# Reducing Uncertainty Through Enhanced BMP Effectiveness Data

*Prioritizing BMPs for RAA and Evaluating Methods for BMP Effectiveness Assessments*

Task 1 Final Report

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# Introduction

Alternative Compliance Pathways (ACP) represent an emerging approach to stormwater management that involves planning for the implementation of stormwater BMPs (best management practices) on a timescale of 20+ years. Because traditional approaches to stormwater management have shown limited progress towards achieving receiving water limitations, ACP has become an attractive approach for many municipal separate stormwater sewer system (MS4) permittees. To increase confidence in ACP outputs, MS4 permittees are required to perform reasonable assurance analysis (RAA). RAA utilizes computer modeling or other quantitative methods to predict future scenarios based on existing conditions. Through RAA, MS4 permittees seek to demonstrate a reasonable likelihood of achieving applicable water quality based effluent limitations (WQBEL) or receiving water limitations (RWL) through the long-term implementation of BMPs; these BMPs have been proposed in Watershed management programs (WMP) or Enhanced Watershed management plans (EWMP).

Statewide, MS4 permittees presently lack clear, best-practices guidance for conducting RAA in a manner that ensures accurate assessments of BMP performance effectiveness. Consequently, MS4 permittees have adopted inconsistent approaches to designing RAA modeling studies, and to reporting and interpreting RAA model outputs. This lack of standardization has the potential to introduce unevenness and bias into how RAA modeling outputs are interpreted, and how progress toward compliance is evaluated. For example, RAA modelers frequently simulate BMP effectiveness using data from the International Stormwater BMP Database (http://www.bmpdatabase.org/). While perhaps the best currently available resource, these self-reported data sets are not necessarily specific or relevant to California environmental conditions. Furthermore, the median or average values for BMP effectiveness are frequently used, even though these values are often derived from datasets containing values that differ by one or more orders of magnitude.

The goal of this project is to compile a BMP effectiveness database to bring consistency and standardization to how RAA is conducted in California. The database will contain only data specific to California; including data specific to the various and diverse regions of the state.

This report summarizes the findings of the first task of this project, which is to prioritize which BMPs should be included in the effectiveness database and to compare various approaches for evaluating the effectiveness of the priority BMPs. The recommendations in this report, if adopted, will be used to inform the design and development of California's BMP effectiveness database.

# Considerations for developing the BMP effectiveness database

RAA involves the following steps:

1. Set numeric water quality objectives based on existing conditions
2. Identify selected BMP types and potential locations
3. Assess compliance based on modeled volumetric or pollutant reductions via selected BMPs

One of the most important assumptions made during RAA is the validity of the BMP effectiveness values; these effectiveness values form the basis for quantifying volumetric and pollutant loading reductions, and thus have a strong influence on the predicted future likelihood of achieving water quality standards through BMP implementation. While existing MS4 permits do not specify the required efficiency of a stormwater BMP (instead, the focus is on the volume of stormwater treated), a reliable

estimate for volume capture/pollutant reduction in a stormwater BMP is critical for long-term stormwater management planning using RAA approach. Indeed, information on the expected efficiency of a stormwater BMP for removing a certain pollutant from stormwater can inform which stormwater treatment BMP(s) to select.

A robust BMP performance database should illustrate the relationship between design and efficiency for each BMP type, and help develop specific design criteria to meet regulatory compliance goals. The volumetric and pollutant load reduction in a stormwater BMP may vary not only with the BMP type and its design specifics, but also with the method used for estimating the efficiency.

Furthermore, current RAA models often simulate BMPs in California based on available effectiveness data from other studies. However, existing data (e.g., the International Stormwater BMP Database) are rarely region-specific; thus, factors such as rainfall, geology, and/or design specifications do not necessarily match the region where RAA would be applied. Therefore, in addition to adopting an appropriate method to assess BMP performance effectiveness, California's BMP effectiveness database also should compile inflow/outflow data from various BMPs specific to California.

## Prioritizing BMPs for inclusion in the BMP effectiveness database

Stormwater BMPs are a critical component of an E/WMP and a total maximum daily load (TMDL) implementation plan. This section defines and classifies stormwater BMPs based on their scope and mode of operation, and establishes criteria to prioritize BMPs for effectiveness assessment.

