Contra Costa Clean Water Program

IMP Monitoring Report

IMP Model Calibration and Validation Project

Municipal Regional Permit Attachment C

Submitted to the
California Regional Water Quality Control Board
San Francisco Bay Region
September 15, 2013

Acknowledgements

Dan Cloak, of Dan Cloak Environmental Consulting, prepared the project plan, oversaw implementation of the model calibration and verification project, and prepared this report.

Tony Dubin, of Dubin Environmental Consulting, was involved in developing the model documented in CCCWP’s 2005 HMP. He conducted the modeling runs, calibrated and verified the model, and prepared the tables, figures, and text in Chapter 6 of this report.

Scott McQuarrie, of the Contra Costa Flood Control and Water Conservation District, designed and implemented the instrumentation, monitored the IMPs, and compiled the data used in the model calibration and verification.

Tom Dalziel, of the Contra Costa Clean Water Program, has provided project management and coordination since the advent of this effort in 2003.

Jolan Longway, of the City of Pittsburg, provided project coordination and troubleshooting during design and construction of the facilities at the Pittsburg Fire Protection Bureau Building.

Carlton Thompson, Michael Hawthorne, and Scott Wikstrom, of the City of Walnut Creek, provided project coordination and troubleshooting during and following design and construction of the facilities at Walden Parks Commons.

Tom Mumley, Dale Bowyer, and Jan O’Hara, of the San Francisco Bay Regional Water Quality Control Board, were involved in developing and negotiating requirements for implementation of HM measures and for the IMP calibration and verification project.

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The Contra Costa Clean Water Program (CCCWP) comprises Contra Costa County and the 19 cities and towns within the County, all of which are Permittees under an NPDES permit issued by the San Francisco Bay Regional Water Quality Control Board (Water Board).

Pursuant to permit provision C.3.g., the Permittees require Hydromodification Management (HM) measures to be implemented on development projects. HM measures are intended to control runoff flows so that they do not exceed pre-project flow rates and durations for a specified range of flows. The requirements apply to projects that create or replace an acre or more of impervious area and increase the total amount of impervious area on the project site.

Criteria for HM measures—including factors for sizing HM facilities, called Integrated Management Practices or IMPs—are incorporated in CCCWP's *Stormwater C.3 Guidebook*. The IMPs include bioretention and variations consisting of bioretention combined with upstream or downstream storage.

The sizing factors were developed using a continuous-simulation computer model. The model uses 30 or more years of hourly local rainfall data and generates corresponding estimates of hourly runoff. Model output is used to compare estimated runoff in the site's pre-development condition to runoff post-development, including incorporation of HM measures. Sizing factors represent the minimum IMP areas and volumes required to fully control runoff flows to match the pre-development condition.

The permit requires CCCWP to implement a model calibration and verification project, which is the subject of this report. The purpose of the project is to determine the flow-control effectiveness of the IMPs. The permit specifies that IMPs at a minimum of five locations be monitored for a minimum of two years and that the observed flows be compared to flows that would be estimated by the model.

Three IMPs (bioretention facilities) at an office building in Pittsburg, and two IMPs (bioretention + downstream vault facilities) at a townhouse development in Walnut Creek, were monitored during the 2011-2012 and 2012-2013 water years. Rainfall data was collected at each location. For the IMPs at the Pittsburg site, the water level in the subsurface storage layer was also continuously monitored.

Results of the comparison show that the IMPs provide considerably greater flow-control effectiveness than predicted by the model. The primary reason is that model inputs underestimated the amount of runoff that would be infiltrated by the IMPs. In addition, it was found that runoff percolated through the IMPs soil/compost planting mix more readily than the model predicted. Following changes to input parameters, including the infiltration rate of underlying soils, the model outputs closely matched observed IMP flows and storage.

Local long-term rainfall records were then input to the calibrated model to analyze how IMPs would perform in comparison to current and potential future permit requirements. The simulation indicates that the IMPs fully control runoff flows between the thresholds specified in the current permit (two-tenths of the 2-year pre-project peak flow, or 0.2Q2, and the 10-year pre-project peak flow, or Q10). The Pittsburg bioretention IMPs also control runoff flows within a range extended to the potential future threshold of one-tenth of the 2-year pre-project peak flow, or 0.1Q2. The Walnut Creek bioretention + vault facilities could control flows within the extended range with minor modifications.

In next steps, CCCWP will work with other Bay Area Permittees, through the Bay Area Stormwater Management Agencies Association (BASMAA), to propose appropriate flow-control criteria and sizing factors to be used during the term of a reissued Regional Municipal Stormwater NPDES permit. Lessons learned with regard to facility design details have already been incorporated into the current 6th edition of the *Stormwater C.3 Guidebook.*

1 · Background: Hydrograph Modification Management

1.1 Permit Definitions and Requirements

Provision C.3.g. in the San Francisco Bay Regional Water Quality Control Board's Municipal Regional Stormwater Permit (MRP), titled "Hydromodification Management" (HM), defines HM projects as those creating or replacing an acre or more of impervious area, subject to various exclusions. Provision C.3.g. requires that:

> The stormwater discharges from HM Projects shall not cause an increase in the erosion potential of the receiving stream over the pre-project (existing) condition. Increases in runoff flow and volume shall be managed so that post-project runoff shall not exceed estimated pre-project rates and durations, where such increased flow and/or volume is likely to cause increased potential for erosion of creek beds and banks, silt pollutant generation, or other adverse impacts on beneficial uses due to increased erosive force.

Specific requirements for design of HM controls are:

> For Alameda, Contra Costa, San Mateo, and Santa Clara Permittees, HM controls shall be designed such that post-project stormwater discharge rates and durations match pre-project discharge rates and durations from 10 % of the pre-project 2-year peak flow up to the pre-project 10-year peak flow. For Fairfield-Suisun Permittees, HM controls shall be designed such that post-project stormwater discharge rates and durations shall match from 20 percent of the 2-year peak flow up to the pre-project 10-year peak flow. Contra Costa Permittees, when using pre-sized and pre-designed Integrated Management Practices (IMPs) per Attachment C of this Order, are not required to meet the low-flow criterion of 10% of the 2-year peak flow. These IMPs are designed to control 20% of the 2-year peak flow. After the Contra Costa Permittees conduct the required monitoring specified in Attachment C, the design of these IMPs will be reviewed.

Nearly identical requirements for new development projects appear in the 2010 East Contra Costa County Municipal NPDES Permit issued by the California Regional Water Quality Control Board for the Central Valley Region.

In the MRP, the referenced Attachment C specifies:

> The Program shall monitor flow from Hydrograph Modification Integrated Management Practices (IMPs) to determine the accuracy of its model inputs and assumptions. Monitoring shall be conducted with the aim of evaluating flow control effectiveness of the IMPs. The Program shall implement monitoring where feasible at future new development projects to gain insight into actual versus predicted rates and durations of flow from IMP overflows and underdrains.
>
> At a minimum, Permittees shall monitor five locations for a minimum of two rainy seasons. If two rainy seasons are not sufficient to collect enough data to determine the accuracy of model inputs and assumptions, monitoring shall continue until such time as adequate data are collected.
>
> Permittees shall conduct the IMP monitoring as described in the IMP Model Calibration and Validation Plan in Section 5 of this Attachment. Monitoring results shall be submitted to the Executive Officer by June 15 of each year following collection of monitoring data. If the first year's data indicate IMPs are not effectively controlling flows as modeled in the HMP, the Executive Officer may require the Program to make adjustments to the IMP sizing factors or design, or otherwise take appropriate corrective action. The Permittees shall submit an IMP Monitoring Report by August 30 of the second year of monitoring. The IMP Monitoring Report shall contain, at a minimum, all the data, graphic output from model runs, and a listing of all model outputs to be adjusted, with full explanation for each. Board staff will review the IMP Monitoring Report and require the Program to make any appropriate changes to the model within a 3-month time frame.

Section 4 of MRP Attachment C states in part:

> Monitoring shall be conducted with the aim of evaluating flow control effectiveness of the IMPs. The IMPs were redesigned in 2008 to meet a low flow criterion of 0.2Q2, not 0.1Q2, which is current HMP standard for Contra Costa County. The Program shall implement monitoring at future new development projects at a minimum of five locations and for a minimum of two rainy seasons to gain insight into actual versus predicted rates and durations of flow from IMP overflows and underdrains. If two rainy seasons are not sufficient to collect enough data to

> determine the accuracy of model inputs and assumptions, monitoring shall continue until such time as adequate data are collected….
>
> ….The principal use of the monitoring data shall be a comparison of predicted to actual flows. The Dischargers shall ensure that the HSPF model is set up as it was to prepare the curves in Attachment 2 of the HMP, with appropriate adjustments for the drainage area of the IMP to be monitored and for the actual sizing and configuration of the IMP. Hourly rainfall data from observed storms shall be input to the model, and the resulting hourly predicted output recorded. Where sub-hourly rainfall data are available, the model shall be run with, and output recorded for, 15-minute time steps.
>
> The Dischargers shall compare predicted hourly outflows to the actual hourly outflows. As more data are gathered, the Dischargers may examine aggregated data to characterize deviations from predicted performance at various storm intensities and durations.
>
> Because high-intensity storms are rare, it will take many years to obtain a suitable number of events to evaluate IMP performance under overflow conditions. Underdrain flows will occur more frequently, but possibly only a few times a year, depending on rainfall and IMP characteristics (e.g., extent to which the IMP is oversized, and actual, rather than predicted, permeability of native soils). However, evaluating a range of rainfall events that do not produce underflow will help demonstrate the effectiveness of the IMP.

Similar, but less detailed, requirements were incorporated into RWQCB Order R2-2006-0050, whereby the San Francisco Bay Regional Water Quality Control Board (Water Board) adopted Contra Costa's HMP in 2006. That Order was superseded by the MRP.

1.2 Hydromodification, Control Methods, and Measurements

1.2.1 Hydromodification and Stream Erosion

The following brief summary of factors affecting stream erosion was included in the HMP Work Plan submitted in November 2004. Subsequent research has upheld these points.

> Contra Costa streams are subject to a myriad of influences, and it is typically difficult, if not impossible,

to generalize regarding causes and effects across the entire County. Further, it is often difficult to attribute any particular observed condition in a specific stream to only one proximate cause. In general, it is necessary to consider many potential causes and to consider their relative significance. For example, Riley (2002) attributes the incision of stream channels in the Bay Area over the past 100 years primarily to climate changes and earth movement, while noting that incision may be induced accelerated by land use change as well.

As an illustration of the interaction of these influences, consider the stream equilibrium equation identified by Lane (1955).

$$(\text{Sediment load} \times \text{sediment size}) \; \alpha \; (\text{slope} \times \text{discharge})$$

A change in any one of these four factors may contribute to disequilibrium (net erosion or deposition stream sediments) and consequent changes in channel width and depth.

- Sediment load may increased by earth movement (e.g., geologic uplift and mass wasting), land disturbance (e.g., agriculture, road construction), or loss of vegetation, or may be decreased by land development (e.g., paving, terracing), by dams, or by dredging.
- Sediment size may be affected by changed balance among different sediment loads (and the erosion of different geologic strata), by dams, or by in-stream mining.
- Stream slopes are often increased by straightening (removal of meanders), or may be increased or decreased by the placement of downstream culverts or grade controls.
- Finally, stream discharge, and particularly rainfall/runoff relationships, may be increased by deforestation, agriculture, and other land use changes, prior to and including urbanization, or may be decreased by dams and diversions.

The above considerations address only system-wide instabilities, those that are in effect over a long reach or series of reaches. Bank erosion at specific sites may be related to the presence or absence of vegetation and to localized channel conditions (e.g., placement or removal of woody debris or riprap upstream or downstream).

1.2.2 Criteria for Control of Runoff Flows from Development Projects

Notwithstanding the complexity of factors affecting stream erosion, and the watershed scale at which those factors interact, California's nine Regional Water Quality Control Boards (Water Boards) have focused on controlling increased flows and durations from individual development sites.

The nine Water Boards have adopted a variety of criteria, using a mix of methodologies and engineering methods, to regulate land development.

Some Water Boards use the estimated peak flow or volume resulting from a specific storm event ("design storm") as a criterion. Examples of "design-storm" based criteria follow:

- No increase in the predevelopment 2-year peak flow (Orange County and the statewide Phase II permit for small municipalities)
- No increase in runoff volume resulting from the 85th percentile storm or 95th percentile storm, depending on development project location (Central Coast Region)
- No increase in 2-year peak flow or peak duration or increase in runoff volume from the 85th percentile storm (North Coast Region)

Criteria required by other Water Boards involve an analysis of rainfall and runoff over 30 years or more. This continuous simulation approach is discussed in Section 2 below. To determine whether the criteria are met, an hourly rainfall record of 30 years or more is used. Hourly runoff volumes are estimated using a continuous-simulation model applicable to the development site. Runoff is simulated in the pre-project condition and in the post-project condition with proposed IMPs or other flow-control facilities.

The pre-project and post-project runoff statistics are compiled to compare the duration of simulated flow at each flow rate, from rare high flows to more frequent low flows.

The post-project flow durations must be equal to or less than the pre-project flow durations for flows within a specified range.

The Water Boards have required different ranges to be used. The basis for setting different ranges is, ostensibly, that different streams have different thresholds of flow at which their beds or banks may be eroded and the resulting sediment transported downstream. However, in fact, the ranges are often applied to all the stream segments on all the streams in a whole city or even an entire county.

The lower limit of the range is more critical to facility design. The lower limit is commonly expressed as a fraction of the 2-year pre-project peak runoff flow (Q2). Here are some low-flow thresholds currently mandated by the various Water Boards:

- Sacramento-area municipalities: 0.25Q2 or 0.45Q2
- San Diego County municipalities: 0.1Q2, 0.3Q2, or 0.5Q2, depending on receiving channel material and dimensions.
- Cities of Fairfield and Suisun City: 0.2Q2
- Santa Clara, Alameda, and San Mateo Counties: 0.1Q2
- Contra Costa County: 0.2Q2 when applied to specified IMPs.

1.3 LID and HM

The California Ocean Protection Council describes Low Impact Development (LID) as a

> … stormwater management strategy aimed at maintaining or restoring the natural hydrologic functions of a site to achieve natural resource protection objectives and fulfill environmental regulatory requirements; LID employs a variety of natural and built features that reduce the rate of runoff, filter pollutants out of runoff, and facilitate the infiltration of water into the ground…
>
> …LID design detains, treats and infiltrates runoff by minimizing impervious area, using pervious pavements and green roofs, dispersing runoff to landscaped areas, and routing runoff to rain gardens, cisterns, swales, and other small-scale facilities distributed throughout a site.

LID was first developed as a comprehensive stormwater management strategy by Prince Georges County (1999). The hydrologic approach is described as follows:

> The LID approach attempts to match the predevelopment condition by compensating for losses of rainfall abstraction through maintenance of infiltration potential, evapotranspiration, and surface storage, as well as increased travel time to reduce rapid concentration of excess runoff.

In essence, LID seeks to address potential hydrologic impacts of land development by maintaining and restoring site characteristics and conditions at the smallest scale possible. Priority is placed on reducing runoff by limiting impervious surfaces, then on dispersing runoff to landscape within a site, and finally by directing runoff to small-scale facilities integrated into the landscape.

In contrast, HM attempts to address hydrologic impacts of land development at a watershed scale. Flow criteria are developed for streams draining the watershed, and those criteria are then translated to criteria for development of sites draining to the watershed. (In the case of the San Francisco Bay Water Board's approach, criteria developed for flows within selected reaches of three streams in Santa Clara County were applied to all Bay Area development sites directly and without further analysis.)

LID promotes a multiplicity of approaches and promotes "green" urban development, while HM specifies that runoff discharges adhere to a specified hydraulic regime.

The HM criteria adopted by the San Francisco Bay Water Board specify the use of flow duration control basins, and require "HM controls shall be designed such that post-project stormwater rates and durations match pre-project discharge rates and durations…." In flow duration control basins, this "match" is achieved through the sizing and placement of orifices draining a basin. Cost-effectiveness and operational considerations favor larger basins (the opposite of LID's small-scale approach). Indeed, the MRP allows compliance through the use of regional-scale flow-duration control basins.

1.4 CCCWP Approach to HM

CCCWP committed to implementing LID beginning in 2003, and published the first edition of the *Stormwater C.3 Guidebook (Guidebook),* emphasizing LID design, in 2004. Faced with the San Francisco Bay Water Board's subsequent emphasis on HM, as opposed to LID, CCCWP sought a way for local developers to meet the HM criteria by using LID. This was accomplished by creating designs for LID IMPs that can also demonstrably meet HM criteria.

CCCWP guidance for HM compliance is incorporated in the *Guidebook.* The *Guidebook* is referenced in stormwater ordinances adopted by each Contra Costa municipality.

The *Guidebook* provides applicants for HM projects the following options for HM compliance. The options also appear in MRP Attachment C:

1. Demonstrate there is no increase in impervious area.
2. Use the HM IMPs in the Guidebook.
3. Use a continuous simulation model and a rainfall record of at least 30 years to show estimated post-project runoff durations and peak flows do not exceed pre-project durations and peak flows.
4. Show that there is a low risk of downstream erosion because all downstream channels are pipes, hardened channels, subject to tidal action, or aggrading, or that a channel restoration project will be constructed that takes the post-project flows into account.

For Option 2, the *Guidebook* incorporates sizing factors that land development engineers may use to determine the minimum required dimensions of a variety of IMPs. The land development engineer divides the development site into discrete Drainage Management Areas (DMAs), determines the amount of equivalent impervious area within each DMA, and uses the *Guidebook* sizing factors to calculate minimum values for the following parameters for an IMP serving that DMA:

- area, **A**
- surface storage volume, **V_1**
- subsurface storage volume **V_2**

See Figure 1-1. The land development engineer then shows how, for each DMA, the IMP meets or exceeds minimum values for each parameter.

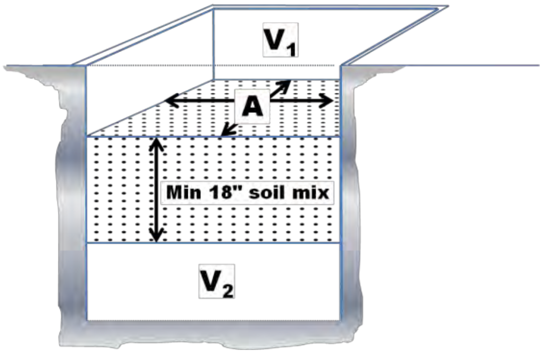

Figure 1-1. A, V_1, and V_2. Note V_2 is the free volume; gravel volume is multiplied by porosity

1.4.1 Bioretention HM Facilities

Bioretention facilities are the most commonly used IMPs on Contra Costa development projects. They are typically constructed for runoff treatment and to maximize retention of runoff via evapotranspiration and infiltration, but the design is adapted to also provide HM. Bioretention facilities work as follows:

Runoff enters the bioretention facility via sheet flow or pipes and is detained in a shallow surface reservoir. The reservoir also serves to spread runoff evenly across the facility surface. Runoff then percolates through an engineered soil (sand/compost mix). Some runoff is retained in soil pores and plant roots and is subsequently evapotranspirated. Runoff that exceeds the moisture-holding capacity of the soil percolates through the soil layer and enters a subsurface storage layer (typically gravel). The treated runoff subsequently then infiltrates into the soils below the facility. If runoff enters the gravel layer more rapidly than it infiltrates, the saturation level in the gravel layer rises until it reaches the discharge elevation for a perforated pipe underdrain. When this occurs, runoff will also discharge through the perforated pipe underdrain to a discharge point (typically connected to the municipal storm drain system). In general, this discharge will occur rarely—a few times per year, or even once in many years.

In facilities constructed for HM, this perforated pipe underdrain is equipped with a flow-limiting orifice. This allows the bioretention facility to act like a flow duration control basin during the infrequent occasions when the storage layer fills, and as a LID facility at other times.

The surface reservoir is also equipped with an overflow that will become active under either of two scenarios: (1) runoff enters the surface reservoir more rapidly than it percolates through the engineered sand/compost mix, and the surface reservoir fills to its maximum volume or (2) runoff enters the facility more rapidly than it leaves via *both* infiltration to the soils below the facility *and* discharge via the underdrain, and this continues until the gravel and soil layers become fully saturated, and the surface reservoir fills to its maximum volume.

In summary, a bioretention facility receives runoff from a specific delineated area, retains that runoff via infiltration and evapotranspiration, and discharges excess runoff via an underdrain and an overflow.

1.4.2 Variations of Bioretention Facilities for HM

The *Guidebook* includes criteria and sizing factors for three design variations:

1. The Flow-through Planter, which can be built above ground or other locations where infiltration to native soils cannot be allowed.

2. Bioretention + Vault, which includes surface storage and engineered soil, but provides for subsurface storage $\mathbf{V_2}$ in a separate structure rather than a subsurface gravel layer.
3. Cistern + Bioretention, which allows for upstream runoff storage $\mathbf{V_1}$ in a tank or basin; runoff is then metered through an orifice to be treated in a bioretention facility.

As described in Section 4, this model calibration and validation project included monitoring of Bioretention + Vault facilities as well as bioretention facilities.

The *Guidebook* also includes design criteria and sizing factors for “direct infiltration” facilities, that is, facilities designed to infiltrate runoff directly, without first routing it through a soil layer to remove pollutants. These design criteria and sizing factors for “direct infiltration” can be used to design infiltration basins, infiltration trenches, and dry wells. This model calibration and validation project did not include “direct infiltration” facilities.

