BMP Database (Clary et al., 2020). In that report, the lowest median TSS concentrations are achieved by biofiltration systems and media filters (4 to10 mg/L). The best performing BMPs for total phosphorus are media filters (i.e., bed filters) and high rate biofiltration (e.g., tree box filters) with total phosphorus median effluent concentrations of 0.05 to 0.09 mg/L. Dissolved phosphorus appears to be most effectively removed by retention ponds, wetland basins, and media filters with median effluent concentrations of 0.04 to 0.06 mg/L.

Removal of nitrogen is more uncertain due to the complexity of the nitrogen cycle. Many BMPs can remove total nitrogen to median effluent concentrations of 1 to 1.4 mg/L and media bed filters and high rate media filters (e.g., cartridge filters) can achieve total Kjeldahl nitrogen (TKN) concentrations of 0.5 to 0.6 mg/L (Clary et al., 2020). However, export of nitrate and nitrite (NOx) is common for media filters and biofilters. An excerpt from Clary et al. (2020) provides a pertinent summary of nitrogen removal and effective BMPs:

> *BMPs with permanent pools (i.e., retention ponds and wetlands) appear to be able to reduce nitrate concentrations but may be ineffective, or potentially increase, organic nitrogen. The opposite appears to be true for biofilters and media filters. Based on the theory of unit processes and knowledge of the nitrogen cycle, it is hypothesized that retention ponds and wetlands sequester nitrate in wetland sediments and vegetation during the growing season and then release nitrogenous solids during vegetation die-off periods. As indicated by the relatively high TKN removal and low NOx removal for media filters, inert filtration appears capable of capturing nitrogenous solids, but the conditions are not as conducive for significant denitrification or nitrogen uptake as compared to bioretention or BMPs with permanent pools (retention ponds and wetland basins). Therefore, a BMP designed for permanently reducing nitrogen may include a permanent wet pool followed by a vegetated swale or media filter. Alternatively, a bioretention cell with pore storage above and below the underdrain may provide aerobic and anaerobic zones for nitrification/denitrification processes (Davis et al. 2006). Harvesting of vegetation and removal of captured sediment may also be key maintenance practices for reliable removal of nitrogen.*

Based on the review of literature and our understanding of unit treatment processes, it is our professional opinion that wetland systems, bioinfiltration and biofiltration systems, and regenerative stormwater conveyance with biochar amendments, especially when used in a treatment train configuration where specific pollutants are targeted in individual steps in the treatment process, have the most promise in the Tahoe Basin. Raingardens, also known as bioinfiltration systems or bioretention cells, have been widely adapted in the United States with good results. They are part of an assortment of green infrastructure alternatives that harness natural hydrologic processes and vegetation, soil, and other ecological features to infiltrate and treat stormwater. Therefore, they are generally cost effective, have minimal impact on the surrounding ecology, require less maintenance, and are aesthetically pleasing. Raingardens can be designed to any shape, size, and depth. They can be shallow and installed in areas where infiltration is constrained by high ground water or shallow bedrock depth. They can also be small and installed in urban areas with little open space for larger infiltration basins or other conventional stormwater infrastructure. They can easily be amended with biochar designed to enhance removal of a variety of pollutants. They could be installed in series where each individual biofilter or “cell” spills over into the next one and each treats a specific pollutant.

Biofiltration systems are very similar to raingardens but tend to be equipped with underdrains and are generally encased in concrete and installed in constrained urban settings. They are less part of the natural landscape, and more part of urban stormwater infrastructure. However, they function in much the same way as raingardens do. Regenerative stormwater conveyance (RSC) is similar to a series of biofilters in that it also has cells that can be individually treated with specific amendments to target specific pollutants but has the added benefit of being able to convey larger volumes of water and reduce flooding in flood-prone areas. Biochar can be used as an amendment in both biofilters and RSC to enhance removal of pollutants as well as support healthy vegetation growth due to its ability to retain soil moisture in the dry Tahoe climate. Sized correctly and placed in the right location to maximize runoff capture, biochar enhanced biofilters and RSC can provide adequate stormwater capture, increased infiltration and groundwater recharge, improved pollutant removal efficiency, including retention of very fine particles, and better carbon capture and soil moisture retention. With the appropriate vegetation and placement, biofilters and RSC are suitable for use in cold climates.

Input from Stakeholders

The intent of the presentation was to get feedback from stakeholders on what types of BMPs they were most interested in, whether included in the presentation or not, if they have considered implementation of any enhanced or innovative BMPs or retrofits, and what they would like to know more about the most potentially applicable BMPs for their installations. Oral input from stakeholders was received directly following the presentation to SWQIC, and written comments followed. Oral and written input is summarized below.

Of the ten BMP options presented to SWQIC, stakeholders were most interested in biochar, raingardens, biofilters, and proprietary filters that work better than what is already being used in the Tahoe Basin. Feedback was also positive for learning more about the modular aspect of the treatment train concept. Interest in learning more about Parjana's® Energy Passive Groundwater Recharge Product (EGRP®) groundwater injection system that promotes lateral infiltration was also expressed, but this technology was not included in the original presentation. One stakeholder had considered the implementation of the Parjana system but found that it could be difficult to get a permit because of the underground injection element of this system.

There was concern about biochar being prohibitively expensive due to limited local suppliers, but Washoe County has a byproduct from a mill that could potentially serve as a collaborative partner to reduce costs. Raingardens have already been used in the Tahoe Basin with some success. They require minimal maintenance and can infiltrate significant volumes of stormwater with a small footprint. Concerns were voiced that it can be hard to get vegetation to grow and stay healthy in cold, dry environments. It may be difficult to sustain healthy vegetation in raingardens that get too much water as well. Therefore, it might not be sensible to depend heavily on vegetation to remove pollutants. One stakeholder used RSC with bioengineered media on a project implemented six years ago, but no effectiveness monitoring was conducted so there is no data on how well it performed. This installation could potentially be targeted for a future performance monitoring study.

Details of BMPs that stakeholders were most interested in learning more about were BMPs that work best for snow storage, BMPs for areas with high groundwater, BMPs best suited to specific land uses, and how much more efficient innovative or retrofitted BMPs would be over current BMPs. Costs were also of interest, including cost for complete installation, cost to maintain a particular BMP to original condition, and cost per acre treated. One stakeholder stated that lots of research has been done on cold weather issues internationally, including issues specific to construction and maintenance, however, guidance is still limited. A cold weather issue experienced by one stakeholder is that electrical pump systems are not able to withstand freezing temperatures.

Maintenance is an issue for every BMP for every jurisdiction. Difficulty maintaining BMPs often results in removing and replacing the BMP instead of maintaining it, but this is not as cost effective as it could be. To date, the best preventative prescription is to have sedimentation of coarse material as a first step to keep systems from clogging. Sizing, number, and location of BMP access ports to facilitate visual inspections, flushing, and vactoring is an ongoing challenge. Stakeholders were interested in the life expectancy of BMPs when well maintained, maintained annually, and not maintained.

Phase II Scope of Work

Stakeholder interest and professional opinion dictate that several BMP options warrant further research. A phase II scope of work should include investigation into operations and maintenance requirements, life-cycle costs, how effectiveness may change over time, and adaptability to cold climates for all or a subset of the BMPs discussed in this report. A phase II scope of work should also include this same investigation into Parjana Systems, including navigating challenges that may be encountered with permitting a groundwater injection system. Proprietary filters that provide better treatment than the ones currently implemented are likewise worth additional investigation. More information on these BMP options could help stormwater managers better implement systems to deal with climate change challenges like intense storm events and growing pressures to find better ways to remove pollutants to continue working towards TMDL goals.

Options Presented to SWQIC

The following sections describe the ten BMP options that were presented to SWQIC. It is important to note that while some of the options below are described as proprietary, non-proprietary designs that provide the same functions are often possible. It is also important to note that some of these systems can be designed as hybrids of two or more components and classification of the various BMPs is not always well delineated.

Raingardens/Bioinfiltration Systems

A raingarden, also known as a bioinfiltration system or bioretention cell, generally consists of several vertical layers (Figure A-1). The vegetation layer is a graded area with plants. It serves to pond incoming stormwater and settle out suspended sediment and slow erosion. The filter media layer is generally clean sand and compost, but other amendments, such as mulch, peat, or coconut coir are sometimes added to retain moisture and support the root zone of the plants and allow for plant uptake of nutrients and pollutants (Deng 2020). Compost has been shown to leach phosphorus, so these other amendments are preferable if there are underdrains. The media layer also affects infiltration and pollutant removal depending on the composition of the media. The grain size distribution of the components should be selected to filter solids but have a high enough saturated hydraulic conductivity to manage inflows. The transitional layer protects the drainage layer from clogging. The drainage layer is the storage zone, storing treated effluent and allowing it to infiltrate into native soil to recharge groundwater or be captured and reused if an underdrain is present (Tirpak et al 2021).