A BMP is a "program, technology, process, siting criteria, operating method, measure, or device, which controls, prevents, removes, or reduces pollution"[1]. While the primary purpose of a stormwater BMP is to mitigate adverse impact from runoff discharge, a wide range of BMPs are available that vary in their scope, scale, and functions. In addition, the nomenclatures used to identify BMPs greatly vary across countries or even regions within the same country.

Stormwater BMPs can be classified based on their scope, scale, or mode of operation. Stormwater BMPs can be structural or non-structural, and their scope of applications can be limited to either source or treatment control or both. Structural BMPs can be employed at the household, distributed, or regional scale. Structural stormwater BMPs also can be categorized by their primary mode of operation, such as infiltration, filtration, conveyance, detention, and retention. Often, multiple modes operate simultaneously in a structural BMP.

Common stormwater BMPs were grouped into based on reach, primary purpose, and their relative benefits in terms of stormwater volume capture and pollutant reduction (Table 1).

[1] Novotny, Vladimir. Non-point pollution and urban stormwater management. Vol. 9. CRC Press, 1995.

Table 1: Various BMPs used for stormwater capture and treatment. Definitions of various terms used in the table are provided in Attachment A. Blue text indicates BMP is recommended for inclusion in BMP effectiveness database.

| Scale of BMP | Primary Purpose | BMP Types | Stormwater Volume Moderation Credit | | Stormwater Contaminant Removal Credit | |
|---|---|---|---|---|---|---|
| | | | Capture | Reduction | Suspended Contaminants | Dissolved Contaminants |
| Regional | Infiltration | 1. Infiltration basin<br>2. Infiltration trench | Assumed 100% | Assumed 100% | Assumed 100% | Assumed 100% |
| | Filtration | 3. Media filters | ** | * | *** | ** |
| | Detention | 4. Dry pond (a.k.a. detention pond/basin) | *** | * | * | * |
| | Retention | 5. Wet pond (a.k.a. retention pond/basin)<br>6. Constructed wetland | ** | ** | ** | ** |
| Distributed | Infiltration | 7. Bioretention w/o underdrains<br>8. Pervious pavement w/o underdrains<br>9. Vegetated buffer strip | Assumed 100% | Assumed 100% | Assumed 100% | Assumed 100% |
| | Conveyance with filtration & infiltration | 10. Vegetated swale | * | ** | ** | * |
| | Filtration | 11. Bioretention with underdrains<br>12. Pervious pavement with underdrains | ** | ** | *** | ** |
| Household Scale | Infiltration | 13. Dry well | * | * | * | * |
| | Capture and Reuse | 14. Rain barrel | ** | * | * | * |
| | Composite | 15. Green roof | ** | ** | *** | * |

From the 15 BMPs mentioned in Table 1, seven priority BMPs were selected that are recommended for inclusion in the BMP effectiveness database. The criteria for BMP screening are described in Table 2. The seven selected BMPs are:

1) Media filters
2) Dry pond
3) Wet pond
4) Constructed wetland
5) Vegetated swale
6) Bioretention with underdrains
7) Pervious pavement with underdrains

The infiltration-based BMPs were not selected because, in California, these BMPs are considered zero discharge BMPs that are 100% effective in contaminant load reduction. Non-structural and household-scale BMPs were not selected because of limited data related to their performance, which preclude representative evaluation of their effectiveness. Bioretention systems and permeable pavements without underdrains were eliminated because, in the absence of an outlet, these BMPs primarily operate as infiltration BMPs.

Table 2: Evaluation criteria for prioritizing BMP selection

| Criteria | Relevance to the project objectives |
|---|---|
| Does not depend solely on infiltration | Infiltration BMPs are assigned 100% load reduction. |
| Provides both volumetric and pollutant load reduction | Both are important in determining the efficiency of a BMP. |
| Is widely used in California | The scope of this project is the state of California. |
| Includes widely available, California-specific monitoring datasets | |
| Has established design standards | Due to design details, performance of two BMPs can greatly vary even if they are classified as the same BMP type. |

## Evaluating approaches for estimating the effectiveness of priority BMPs

Several approaches can be used for evaluating the effectiveness of a BMP. The appropriateness of an effectiveness evaluation method varies with the available monitoring data, design specifics for the BMP monitored (i.e., mode of operation, presence/absence of well-defined inlet/outlet), and the information sought from the effectiveness analysis. For example, some evaluation methods require paired inflow/outflow data, whereas the others can estimate effectiveness using statistical approach from unpaired datasets. Selecting improper methods for estimating removal efficiency of a BMP is likely to result in a lack of clarity over whether the BMP causes an improvement or adverse impacts on downstream water quality.