2 · Model Representation of Hydrologic Performance

A project team comprising hydrologists and engineers from Philip Williams & Associates and Brown & Caldwell developed the continuous simulation model that is the subject of this model verification and calibration project. The work was done during 2004-2005. The modeling results formed the basis for the designs and sizing factors proposed in the CCCWP’s Hydrograph Modification Management Plan (HMP), submitted to the Water Board in May 2005 and approved by the Water Board, with minor changes, in July 2006.

In 2009, Brown and Caldwell used the same continuous simulation model—with the same input parameters and assumptions—to create sizing factors for new IMP designs. The new IMP designs and sizing factors were incorporated into an addendum to the 4th Edition of the *Stormwater C.3 Guidebook,* and subsequently carried forward through the 5th and 6th (most recent) *Guidebook* edition.

The model was created in HSPF (Hydrologic Simulation Program – Fortran). HSPF has a history going back to the 1960s, has been used and endorsed by USEPA, and has been embraced in many parts of the US for evaluation and design of the hydrologic impacts of new developments. The Western Washington Hydrologic Model (WWHM) consists of an HSPF-based simulation and a user interface, as does the Bay Area Hydrology Model

(BAHM) currently used in Alameda, Santa Clara, and San Mateo Counties. Because HSPF is widely used, there is a significant body of literature and a community of practitioners to support use of the model in HSPF applications.

In HSPF, the various hydrologic processes are represented as flows and storages. Each flow is an outflow from a storage, which, at each time step, is typically a function of the storage volume at that time step and the physical characteristics of the storage. For undeveloped watersheds, HSPF models the movement of water along three paths: overland flow, interflow, and groundwater flow. A variety of storage zones are used to represent storage that occurs on the land surface and in the soil horizons.

The continuous-simulation model was developed and used to demonstrate that, with the inclusion of appropriately sized IMPs in a development project, increases in runoff flow and volume are managed so that post-project runoff does not exceed estimated pre-project rates and durations.

This requires that the model generate representation of pre-project flows at each time step over a long period, as well as post-project flows at each time step during that same period. It is then possible to make statistical cumulative comparisons of the two sets of generated data.

To develop the model, the consultant team:

- Characterized pre-project runoff peaks and durations for a range of soil groups, vegetation, and rainfall patterns characteristic of Contra Costa County development sites.
- Modeled outflow peaks and durations from several IMP designs (based on a unit area of new impervious surface draining to the IMP).
- Compared modeled pre-project flows to modeled post-project-with-IMP flows, using conservative assumptions.
- Developed calculations for sizing factors for each IMP associated with each pre-project condition.

To model the IMPs, the project team constructed representations of each IMP in HSPF. For example, a bioretention facility is represented in HSPF by length, cross-section geometry, layers of soil and underdrain material, and transmissivity of underlying soils.

3 · Model Verification and Calibration Project Design

This project compared model-predicted hydrologic performance to actual hydrologic performance for five facilities at two test sites.

3.1 Steps for Model Verification and Calibration

The experimental design of this project can be summarized as follows:

1. Create a customized version of the HSPF model for each test facility and its corresponding tributary area to continuously simulate inflow, infiltration, evapotranspiration, and underdrain discharge for that test facility. The customized versions use the same values as the 2004-2005 model for soil permeability and bioretention planting soil characteristics, and facility-specific values for the tributary drainage area size and runoff factors and for facility dimensions.
2. Measure rainfall at each test site at each time increment.
3. Input site rainfall data, and use the model to predict, for each time increment, the rates and volumes of inflow, infiltration, evapotranspiration and underdrain discharge for each test facility, as well as storage within each component of the facility.
4. Directly measure the underdrain discharge for each facility at each time increment. (Also, for three of the test facilities, the saturation level in the gravel layer was measured at each time increment.)
5. Compare predicted to measured flows and storage.
6. Adjust the previously assumed model parameter values so that predicted flows and storage more closely approximate measured flows and storage at each time increment (that is, calibrate the model).

3.2 Evaluation of Sizing Factors

The procedure for calculating sizing factors, previously implemented in 2004-2005 and again in 2009, was used with the now-calibrated model to evaluate whether the current sizing factors for bioretention and bioretention + vault facilities are adequate.

Long-term hourly rainfall records from two of the same rain gauges previously used for calculating the sizing factors were input into one of the calibrated site-specific models to examine whether the facility met regulatory criteria.

This procedure was completed for two regulatory scenarios:

1. For a low-flow criterion of 0.2Q2, as specified under the MRP adopted in 2009.
2. For a low-flow criterion of 0.1Q2.

Results are in Section 6.

4 · Project Test Facility Characteristics and Parameters

The CCCWP sought to identify development projects with the following characteristics (Cloak, 2009):

- One or more facilities (bioretention, flow-through planter, bioretention + vault, or cistern + bioretention).
- Facilities must include an underdrain (as required on sites where native soils are in Hydrologic Soil Groups “C” or “D”).
- Clearly defined and accurately sized Drainage Management Areas.
- Facilities designed according to the criteria in the Guidebook 4th Edition, including documentation and calculations of minimum and provided bioretention surface area, surface storage volume, diameter of circular orifice, and subsurface storage volume.
- Arrangements/permissions to work with the project contractor and inspector to document and verify construction of the facilities.
- 24-hour access and permission from site owner to access facilities to maintain monitoring equipment.
- Above-ground location to mount a datalogger, rain gauge, and telemetry.

There were five test facilities at two test sites. Three bioretention facilities were monitored at the Pittsburg Fire Prevention Bureau Building, and two bioretention + vault facilities were monitored at Walden Park Commons, a 65-unit townhouse development in Walnut Creek.

4.1 Pittsburg Fire Protection Bureau Building

4.1.1 Site Description

The Pittsburg Fire Protection Bureau Building is located at 2329 Loveridge Road in Pittsburg. Total project site area is 1.09 acres. The site is nearly flat. A single-story building of about 19,000 square feet houses offices of the Contra Costa Fire Protection District. There is an accompanying parking lot with 35 spaces and a trash enclosure. The site includes landscaping around the building, around the perimeter of the site adjacent to Loveridge Road and Loveridge Circle, and in parking medians. The project was constructed during 2011.

As originally designed, the project included a paved overflow parking area. With this area, the total new impervious surface exceeded one acre. The City of Pittsburg required HM compliance for the project. In later revisions to the project scope, the overflow parking area was left graveled rather than paved and the total new impervious area was reduced to 26,457 square feet.

Figure 4-1.
Pittsburg site pre-project

4.1.2 Pre-Project Condition and Site Soils

Figure 4-1 shows the site in its pre-project condition. As can be seen in the photo, the site was previously undeveloped; however, it had been used for parking and perhaps as a construction staging area.

Figure 4-2. Excavation of IMP #2 at Pittsburg Site.

Borings on the site were taken in 2004. According to the report by Kleinfelder (2004), subsurface soils “consisted predominantly of stiff to hard, moderately to highly plastic silty clays, extending to depths ranging from about 4 to 14 feet below existing site grade.” This covers the range of depths at the bottom of the bioretention facilities. Surface soils were found to have high shear strength and be highly plastic, as indicated by Atterberg Limits: a Liquid Limit of 59% and a corresponding Plasticity Index of 37. This indicates high expansion potential. The shear strength of the soils is apparent in Figure 4-2.

Boring depths extended as deep as 31 feet, and groundwater was not encountered.

4.1.3 Drainage Management Areas

The Pittsburg Fire Protection Bureau Building design for treatment and HM compliance incorporates eight DMAs.

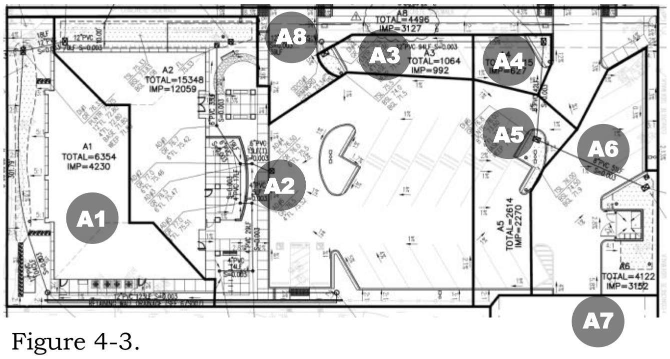

Figure 4-3.
Pittsburg site Drainage Management Areas.

For the model verification project, the completed site was inspected to verify that DMA delineation corresponded to site drainage as built. This included visual verification of the location of rain gutters and downspouts. In addition, the parking lot and grounds were inspected to verify that grade breaks correspond to the DMA boundaries shown in the project plans.

See Figure 4-3 and Table 4-1.

DMA 7 is a self-treating pervious graveled area. DMA 8 consists of driveway and sidewalk areas that could not be made to drain to treatment facilities. The remaining six DMAs each drain to a bioretention facility. Three of these six bioretention facilities were selected to be monitored as part of this project; these are designated as A2, A4, and A6 in Table 4-1.

Table 4-1. Pittsburg Fire Protection Bureau Building Facility Dimensions.

	Tributary Area		Bioretention Facility Dimensions						
	Landscaped (SF)	Impervious (SF)	A (SF)	A* (gravel layer)	V_1 (CF)	Surface Depth (in.)	V_2 (CF)	Gravel Depth (in.)	Orifice diameter (In.)
A1	1582	4230	558	558	316	7	379	21	0.51
A2	2415	12059	886	886	874	12	961	33	0.81
A3	0	992	60	72	72	12	72	30	0.21
A4	0	627	67.5	82.5	44	6	44	15	0.17
A5	180	2270	170	195	130	9.5	170	31	0.32
A6	562	3152	340	340	204	6	258	19	0.41

*The gravel layer on some facilities extended beyond the surface dimension due to installation of a curb that extended only to top of the gravel layer.

4.1.4 Design of Bioretention Facilities

Each of the three test bioretention facilities was constructed using the cross section and key features specified in the 4th Edition of the *Guidebook*. Some specifications that were new for the 5th ("MRP") Edition were incorporated. All three facilities have:

- Surface reservoir depth as required for V_1
- 18-inch depth sand/compost mix
- Subsurface reservoir of Class 2 permeable (Caltrans Specification 68-1.025), as required for V_2
- Underdrain of PVC SDR 35 perforated pipe
- Underdrain discharge orifice
- Curb inlets; these are constructed somewhat differently from the standard 12-inch-wide curb cut and consisted of pipe sections in the curb face.
- Outlet structures consisting of 24" × 36" precast catch basins; this larger size was to ensure the instrument technician would be able to enter and access the tipping buckets located where the underdrain discharges to the outlet structure.
- Monitoring wells, composed of a section of 6-inch PVC pipe extending vertically through the soil and gravel layers.

Bioretention facilities A2 and A4 were designed with perimeter walls. Bioretention facility A6 was designed without perimeter walls.

A discharge orifice design was developed for this project; the design was subsequently included in the 5th Edition of the *Guidebook*. The design incorporates a solid PVC pipe extending through the wall of the outlet structure; the pipe is fitted with a threaded cap. The orifice is drilled into the cap. This allows the cap to be removed so that the orifice and pipe can be cleaned if necessary; it also allows the cap to be

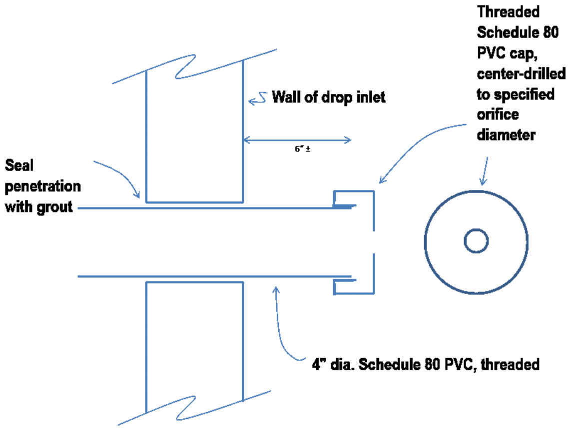

Figure 4-4. Underdrain Orifice Detail.

replaced if the orifice size needs to be adjusted. See Figure 4-4.

As is typical on development sites, the area for some of the IMPs substantially exceeds the minimum. See Table 4-1. This is done for constructability. It is often easier and more cost-effective to build a facility with dimensions that coincide with the available space (such as a parking median) than to build the additional walls and other structure necessary to minimize the size of the IMP.

4.1.5 Construction of Bioretention Facilities

The bioretention facilities were constructed consequent with the construction of the Fire Protection Bureau Building during 2011.

The facilities were constructed generally as designed. The following issues were encountered during construction:

The outfall structures had to be constructed deep enough to fit tipping buckets beneath the underdrain discharge elevation. Because the site is flat, and because the municipal storm drain in Loveridge Road is shallow, there was concern that during storm events flow from the municipal storm drain would back up into the site storm drains and flood the tipping buckets. To address this concern, the most downstream on-site drainage structure (not a bioretention outfall) was fitted with a weir wall and a pump placed on the upstream side with discharge to the downstream (municipal storm drain) side. The pump operated successfully to maintain drainage over the weir wall.

The addition of curbs and widening of curbs for structural stability resulted in reductions to the surface area of each test facility. The reduced areas were noted in updated drawings (and in Table 1) and incorporated into the customized model for each facility.

Following excavation, the native clay soils at the bottom of each bioretention facility were “ripped” using the toothed bucket of the excavator.

4.1.6 Instrumentation

A rain gauge was located on the roof of the trash enclosure.

Each of the three bioretention facilities was equipped with the following measuring devices:

- A tipping bucket, Model TB1L made by Hydrological Services Ltd., located in the facility overflow structure to measure flows discharged through the underdrain orifice

- A piezometer, located in a monitoring well

The instruments were connected to a datalogger on the site via wired connections. Some of the wired connections were strung through the site storm drains—a notable convenience. The datalogger was connected via telemetry to the County Flood Control District's data system.

4.2 Walden Park Commons

Walden Park Commons is a 65-unit multi-family development on a 4.59-acre site fronting Oak Road in Walnut Creek. The site is flat, sloping less than 0.5% away from Oak Road.

4.2.1 Pre-Project Conditions and Site Soils

The site was previously occupied by ten single-family homes with pools, sheds, and associated driveways. These accounted for 74,000 square feet (1.7 acres) of pre-project impervious area.

A geotechnical study of the site (Korbmacher Engineering, 2006) found site soils were native to the site (that is, not fill), and that soils "consisted of a medium stiff to very stiff silty clay and sandy clay." The near-surface soils have moderate expansion potential.

The Korbmacher report indicates groundwater was encountered in borings at a range of 7 to 11 feet below existing grade.

4.2.2 Drainage Management Areas

The applicant was required to ensure all site impervious surfaces drain to LID treatment. The applicant was allowed to size and design bioretention facilities for "treatment only" for new impervious areas equivalent to the pre-project impervious area. For the remainder of the site (corresponding to the increase in impervious area as a result of the project), the applicant was required to provide both treatment and HM control. See the CCCWP's "Guidance on Flow Control for Development Projects on Sites that are Already Partially Developed," (March 2009).

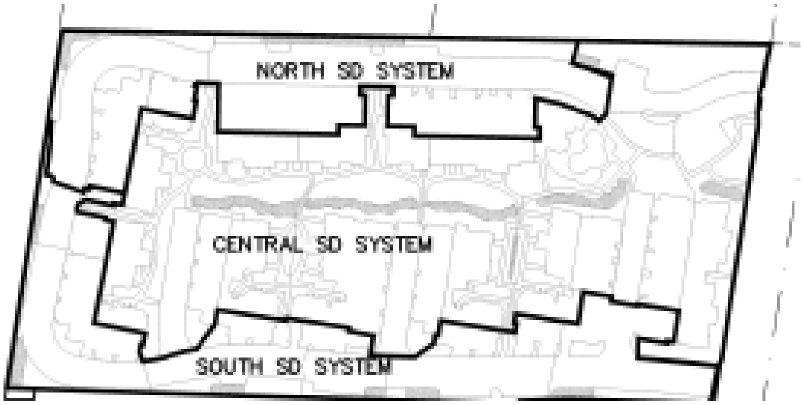

Figure 4-5.
Walden Park Commons Storm Drainage Areas

The site was divided into North, Central, and South areas, with the Central area being routed to treatment-only bioretention facilities. See Figure 4-5. The Central area DMAs and treatment facilities are not considered further in this report.

The North Area is divided into eight DMAs. There are six impervious DMAs totaling 33,301 square feet of impervious roof and driveway, and two landscaped DMAs with 5,948 square feet of pervious area.

The South Area is divided into 19 DMAs. There are 14 impervious DMAs with 36,257 square feet of impervious area, and five landscaped DMAs with 7,495 square feet of pervious area.

All DMAs in the North and South Areas were drained to bioretention facilities. Landscaped DMAs were assigned a runoff factor of 0.7 as specified in the 2005 HMP; that is, landscaped areas were assumed to be 70% impervious. Roofs and paved areas were assumed to be 100% impervious.

4.2.3 Design of Bioretention Facilities

A sizing factor of 0.04 was applied to the resulting equivalent impervious area. Bioretention facilities were sized to exceed this minimum.

Key characteristics of the bioretention facilities are:

- 18 inches of sand/compost mix
- Class 2 permeable drainage layer
- Overflow constructed of vertical ADS pipe, cut to design height
- 6-inch perforated pipe underdrain
- Overflow and underdrain connected to large-diameter storage pipe

The bioretention facilities are located between the site's loop road and the site perimeter fence and are generally configured as linear swales. According to construction drawings, the bottom of the excavation was sloped toward a central line running the length of the swale. The gravel (Class 2 permeable) layer is likewise sloped. The upstream sections do not have underdrains; the most downstream section of the bioretention facilities (near the rear of the development) includes a perforated pipe underdrain See Figure 4-6.

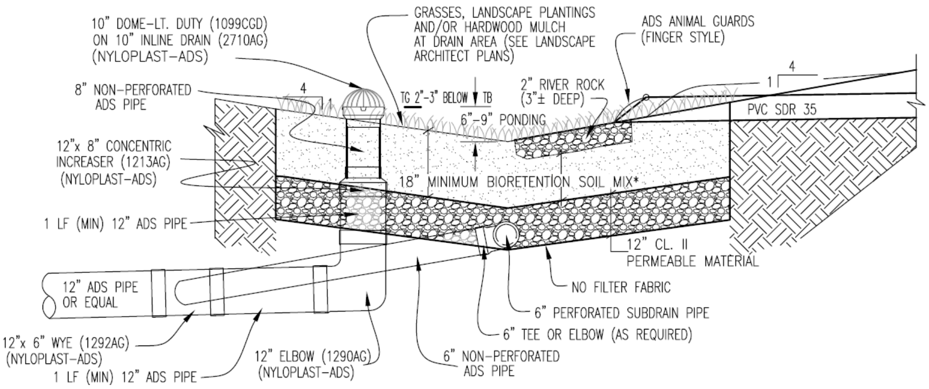

Figure 4-6. Configuration of Walden Park Commons Bioretention Facilities

This configuration allows runoff to infiltrate over much of the bioretention facility area; however, runoff pooling in the gravel layer of the most downstream section will tend to enter the underdrain pipe rather than infiltrate.

4.2.4 Design of Downstream Storage

The underdrain/overflow from the bioretention facilities is routed to common storage facilities—one for the North Area and one for the South Area. The storage consists of reinforced concrete pipe of 30" and 42" diameter set at a slope of 0.005. This information was used to establish stage-storage relationships within the model (See Section 6.)

The concrete pipe storage facility is sealed, preventing exfiltration to the Class A/B backfill material around the pipes and eliminating the opportunity for subsequent infiltration to the native soils around and beneath the storage pipe. This is a significant variance from the design intent for Bioretention + Vault facilities. The *Guidebook* design detail for Bioretention + Vault shows a chamber with an open bottom.

The storage pipes for the North Area and South Area each discharge into concrete vaults at the rear of the development. Each vault is equipped with a weir wall. A pipe through each weir wall conveys metered flows. Each of these pipes is equipped with a PVC pipe and threaded cap. An orifice drilled into the cap meters flows.

Should either of the storage pipes become full, flows would overtop the corresponding weir wall. Downstream of the weir walls, the vaults discharge to the City of Walnut Creek storm drain system.

4.2.5 Construction of Facilities

Drainage facilities were constructed, along with most of the townhouses, during 2011. The following were noted following construction:

Because the bioretention facilities were designed without a hard delineation of their perimeter (that is, they slope seamlessly to surrounding landscaping), it is difficult to visually discern their areal extent. The facilities were surveyed post-construction to confirm the floodable area (that is, the area that lies below the overflow height) corresponded to the areas shown in the descriptions and calculations submitted by the applicant.

Data from the initial storm showed vault outflows began soon after the beginning of a rain event, the facilities were inspected for construction errors that might cause short-circuiting. It was found that the overflow pipe risers had been constructed with perforated pipe, which could have allowed ponded runoff to enter the overflow rather than percolating through the soil/compost mix layer. This was corrected on March 6, 2012.

4.2.6 Instrumentation

Because the bioretention areas were routed to common detention vaults, the total area tributary to the vault is relatively large, and the allowable discharge rate is correspondingly large. To illustrate, the 0.1Q2 discharge from the North and South Areas at Walden Park Commons is 0.07 and 0.08 cfs, respectively, compared with 0.02 cfs for the largest of the bioretention facilities (Facility A2) at the Pittsburg Fire Protection Bureau Building. The larger flow rates allowed the use of electromagnetic flow meters (“magmeters”) rather than tipping buckets. Model #EX 81P-40 by Seametrics was selected. The correspondingly larger orifice sizes (over an inch) also helped alleviate concerns about potential orifice clogging.