Targeted Pollutants

Sediment	√
Nitrogen	√
Phosphorus	√
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

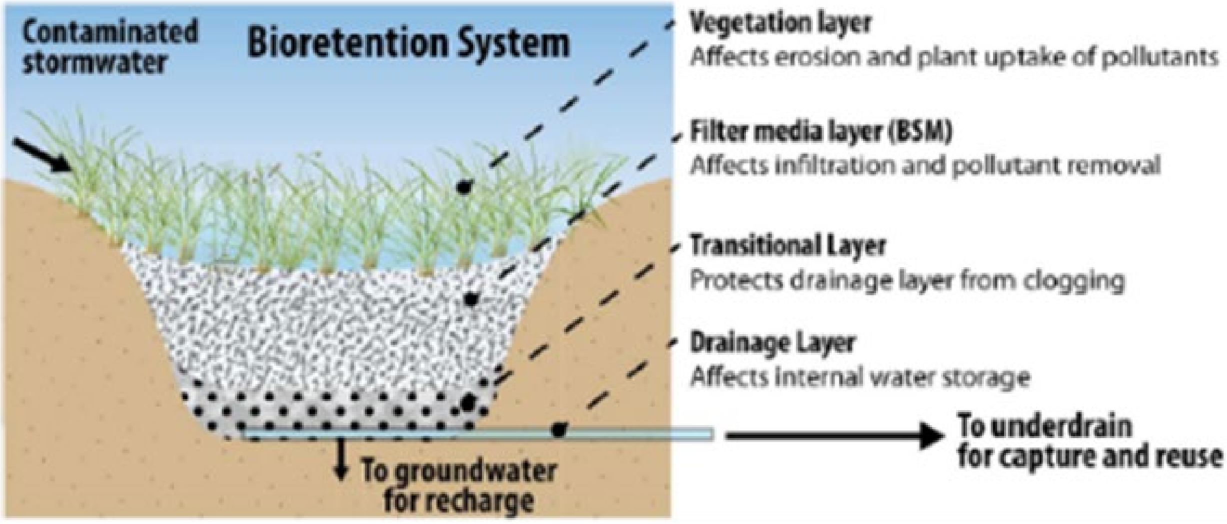


Figure A-1: Schematic of a raingarden, bioinfiltration system, or bioretention system. Tirpak et al 2021.

Typical Bioretention Soil Media (BSM) used in the filter media layer consists of clean sand mixed with topsoil or compost at a specified ratio to achieve a desired hydraulic conductivity. The sand fraction in traditional BSM permits rapid infiltration of stormwater, while silt, clay and an organic amendment (e.g., topsoil or compost) increase water retention for plant uptake and are critical to contaminant removal. The BSM can also be blended to target specific contaminants using different physical and biogeochemical processes (Mohanty et al 2018). For instance, to target phosphate, a positively charged ion, recommendations are to use organic amendments with negatively charged surface groups to most effectively adsorb phosphate. Alternatively, to target nitrate and nitrite, designs should increase denitrification by creating an anoxic (or submerged) zone or by adding some form of organic carbon, such as wood chips, that best serves as an electron donor to reduce nitrate/nitrite to nitrous oxide or gaseous nitrogen. Internal water storage to promote anoxia below the media bed can be created by using a liner and raised underdrain (or upturned elbow or riser attached to the outlet of the underdrain).

As with most BMPs, the performance of a BSM would ultimately depend on land use, climate, precipitation patterns, hydraulic loading ratio (i.e., ratio of contributing catchment area to bioretention surface area), and contaminant concentrations. Maintenance could consist of removing vegetation and accumulated sediment and/or replacing the filter media layer. An added benefit to rain gardens is that they can potentially improve the aesthetics of a site. This BMP would potentially be an improvement on a dry basin, (see excerpt of Table 2.6, NHC 2017).

POST (Phosphorus Optimized Stormwater Treatment)

Targeted Pollutants

Sediment	√
Nitrogen	
Phosphorus	√
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

Phosphorus Optimized Stormwater Treatment (POST) systems (Figure A-2) have been certified by the Washington State Technology Assessment Protocol – Ecology (TAPE) program, designed to evaluate and certify new and innovative stormwater treatment technologies. POST systems are biofiltration systems that use several vertical layers to optimize treatment of stormwater for phosphorus removal. The first layer generally consists of a mulch prefilter that removes gross solids, debris, oils, and larger particulates. This layer also helps retain moisture to support plant growth, reduces erosion of the media bed beneath during high flow events, and reduces weed growth. The next layer is a primary media bed optimized for the physical filtration of total suspended solids (TSS), and dissolved pollutant sorption. An example of the engineered media in this layer would be an 18-inch deep layer consisting of 70% coarse, clean sand, 20% coconut coir, and 10% high-carbon wood ash. The third layer is a secondary or polishing media bed specifically formulated for dissolved phosphorus and metals removal. An example of the engineered media in this layer would be a 12 inch deep layer consisting of 80% coarse, clean sand, 17% activated alumina, and 3% iron filings. Stormwater is discharged from the POST system via underdrains. Maintenance could include cleaning underdrains, removing accumulated sediment and trash, and replacing vertical filtration media. This BMP would potentially be an improvement on a bed filter, (see excerpt of Table 2.6, NHC 2017).

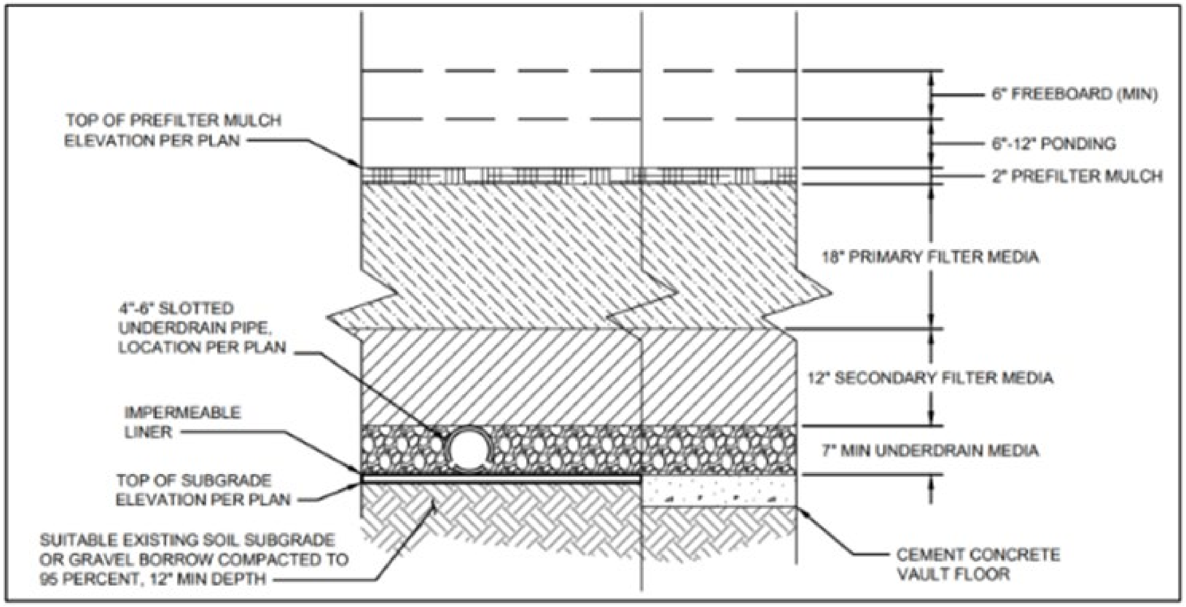


Figure A-2: Schematic of a phosphorus optimized stormwater treatment system.