An overview of the four most commonly used BMP effectiveness evaluation methods is presented below, followed by a recommendation for which method should be used to estimate effectiveness of priority BMPs.

### Percent concentration reduction approach

If WQBEL is considered to be the primary endpoint of stormwater management regulatory compliance, the percent reduction of pollutant concentrations is the most appropriate method for evaluating the efficiency of a BMP. This simple, intuitive method calculates BMP efficiency from a set of paired influent/effluent concentrations. Depending on the type of the samples collected, the pollutant concentrations can be event mean concentration, EMC (for composite samples), or mean concentration (in case of grab samples). The following general equation (Equation 1) is used for calculating BMP efficiency using this approach:

$$\text{BMP Efficiency (\%)} = \frac{C_{in}-C_{eff}}{C_{in}} \text{x}100 \quad \text{.....(Equation 1)}$$

Here, $C_{in}$ is the average inlet concentration or inlet EMC, and $C_{eff}$ is the average outlet concentration or outlet EMC. We applied this approach to calculate the average fecal coliform removal efficiency (based on 25 data pair) of media filters in California. The data were collected from the international BMP database, and the calculated fecal coliform removal efficiency was -35% (net export).

The percent reduction approach assigns an equal weight for all monitored storm events. For example, a monitoring event with a high inflow concentration or volume is treated similarly as an event with a lower inflow/cleaner stormwater. Such assumption reduces potential biases in efficiency calculation when the monitoring data represents a comparable number of very large or very small storm events. It also mitigates impacts of highly polluted or very clean incoming stormwater on the actual effectiveness calculation.

However, the percent concentration reduction approach does not always accurately represent the treatment capacity of a stormwater BMP. For many BMPs, the influent concentration influences the percent removal in the BMP where the effluent concentrations are not normally distributed. For example, filtration BMPs (i.e., media filters) may treat stormwater to a relatively constant output concentration regardless of the input concentration. Therefore, the accuracy of percent concentration reduction approach depends on the type of the stormwater BMP. Moreover, regional precipitation patterns (i.e., the occurrence of many small and few large events, or vice versa) may impact the BMP efficiency estimated using this approach.

## Percent load reduction approach

From a TMDL implementation perspective, it makes the most sense to estimate the efficiency of a stormwater BMP in terms of its capacity to reduce pollutant load (rather than only concentration). The inflow/outflow load can be calculated as total pollutant mass (concentration*flow volume) incoming/exiting a stormwater BMP within a given period of time.

The load reduction can be estimated using summation of load (SOL) or efficiency of individual storm loads (ISL) method. In SOL, pollutant loads in a BMP over the monitoring period are summed up to calculate the total input and total output load. The BMP efficiency is computed using Equation 2.

$$\text{BMP Efficiency (\%)} = \frac{Total\ Load_{in} - Total\ Load_{out}}{Total\ Load_{in}} \times 100 \quad \text{(Equation 2)}$$

In the ISL method, individual input and output loads are used to calculate the efficiencies of the BMP for individual monitoring events (Equation 3). Next, the arithmetic average of the individual efficiencies is reported as the efficiency of the BMP (Equation 4).

$$\text{Efficiency for individual storm (\%)} = \frac{Load_{in} - Load_{out}}{Load_{in}} \times 100 \quad \text{(Equation 3)}$$

$$\text{BMP Efficiency (\%)} = \frac{\sum_{n}^{1} Efficiency\ for\ individual\ storm}{n} \quad \text{(Equation 4)}$$

Here, n = total number of storm events for which the individual efficiencies were calculated.