The magmeters were installed in 1.5" diameter sections of pipe extending upstream of the orifice discharge and through the weir.

The selected magmeter sensors generate a frequency range from 0 – 550Hz over a velocity range of 0.28 – 20 feet per second respectively. This frequency was sampled by the data logger every 15 minutes and velocity was calculated from frequency.

A rain gauge was located in the central courtyard of the development.

The data was transmitted every half hour to a County mountain top repeater and to the office base station where the entire data base is maintained.

5 · Data Collection and Review

Instrumentation and telemetry were established in September 2011 and maintained through May 2013. The instrumentation was operating for all storms during this period. Following is a list of occurrences that affected data collection.

5.1 Exceptions Affecting Data Collection—Pittsburg

5.1.1 Tips When Piezometer Levels Show No Outflow

During each sizable storm, tipping buckets recorded a single tip although piezometer levels indicated the saturation level in the gravel layer had not reached the height of the underdrain. These tips could have been caused by small amounts of runoff entering the underdrain rather than percolating through the unsaturated gravel layer, or by rain falling directly into the tipping bucket.

5.1.2 Data Loss on October 22, 2012

Data for a storm on this date showed very high flows entering the tipping bucket for IMP #2. On examination of the data, it was determined that the recorded flows were outside the range of the tipping buckets ability to record. On further investigation, it was determined that moisture had caused wired connections between the tipping buckets and the datalogger to short-circuit. The wired connections were insulated with silicone rubber sealer. The erroneous data was taken out of the data base at that time.

5.2 Exceptions Affecting Data Collection—Walden Park

5.2.1 Construction Error on Overflow Risers

As noted above, a construction error may have allowed short-circuiting of flows during storms prior to March 6, 2012.

5.2.2 Cut-out at High Flows

It was noted that data for some events showed flows rising following the onset of rain, suddenly dropping to zero, and then resuming with a falling limb as the storage pipe drained. On investigation it was determined the most likely cause was turbulent flow within the discharge pipe.

As a backup method of measuring flows, on January 17, 2013 level sensors were installed in the discharge vault. Also at this time two feet of linear pipe was installed upstream of the magmeters. It was planned to correlate the water levels and measured flows to establish a rating curve and to use the rating curve to estimate flows during intervals when the flow sensor was not registering. However, there were not enough subsequent storms to establish the rating curve, and no subsequent flows were high enough to cause recurrence of the problem.

5.3 Data Review and Consistency Check

Data were reviewed for internal consistency and consistency with expectations and visual observations. The following were noted:

- Rainfall data was consistent with observed events and other rain gauge data collected by the District.
- Saturation levels in the Pittsburg bioretention facilities rose to relative levels consistent with rainfall depths and with facility sizing.
- Discharge measured at the Walden Park facilities was recorded at relative flows consistent with rainfall intensity and depths.

In summary, the data collected covered most but not all storm events during the monitoring period. In addition, the 2-year monitoring period corresponded to a time of relatively few rainfall events, and smaller rainfall events, compared with long-term averages. There were no events intense enough to cause overflow of bioretention facility surface reservoirs at either site, or with enough intensity and volume to cause underdrain discharge at the Pittsburg facilities.

However, the data collected are sufficient for comparison of facility performance with the performance predicted by the model. See Section 6.

6 · Analysis and Results

This section describes the modeling and data analysis methods that were used together to characterize the performance of the Pittsburg and Walden Park Commons IMPs. This section contains the following details:

- Evaluation of rain gauge data for the monitoring period and a comparison of monitored storm events to long-term rainfall statistics for the area.
- Evaluation of IMP monitoring data and the potential implications of the hydraulic characteristics on long-term IMP performance.
- Comparison of HMP model results and IMP monitoring data.
- Description of model parameter adjustments to produce closer agreement between the model outputs and IMP monitoring data.
- Discussion of the current IMP sizing factors and their adequacy for meeting the NPDES permit's flow duration control standard.

Additional modeling and analysis details are contained in Appendix A.

6.1 Comparison of Simulated and Recorded Data

6.1.1 Storm Characteristics

Rainfall accumulations for the 2011-12 and 2012-13 monitoring periods were examined to determine how the monitoring period compares to long-term trends in the Pittsburg and Walnut Creek areas. The purpose of this analysis was to assess whether the monitored storms are representative for the area and whether the storms produced enough rain to adequately characterize the long-term performance of the IMPs at the Fire Prevention Bureau Building in Pittsburg and Walden Park Commons in Walnut Creek.

For the Pittsburg site, the closest rain gauge with a long-term record is Los Medanos, which is located between Pittsburg and Antioch. For Walnut Creek, the closest representative rainfall gauge with a long-term record is the FCD11 gauge located in Martinez.

Table 6-1 shows the seasonal rainfall totals at each project rain gauge and the long-term seasonal averages at the Los Medanos and Martinez gauges. At Pittsburg, the total rainfall was 13 percent below average for the first monitoring season and about average for the second season. At Walden Park Commons, the rainfall was 5 percent below average for the first monitoring season and 24 percent below average for the second season.

Table 6 1. Seasonal Rainfall Totals

Pittsburg Fire Prevention Bureau

Season	Dates	Project Site Rainfall (in)	Los Medanos Avg. Rainfall (in)	Difference
1	Oct-2011 – Apr-2012	6.84	7.85	-13%
2	Sept-2012 – May-2013	8.14	8.20	-1%

Walden Park Commons

Season	Dates	Project Site Rainfall (in)	Martinez Avg. Rainfall (in)	Difference
1	Nov-2011 – Apr-2012	17.19	18.05	-5%
2	Sept-2012 – May-2013	14.69	19.31	-24%

Even though the total rainfall was less than average over the monitoring period, there were several significant events during each season. Table 6-2 and Table 6-3 list the 10 and 13 largest rainfall events that were recorded during the monitoring period at the Fire Prevention Bureau and Walden Park Commons, respectively. The Walden Park Commons list was expanded to capture three events for which both outflow rates and storage pipe levels were recorded. The “recurrence” column in the two tables refers to how often a storm of similar magnitude would be expected to occur, based on the long-term rainfall data. Depth-duration-frequency curves were developed for the Los Medanos and Martinez sites for this analysis.

Table 6 2. Pittsburg Fire Prevention Bureau Site Storm Events

Start Date	Duration (hours)	Total (in)	Recurrence (12-hr)
1/19/2012	90	1.45	3-month
3/15/2012	49	0.66	3-month
3/24/2012	13	0.65	3-month
4/12/2012	40	1.20	3-month
10/22/2012	26	0.51	<3-month
11/21/2012	9	0.45	<3-month
11/28/2012	56	1.64	2-year
12/1/2012	17	1.12	1-year
12/21/2012	46	1.00	3-month
12/25/2012	14	0.50	3-month

Table 6 3. Walden Park Commons Site Storm Events

Start Date	Duration (hours)	Total (in)	Recurrence (12-hr)
1/19/2012	95	3.51	1-year
2/29/2012	36	1.01	<3-month
3/13/2012	109	2.59	3-month
3/24/2012	17	1.03	3-month
3/27/2012	16	0.89	<3-month
4/10/2012	79	2.81	3-month
11/20/2012	11	0.92	3-month
11/29/2012	69	4.64	2-year
12/21/2012	69	2.32	3-month
12/25/2012	24	0.79	<3-month
2/19/2013	9	0.34	<3-month
3/30/2013	36	0.76	<3-month
4/4/2013	8	0.29	<3-month

The number of significant storm events during the monitoring period is very consistent with the long-term local rainfall record. For example, there were 8 events that exceeded the 3-month recurrence (for 12-hour rainfall accumulations) at the Fire Prevention Bureau site and 7 events surpassing this threshold at the Walden Park Commons site. This is important, because 3-month storm events would be expected to produce flow rates that approach the lower control threshold flow rate in the County's current NPDES permit (two-tenths of the two-year flow rate, or 0.2Q2). Additionally, the Fire Prevention Bureau and Walden Park Commons sites both experienced 2 rainfall events that were larger than the 1-year (12-hour) storm. In conclusion, the monitoring period included enough storms across a range of intensities and total accumulations to adequately demonstrate how the IMPs perform.

6.1.2 Observed IMP Performance Characteristics

For each significant storm event, IMP monitoring data were examined to better understand the following soil hydraulics and performance characteristics:

1. Percolation of stormwater from the ponding layer through the bioretention soils into the storage layer
2. Infiltration of treated stormwater from the storage layer to the surrounding soils (note: this applies only to the Fire Prevention Bureau bioretention IMPs)
3. Performance of storage layer and frequency of underdrain discharges
4. Any evidence of performance problems

Percolation Characteristics

At the Fire Prevention Bureau site, a slotted-standpipe monitoring well was installed within the gravel storage layer of each monitored IMP. At the Walden Park Commons site, water levels were monitored in the vaults at the downstream end of the storage pipes. The IMP percolation characteristics were examined by comparing the timing and volume of rainfall to the appearance of water within the storage layer at each IMP.

The monitoring data shows that percolation begins after relatively modest levels of rainfall. In the 2004-2005 HSPF model, bioretention soils were modeled using the van Genuchten relationship for water retention. This relationship dictates that percolation rates in sandy-loamy soils would be minimal until the soil reached about three-quarters saturation. However, water appeared in the gravel layer before that volume was reached.

Similar runoff and percolation characteristics were observed at the Fire Prevention Bureau and Walden Park Commons IMPs. The bioretention soils are faster-draining than we expected when creating HSPF models for the HMP.

Figure 6-1 shows an example percolation response for the March 16-18, 2012 storm event at IMP #2 at the Fire Prevention Bureau. The observed depths in the gravel storage layer begin to climb after the first 0.07 inches of rainfall. Based on the tributary area and our initial assumptions about the soil's water retention characteristics, we expected this initial runoff to be fully absorbed within the bioretention soils, filling the available pore spaces like water fills the void spaces in a sponge.

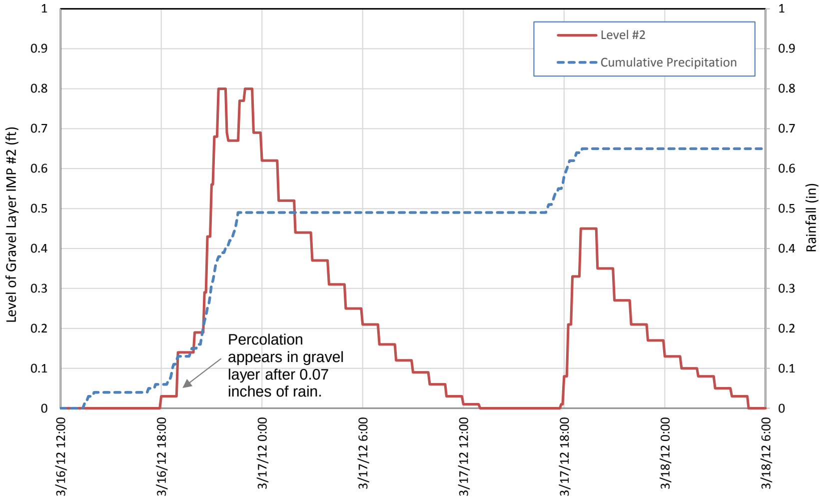

Figure 6-1. Percolation and infiltration, Fire Prevention Bureau IMP #2.

In general percolation in IMP #2 occurred after 0.07 to 0.16 inches of rain, except during an extended wet period from late-November through December 2012 when soils remained wet between storms and percolation began almost immediately after the start of a rain event. In IMP #6 percolation started later in storm events, usually after 0.3 to 0.8 inches of rain (Figure 6-2). IMP #4 is much smaller than the other IMPs and is about two-thirds larger the necessary, based on the HMP sizing factors. IMP #4 did not produce a consistent response to rainfall.

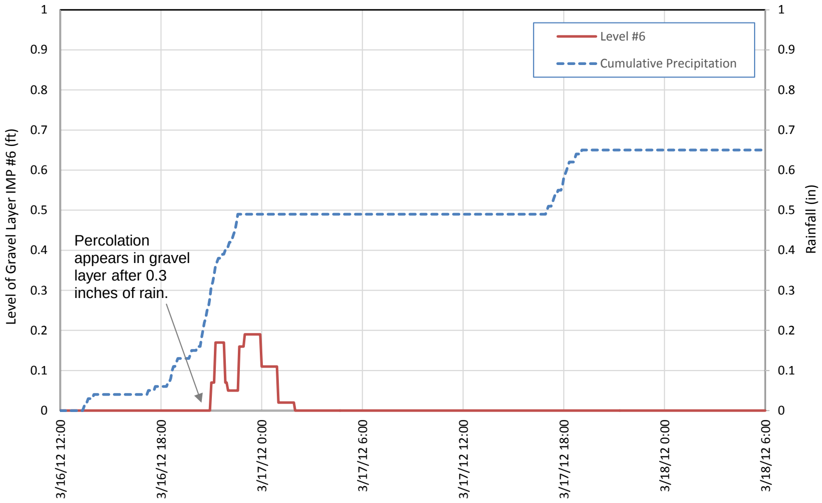

Figure 6-2. Percolation and Infiltration, Fire Prevention Bureau IMP #6.

The reasons for the different response times at IMP #2 and IMP #6 were evaluated. The large roof area adjacent to IMP #2 discharges water via three downspout connections. This water may be saturating the soils in the immediate vicinity of the downspouts and generating percolation to the gravel layer without wetting other portions of the bioretention facility.

Conversely, IMP #6 spreads inflows more broadly and provides a larger soil volume to capture stormwater runoff.

At Walden Park Commons stormwater quickly appears in the storage layer soon after rainfall begins. Figure 6-3 shows accumulated rainfall and IMP outflow for an April 2012 storm event at IMP #1 (North). The storage pipe has received enough percolation to produce outflow after 0.1 inches of rainfall is recorded.

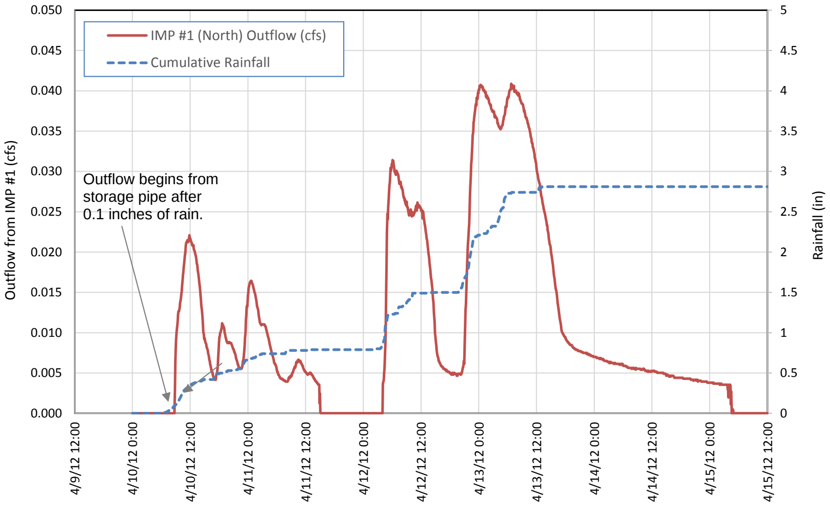

Figure 6-3. Stormwater appears in storage pipe shortly after rain begins IMP #1 (North).

Figure 6-4 shows the start of percolation at IMP #2 (South). The percolation starts later in IMP #2 (South) because a) bioretention area is larger and b) more of the tributary area contains pervious surfaces. The relative responses at IMP #1 (North) and IMP #2 (South) are similar for other storm events.

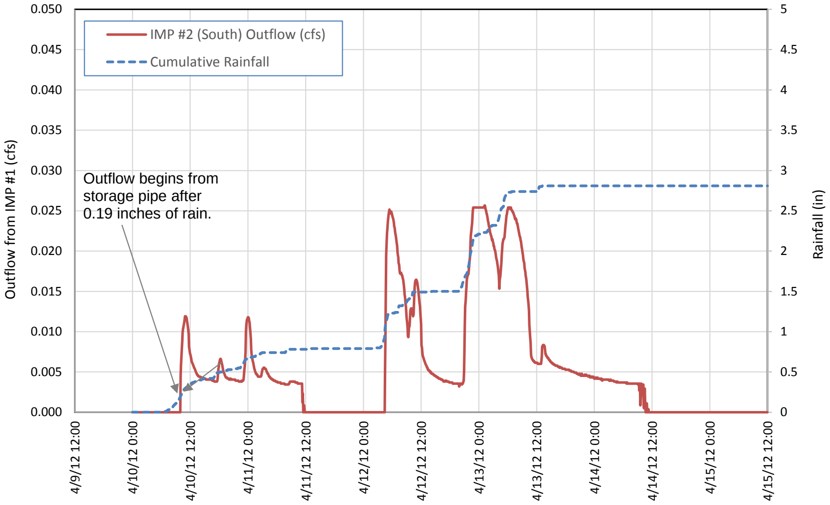

Figure 6-4. At IMP #2 (South) stormwater runoff appears in storage pipe more slowly than in IMP #1 (North)

In conclusion, the bioretention soils appear to allow percolation at lower soil moisture content levels than we expected when preparing the HMP. The effect is less pronounced in over-sized bioretention installations, such as Fire Prevention Bureau IMP #6 and Walden Park Commons IMP #2 (South). This characteristic will probably have a negligible effect on IMP performance. One potential benefit of the fast-percolating soils is the reduced likelihood stormwater building up in the ponding layer and spilling into the overflow in response to high-intensity rainfall.

Infiltration Characteristics

The infiltration characteristics of the surrounding soils were first evaluated at the Fire Prevention Bureau site, where the IMP gravel layers discharge directly to the surrounding soils. Figure 6-5 shows the recorded water levels in the storage layer at Fire Prevention Bureau IMP #2 for the November 28-30, 2012 storm event. Figure 6-6 shows the same storm event at IMP #6.

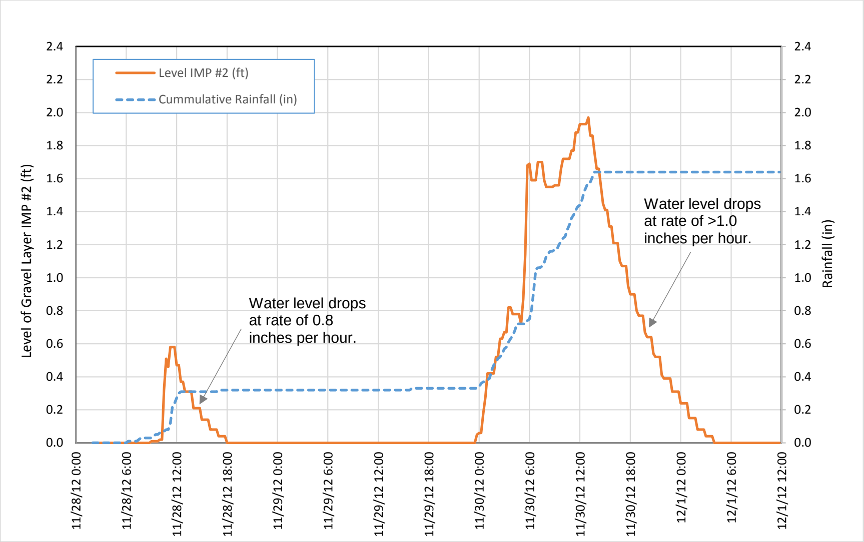

Figure 6-5. Storm recession rates at Pittsburg Site37 IMP #2

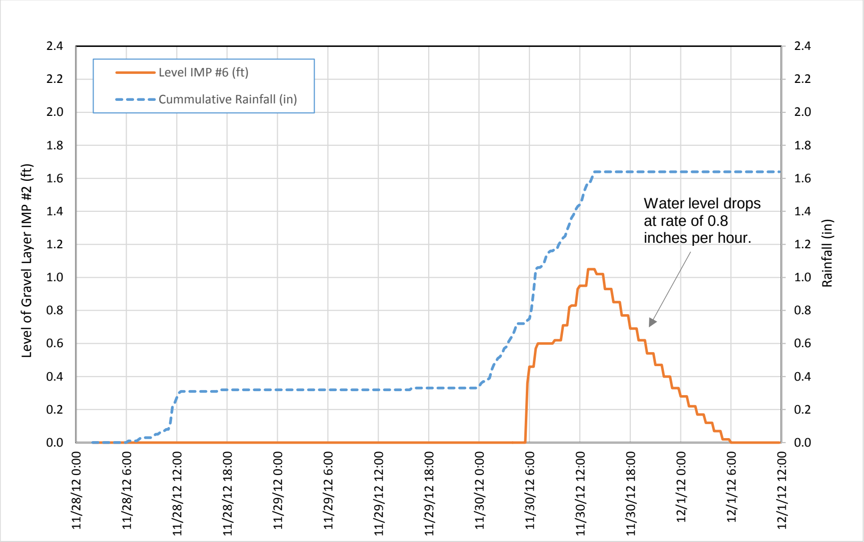

Figure 6-6. Storm recession rates at Fire Prevention Bureau IMP #6

After the rain stops, the water level in the storage layer decreases quickly—at a rate between 0.8 inches per hour and more than 1 inch per hour. Several storm events were examined and while the rate varied by storm in all cases the recession rate was higher than expected for NRCS Group D soils. Even late in the winter season, there was no noticeable groundwater mounding-related reduction in infiltration capacity. The Fire Prevention Bureau infiltration rates surpass the assumed rate of 0.024 inches per hour used in the 2004-2005 HSPF model.