Biofiltration Systems (proprietary version)

Targeted Pollutants

Sediment	√
Nitrogen	
Phosphorus	
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

Contech's Filterra and StormTree's Tree Filter have been certified by the Washington State Technology Assessment Protocol – Ecology (TAPE) program, which is designed to evaluate and certify new and innovative stormwater treatment technologies (Figure A-3). These biofilters work much like a raingarden but are equipped with underdrains (and thus do not infiltrate) and have been optimized for treatment of high volumes or flows and maximum pollutant removal. Due to their small size, they can be used in highly urbanized areas where space constraints are an issue. These systems are very adaptable and can be used alone or in combination with other BMPs. The systems support healthy trees and provide stormwater volume reduction and pollutant removal. Some concrete boxes are open, allowing tree roots to grow unrestrictedly. Stormwater enters through a curb-cut, flows through a filter media mixture that captures and immobilizes pollutants that can then be decomposed, volatilized and/or incorporated into the biomass of the system's micro/macro fauna and flora. Treated stormwater then flows into an underdrain at the bottom of the system and is discharged. Using biochar in biofilters can improve the removal of important stormwater pollutants. (Boehm et al 2020). Maintenance could consist of cleaning concrete enclosure and underdrain, replacing vegetation and soil media, and removing accumulated pollutants and trash. This BMP would potentially be an improvement on a bed filter, (see excerpt of Table 2.6, NHC 2017).

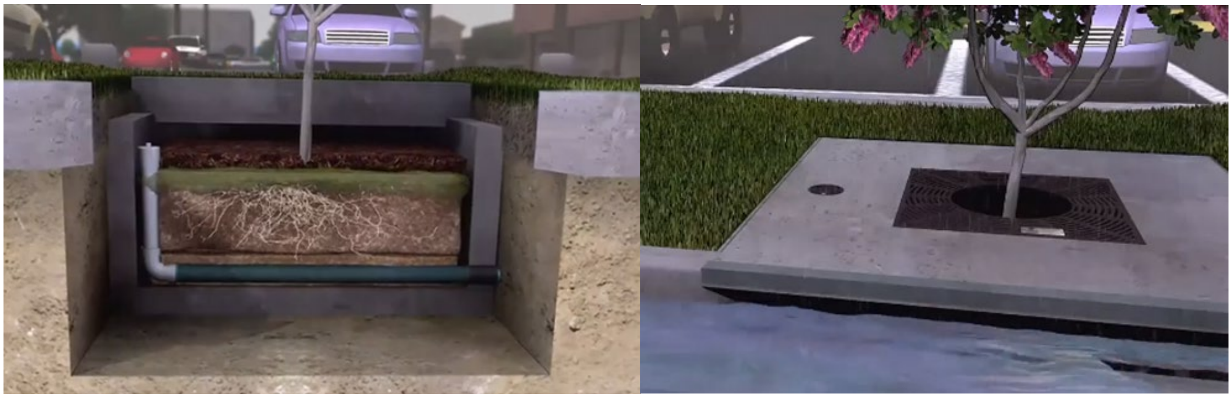


Figure A-3: Schematic of proprietary biofiltration systems. Washington State TAPE https://ecology.wa.gov/.

Regenerative Stormwater Conveyance

Targeted Pollutants

Sediment	√
Nitrogen	√
Phosphorus	√
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

Regenerative Stormwater Conveyance (RSC) is an innovative approach to provide stormwater treatment, infiltration, and conveyance within one system (Figure A-4). They are an open channel, sand-filtering system comprised of a series of shallow aquatic pools, riffle weirs, native vegetation and underlying media beds (Thompson et al 2020). Organic matter (mulch) can be added to the sand to encourage microbial activity to increase denitrification (Duan et al 2019). Biochar could also be added to increase removal of targeted pollutants.

Surface runoff entering an RSC is conveyed as nonerosive surface flow and subsurface seep through the media, before exiting the system as surface flow, seep out, exfiltration into parent soil, or evapotranspiration. The conversion of surface runoff to seep out can be beneficial for stormwater mitigation, releasing filtered water at slower rates than conventional conveyance channels, similar to undeveloped watersheds. Hydrologic and water quality benefits are maximized where groundwater intrusion is minimal and conversion to subsurface flow is high. Increased contact with soil filter media encourages several mechanisms of pollutant removal including microbial activity and sorption. RSC has the potential to serve as a treatment train, where each cell of the RSC is designed to target a particular pollutant through selection of the proper filter media and different levels of saturation, Maintenance may include replacing filtration media, removing accumulated sediment and trash, and rearmoring channels and pools (Koryto et al 2018). This BMP would potentially be an improvement on a bed filter or dry basin, (see excerpt of Table 2.6, NHC 2017).

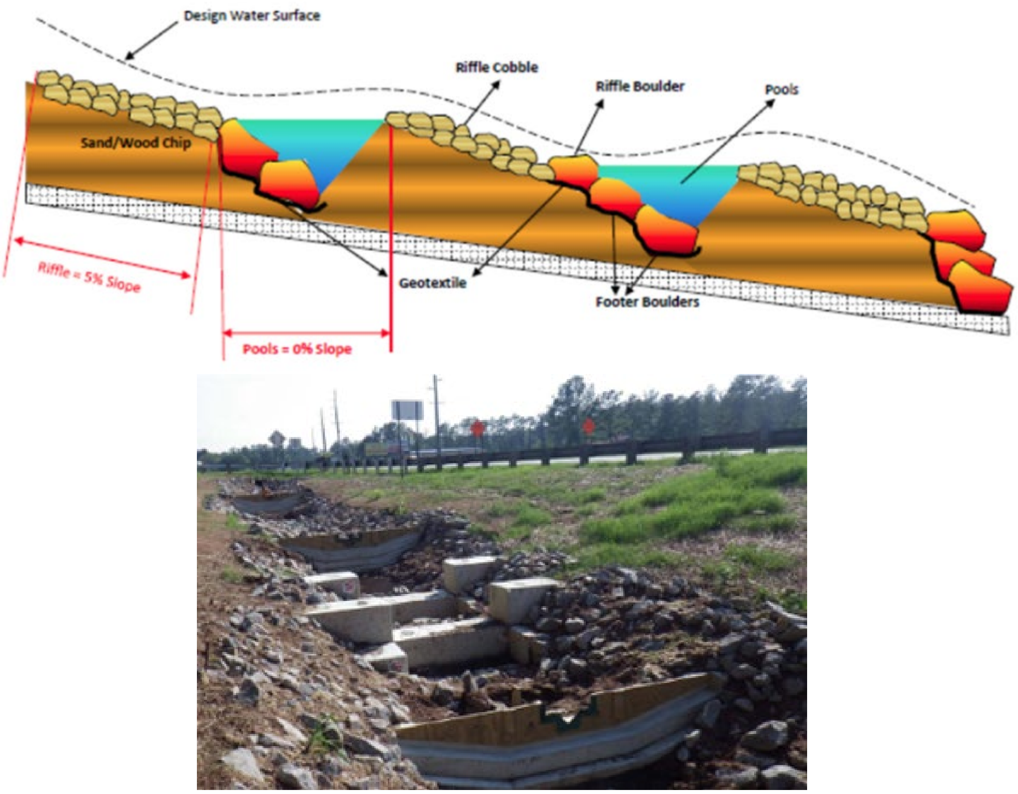


Figure A-4: Schematic of regenerative stormwater conveyance. Cizek et al 2017.

Biochar Amendments

Targeted Pollutants

Sediment	√
Nitrogen	√
Phosphorus	√
Trash	
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

An emerging technology is to create biochar from organic waste products to enhance the organic compound's ability to remove pollutants (Figure A-5, Biswal et al 2022). Biochar is generally made by pyrolysis of organic waste material. Commonly used waste materials include sawmill waste, agricultural crop waste, wood scraps, and animal or human sludge. Pyrolysis entails heating organic waste to temperatures high enough to deconstruct the strong bonds in the organic matter (generally above 500°C) resulting in larger pores, greater surface area, and more negatively charged surface functional groups. These characteristics offer an increased water retention capacity to support plant growth during prolonged dry periods and a high surface area for many mechanisms of chemical bonding and adsorption (including electrostatic interactions, hydrogen bonding, pore filling, ion exchange, and surface precipitation for removal of nitrogen, phosphorous, heavy metals, organic matter, and bacteria). The surface also supports biofilm growth of bacterial and fungal communities to enhance biodegradation and denitrification. Biochar-amended biofiltration systems efficiently remove diverse pollutants such as total nitrogen

(32 – 61%), total phosphorus: (45 – 94%), heavy metals (27 – 100%), organics (54 – 100%) and microbial pollutants (log10 removal: 0.78 – 4.23) from urban runoff (Biswal et al 2022). The variation of biofiltration performance is due to differences in biochar characteristics, the abundance of dissolved organic matter and/or stormwater chemistry. This BMP does not have an analogous traditional BMP but is designed to enhance pollutant removal and could be used in dry basins or bed filters (see excerpt of Table 2.6, NHC 2017).