However, the sole focus of the percent load reduction approach on pollutant mass may misrepresent the capacity of a stormwater BMP. BMPs with volume reduction may receive credit as very efficient BMPs, even though they may provide little or no improvement in water quality; conversely, BMPs that don't achieve sufficient volume reduction may not be credited as efficient, even if they do improve water quality. For example, this approach would assign high efficiency to a BMP with a large permanent pool and low outflow volume, even if there is little or no reduction in effluent concentration. Also, the presence of a few large storms may impart bias to the calculated efficiency due to high inflow stormwater volume. In addition, unlike pollutant concentration reduction approach, the load reduction approach requires paired (influent and effluent) datasets for both pollutant concentration and flow. For example, this approach could not be applied to calculate load reduction efficiency of media filters in California from the data available in the international BMP database because the flow data are missing.

## Regression analysis

The effectiveness of a stormwater BMP can be conceptualized as the relationship between the influent and effluent from the BMP during a storm event under a given design condition. Regression analysis (i.e., statistical modeling to identify such relationship) has been used in some studies to determine the efficiency of a stormwater BMP. Regression analysis for BMP effectiveness is performed in three steps:

1. Available data are analyzed to determine if there are statistically significant differences between influent and effluent concentrations.
2. A correlation analysis is performed to determine if there is any monotonic relationship between influent and effluent concentrations.
3. Linear or log-linear regression is performed to develop a functional relationship between the influent and effluent concentration.

We will discuss the two most commonly used regressions for BMP effectiveness evaluation: ordinary least square and Kendall-Theil regressions.

The influent-effluent fecal coliform concentrations (25 data pairs from media filters in California with Pearson's correlation coefficient of 0.67) were used to perform ordinary least square (Figure 1) regression. Least square regression equation and $R^2$ for the influent and effluent plot (non-transformed concentration data) are shown in the figure, where X and Y denotes influent and effluent concentrations, respectively. The low R value can be attributed to the presence of many outliers in the dataset.

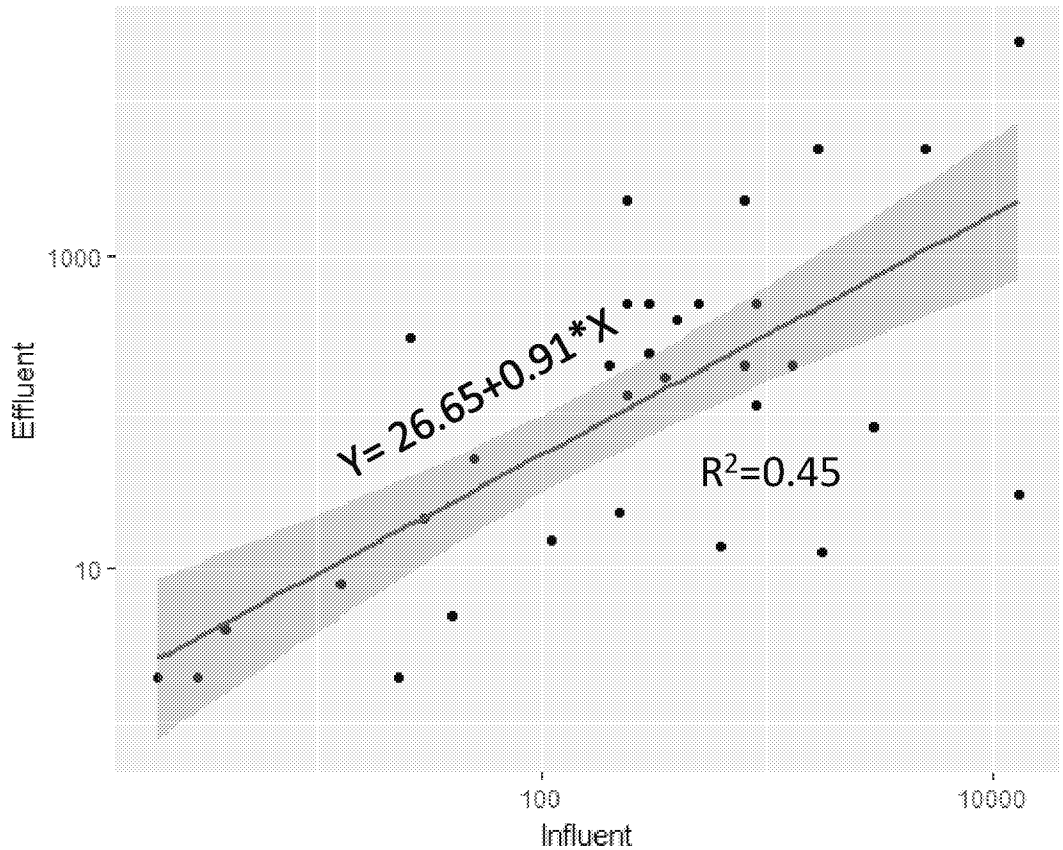


Figure 1: Ordinary least square (OLS) regression analysis using 32 influent and effluent data pairs for fecal coliform (FC) concentrations. The FC data for media filters were obtained from the international BMP database.