In conclusion, soils at the Fire Prevention Bureau infiltrate runoff more rapidly than the reference values for NRCS Group D soils. IMPs at this site will provide a higher overall onsite stormwater capture fraction than previously expected. These IMPs should also provide a higher level of performance relative to the NPDES permit's flow duration performance standard.

The native soil characteristics for the Walden Park Commons site were indirectly evaluated using a combination of monitoring data and modeling (see Section 6.1.3).

Storage Layer and Underdrain Performance

The Fire Prevention Bureau monitoring data for IMP #2, IMP #4 and IMP #6 were also examined to determine a) how often the flow monitoring equipment registered underdrain discharge, and b) whether these discharges were caused by the filling of the gravel layer.

The items below describe the monitoring data results, which are also summarized in Table 6-4.

- IMP #2: Small underdrain discharges were recorded at 10 separate days over the 20 month monitoring period. The total volume of these discharges was less than 3 cubic feet. None of the discharges lasted more than 15 minutes and only four occurred during the 10 largest rainfall events. In all cases the corresponding water depth did not reach the level of the discharge pipe. The mostly likely reasons for the underdrain discharge are that a small amount of water migrated into the underdrain pipe as it was descending into the gravel layer, and/or that rain fell directly into the tipping bucket.
- IMP #4: Small underdrain discharges were recorded on 16 separate days with the total discharge over 20 months of 4.4 cubic feet. Similar to IMP 2, the discharge volumes are very small and not continuous. The observed water level in the gravel layer never reached the elevation of the under-drain pipe.
- IMP #6: Small underdrain discharges were recorded on 21 separate days with the total discharge over 21 months of 6.6 cubic feet. Similar to IMP 2 and IMP 4, the discharge volumes are very small and not continuous. The observed water level in the gravel layer never reached the elevation of the underdrain pipe.

Table 6 4. Pittsburg Fire Prevention Bureau Monitored Discharge Events			
IMP	Number of Underdrain Discharge Events*	Number of Events Due to Filling of Underdrain Layer	Total Volume
IMP #2	10	0	2.7 ft^3
IMP #4	16	0	4.4 ft^3
IMP #6	21	0	6.6 ft^3

*These discharge events each produced a small volume of water and were most likely due to the migration of water into the underdrain pipe as the water descended into the gravel layer, and/or rain falling directly into the tipping bucket.

Evidence of IMP Performance Issues

No significant or systematic IMP performance issues were evident from the monitoring data or from anecdotal observations during storm events. As noted in Section 5, the overflow risers in the bioretention facilities at Walden Park Commons were installed using perforated pipe, rather than the specified solid pipe. This allowed an unknown portion of stormwater flow to bypass the bioretention treatment. The contractor for the Walden Park Commons project corrected the problem on March 6, 2012.

Summary of Observed IMP Performance

The IMPs at the Pittsburg Fire Prevention Bureau Building and Walden Park Commons successfully captured, treated, detained, and slowly discharged stormwater from all storms during the two-year monitoring period. There were no overflows or significant performance issues.

The infiltration capacity of the native soils at the Pittsburg site will provide a higher level of onsite stormwater control and should allow these IMPs to surpass the flow control requirements of the NPDES permit. Additionally, the bioretention soils allow for faster percolation than was assumed when preparing the HMP. While this difference is not likely to affect the IMP sizing factors, it will protect the system from overflows during periods of very intense rainfall.

6.1.3 Comparison of Model Predictions to Measured Results

Model predictions and monitoring data (primarily water level) were compared for the 10 largest storm events during the 20-month monitoring period at the Fire Prevention Bureau (see Table 6-2 above for list of events).

Figure 6-7 shows an example comparison for Fire Prevention Bureau Building IMP #2 for the April 10-14, 2012 storm event.

Figure 6-8 shows the same storm event for IMP #6. As expected from the monitoring data review, the models do not produce early-storm percolation to the gravel storage layer that was observed in the monitoring data. The models also allow water to remain in both IMP layers for longer periods, which will make the Pittsburg site's model simulations overstate the site's sensitivity to back-to-back storms.

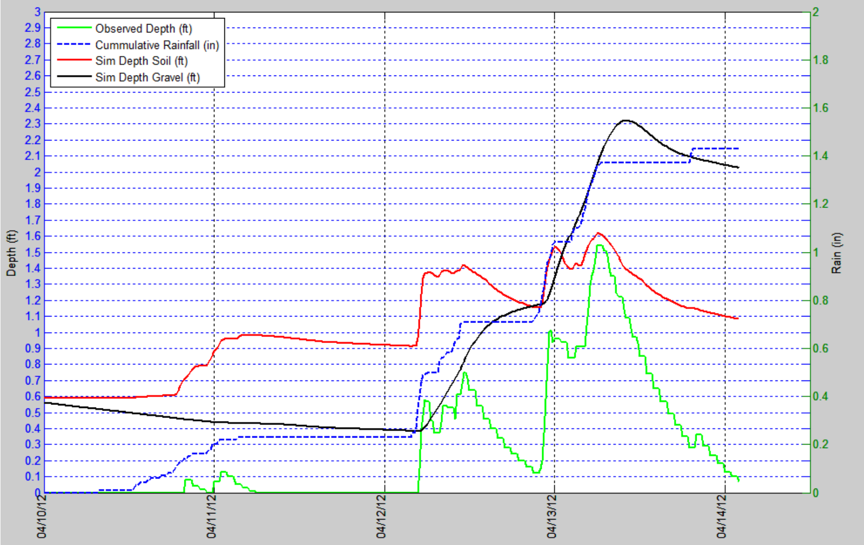

Figure 6-7. Model output and monitoring data comparison at IMP #2 from 4/10/12 to 4/14/12

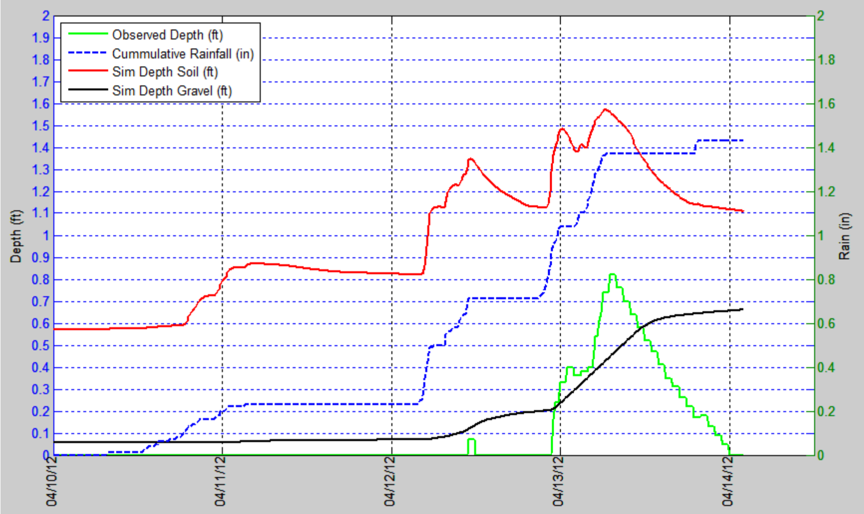

Figure 6-8. Model output and monitoring data comparison at IMP #6 from 4/10/12 to 4/14/12

The number of simulated and observed underdrain discharge events was also compared for IMP #2, IMP #4, and IMP #6. The

HSPF model predicts more frequent discharges through the underdrain pipe. Table 6-5 summarizes the model results.

Table 6 5. Pittsburg Fire Prevention Bureau Model Discharge Events

IMP	Number of Underdrain Discharge Events	Total Volume	Notes
IMP #2	6	2,700 ft3	Each event lasts several hours
IMP #4	0	0 ft3	
IMP #6	2	87 ft3	Each event lasts several hours

At the Walden Park Commons site, there were a limited number of storms with water level data, but flow rates were recorded through both monitoring seasons. Therefore the simulated and observed outflow volumes were compared for the 13 largest rainfall events during the monitoring period. Figure 6-9 and Figure 6-10 show example results for two separate storm events for IMP #1 (North), which is located in the northwest corner of the Walden Park Commons development. Similar to the initial Fire Prevention Bureau comparison, the monitoring data shows a faster percolation response in the IMP. The model simulation produces higher outflow volumes than were measured.

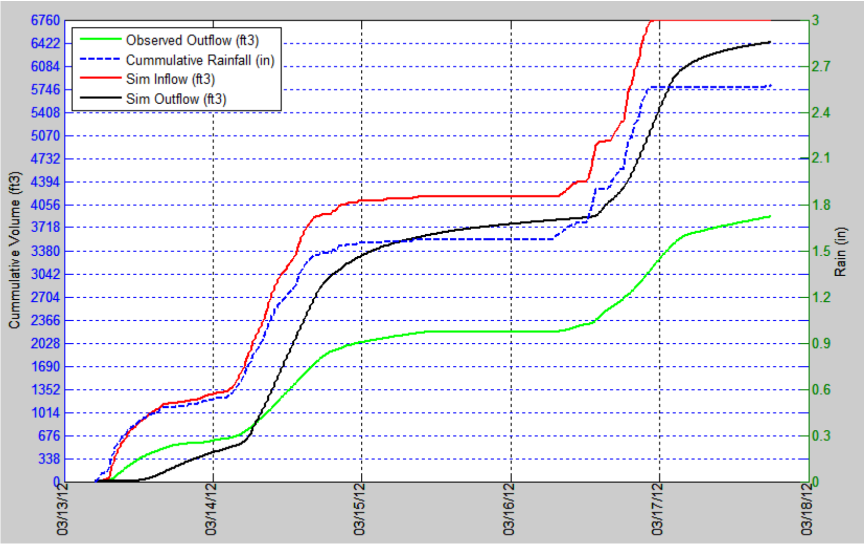

Figure 6-9. Model output and monitoring data comparison at Walden Park Commons IMP #1 (North) from 3/13/12 to 3/18/12

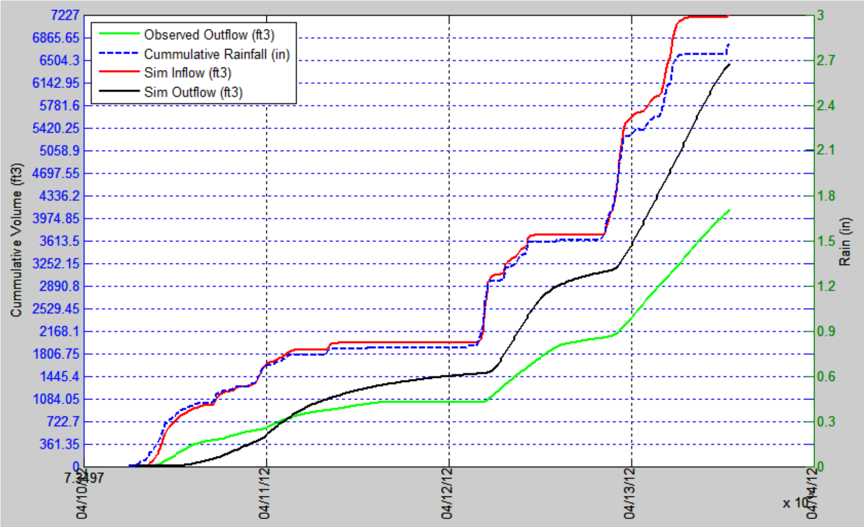

Figure 6-10. Model output and monitoring data comparison at Walden Park Commons IMP #1 (North) from 4/10/12 to 4/14/12

Figure 6-11 and Figure 6-12 compare the simulated and measured cumulative outflow volume for Walden Park Commons IMP #2 (South) for March and April 2012 storm events. The results of the comparison are similar to results for IMP #1 (North). The model simulation produces larger outflow volumes than were observed in the monitoring data.

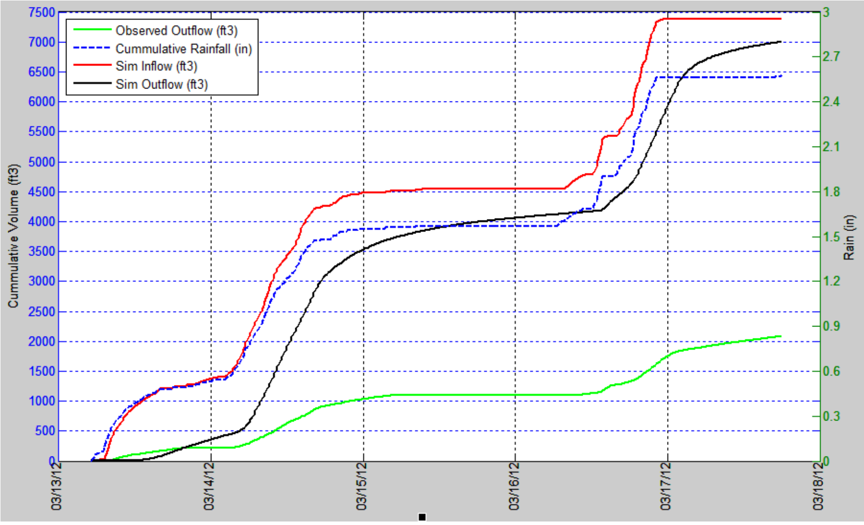

Figure 6-11. Model output and monitoring data comparison at Walden Park Commons IMP #2 (South) from 3/13/12 to 3/18/12

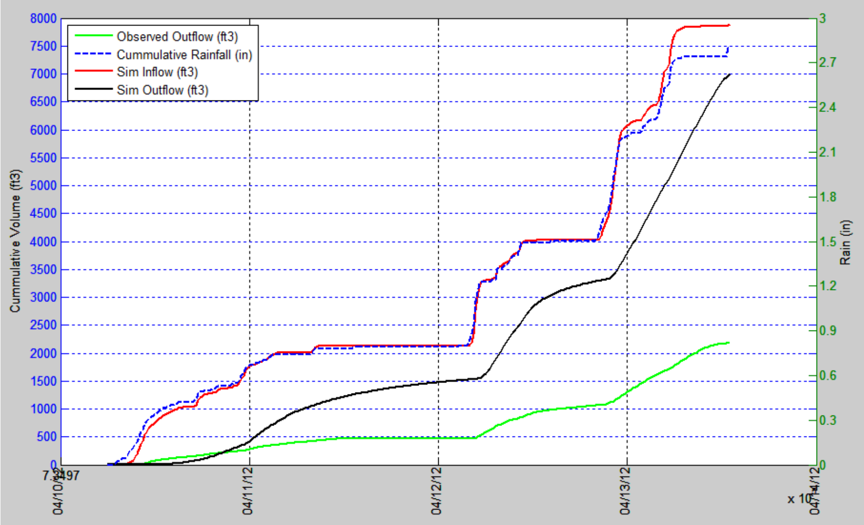

Figure 6-12. Model output and monitoring data comparison at Walden Park Commons IMP #2 (South) from 4/10/12 to 4/14/12

6.2 Adjustment of Model Parameter Values

To reduce the simulated IMP outflow and better match the monitoring data, the infiltration characteristics of each IMP were adjusted. The initial effort focused on the following revisions to Walden Park Commons IMP #1 (North):

1. The relationship between soil moisture and percolation in the bioretention soil was modified to allow percolation to begin soon after water enters the soil. The previous version of the HPSF model held back most percolation until the moisture content reached about 80 percent of saturation.
2. A zone of influence was established around the bioretention layer's underdrain. Because the monitored outflow was significantly less than the estimated inflow to the IMP, we assumed a portion of the stormwater entering the bioretention portion of IMP #1 (North) was infiltrating to surrounding soils. Similar losses to infiltration were evident in the data for IMP #2 (South).

The zone of influence value was iteratively modified until the IMP outflow volume better matched the monitoring data across a range of storm events. Figure 6-13 and Figure 6-14 show the updated results for the same two storm events included in the previous section (see Figures 6-9 and 6-10). For the zone of influence value selected, the simulated outflow volume closely matches the monitored outflow volume. For this value, 60 percent of the bioretention area drains to the underdrain and storage pipe, and the remainder infiltrates runoff to the underlying soils.

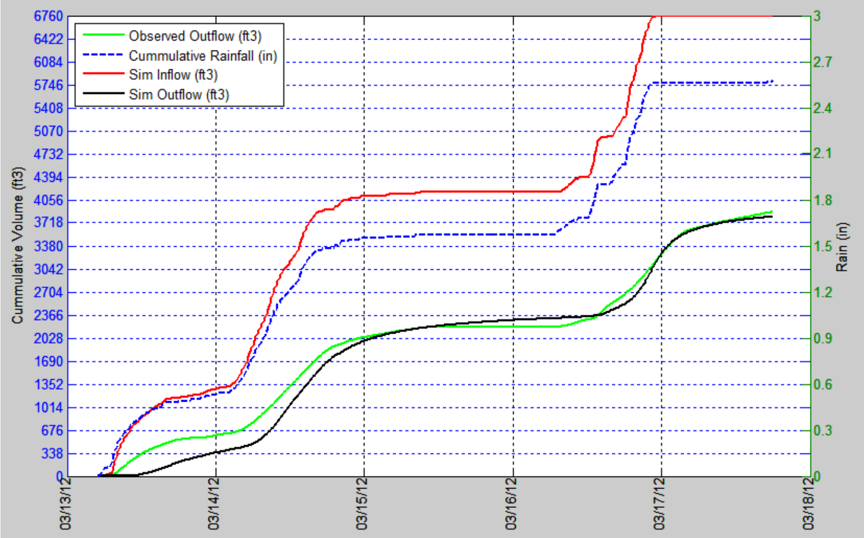

Figure 6-13. Updated model output and monitoring data comparison at Walden Park Commons IMP #1 (North) from 3/13/12 to 3/18/12

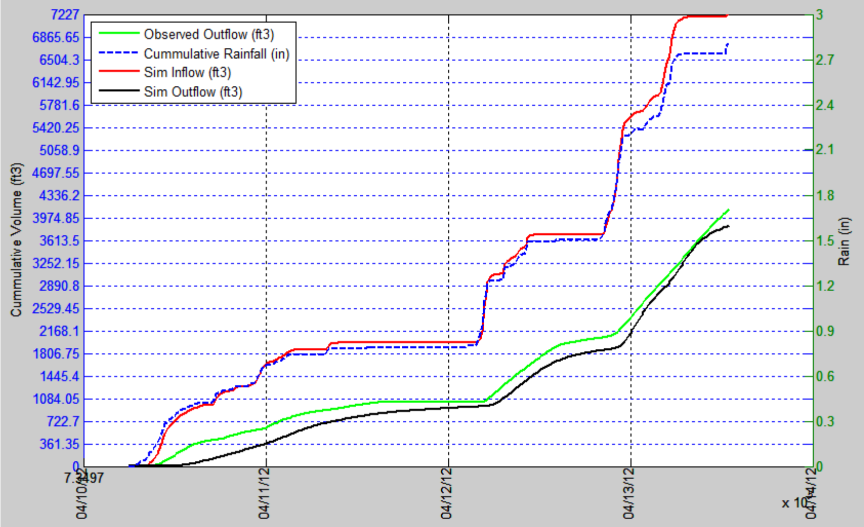

Figure 6-14. Updated model output and monitoring data comparison at Walden Park Commons IMP #1 (North) from 4/10/12 to 4/14/12

The model was also calibrated to match the response of IMP #6 at the Fire Prevention Bureau. The IMP model parameters were adjusted to a) represent the capacity of the bioretention soils to hold water prior to start of percolation, b) mimic the rapid percolation that occurs once the soil moisture threshold is met, and c) approximate the rate at which water drops in the gravel layer by adjusting the infiltration rate to surrounding soils. This parameter also affects the simulated water level in the gravel layer during storm events.

Figure 6-15 shows an example of the calibrated model's response for the November 28, 2012 storm event. This was the largest event during the monitoring period and represents about a 2-year storm for the Pittsburg area. During the initial stages of the storm the simulated water moisture content rapidly accumulates in the bioretention soil while very little water appears in the gravel layer. When the second phase of the storm occurs, percolation occurs rapidly and the gravel layer fills with more than 1 foot of water (note: the underdrain is located about 2½ feet above the bottom of the gravel layer). The simulated maximum depth matches the monitored maximum depth to within 1 inch. The simulated gravel water level recession is a little more rapid than the monitored recession. In general, the simulated and observed recession rates are similar across the range of storm events.