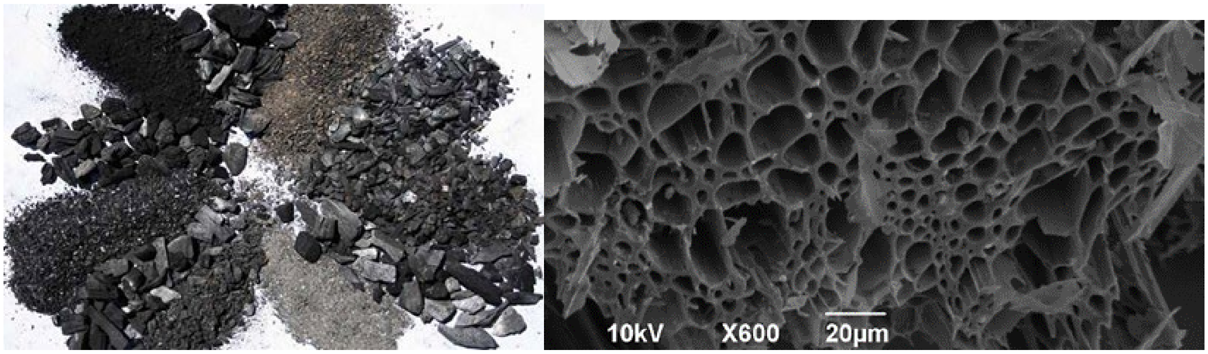


Figure A-5: Images of biochar. Biswal et al 2022

Modular Wetlands (proprietary version)

Targeted Pollutants

Sediment	√
Nitrogen	√
Phosphorus	√
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

Modular wetlands, also known as pocket wetlands, have been certified by the Washington State Technology Assessment Protocol – Ecology (TAPE) program, which is designed to evaluate and certify new and innovative stormwater treatment technologies (Figure A-6). They utilize three chambers for treatment and stormwater flows through the system horizontally rather than vertically. Two of the chambers (the pre-treatment chamber and the discharge chamber) are subsurface and accessible for inspection and maintenance through manholes. The third chamber (the biofiltration chamber in the middle) is densely populated with biofiltration media and vegetation and is accessible from ground level. The pre-treatment chamber captures trash, debris, and coarse sediment, while the biofiltration chamber aids in the capture, retention, and transformation of several pollutants. It is important to maintain a saturated anoxic zone in order for this system to operate like a wetland. This requires a gravel layer or something similar at the bottom of the middle chamber. However, maintaining a saturated zone and ensuring a residence time in that zone sufficient for the chemical transformation of pollutants can be difficult. In the absence of this feature, these modular wetlands can behave more like a modular biofiltration system. They can also be used with different plants that are suited to the alpine environment, targeting different pollutants and the smaller FSP fraction.

This system can be used in highly urbanized areas with space constraints. Additionally, plants can be harvested more regularly than trees to remove pollutants from the system. Maintenance could include harvesting vegetation, cleaning the pre-treatment and discharge chambers of accumulated sediment and trash, and replacing the biofiltration media. This BMP would potentially be an improvement on a wet basin (see excerpt of Table 2.6, NHC 2017).

Figure A-6: Schematic of modular wetlands. Washington State TAPE https://ecology.wa.gov/.

Subsurface Gravel Wetlands

Targeted Pollutants

Sediment	√
Nitrogen	√
Phosphorus	√
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	√

The subsurface gravel wetland is designed as an underground flow-through treatment system, preceded by a sedimentation forebay, where the stormwater is temporarily retained in the basin above the wetland soil, but ultimately travels horizontally through a saturated gravel substrate with a microbe-rich environment (Figure A-7, Houle et al 2020). The primary pathway for stormwater to enter the gravel beds below is through vertical risers (hydraulic inlets) in each cell and then through horizontal subdrains that distribute the flow across the width of the gravel. The flow then passes through the gravel substrate to subdrains that deliver it to the next cell and ultimately through to the outflow. A smaller amount of water may penetrate through the wetland soil to get to the gravel below. However, by design the wetland soil is not very permeable, which helps maintain low dissolved oxygen (DO) levels in the gravel below. This anaerobic condition in the subsurface gravel layer is created by maintaining saturation and encourages microbial transformation of nitrate to nitrogen gas. The removal processes involved in this type of system include sedimentation, filtration, physical and chemical sorption, microbially mediated transformations, vegetative uptake, evapotranspiration, and surface storage. Pollutant removal efficiencies are high for many types of pollutants including sediment, heavy metals, hydrocarbons, and total phosphorus, but it is especially well suited for nitrogen removal. Maintenance may include removing accumulated sediment and trash, replacing or washing subsurface gravel, and cleaning riser pipes and subdrains. This BMP would potentially be an improvement on a wet basin (see excerpt of Table 2.6, NHC 2017).

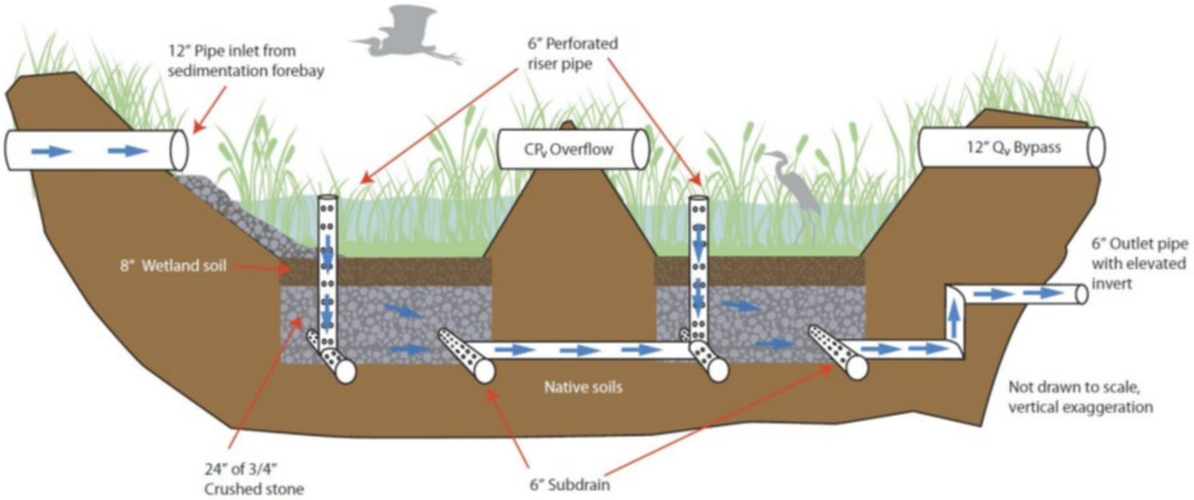


Figure A-7: Schematic of subsurface gravel wetlands. Houle et al 2020.

Floating Treatment Wetlands

Floating treatment wetlands utilize natural substrates, plants, and microbes for enhanced decontamination of stormwater stored in wet basins (Figure A-8, Sharma et al 2021). These passive phyto-systems provide the benefits of wetland plants without needing to ensure that the wet basin can support wetland vegetation in and around the wetted perimeter. Macrophytes grow on a floating raft with their roots in permanent contact with the water to remove pollutants via several physical and biological processes. The roots of the wetland plants become covered with biofilms that can remove nutrients, fine sediment, and heavy metals. Pollutant removal efficiency is dependent on many factors including floating wetland configuration, substrate or soil media, vegetation, ambient temperature and seasonal changes, oxygen levels and hydraulic retention time (Hartshorn et al 2016). Plants are harvested regularly to permanently remove pollutants from the system. Because the floating treatment wetland can move with fluctuating water levels, it can treat highly variable flows. These systems offer a low burden, environmentally friendly, and operationally flexible method to enhance pollutant removal. They also improve the aesthetic view and provide wildlife habitat. Maintenance considerations are harvesting and replanting vegetation in new or replenished soil. This BMP would potentially be an improvement on a wet basin (see excerpt of Table 2.6, NHC 2017).