Kendall-Theil Robust Line (KTRL) regression has been reported to provide better prediction than OLS or other linear regression methods for effluent concentration from influent concentration[2]. Using the same data pairs as in Figure 1, KTRL regression was conducted using non-transformed, log (base 10)-transformed, and log (base e)-transformed data (Figure 2). The log-transformed data provided the best maximum absolute deviation (MAD) value with the following regression equation:

[2] Oregon State University. Department of Civil, et al. Evaluation of Best Management Practices for Highway Runoff Control. No. 565. Transportation Research Board, 2006.

Log(effluent) =-0.03726177+.9037874*Log(influent).....(Equation 5)

Equation 5 can be used to determine the efficiency of a media filter from a given influent fecal coliform concentration. For example, the removal efficiencies are 37% and 50% for FC concentrations of 50 and 500 MPN/100 mL, respectively.

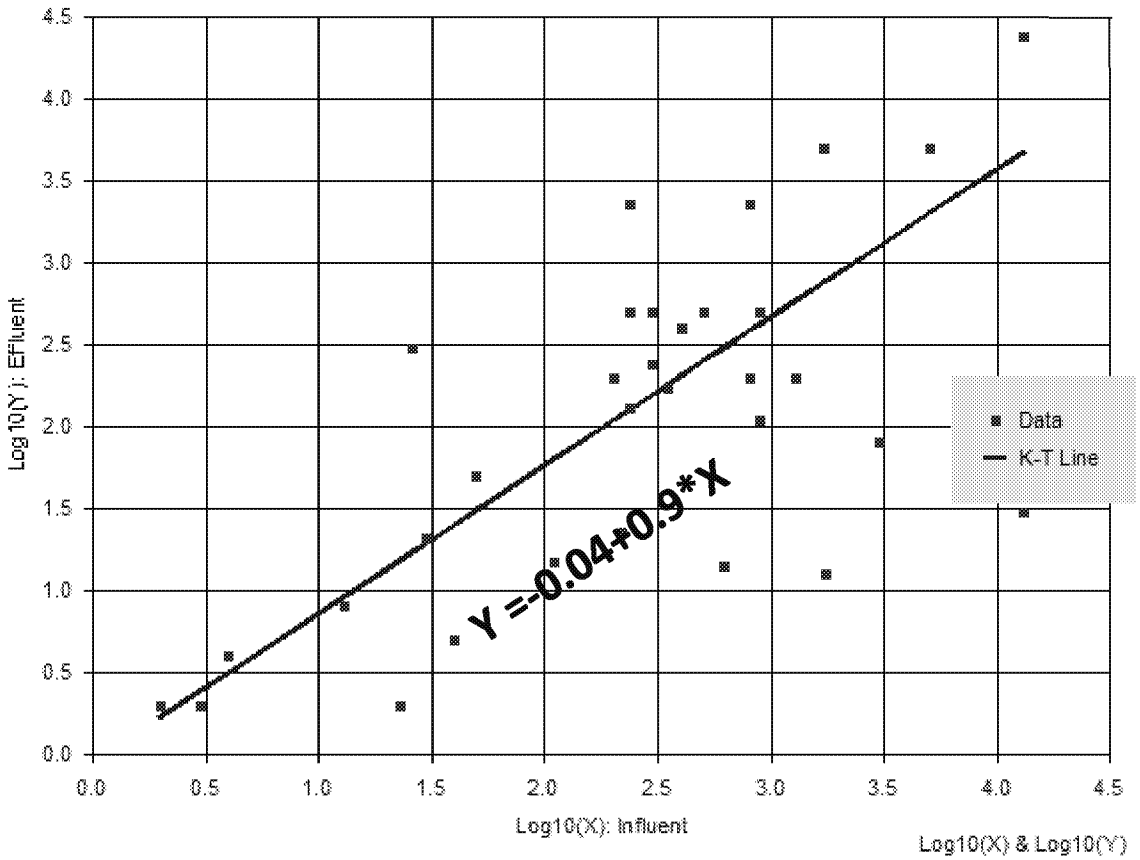


Figure 2: Kendall-Theil Robust Line regression analysis using 32 influent and effluent data pairs for fecal coliform (FC) concentrations. The FC data for media filters were obtained from the international BMP database.