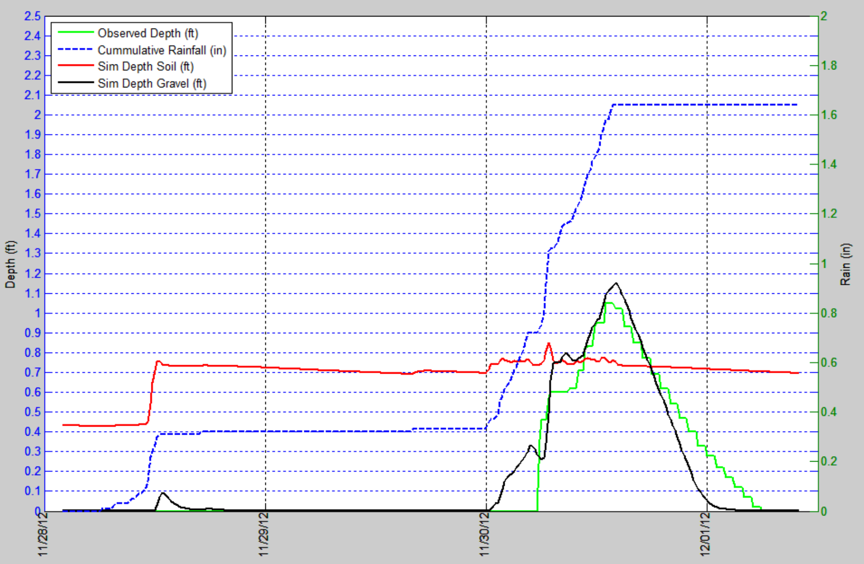

Figure 6-15. Updated model output and monitoring data comparison at Fire Prevention Bureau IMP #6 from 11/28/12 to 12/1/12

Figure 6-16 shows calibration results for a smaller storm event that occurred on March 25, 2012. This 0.65-inch event has about a 3-month (12-hour) recurrence interval. Similar to the larger event shown above, the initial rainfall is captured and held within the bioretention soils. Once the soil moisture threshold is met, stormwater percolates to the gravel layer. The simulated and monitored water levels match precisely and recession rates also agree very closely. There is an approximately one-hour offset between the simulated and monitored peak water levels, which will have no impact on the ability of the model to predict long-term IMP performance.

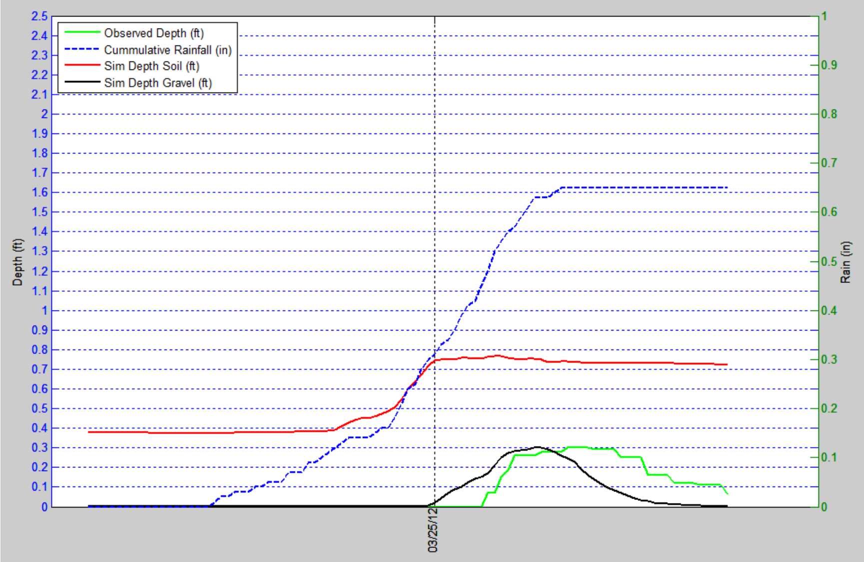

Figure 6-16. Updated model output and monitoring data comparison at Fire Prevention Bureau IMP #6 from 3/24/12 to 3/25/12

In conclusion, the bioretention characteristics were adjusted at the Walden Park Commons and Fire Prevention Bureau sites to achieve a closer agreement between the HSPF model predictions and the monitoring data. The infiltration rate to the surrounding soils was increased to 0.24 inches per hour for all the Fire Prevention Bureau IMPs.

The calibrated model adequately represents the key processing during and after storm events, specifically; a) the build-up of soil moisture, b) the percolation from bioretention soils to the storage layer and, c) the recovery of the IMP capacity through infiltration to surrounding soils (at the Fire Prevention Bureau). The calibrated model is suitable for the analysis of long-term IMP performance.

6.3 IMP Performance Compared to Flow Duration Standard

The IMP performance monitoring data review suggested the bioretention facilities at the Fire Prevention Bureau and the bioretention plus vault facilities at Walden Park Commons are likely to meet the NPDES permit requirements and may be performing in excess of these requirements by reducing flow durations below the pre-project flow durations for the specified range of flows (0.2Q2 to Q10).

Long-term HSPF simulations were run for the IMPs at both project sites to more fully test the IMP performance against the NPDES permit's flow control standard. The Fire Prevention Bureau simulations used hourly rainfall data collected at the Los Medanos gauge from 1972 through May 2013. The Walden Park Commons simulations used hourly data from the FCD 11 gauge in Martinez gauge from 1969 through May 2013. The following statistical analyses were then performed on the model outputs:

- Flow frequency statistics. The model outflow time series was divided into discrete flow events (i.e., a partial-duration series) using a 24-hour period of no flow to indicate the end of an event. The resulting table of events was sorted and ranked based on the peak flow rate. Each event was assigned a recurrence interval (sometimes referred to as a return period) using the Cunnane plotting position method. Partial duration series statistics were computed for the pre-project runoff and the post-project IMP outflows.
- Flow duration statistics. The model outflow time series was divided discrete bins (flow ranges). The number of hours – or duration – for which outflow occurred in each bin's flow range was then counted. These durations were computed for the pre-project runoff and the post-project IMP outflows.

Figure 6-17 shows the peak flow frequencies for the pre-project runoff and post-project (i.e., existing) outflow for Fire Prevention Bureau IMP #2.

Figure 6-18 compares flow durations for the pre-project and existing conditions. In both figures, the IMP outflows are below the pre-project flows between 0.2Q2 and Q10. Additionally, IMP #2 outflows are below the pre-project site flows down to the 0.1Q2 threshold. Because IMP #2 was constructed with dimensions that are very similar to the minimum required dimensions included in the HMP, this suggests IMP #2 would comply with a stricter lower control threshold of 0.1Q2. The infiltration rates at the Fire Prevention Bureau site allow for this level of performance.

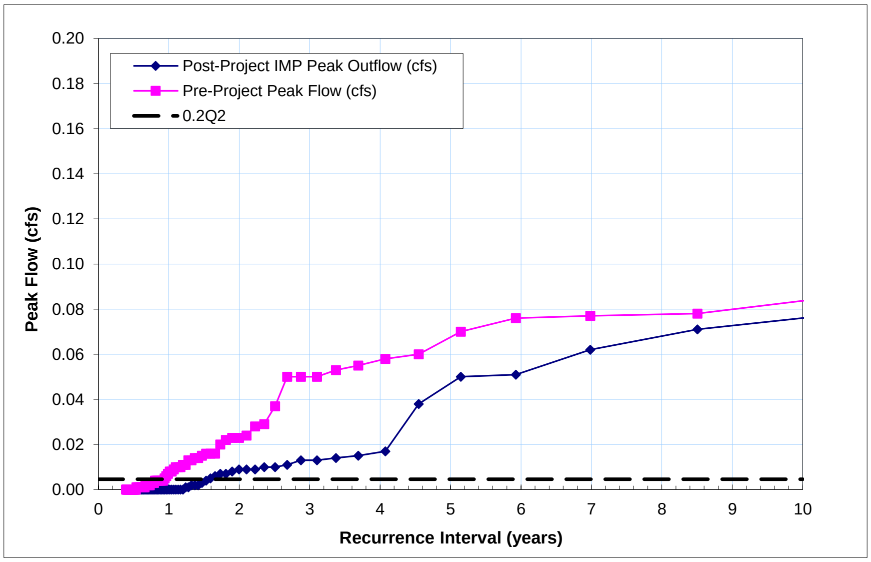

Figure 6-17. Peak flow frequency comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #2

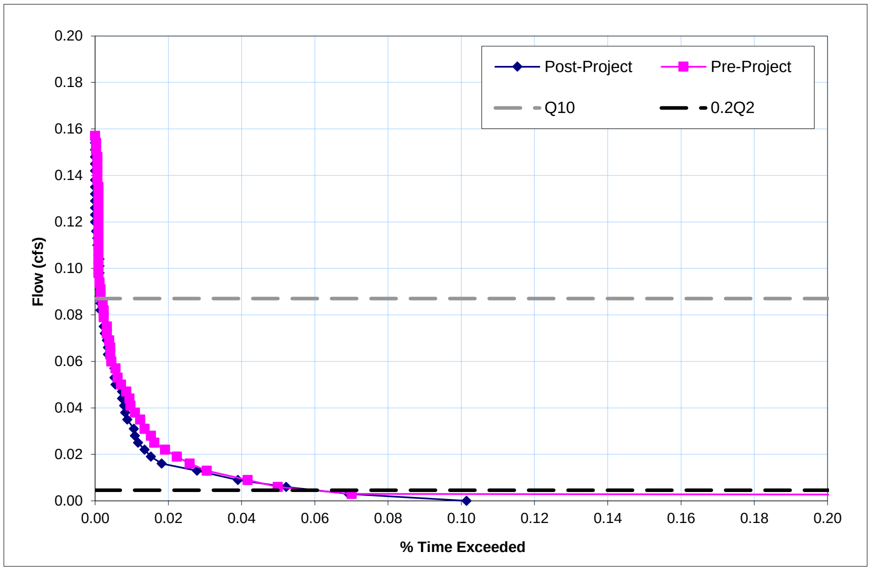

Figure 6-18. Flow duration comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #2

Figure 6-19 and Figure 6-20 compare peak flow frequencies and flow durations for Walden Park Commons IMP #1 (North), respectively. IMP #1 (North) reduces site runoff to levels below the pre-project conditions between 0.2Q2 and Q10. However, the model results indicate that IMP #1 (North) does not control flows down to the 0.1Q2 flow rate. To meet this standard, the flow control orifice diameter would need to be reduced and the storage volume potentially increased by a modest amount, and/or the storage volume would need to be allowed to infiltrate to subsurface soils—as in the *Guidebook* criteria for bioretention + vault facilities.

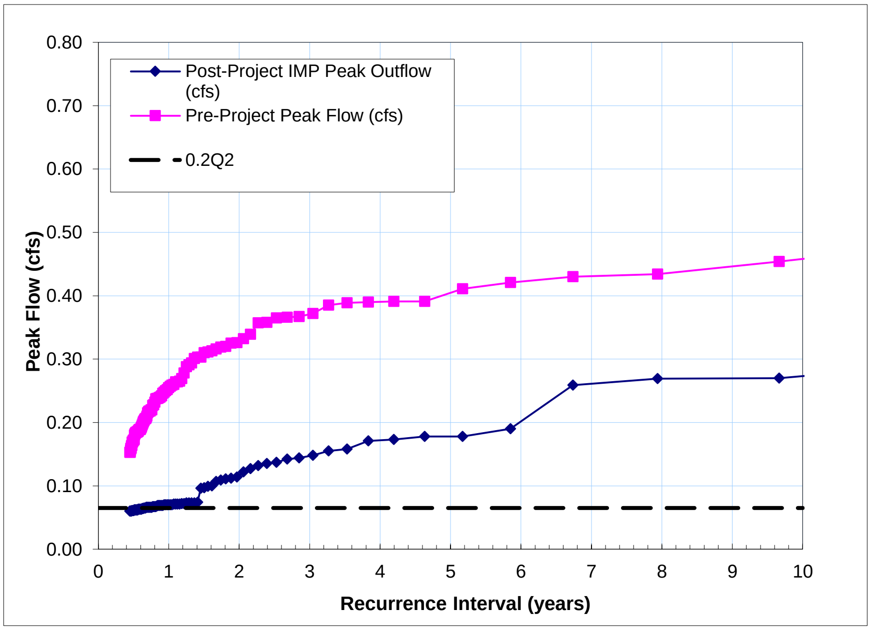

Figure 6-19. Peak flow frequency comparison for pre-project runoff and post-project outflows at IMP #1 (North)

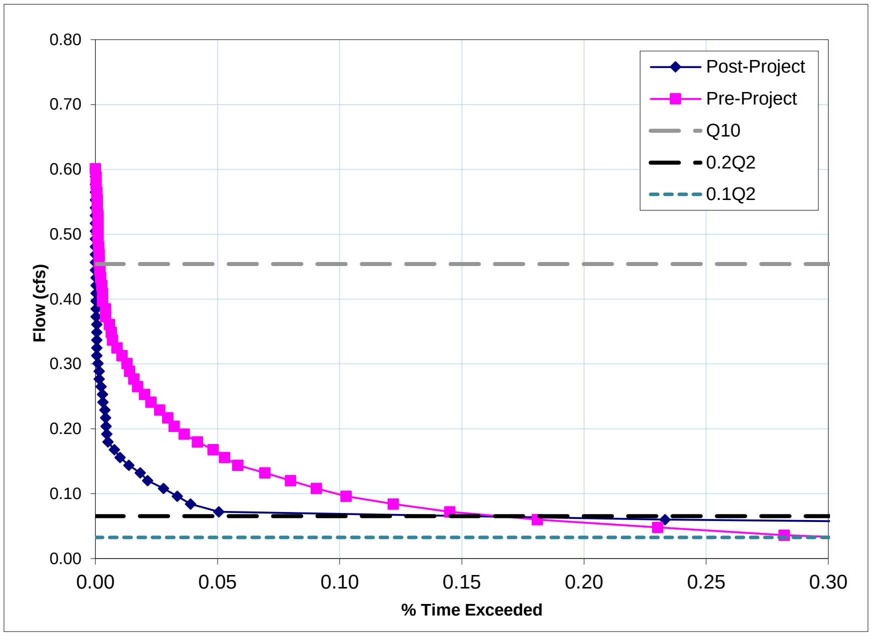

Figure 6-20. Flow duration comparison for pre-project runoff and post-project outflows IMP #1 (North)

All the IMPs successfully control outflows to their pre-project levels from 0.2Q2 to Q10. The Fire Prevention Bureau IMPs also control flows down to the 0.1Q2 threshold – benefitting from the infiltration capacity of site soil conditions. The Walden Park Commons do not control IMP outflows to the 0.1Q2 threshold, but the modeling results suggest this additional level of control could be achieved by a one or more of the following: modifying the orifice configuration, by allowing stored runoff to infiltrate to underlying soils, or by increasing the storage volume modestly.

7 · Discussion

7.1 Why These Results Are Important

The principal advantage of environmental modeling is the capability of modeling to extrapolate limited data sets to make predictions over an extended period and wide variety of conditions. However, because of limited data and the unpredictability of environmental conditions, a “garbage in, garbage out” scenario can occur, where model results are primarily a reflection of guesses and assumptions input to the model.

The 2004-2005 model used to determine CCCWP IMP sizing factors had the advantage of representing a relatively controlled system and the disadvantage of a paucity of available data representing bioretention system performance. That is, the model did, in concept, accurately represent the structure and function of bioretention facilities as they are actually built; however, there was a near-absence of data to inform the selection of values for the parameters that most strongly affect bioretention performance—most notably the rate at which treated runoff infiltrates to native soils.

Data collection for this project fills this gap, and greatly advances the CCCWP model. Previously the CCCWP model was dependent primarily on guessed and assumed values for the most important parameters; now it is based on empirically derived values. The CCCWP data may also be useful in updating similar models, such as the Bay Area Hydrology Model, that currently use guessed and assumed values for the model parameters that most strongly affect facility performance and HM compliance.

7.2 Percolation Through Bioretention Planting Media

As noted in Section 6, the model was set up with the assumption that the entire planting media layer would become mostly saturated before treated runoff proceeded to percolate into the underlying gravel layer. When modeled and measured results were compared, it was noted that runoff was measured in the gravel layer of the bioretetention facilties (at the Pittsburg Fire Protection Bureau Building) and in the storage vaults (at Walden Park Commons) much more quickly than the model predicted.

This may be occurring either because runoff percolates rapidly downward near the inlet, and much of the planting media layer did not get wet, or because the soil media exhibits less moisture-holding capacity and matric head than the model predicted, or both.

7.3 Infiltration to Native Soils

The capability of a bioretention facility to control volumes and durations of discharge is dependent on, among other factors, the rate of infiltration to native clay soils. This study demonstrated that infiltration at the five test locations is approximately 10 times faster than estimated in the 2004-2005 CCCWP model.

The estimate in the 2004-2005 CCCWP model was drawn from guidance for the use of HSPF at the watershed scale. The values selected for continuous-simulation models are typically based on calibration of models of runoff at the watershed scale—that is, to data sets consisting of local rainfall data and stream gauge data. The stream gauges represent flows collected from watersheds ranging from tens of acres to hundreds of acres.

Importantly, the resulting calibrated model values for key parameters representing losses of surface runoff to infiltration (in HSPF, "INFILT" is such a key parameter) do not necessarily correspond to results of infiltrometer tests or other direct tests of soil permeability. In fact, surface runoff losses at the watershed scale and movement of water through the pores of saturated soil are somewhat different physical processes.

The data collected by this project provide rare (perhaps unique) infiltration rate data and represent actual bioretention performance, rather than using an estimate of performance extrapolated from watershed-scale model calibrations or soil testing. Although limited to three bioretention facilities around a single 1-acre site, the data show that silty clays can, at least in some circumstances, infiltrate at rates in excess of 0.2 inches per hour—as measured by the recovery of a bioretention subsurface reservoir—and that these higher-than-expected rates are consistent throughout the season, for a range of storm sizes, and from facility to facility.

7.4 Applicability of Results Region-wide

The five IMP monitored locations are representative of typical Bay Area development patterns and conditions.

As noted in Section 5, the two bioretention + vault facilities at Walden Park Commons were constructed with some exceptions to current *Guidebook* design recommendations; these exceptions were incorporated into the customized model for the purposes of model calibration. The three facilities at the Pittsburg Fire Prevention Bureau Building were built very close to current *Guidebook* design criteria and design recommendations.

As previously noted, the rate at which runoff infiltrates to soils beneath the facility is a key factor determining overall performance. Are the infiltration rates found at the Pittsburg site representative of development sites in Contra Costa, or in the Bay Area as a whole?

There are no observed characteristics that would suggest otherwise. The site soils, described as "stiff to hard, moderately to highly plastic silty clays" in the site geotechnical report (Kleinfelder 2004) are typical of development sites throughout the Bay Area. The site is quite flat. Only the lack of near-surface groundwater would tend to suggest this site's soils could be better-draining than similarly classified soils at another Bay Area development site.

Collection of data from bioretention facilities at additional locations would be necessary to accurately estimate the average and variance of infiltration rates that might occur in similar soils.

8 · Conclusions and Recommendations

This project demonstrated that the IMPs and sizing factors approved by the Water Board in 2006—and updated in subsequent editions of the *Guidebook*—are adequate to meet current regulatory requirements.

8.1 Next Steps for Use of the Calibrated and Validated Model

MRP Attachment C requires:

> By April 1, 2014, the Contra Costa Clean Water Program shall submit a proposal containing one or a combination of the following three options (a.-c.) for implementation after the expiration and reissuance of this permit:
>
> a. Present model verification monitoring results demonstrating that the IMPs are sufficiently overdesigned and perform to meet the 0.1Q2 low flow design criteria; or
>
> b. Present study results of Contra Costa County streams geology and other factors that support the low flow design criteria of 0.2Q2 as the limiting HMP design low flow; or
>
> c. Propose redesigns of the IMPs to meet the low flow design criteria of 0.1Q2 to be implemented during the next permit term.

CCCWP intends to work with other Permittees (through BASMAA, the Bay Area Stormwater Management Agencies Association) and with Water Board staff to develop and agree upon revised HM permit requirements applicable to all MRP Permittees that:

- Favor, rather than constrain, the implementation of LID to meet HM requirements
- Consider a potential range of low flow thresholds for streams, with the aim of revising the thresholds to provide for reasonable protection of beneficial uses
- Have a more technically defensible basis for translation of in-stream criteria to LID facility discharge criteria; this basis should include consideration of the potential future

extent of watershed development and the proportion of the watershed that the proposed development represents

- Take into account that IMPs tend to reduce flow durations to below pre-project levels for flows in the middle of the range (the most geomorphically significant range, between 0.2Q2 and Q2)
- Consider the extent of potential Bay Area development that may be subject to HM requirements vs. the effort expended so far, and that may be expended in the future, on developing and implementing HM regulations
- Apply exceptions, exclusions, and thresholds uniformly among MRP Permittees
- Incorporate design requirements and sizing factors that reflect the results of this study

8.2 Insights Concerning Bioretention Design and Construction

The CCCWP project team worked with City of Pittsburg and City of Walnut Creek staff and with the engineers and construction project managers for each of the two developments. Overall cooperation was excellent and contributed greatly to the success of the CCCWP project.

The following insights are the author’s but resulted from the work of all involved.

8.2.1 Bioretention Design

To maximize the volume of runoff infiltrated, the facility must be configured so that each layer “fills up like a bathtub.” The top of gravel layer should be at a consistent elevation so that all pore areas within the gravel layer are filled evenly; likewise for the soil layer and for the surface reservoir. The surface reservoir should be surrounded by concrete curbs or landscape timbers to maximize its volume (as compared to sloping sides toward the center of the facility) and to facilitate verification that the reservoir is level and will fill evenly.

The project design should be reviewed prior to construction to ensure the stability of roads, walkways, and structures adjacent to bioretention facilities has been adequately considered. Because bioretention soils cannot be compacted, bioretention walls must effectively resist lateral pressure from surrounding soils. Where necessary, bioretention walls can be made impervious as a precautionary measure to protect adjacent roads, walkways, and structures while leaving the bottom of the bioretention facility open for infiltration.