Targeted Pollutants

Sediment	
Nitrogen	√
Phosphorus	√
Trash	
Metals	
Bacteria	
Oil and Grease	
Organics	

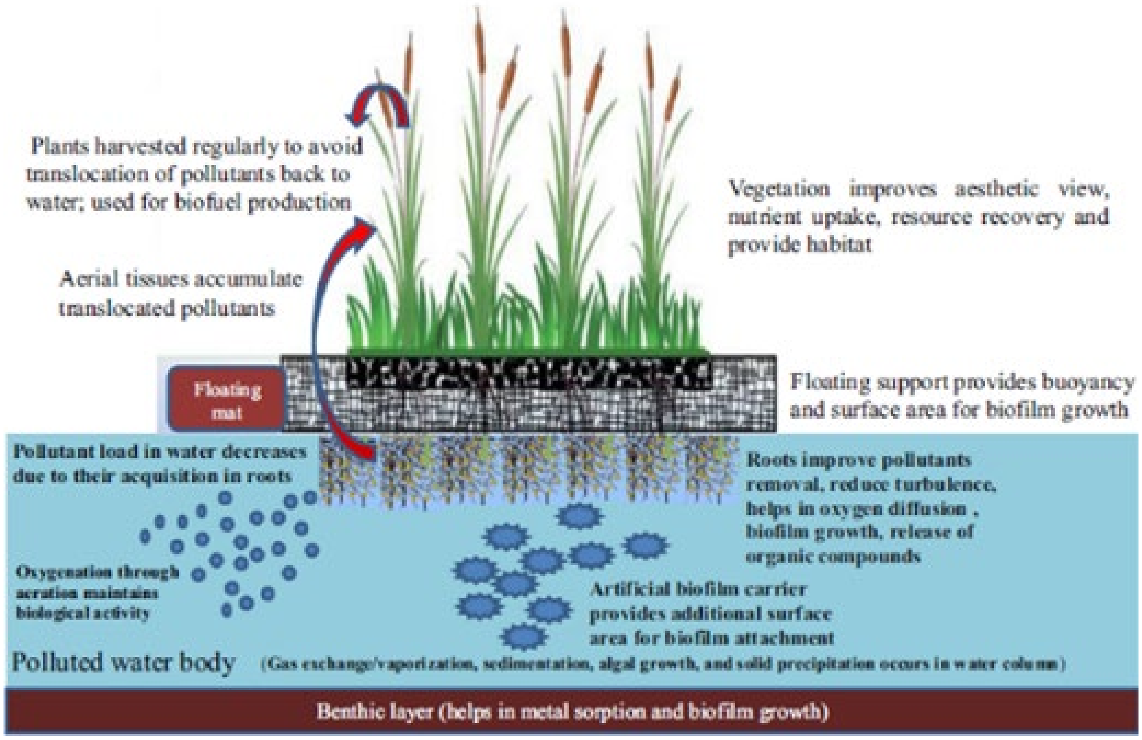


Figure A-8: Schematic of floating treatment wetland. Sharma et al 2021.

Floating Media Bed Reactors

Targeted Pollutants

Sediment	
Nitrogen	√
Phosphorus	√
Trash	
Metals	√
Bacteria	
Oil and Grease	√
Organics	√

Some BMPs, like constructed wetlands, wet ponds, and retention ponds help reduce the impact of flooding, but may not do enough with regards to nutrient removal to meet water quality goals (Figure A-9, Chang et al 2016). A floating media bed reactor (FMBR) can be used in wet detention ponds to enhance the removal of total nitrogen and total phosphorus. The FMBR is filled with an engineered mixture of adsorption media and uses a pump to continually pump water from the pond, through the media, and out the effluent pipe. Only small pumps are needed, so they can be solar powered. The media aids in the physiochemical sorption and precipitation of orthophosphates and in the biological transformation of ammonia, nitrates, and nitrites. Maintenance includes removing and replacing sorption media, ensuring that the battery is sufficiently charged by the solar panel and that the pump is functioning correctly. This BMP would potentially be an improvement on a wet basin (see excerpt of Table 2.6, NHC 2017).

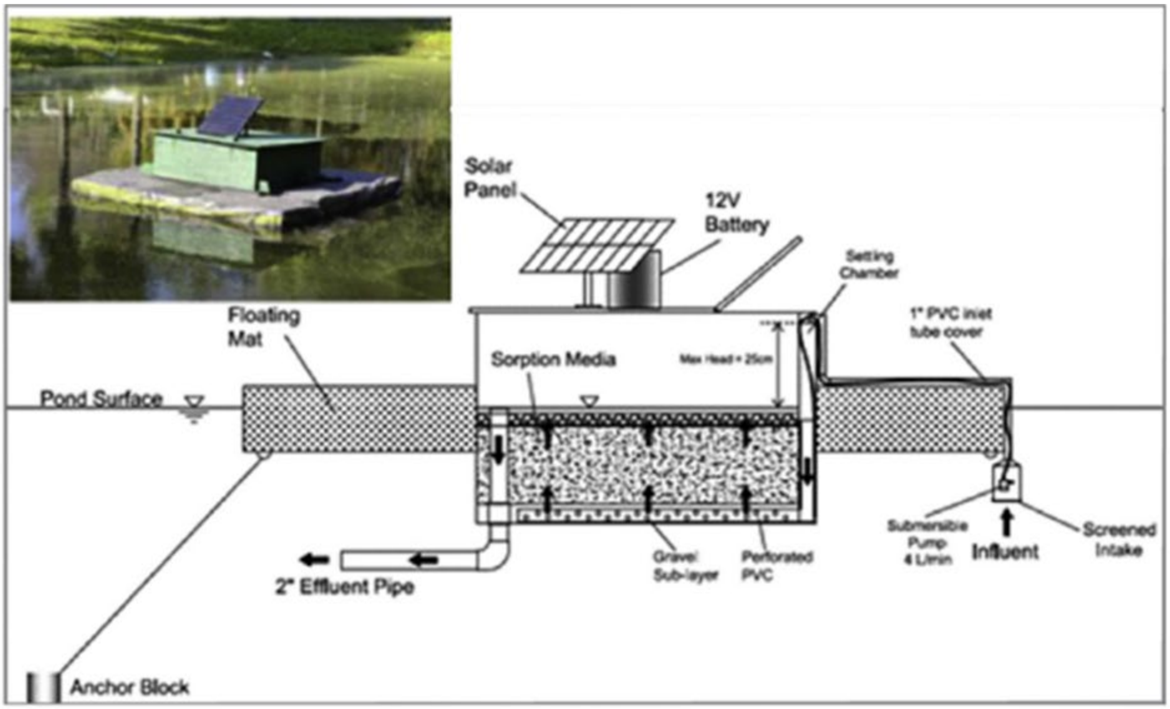


Figure A-9: Schematic of floating media bed reactor. Chang et al 2016.

Filters for Fine Particles (proprietary version)

New filter systems may be more effective at removing very fine particulates and have been certified by the Washington State Technology Assessment Protocol – Energy (TAPE) program, designed to evaluate and certify new and innovative stormwater treatment technologies (Figure A-10). In this example, water flows upward through filter media ribbons made of polyethylene felt designed to capture very fine particulates (generally in the silt/clay classification of less than 63 microns). Oil and floatables rise to the surface while coarser sediment settles in the sump. During peak flows, excess water can discharge through a bypass hood which also prevents the escape of oil and trash. Because of the difficulty in removing the extremely fine sediment (1-5 microns) that is of concern in the Tahoe Basin, stormwater managers could work with manufacturers to target the level of treatment needed. Frequent maintenance to clean or replace filter ribbons to maintain FSP removal efficiencies would likely be required. This BMP would potentially be an improvement on a cartridge filter (see excerpt of Table 2.6, NHC 2017).

Targeted Pollutants

Sediment	√
Nitrogen	
Phosphorus	√
Trash	√
Metals	√
Bacteria	√
Oil and Grease	√
Organics	

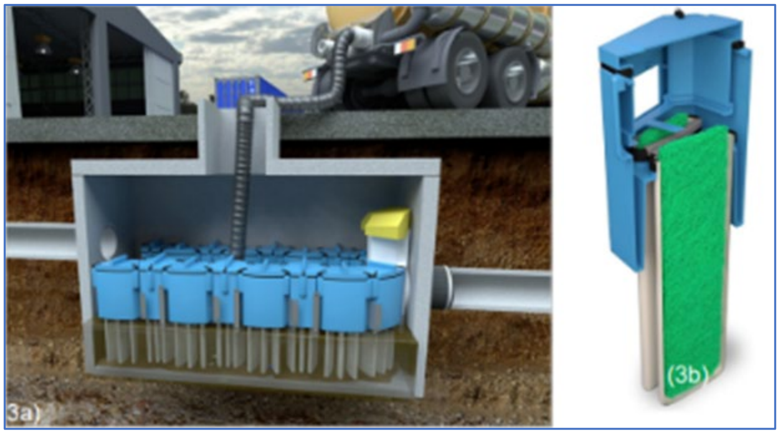
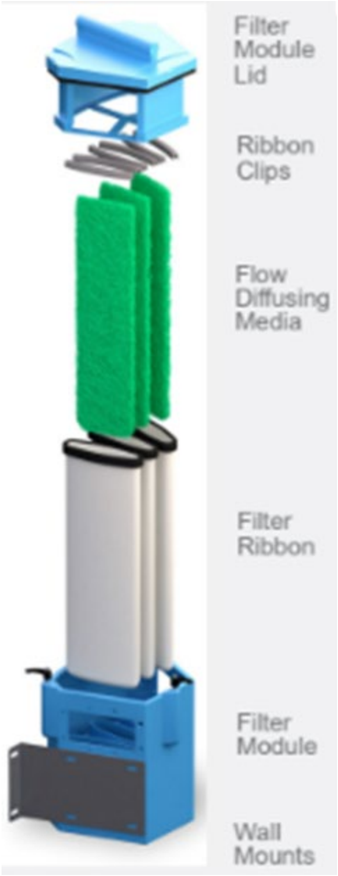


Figure A-10: Schematic of a filter for very fine particles. Washington State TAPE https://ecology.wa.gov/.



Treatment Trains

The BMPs above, as well as existing practices, can be used to design treatment trains that target multiple pollutants, improve maintainability, and are more resilient to clogging failure and changing inflow conditions. As discussed, bioinfiltration, biofiltration, and modular wetland systems can be designed with custom media, liners, underdrains, and flow controls to create aerobic and anoxic zones to target different pollutants:

- Aerobic Zone - Remove sediment, immobilize phosphorus, adsorb dissolved metals and organics, and promote nitrification.
- Anoxic Zone - Assimilate biological oxygen demand (BOD) and promote denitrification.

Aerobic zones can be created by keeping the media well-drained. Slotted underdrains (also called well screens) can be very effective at maintaining filtration and are resilient to clogging. These underdrains can also serve as a backup resiliency measure if the underlying soils become clogged. Anoxic zones can be created in the lower portions of the media bed and gravel underdrain layer (if present). Internal water storage with the presence of a carbon source such as wood chips can promote anoxia and can be created by using raised underdrains, upturned outlets, or orifice risers.

One conceptual design may include a cascading system of treatment cells as shown in Figure A-11, with bioinfiltration as the final step if soils are amenable to infiltration:

Figure A-11: Schematic of a treatment train example.

Proprietary and non-proprietary BMPs could be used to create this treatment train. Forebays, detention cells, hydrodynamic separators, and other vaults could be used for pre-settling and sedimentation. Vegetated media filtration systems (basin, vault, or hardscape-contained configurations) with bottom underdrains could be used for aerobic biofiltration. Vegetated media filtration systems with internal water storage, modular wetlands, or subsurface flow wetlands could be used as the polishing, anoxic filtration step. Controlled surface discharge and/or bioinfiltration could be the final step. This treatment train design concept could be implemented as a series of discrete treatment cells or within the step-pools and hyporheic zones of a regenerative stormwater conveyance.

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Appendix B. Precipitation Data Analysis

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The team thoroughly investigated several options for extending the PLRM (Pollutant Load Reduction Model) meteorological database to include precipitation data past the current 2006 end date.

The first choice was to utilize the SNOTEL hourly gage data directly. Unfortunately, after reviewing the data and discussing with Jeff Anderson of NRCS, SNOTEL monitoring equipment and data QA are configured to be accurate for daily precipitation accumulation, but the hourly records contain significant artifacts caused by snow plugging the gage and then getting recorded as a large pulse when melted. Figure B-1 illustrates the issue.

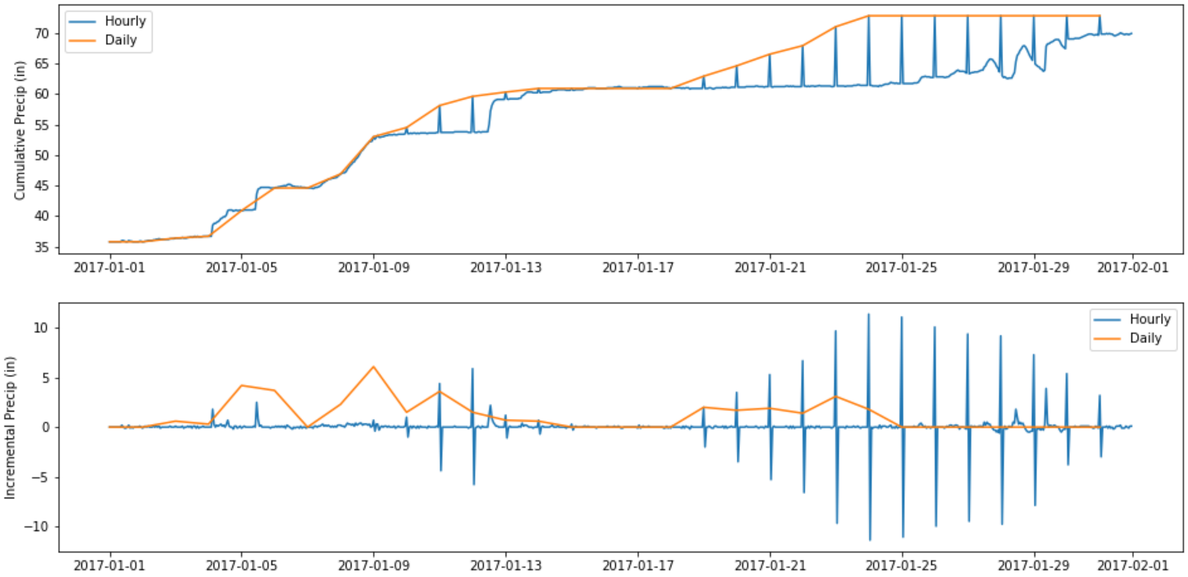


Figure B-1: Plot of SNOTEL data.

The second choice was to leverage recent efforts by the Western Regional Climate Center (WRCC) to build data processing procedures to clean up the hourly SNOTEL records. In discussing this with them, we found their methods are promising but labor intensive. They utilize interns and graduate students to first make manual corrections and then process the partially cleaned data using a machine learning algorithm to perform further corrections. The WRCC team working on this effort could be valuable partners in a future separately funded endeavor to extend the PLRM precipitation dataset (or revisit and replace the dataset entirely). However, their team lacked the bandwidth to support this effort.

As a third option, the project team considered the possibility of replicating the prior work performed by Tetra Tech to build the precipitation timeseries that are currently embedded in the PLRM tool for the period 1988-2006. However, the methodology is not completely documented, and it is not clear how they handled the issue illustrated above. Even if Tetra Tech's method was fully documented and appropriately addressed the hourly data issues, the project team lacked the budgetary resources to process, document, and quality control the processed data. Therefore, the project team instead leveraged the existing precipitation records embedded in PLRM to serve as the reference data for the upsampling methodology.

The algorithm for estimating the hourly precipitation for daily GCM data requires two input datasets. First is the daily GCM (GCM-Daily) precipitation data for the period of interest, which for this assessment are the future years 2030-2060. The second input into the algorithm is the hourly precipitation reference dataset. The reference dataset for this assessment is the data currently in use in the Lake Tahoe PLRM model, which begin in 1988 and end in 2006, providing 18 years of continuous hourly precipitation data (Ref-Hourly). The Ref-Hourly dataset is resampled to produce a record of daily total precipitation volumes (Ref-Daily) for use by the algorithm.

In general terms, for a given day of the GCM-Daily dataset the methodology identifies a best-matching day from the Ref-Daily dataset and uses that day from the Ref-Hourly to assemble the output GCM-Hourly dataset. This process is shown in Figure B-2, and its steps are discussed in further detail below.