Overflow structures are best constructed from precast manholes or catch basins. Construction crews have experience setting these structures at a precise elevation. Use of an adequately sized catch basin with a grate makes it possible to verify underdrain discharge visually and to access the underdrain pipe for cleaning or maintenance. Setting the underdrain discharge elevation at the top of the gravel layer may reduce the required depth of the overflow structure.

Overflow structures can also accommodate connections to site storm drainage pipes routed through the bioretention facilities.

Orifices on underdrains may be constructed of solid PVC pipe extending a few inches into the overflow catch basin structure, threaded, and equipped with a cap. The orifice is drilled into the cap as shown in Figure 4-4.

8.2.2 Bioretention Construction

It is necessary to have an engineer familiar with the structure, function, and details of bioretention to review construction at each stage (layout, excavation, installation of underdrains and overflows, installation of gravel and soil mix, irrigation systems, and planting). In particular, elevations should be checked and it should be ensured that the soils at the bottom of the excavation are ripped.

8.3 Recommendations for Instrumentation

Success in data collection was largely attributable to the participation of an experienced instrumentation technician (Scott McQuarrie, of the Contra Costa Flood Control and Water Conservation District). Installation of rain gauges, tipping buckets, magnetic flow meters, piezometers, dataloggers, and telemetry required considerable technical ingenuity and experience to configure at each site.

For future projects monitoring the hydrologic performance of bioretention facilities, including bioretention + vault facilities, it would be possible to rely on level sensors (piezometers) rather than flow sensors or tipping buckets. Piezometers are more reliable to operate and also provide information on saturation levels. Orifice factors and/or rating curves for each fabricated orifice could be determined prior to installation. This could be done by plumbing the fabricated orifices to a small tank or reservoir and timing the falling head. Once installed, the discharge rate through the orifice, for each time interval, could be calculated from the corresponding piezometer reading.

8.4 Further Research

As noted above, it would be meaningful to obtain data from bioretention facilities installed in clay soils at additional sites. An additional 3-8 sites could be sufficient to demonstrate the regional applicability of the results found here.

This study showed the value of obtaining time-series for (1) rainfall and (2) saturation depth of the subsurface storage (gravel layer). It is recommended to select, where possible, facilities located on public development projects, as it is easier to coordinate documentation of design and construction of bioretention facilities on these projects.

As noted above, the monitoring effort could be reduced by installing only rain gauges at each site and only piezometers in each facility. As a rough estimate, instrumentation could be installed at an equipment cost of $7,000 and about 12 hours of technical labor for each facility. This does not include the cost of maintaining the instrumentation and downloading the data.

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APPENDIX A
IMP Modeling Analysis and Results

This appendix supplements the modeling and data analysis results included in Section 6 of the HMP Model Calibration and Verification report. This appendix includes a detailed description of the project site model development, rainfall analysis, model calibration and long-term simulation results.

Section 1: Project Site HPSF Model Development

HSPF models were constructed for the Fire Prevention Bureau site in Pittsburg and the Walden Park Commons site in Walnut Creek. The models were adapted from the HPSF models that were developed for the HMP by including the drainage management area characteristics, IMP configurations of each site, and time series input data for each site.

The following site-specific modifications were made:

1. Setting up subcatchment areas within HSPF to represent the project site area
2. Modifying the bioretention IMP setup to represent the actual configurations of the IMPs – the constructed areas and volumes instead of the volumes required by the HMP.
3. Incorporating local time series data, including project site rainfall data in 15-minute increments.
4. Changing the model time step from 1 hour to 15 minutes. This also necessitated changing several conversion factors within HSPF – particularly for quantities that are calculated in HPSF as volumes or depths per time step (rather than per second or per hour).

Following these modifications, various QA/QC checks (e.g., comparing IMP inflow to rainfall volumes, comparing IMP layer 1 outflow and layer 2 inflow volumes) were performed to validate the model response.

1.1 Drainage Management Areas

The HPSF model's Drainage Management Area (DMA) characteristics were derived from drainage planning information provided by the Clean Water Program. For the Fire Prevention Bureau site, the Stormwater Treatment Plan (drawing sheet C-6, dated September 2009) included the drainage areas, soil types and other information needed for the model. For the Walden Park Commons site, the C.3 Plan – Stormwater Treatment Control Plan (drawing sheet C-1, dated July 2008) were used to characterize the DMAs. Table 1 lists the Fire Prevention Bureau DMA characteristics and Table 2 lists the Walden Park Commons DMA characteristics.

Table 1. Pittsburg Fire Prevention Bureau Site DMA Characteristics^{A}

DMA	Impervious Area		Pervious Area		Total Area	
	ft2	acres	ft2	acres	ft2	acres
DMA 2 (trib. to IMP 2)	12,059	0.2768	2,415	0.0554	14,474	0.3323
DMA 4 (trib. to IMP 4)	627	0.0144	0	0.0000	627	0.0144
DMA 6 (trib. to IMP 6)	3,152	0.0724	562	0.0129	3,714	0.0853

A. All pervious areas were simulated as NRCS Group D soil (PERLND 102)

Table 2. Walden Park Commons Site DMA Characteristics[A]

DMA	Impervious Area		Pervious Area		Total Area	
	ft2	acres	ft2	acres	ft2	acres
Tributary to IMP #1 (North)						
M	11,606	0.2664	2,153	0.0494	13,759	0.3159
N	21,695	0.4980	3,795	0.0871	25,490	0.5852
Total IMP #1 (North)	33,301	0.7645	5,948	0.1365	39,249	0.9010
Tributary to IMP #2 (South)						
D	7,780	0.1786	1,381	0.0317	9,161	0.2103
E	7,574	0.1739	1,252	0.0287	8,826	0.2026
J	5,382	0.1236	2,120	0.0487	7,502	0.1722
K	8,996	0.2065	1,658	0.0381	10,654	0.2446
L	3,198	0.0734	575	0.0132	3,773	0.0866
P	3,597	0.0826	509	0.0117	4,106	0.0943
Total IMP #2 (South)	36,527	0.8385	7,495	0.1721	44,022	1.0106

A. All pervious areas were simulated as NRCS Group D soil (PERLND 102)

1.2 IMP Characteristics

The DMA source data also contained information about the site IMPs. For the Walden Park Commons site, the *SWQ and Hydrology Study for Subdivision 9147* drainage report, dated October 2010, was also reviewed to obtain the total volume included in the storage pipes. Table 3 lists the Fire Prevention Bureau IMP dimensions and Table 4 lists the Walden Park Commons IMP dimensions.

At the Fire Prevention Bureau site, the IMPs were generally constructed with dimensions that were close to the requirements of the HMP. For example, the A (area) and V2 (gravel volume) components are IMP #2 are close to the IMP requirements while the V1 (ponding layer) component was larger than required. IMP #4 and IMP #6 were constructed with larger plan areas (A) but the volume ponding layer volume and gravel volume were close to the amount required by the HMP. The underdrain piping for the Fire Prevention Bureau IMPs were located near the top of the gravel layer to provide an opportunity for more of the treated water to infiltrate to the surrounding soils.

Table 3. Pittsburg Fire Prevention Bureau Site IMP Dimensions

IMP	Required Areas, Volumes			Constructed Areas, Volumes			Constructed Depths			Orifice Diameter (in)
	A (ft2)	V1 (ft3)	V2 (ft3)	A (ft2)	V1 (ft3)	V2 (ft3)	Ponding (in)	Soil (in)	Gravel (in)	
IMP #2	873	734	960	886	886	975	12	18	33	0.81
IMP #4	40	34	44	82.5	41	41	6	18	15	0.17
IMP #6	225	189	247	340	170	215	6	18	19	0.41

The Walden Park Commons bioretention plus vault IMPs were constructed with storage volume (V) components that approximated the HMP requirements. IMP #2 (South) was constructed with a bioretention area that is approximately 20 percent larger than required by the HMP.

Table 4. Walden Park Commons Site IMP Dimensions

IMP	Bioretention Area (ft2)	Storage Volume (ft3)	Orifice Diameter (in)
IMP #1 (North)	1,500	2,419	1.24
IMP #2 (South)	1,917	2,698	1.31

1.3 Time Series Data

Time series data were used to provide rainfall and evapotranspiration inputs to the HSPF model. Table 5 lists the time series datasets used and the periods covered by these datasets.

Table 5. HPSF Model Time Series Datasets

Dataset	Type	Source	Period	Usage
Fire Prevention Bureau Rainfall	Rainfall tipping bucket processed in 15-min increments	Contra Costa Flood Control District	Oct-2011 to May-2013	IMP hydraulic review and model calibration
Walden Park Commons Rainfall	Rainfall tipping bucket processed in 15-min increments	Contra Costa Flood Control District	Nov-2011 to May-2013	IMP hydraulic review and model calibration
Los Medanos Rainfall	Long-term rainfall in hourly increments	Contra Costa Flood Control District	Jul-1974 to Aug-2013	Long-term model simulations for Fire Prevention Bureau site
FCD11 Rainfall in Martinez	Long-term rainfall in hourly increments	Contra Costa Flood Control District	Feb-1969 to Aug-2013	Long-term model simulations for Walden Park Commons site
Brentwood Evaporation	Long-term ET data in hourly increments	CIMIS	Jan-1986 to Aug-2013	Model calibration and long-term simulations (with Los Alamitos ET data)
Los Alamitos Evaporation	Long-term ET data in hourly increments	EPA Basins software	Jul-1948 to Dec-1985	Long-term simulations combined with Brentwood. Provided pre-1986 ET data.

1.4 Model Time Step Adjustment

The HSPF models were adapted to run in either 15-minute or hourly time steps. The shorter time step provided better resolution of the IMP hydraulic processes during the model calibration process whereas hourly time steps were needed for the long-term simulations to match the available input time series data sources. Several hydrologic variables are computed by HSPF in time-dependent units (e.g., inches per time step), so conversion factors were needed to allow the model to run with different time steps. These conversions are documented within the HPSF input files (i.e., the UCI files) and listed in Table 6.

Table 6. HSPF Model Time Step Adjustments and Conversion Factors

HSPF Block	Description	Conversion Factor Revision
NETWORK	Outflow from upper layer of IMP (HYDR) is computed in cfs whereas input to lower layer (IVOL) is computed in acre-feet per time step	For 15-minute time steps: CONVERSION = [1 FT3/S] * [1/43560 AC/FT2] * [900 S/TS] CONVERSION = 0.0207 For 1-hour time steps: CONVERSION = [1 FT3/S] * [1/43560 AC/FT2] * [3600 S/TS] CONVERSION = 0.0826
NETWORK	IMP inflows (IVOL) are computed in units of acre-foot per time step and these data are converted to cfs for reporting via the PLTGEN file	For 15-minute time steps: CONVERSION = [43560 FT3/AC-FT] * [1/900 TS/S] CONVERSION = 48.4 For 1-hour time steps: CONVERSION = [43560 FT3/AC-FT] * [1/3600 TS/S] CONVERSION = 12.1
NETWORK	Pre-project site runoff rates (PWATER SURO) are computed in units of inches per time step. These data are converted to cfs for reporting via the PLTGEN file	For 15-minute time steps: CONVERSION = [43560 FT2/AC] * [1/12 FT/IN] * [1/900 TS/S] * [AREA in AC] CONVERSION = 4.0333 * [AREA in AC] For 1-hour time steps: CONVERSION = [43560 FT2/AC] * [1/12 FT/IN] * [1/3600 TS/S] * [AREA in AC] CONVERSION = 1.0083 * [AREA in AC]

After the conversions were applied, the model outputs were tested through a QA/QC process to validate the results.

Section 2: Rainfall Characteristics

This section supplements the description included in Section 6.1.1 of the HMP Model Calibration and Verification report, specifically the estimate of recurrence intervals for the storms that were recorded during the monitoring period.

To understand the monitored storm events within the context of long-term local rainfall characteristics, depth-duration-frequency curves were developed from the long-term hourly datasets recorded at the Los Medanos gauge and the FCD11-Martinez gauge. The following method was used to develop the curves:

5. The rainfall data was parsed into discrete storm events. A dry period of 24-hours was used to separate rainfall into distinct, independent events. The resulting set of storm events is called as a partial-duration series.
6. Each rainfall event was examined to determine the maximum amount of rain that occurred within specific periods of the storm (e.g., the maximum 3-hour accumulation, 6-hour accumulation) from durations of 1-hour to 72-hours.
7. The accumulations for each duration were ranked and assigned a recurrence interval using the Cunnane plotting position method (e.g., all 12-hour accumulations were ranked, all 24-hour accumulations were ranked).
8. A logarithmic regression relationship was developed to relate rainfall depth to recurrence interval for each storm duration from 1-hour to 72-hour. The regression equations were then used to compute curves shown in Figure 1 and Figure 2. The plots only include the computed durations up to 24-hours.

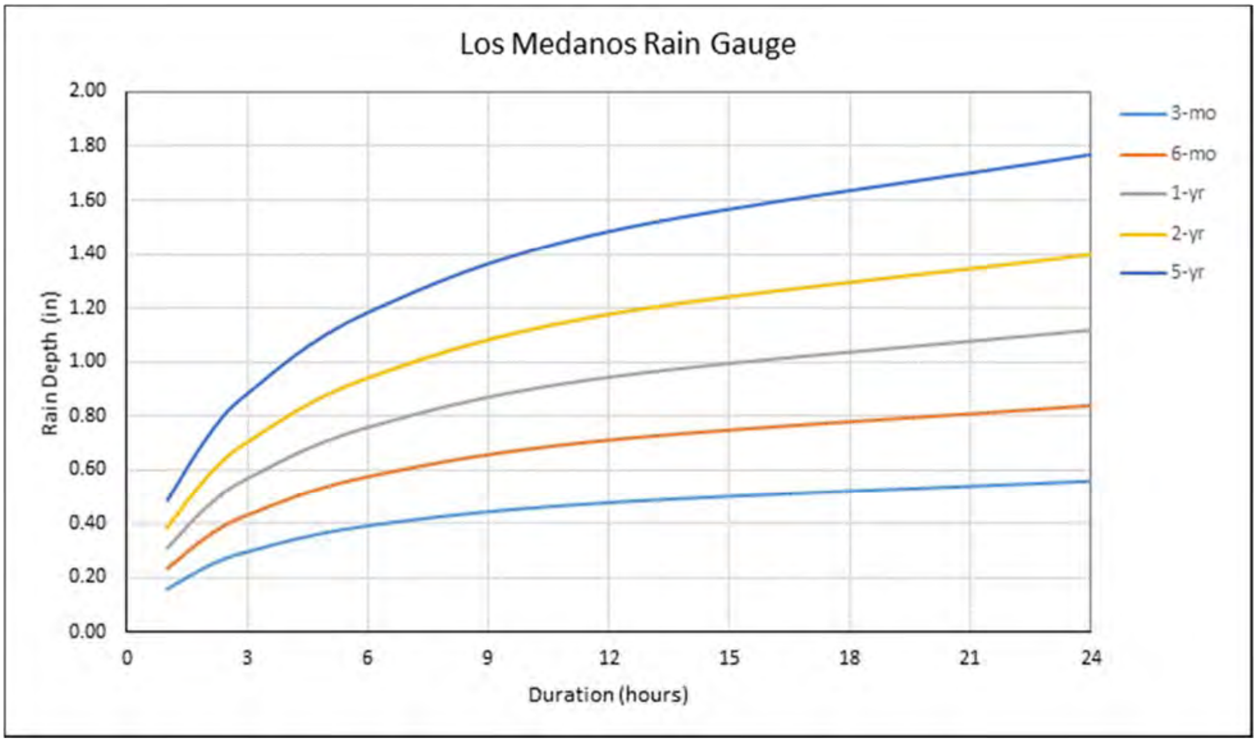

Figure 1. Depth-Duration Frequency curve for Los Medanos rain gauge. Curve was used to estimate the recurrence interval for storms monitored at the Fire Prevention Bureau site.

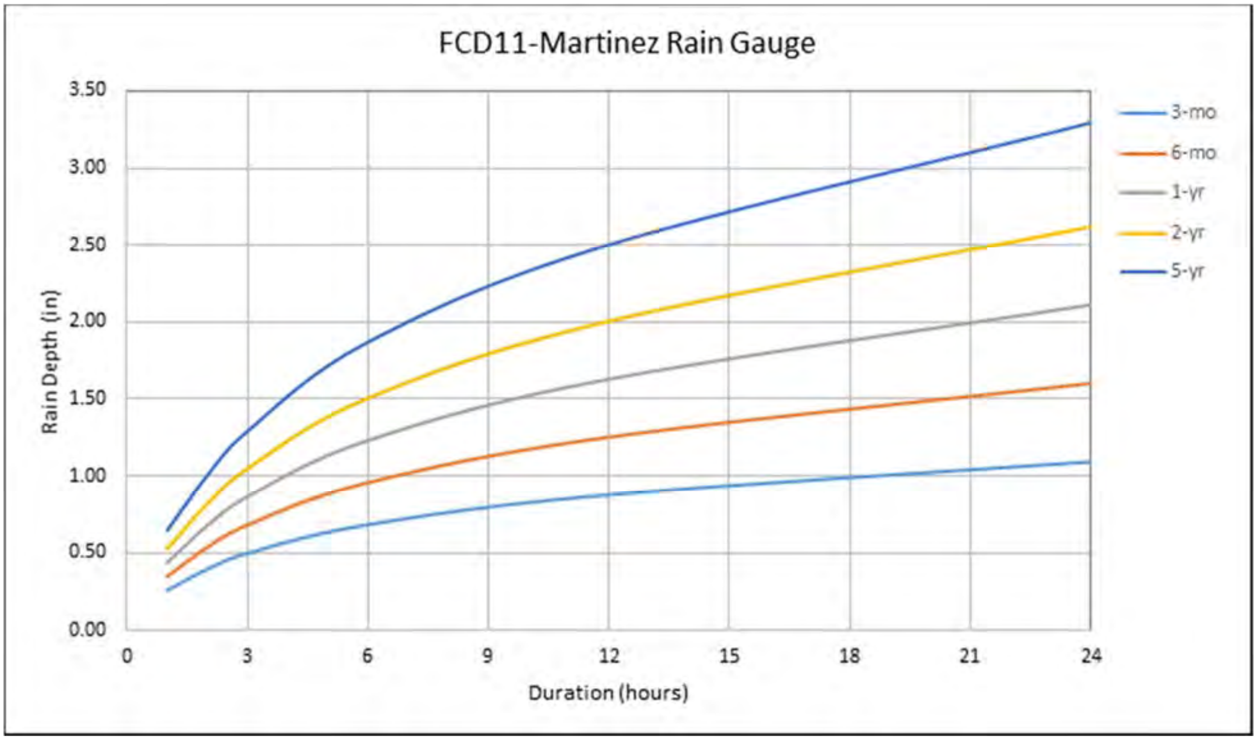

Figure 2. Depth-Duration Frequency curve for FCD11-Martinez rain gauge. Curve was used to estimate the recurrence interval for storms monitored at the Walden Park Commons site.

After the depth-duration-frequency curves were computed from the long-term rainfall datasets, similar partial-duration series rainfall accumulations were computed for the Fire Prevention Bureau and Walden Park Commons rain gauge data. The rainfall depth was computed for each significant storm for durations ranging from 1 hour to 72 hours. The accumulations were then compared to the long-term curves (either Figure 1 or Figure 2) to determine the recurrence interval for the monitored data.

Table 7 and Figure 3 provide an example of how the monitoring period storm recurrence intervals were estimated. The 11/28/2012 storm data provided a total of 1.64 inches of rain at the Fire Prevention Bureau gauge and Table 7 lists the maximum rainfall accumulation for specific periods within the storm event. These data are plotted over the long-term Los Medanos depth-duration-frequency curve in Figure 3 to provide context. The 11/28/2012 storm was approximately a 6-month to 1-year event for durations less than 6 hours. The 12-hour and 24-hour accumulations were approximately equal to a 2-year storm event.

Table 7. Rainfall Accumulations the 11/28/2012 Storm at the Fire Prevention Bureau

Duration (hour)	Rainfall (in)
1	0.31
2	0.38
3	0.44
6	0.69
12	1.20
24	1.32
48	1.33
72	1.64

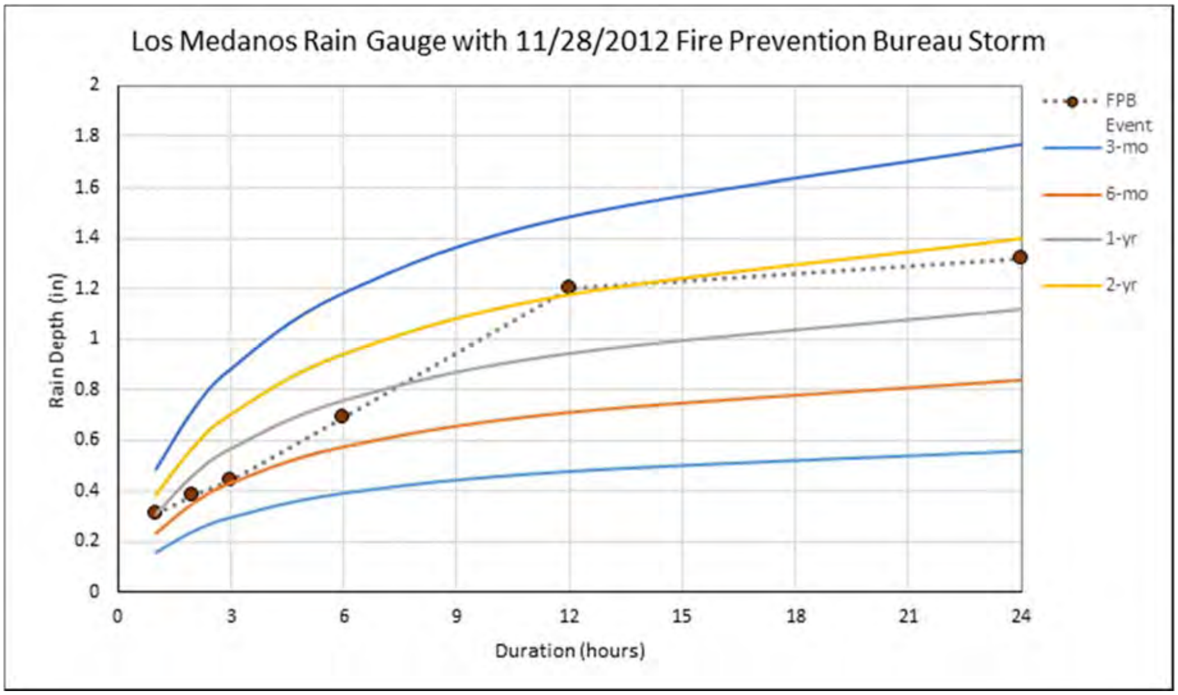

Figure 3. The 11/28/2012 storm event at the Fire Prevention Bureau was approximately a 2-year storm over a 12-hour duration.

Rainfall accumulations were compared to the depth-duration-frequency curves for all of the significant storm events listed in Table 6-2 and Table 6-3. The approximate recurrence interval was reported for 12-hour durations. This duration was selected because it balances both the short-term intensities and long-term accumulations that can affect IMP performance.

Section 3: HSPF Modeling Results

This section supplements the discussion included in Section 6.2 and 6.3 of the HMP Model Calibration and Verification report. It describes he model calibration process in greater detail and provides long-term simulation results for all IMPs.

3.1 Model Parameter Adjustments

This section describes how the model parameters were adjusted and provides additional example calibration results.

3.1.1 Bioretention Soil Characteristics

As described in Section 6.1.3, Fire Prevent Bureau bioretention soils produces faster percolation rates earlier and respond earlier in storm events than was predicted by the HPSF model used to develop the HMP. Additionally, the Fire Prevention Bureau IMPs produced significantly more infiltration to surrounding soils than the HPSF model predicted. The model calibration effort focused on these two key differences.

Rainfall and water level monitoring data and modeling results were examined to approximate a) what level of soil moisture is needed to initiative percolation from the bioretention soil to the gravel layer and b) at what rate does the percolation occur. The bioretention soils appear to produce little percolation until the soils reach about 50 percent of saturation. At this point, percolation occurs rapidly. While the precise rate was difficult to isolate, the monitoring data suggested percolation rates of up to 7.5 inches per hour could occur.

The HSPF model’s representation of the bioretention soils was iteratively modified based on the percolation response of Fire Prevention Bureau IMP #6 for different storm events. The adjustments focused on a) allowing the bioretention soils to hold almost all runoff during small storm events and b) percolating the appropriate volume of stormwater to the gravel layer during large storm events.

Figure 4 illustrates how the percolation characteristics were adjusted by showing the soil moisture-percolation relationship used in the HMP models and the modified relationship that was developed by examining the Fire Prevention Bureau monitoring data. The calibrated relationship allows water to move rapidly into the gravel layer when the bioretention soils fill with water and provides the appropriate level of soil drying between storm events.

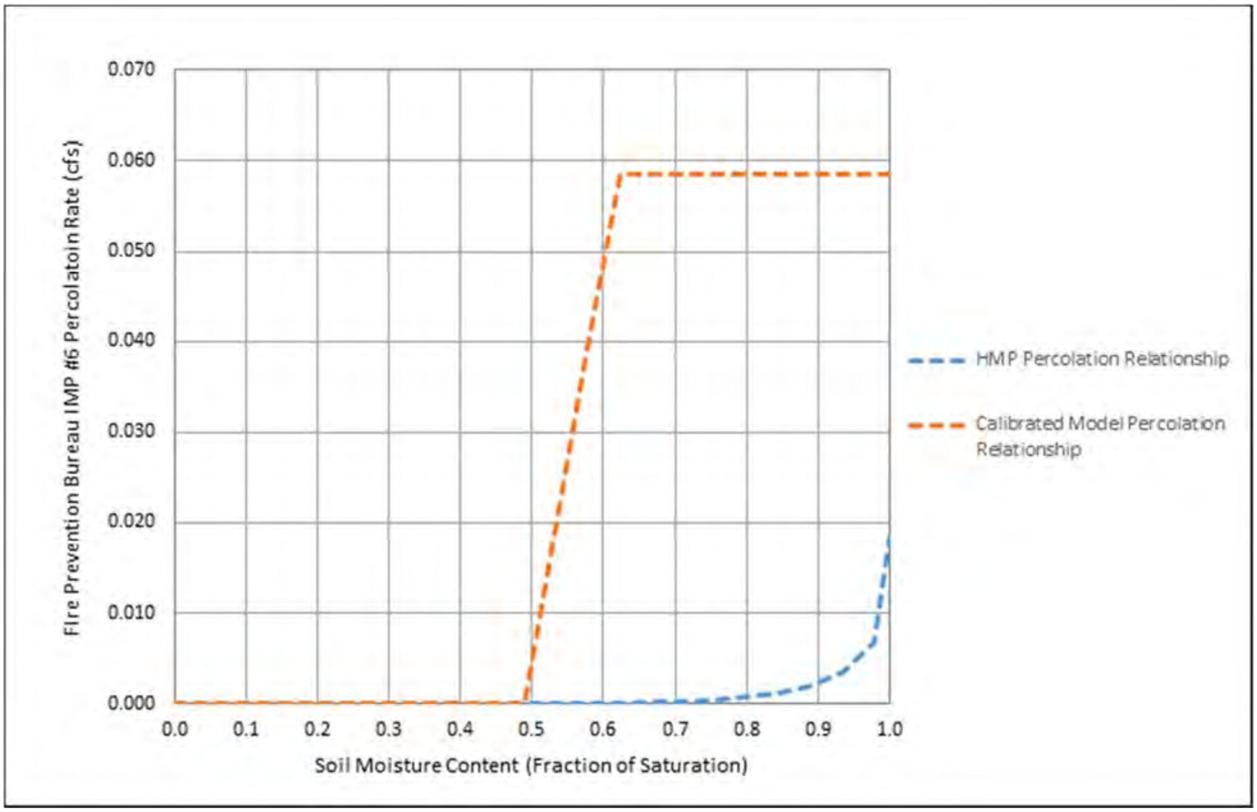

Figure 4. Soil moisture-percolation relationship for bioretention soils at the Fire Prevention Bureau

3.1.2 Infiltration to Surrounding Soils

The observed water level recession rates indicate that the NRCS Group D soils at the Fire Prevention Bureau allow for a greater level of infiltration than was expected when preparing the HMP. The HSPF model's rate of infiltration from the IMP gravel layer to the surrounding soils was adjusted iteratively until the shape of the water level curve approximated the level monitoring data across the largest storm events.

Several gravel layer-to-surrounding soils infiltration rates were tested and the best-fit rate for Fire Prevention Bureau IMP #6 was 0.24 inches per hour. Figure 5, Figure 6 and Figure 7 show the model results for the 11/28/2012 storm event with infiltration rates of 0.20 in/hr, 0.24 in/hr and 0.28 in/hr, respectively. The closest match occurs with the 0.24 in/hr simulation.

The IMP #6 calibration was then applied to the other Fire Prevention Bureau IMPs. The simulation results and monitoring data were compared for IMP #2 and the model results provided a good approximation of the monitoring data. A similar comparison was not practical at IMP #4 due to its small dimensions at IMP #4 and lack of a defined gravel layer response to rainfall.

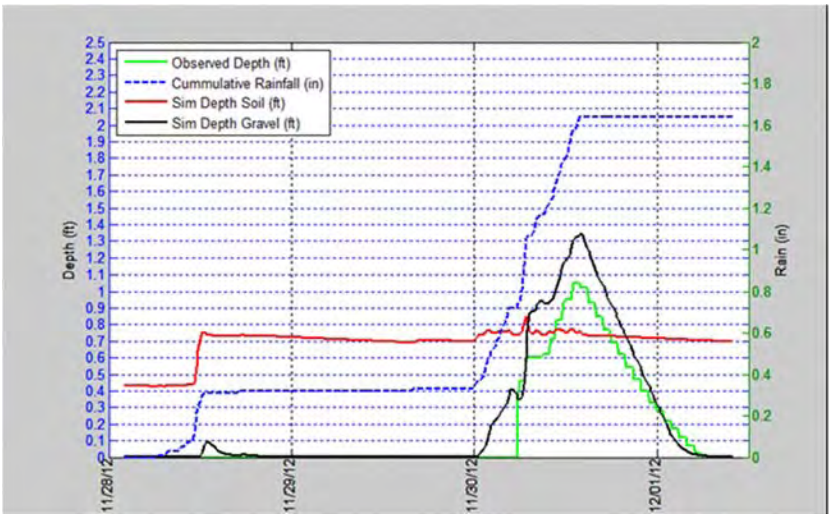

Figure 5. IMP #6 infiltration = 0.20 in/hr. Simulation > monitoring data

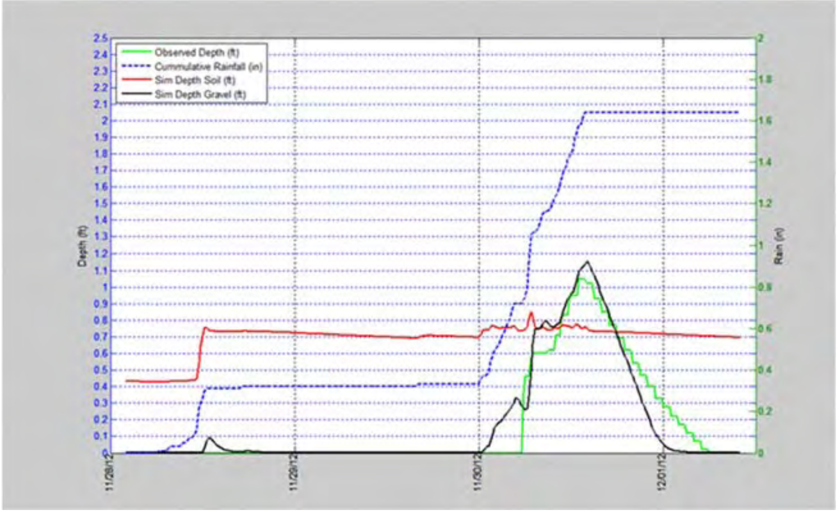

Figure 6. IMP #6 infiltration = 0.24 in/hr. Simulation ~ monitoring data

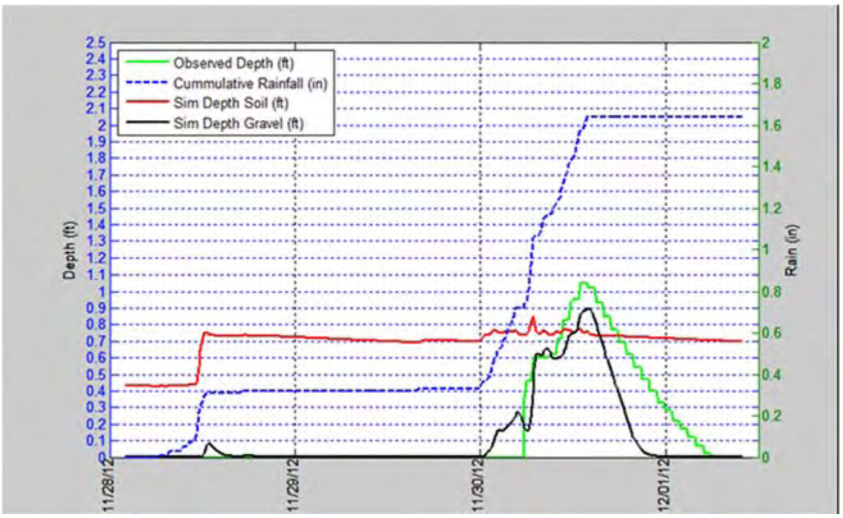

Figure 7. IMP #6 infiltration = 0.28 in/hr. Simulation < monitoring data

3.2 Long-Term Model Performance

This section describes the process for setting up the long-term model simulations and using the results to assess the performance of the Fire Prevention Bureau and Walden Park Commons IMPs in comparison to the HMP's peak flow and flow duration control standard.

3.2.1 Long-Term Simulation Setup

The calibrated models for the Fire Prevention Bureau IMPs and Walden Park Commons IMPs (see Section 6.3 for these examples) were used to prepare long-term simulations. The following steps were needed to prepare the long-term simulation models:

1. The FTABLE representations of the calibrated IMPs were copied into the HSPF long-term simulation input file.
2. The HSPF input file was linked to the long-term time series datasets described above in Table 5. The Fire Prevention Bureau simulations used hourly rainfall data collected at the Los Medanos gauge from 1974 through May 2013. The Walden Park Commons simulations used hourly data from the FCD11 gauge in Martinez from 1969 through May 2013. The evaporation time series dataset was composed of Los Alamitos data (pre-1985) and Brentwood data (1986 and later).
3. The HSPF input file unit conversions were applied as needed for the long-term simulations hourly time steps (see Table 6 for details).
4. The list of variables included model's time series output file (i.e., the PLTGEN file) were modified to allow for a comparison of pre-project and post-project conditions.

3.2.2 Long-Term Simulation Results

The long-term simulation outputs were evaluated using flow frequency statistics and flow duration statistics (see Section 6.3). Next, the IMP outflows were compared to pre-project flows to determine of the IMPs reduced peak flows and flow durations below pre-project levels. This section includes peak flow and flow duration graphics for all of the IMPs. Figure 8 through Figure 13 show results for the Fire Prevention Bureau site and Figure 14 through Figure 17 show results for the Walden Park Commons sites. All IMPs control flows to down to the current 0.2Q2 lower control threshold. Additionally, the Fire Prevention Bureau sites control flows down to the 0.1Q2 lower control threshold. The Walden Park Commons sites do not meet the stricter lower control threshold.

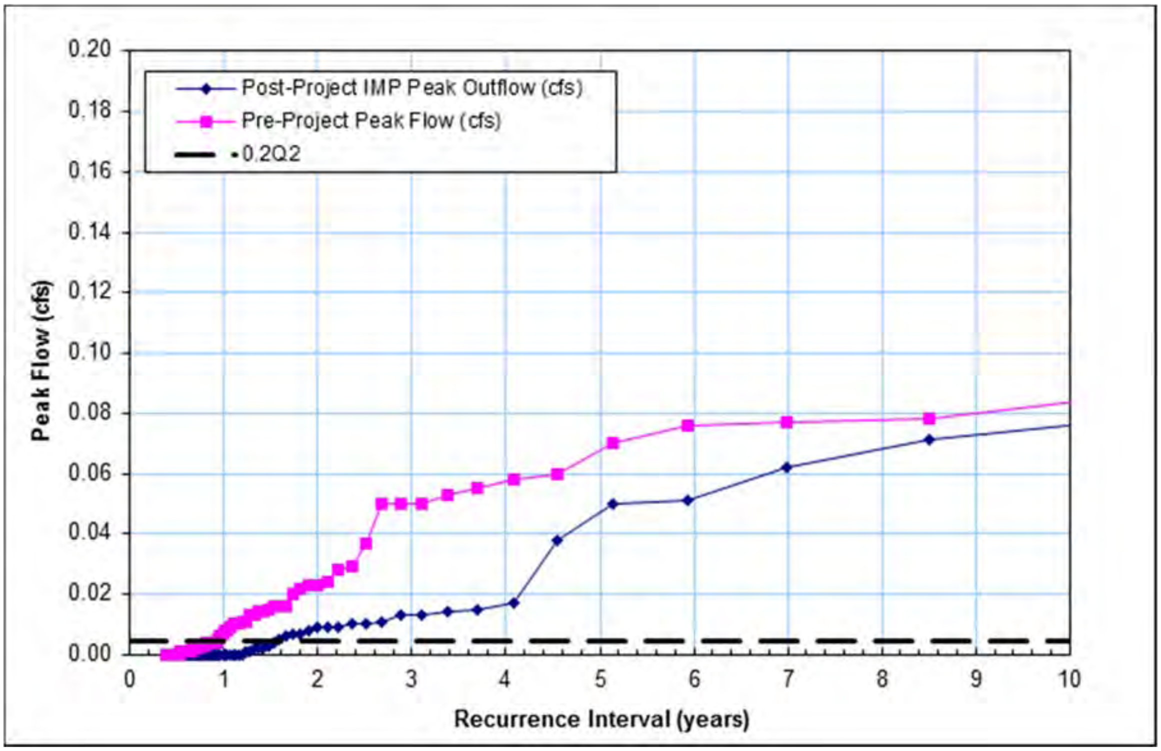

Figure 8. Peak flow frequency comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #2

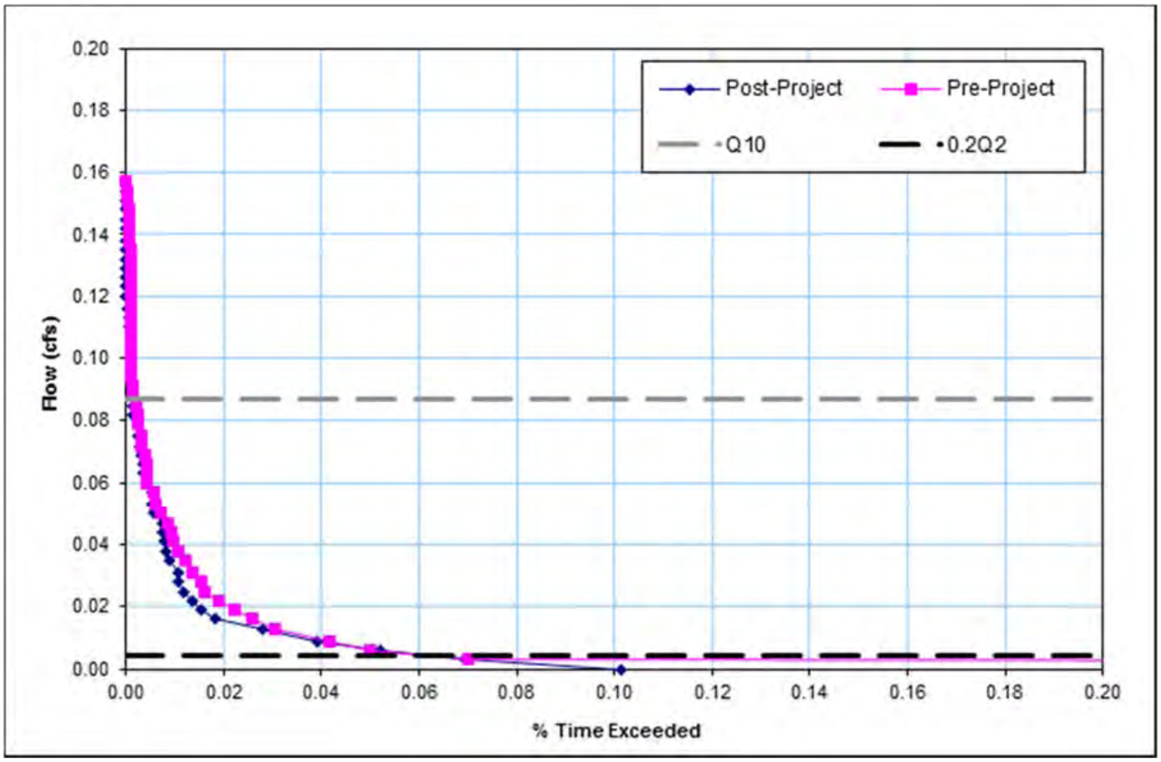

Figure 9. Flow duration comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #2

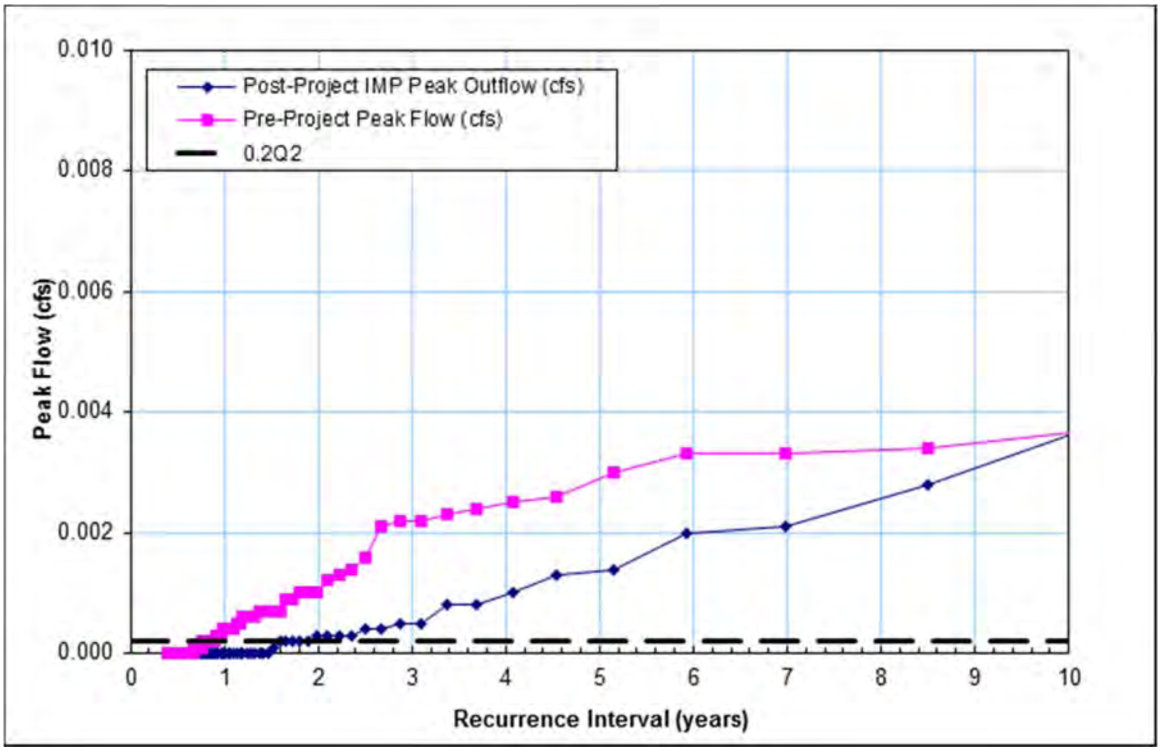

Figure 10. Peak flow frequency comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #4