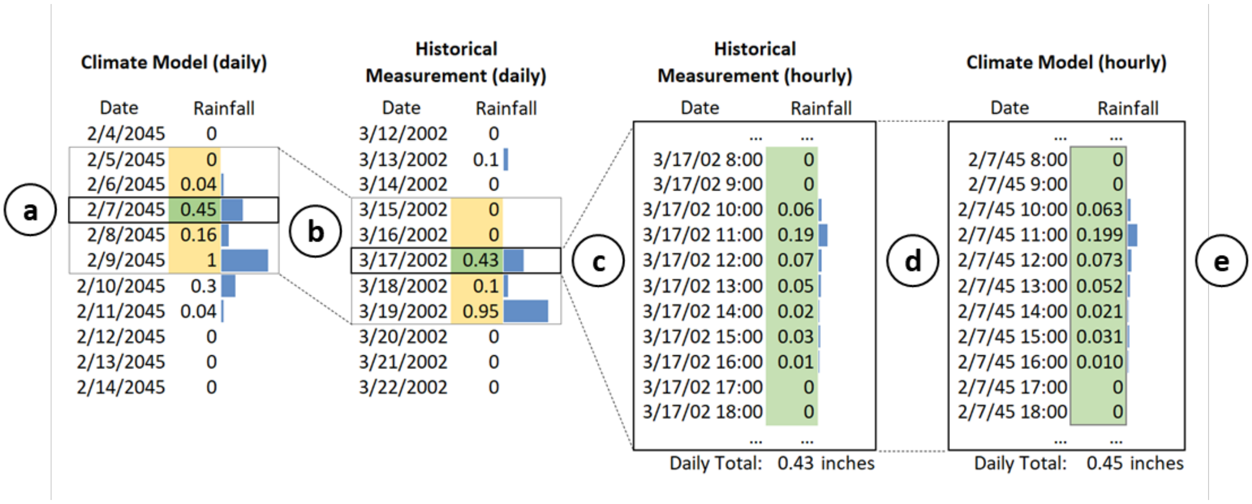


Figure B-2: The precipitation upsampling algorithm.

Following the minimal data preparation described above to generate the Ref-Daily dataset, the steps of the algorithm are as follows for each daily observation in the GCM-Daily dataset:

a. For the current day under analysis for the GCM-Daily dataset (shown in green in Figure B-2) the algorithm considers a rolling 5-day window of antecedent precipitation conditions and consequent precipitation conditions centered on the current day. These 5 ordered values are used as the bases for determining the best matching day in the Ref-Daily dataset.
b. The current days 5-day precipitation sequence is compared to all the 5-day sequences in the Ref-Daily dataset to find the best match. Each comparison finds the element-wise weighted log-normal distance between the current day in the GCM-Daily sequence and the potential matching day (also shown above in green) according to the following formulas:

$$lognormal\ distance = [0.25 \quad 0.5 \quad 1 \quad 0.5 \quad 0.25] \cdot \begin{bmatrix} \ln\left(\frac{GCMprecip_{-2} + 1}{REFprecip_{-2} + 1}\right) \\ \ln\left(\frac{GCMprecip_{-1} + 1}{REFprecip_{-1} + 1}\right) \\ \ln\left(\frac{GCMprecip + 1}{REFprecip + 1}\right) \\ \ln\left(\frac{GCMprecip_{+1} + 1}{REFprecip_{+1} + 1}\right) \\ \ln\left(\frac{GCMprecip_{+2} + 1}{REFprecip_{+2} + 1}\right) \end{bmatrix}$$

Where the subscript on precipitation indicates the lag/lead of the value in the sequence.

Some sequences of 5-day precipitation are quite common, and a large number of acceptable matches can be found by this method. It is therefore useful to include a weight parameter to prioritize matches that are similar in season to the current day being matched as a tie breaking measure. The distance between the matched date pairs is added to the distance function as follows:

$$distance = lognormal\ distance + W * \ln\left(\frac{1}{1 + \frac{N}{183}}\right)$$

Where:

N = the number of calendar days between the current day in the GCM-Daily dataset and the potential matching day in the Ref-Daily dataset, irrespective of year.

W = the weight factor for the effect of date distance.

This distance function is computed for every day in the Ref-Daily dataset to determine the day with minimum distance from the current day in the GCM-Daily dataset. If multiple matches are found to be equally suitable because they have the same, or nearly the same distance from the current day in the GCM-Daily dataset the algorithm will choose one with a uniform random choice function.

c. Once the matching day is selected from the Ref-Daily dataset, the Ref-Hourly dataset from that day is retrieved.
d. The matching sequence of hourly records is re-scaled so that the total daily volume exactly matches the current day volume from the GCM-Daily records.
e. These records are then stored in a new dataset, the GCM-Hourly dataset, for the current day. This process is then repeated for the next day of the GCM-Daily dataset.

The above process allows for the resulting GCM-Hourly dataset to have identical daily precipitation statistics as the original GCM model while having more natural hourly statistics.

Appendix C. GCM Comparisons

Appendix C. GCM Comparisons

The precipitation and temperature timeseries for the four GCMs (CanESM2, CCSM4, CNRM-CM5, and MIROC5) have the spatial resolution of the LOCA grid cells shown in the figure below. Three LOCA grid cells were selected corresponding to the locations of the three project sites. The numbers given to the grid cells in the figure were assigned to refer to the specific grid cells for the purposes of this study only. The LOCA grid cells were selected by geospatial overlay with the project site catchment and BMP location. If multiple candidate grid cells intersected the project site catchment and/or BMP location, the grid cell closest to the lake shore was selected to minimize the effect of elevation gain on precipitation due to the relatively coarse resolution of the LOCA grid (Figure C-1).

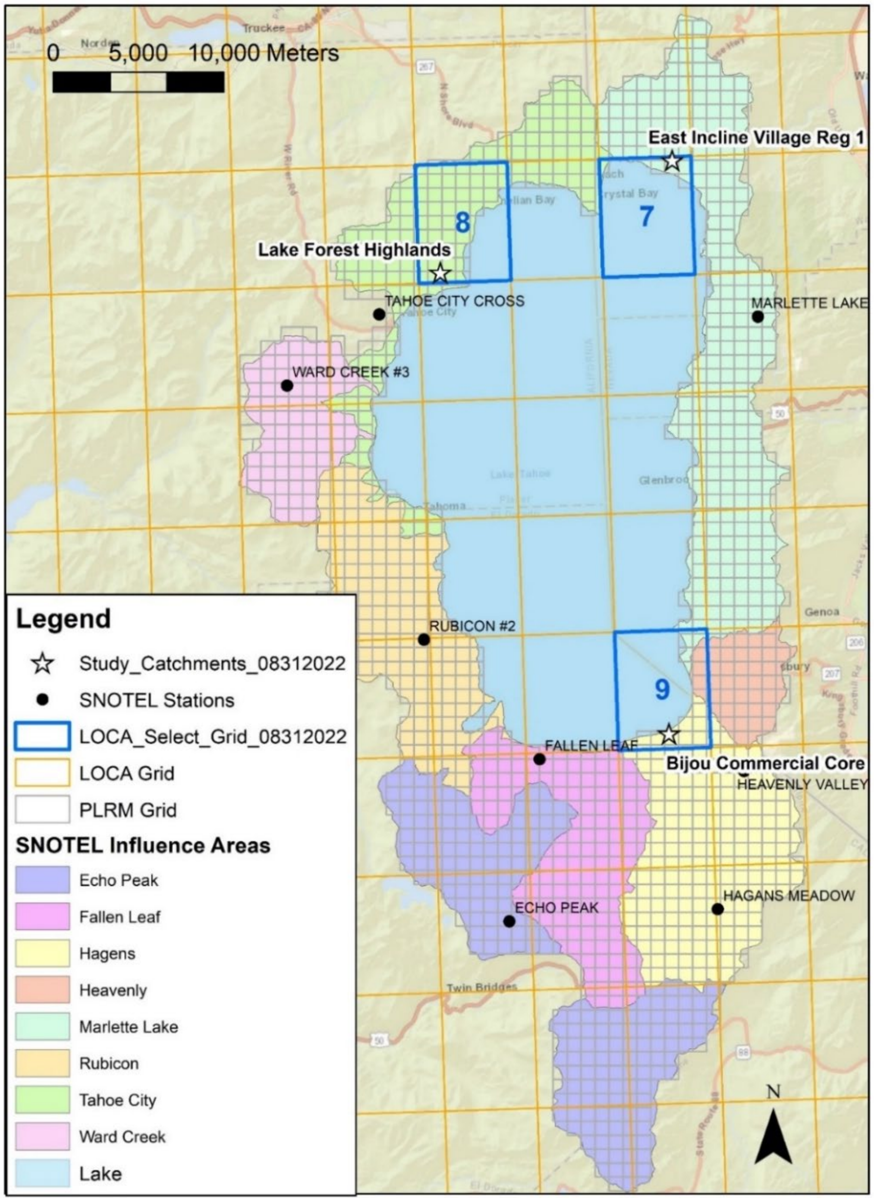
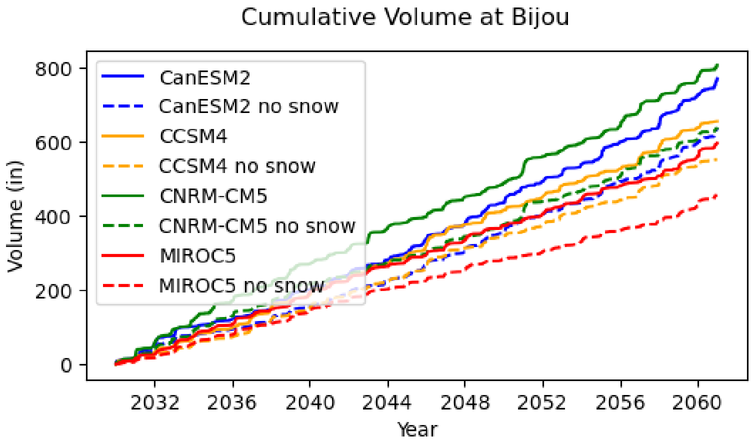
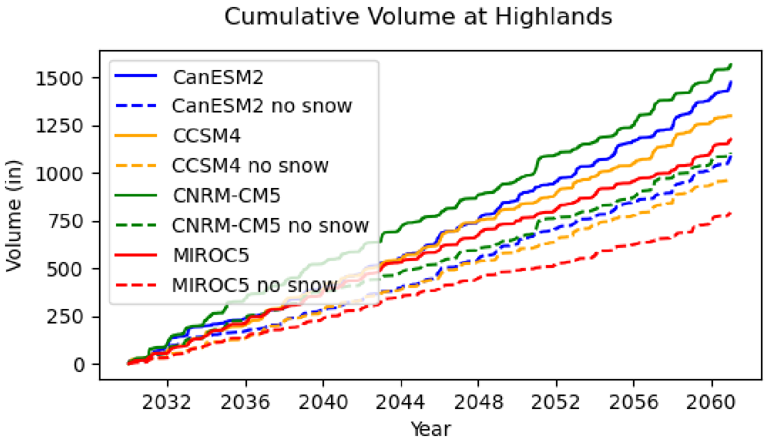