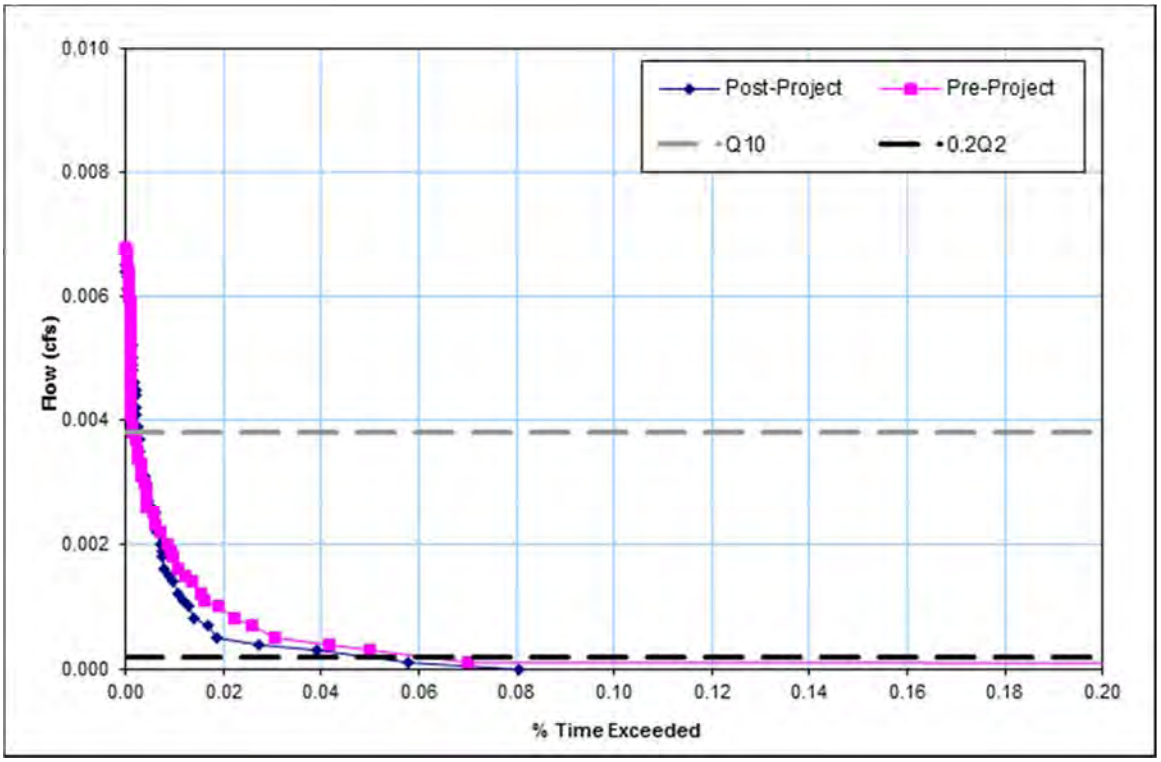

Figure 11. Flow duration comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #4

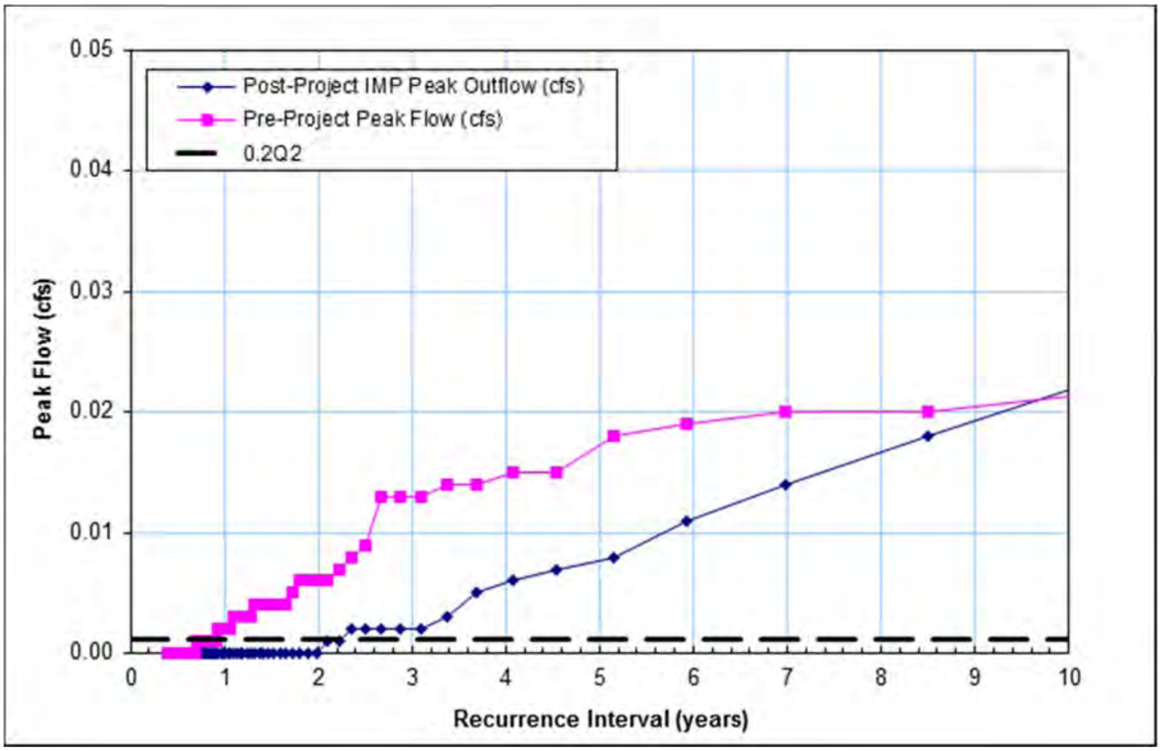

Figure 12. Peak flow frequency comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #6

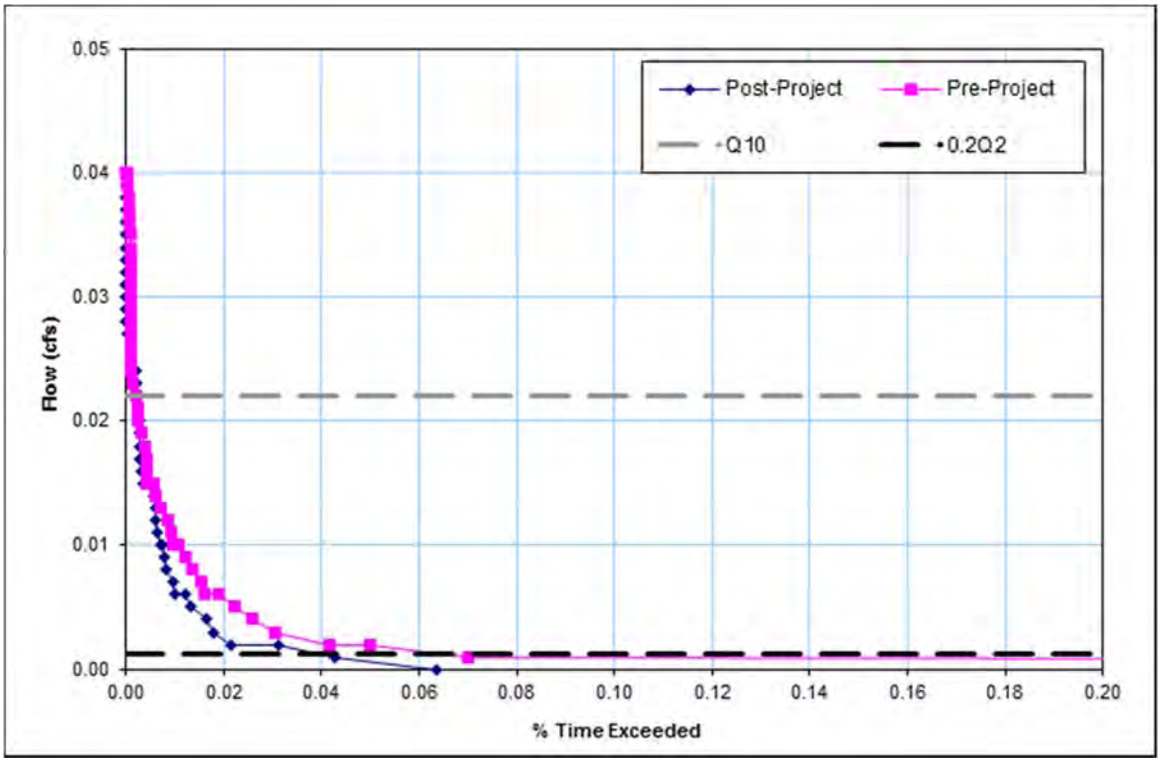

Figure 13. Flow duration comparison for pre-project runoff and post-project outflows for Fire Prevention Bureau IMP #6

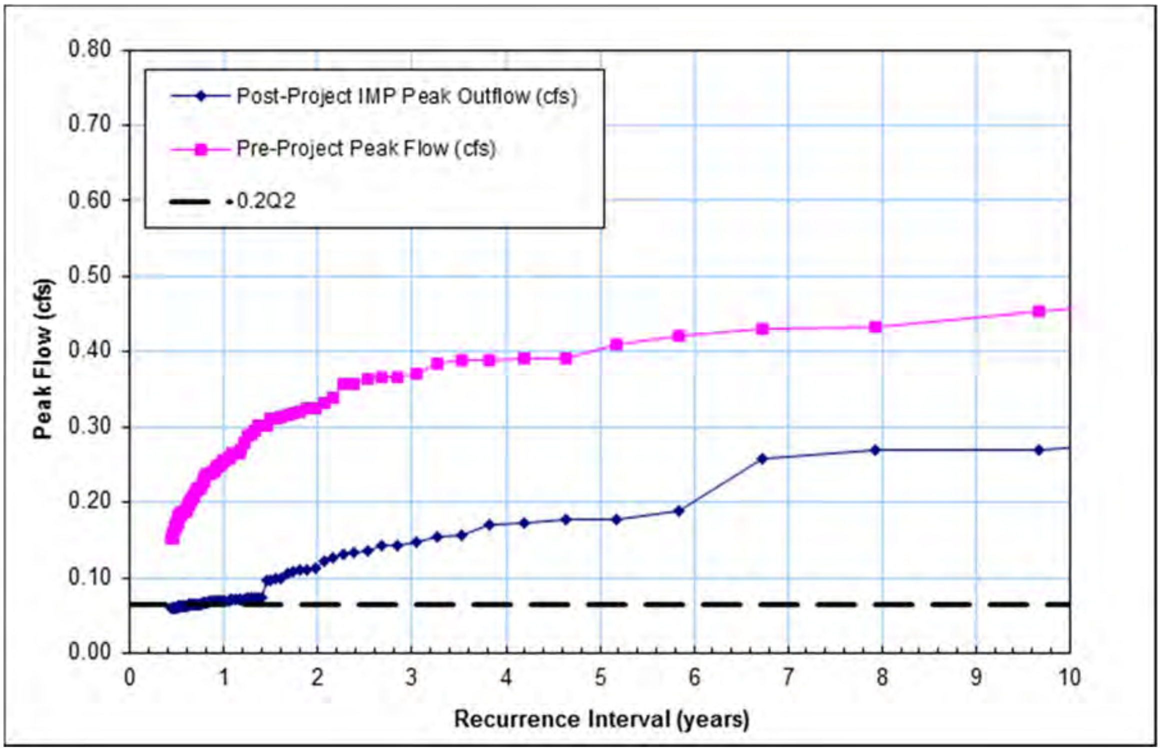

Figure 14. Peak flow frequency comparison for pre-project runoff and post-project outflows for Walden Park Commons IMP #1 (North)

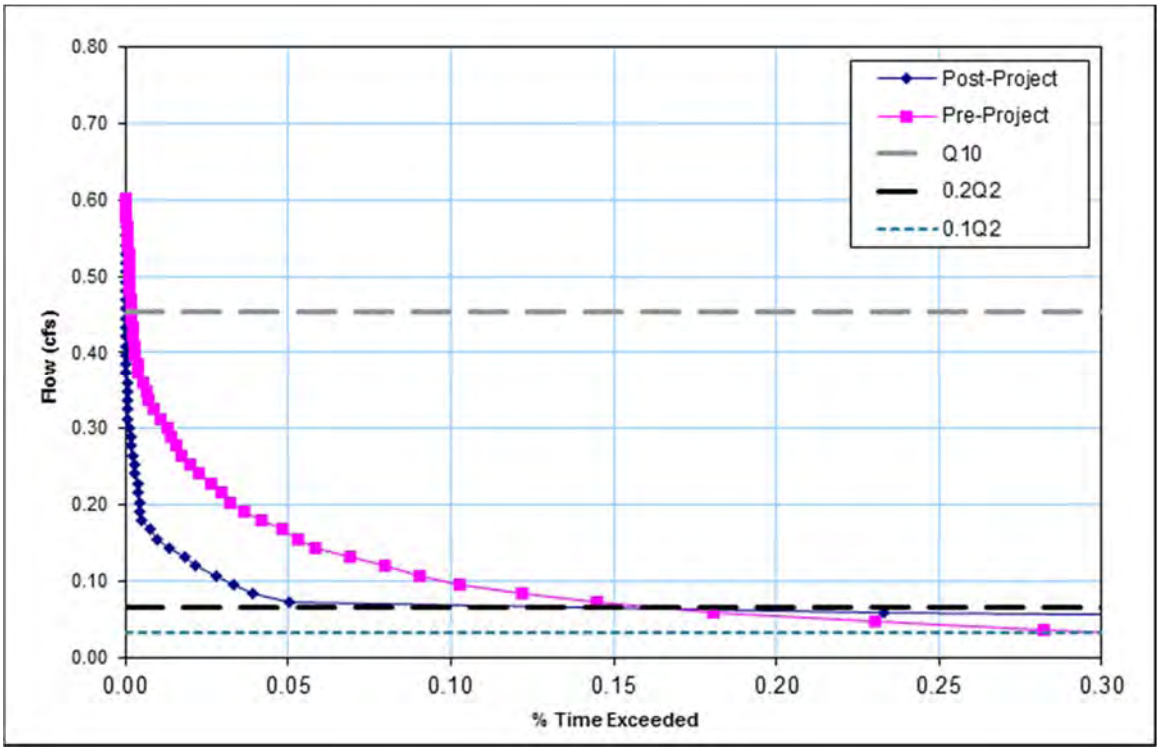

Figure 15. Flow duration comparison for pre-project runoff and post-project outflows for Walden Park Commons IMP #1 (North)

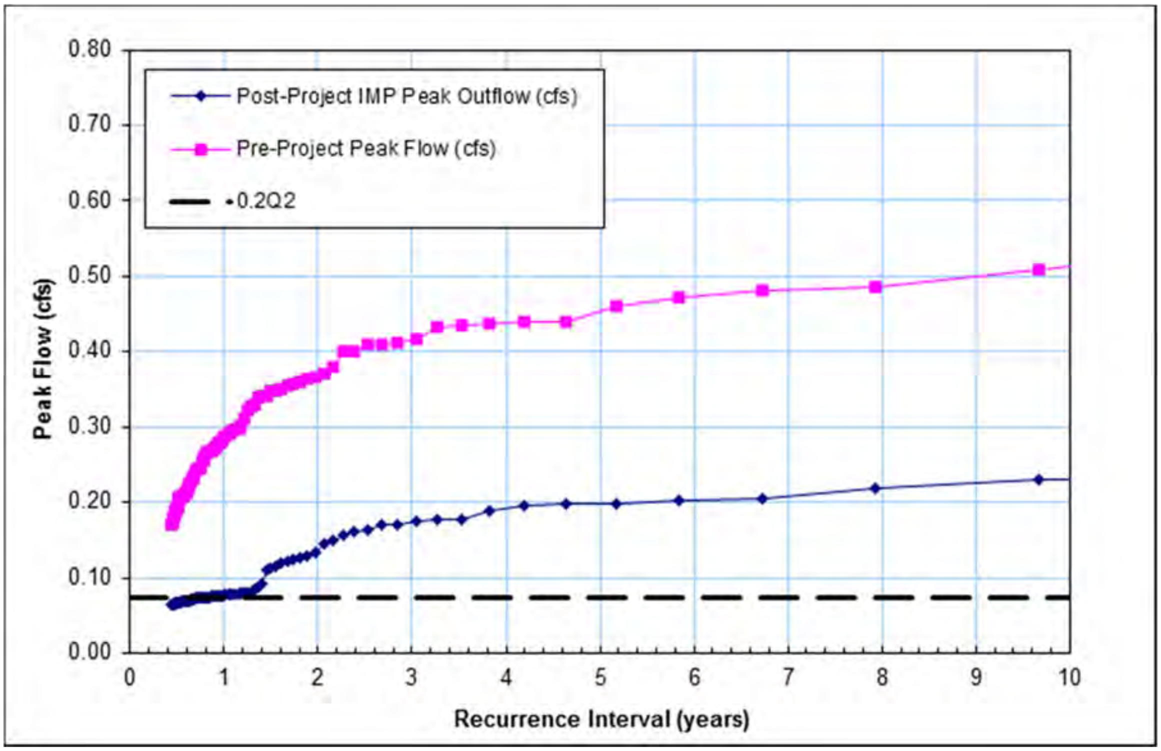

Figure 16. Peak flow frequency comparison for pre-project runoff and post-project outflows for Walden Park Commons IMP #2 (South)

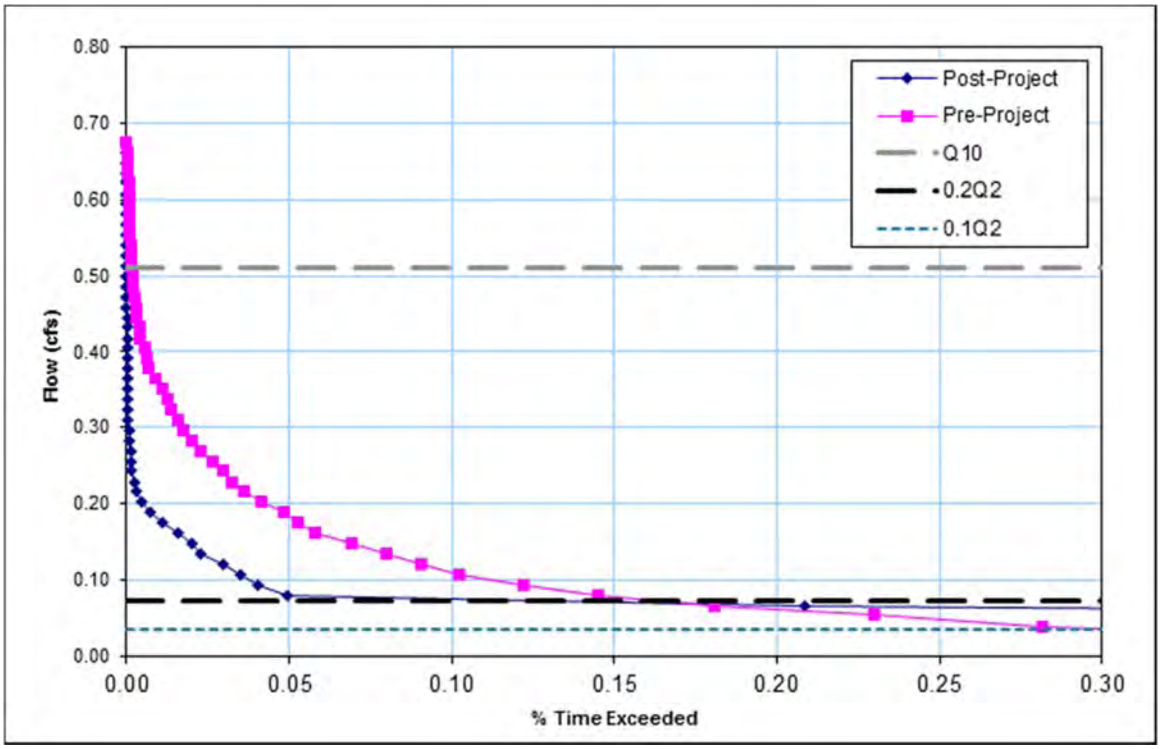

Figure 17. Flow duration comparison for pre-project runoff and post-project outflows for Walden Park Commons IMP #2 (South)