Figure C-1: LOCA grid cells.

The daily precipitation and temperature timeseries for the four GCMs were then extracted for each of the three grid cells. These records were analyzed and compared to understand variability in precipitation volume and intensity across GCMs and locations. Cumulative sum plots for both total precipitation (including snow) and total rainfall (not including snow, defined as precipitation that occurs when the air temperature is greater than 32 degrees F) are shown in Figure C-2.





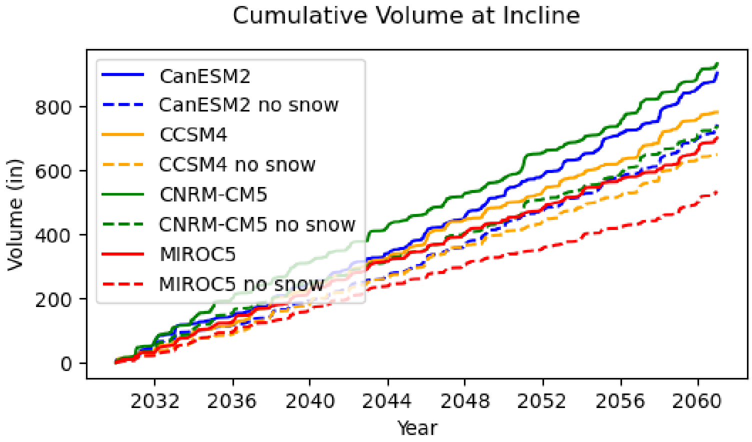


Figure C-2: Cumulative sum plots for total precipitation and total rainfall.

Mean Annual Total Precipitation (in):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	20.8	18.2	20.2	18.6	20.1
Incline	22.8	21.5	23.3	22.1	22.7
Highlands	34.8	36.0	39.4	37.0	37.5

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	24.4	21.4	26.1	18.9
Incline	28.8	25.5	30.1	22.3
Highlands	47.0	42.6	50.8	37.4

Mean annual total precipitation is defined as the sum of the total precipitation (including snow) during the time period divided by the number of years in the time period.

Mean Annual Rainfall (in):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	11.5	12.2	14.9	13.1	14.3
Incline	10.7	14.4	16.8	15.5	15.8
Highlands	19.4	19.9	23.3	21.3	21.9

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	20.2	18.2	20.8	14.4
Incline	23.8	21.3	23.9	16.8
Highlands	34.5	31.7	35.9	25.1

Mean annual rainfall is defined as the sum of the rainfall (precipitation that occurred when the air temperature was greater than 32 degrees F) during the time period divided by the number of years in the time period.

20yr, 1hr Design Storm Depth (in):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	0.137	0.139	0.145	0.146	0.151
Incline	0.131	0.131	0.142	0.136	0.144
Highlands	0.190	0.179	0.195	0.181	0.188
Mean	0.153	0.150	0.161	0.154	0.161
% Diff from Obs	0.000	-1.965	5.240	1.092	5.459

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	0.161	0.160	0.167	0.149
Incline	0.154	0.143	0.153	0.140
Highlands	0.204	0.194	0.205	0.190
Mean	0.173	0.166	0.175	0.160
% Diff from Hist	15.590	3.112	13.391	-0.828

The 20-year, 1 hour design storm depth is defined as the depth of precipitation that occurs during 1 hour with a 20-year return period. This is equivalent to the 1-hour precipitation depth with a 5% chance of being exceeded in any given year, or a 95% chance of non-exceedance.

85th Percentile, 24 hour Storm Depth (in):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	0.630	0.610	0.633	0.631	0.685
Incline	0.670	0.652	0.685	0.687	0.701
Highlands	1.010	0.972	1.026	1.028	0.976
Mean	0.770	0.745	0.782	0.782	0.787
% Diff from Obs	0.000	-3.246	1.496	1.597	2.225

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	0.745	0.719	0.733	0.674
Incline	0.788	0.771	0.791	0.690
Highlands	1.177	1.172	1.173	1.011
Mean	0.903	0.887	0.899	0.792
% Diff from Hist	21.263	13.546	14.931	0.588

The 85th percentile, 24 hour storm depth is the 85th percentile volume of precipitation that occurs in a single day, only considering days with total precipitation greater than 0.1 inch.

Percentile of 1in, 24hr Storm (%):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	94.61	95.20	94.07	95.40	93.72
Incline	93.57	94.71	93.77	94.49	93.16
Highlands	84.69	85.98	83.97	84.14	85.85
Mean	90.95	91.97	90.60	91.34	90.91
% Diff from Obs	0.00	1.11	-0.39	0.42	-0.05

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	91.98	92.12	91.13	94.97
Incline	91.08	91.47	90.71	93.72
Highlands	81.32	81.38	80.52	84.86
Mean	88.13	88.32	87.46	91.18
% Diff from Hist	-4.17	-2.52	-4.25	0.30

Median Event Duration (hour):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	10.0	7.0	9.0	7.0	8.0
Incline	11.0	10.0	10.0	10.0	10.0
Highlands	9.0	9.0	8.0	9.0	7.0
Mean	10.0	8.7	9.0	8.7	8.3
% Diff from Obs	0.0	-13.3	-10.0	-13.3	-16.7

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	8.0	8.0	7.0	8.0
Incline	10.0	10.0	10.0	10.0
Highlands	8.0	8.0	8.0	9.0
Mean	8.7	8.7	8.3	9.0
% Diff from Hist	0.0	-3.7	-3.8	8.0

Median Event Volume (in):

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	0.250	0.206	0.226	0.219	0.223
Incline	0.270	0.253	0.259	0.262	0.254
Highlands	0.300	0.304	0.324	0.319	0.289
Mean	0.273	0.254	0.270	0.266	0.255
% Diff from Obs	0.000	-7.012	-1.280	-2.500	-6.585

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	0.233	0.228	0.229	0.216
Incline	0.288	0.267	0.270	0.254
Highlands	0.328	0.320	0.316	0.311
Mean	0.283	0.272	0.272	0.260
% Diff from Hist	11.344	0.618	1.939	1.958

Median Event Antecedent Dry Days:

1988-2006

	Obs	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	55.0	55.0	38.0	48.0	56.0
Incline	47.5	29.0	25.0	35.0	33.0
Highlands	43.0	31.0	28.0	35.0	30.0
Mean	48.5	38.3	30.3	39.3	39.7
% Diff from Obs	0.0	-21.0	-37.5	-18.9	-18.2

2030-2060

	CanESM2	CCSM4	CNRM-CM5	MIROC5
Bijou	38.5	47.0	41.0	51.0
Incline	28.0	29.0	28.0	32.0
Highlands	28.0	27.0	25.0	29.0
Mean	31.5	34.3	31.3	37.3
% Diff from Hist	-17.8	13.2	-20.3	-5.9