Regression analysis for BMP effectiveness estimation eliminates several limitations of the percent concentration or percent load reduction approach. First, the possibility of bias from a disproportionate number of very large or very small storm events gets reduced. Second, imprecise estimation of high (or low) efficiency for filtration BMPs (due to relatively constant effluent concentrations regardless of influent concentrations) can be avoided. In addition, the influent versus effluent EMC plot with established relationships visually presents the expected effluent concentration for a measured influent concentration.

However, datasets used in the regression analysis approach need to be paired, and a large volume of data is required for improved accuracy. Moreover, for some BMPs (i.e., media filters), the correlation between the influent can be weak or non-existent. In such cases, it can be challenging to predict the

effluent concentration using this approach from a given influent concentration. Besides, the relationship established via regression is only valid within the range for which the relationship was developed.

## Effluent probability method (EPM)

The effluent probability method is a qualitative approach for BMP performance evaluation that visually represents the frequency distribution of influent and effluent concentrations (or loads) for a stormwater BMP. The separation between the influent and effluent frequency distribution qualitatively indicates the efficiency of a BMP. The concentrations used for effluent probability plots can be paired or unpaired. EPM assumes that the BMP removal efficiency is independent of influent concentrations.

The EPM graphically illustrates the probability of occurrence (or exceedance) of a certain influent or effluent concentration (or load) in a stormwater BMP. EPM plots are generated as follows:

1. A statistical test is conducted to determine if the influent and effluent data is log-normally distributed.
2. Available datasets (paired or unpaired) are tested to check if there is a statistically significant difference between influent and effluent EMC or loads.
3. A normal probability plot (against the influent/effluent EMC or loads) is prepared using the log-transformed data for all storm events.

All available fecal coliform data points (influent and effluent; paired and unpaired) for media filters in California were used to develop a probability distribution using the effluent probability method (Figure 3). A variable separation between the influent and effluent probability distribution indicates the changes in the efficiency of media filters depending on the range of influent/effluent concentration.

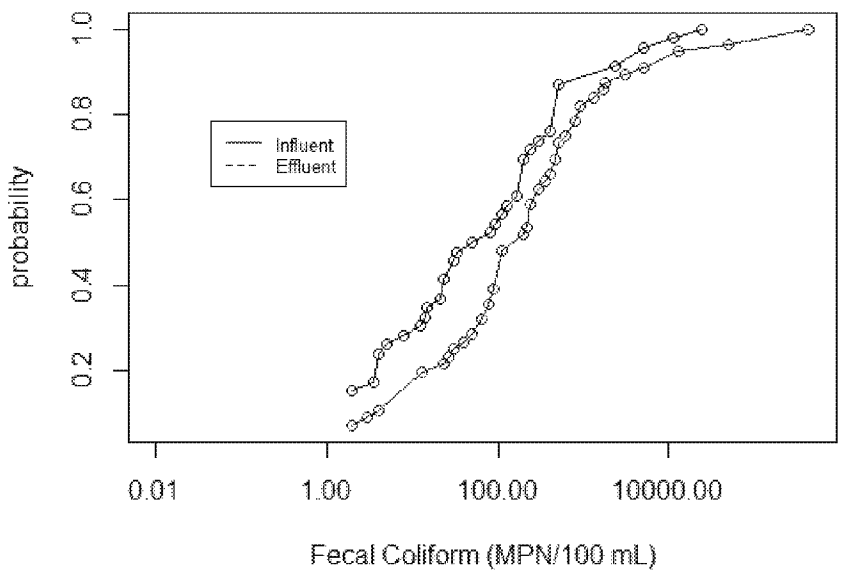


Figure 3: Effluent probability plot using influent and effluent fecal coliform (FC) concentrations. The plot represents 46 effluent and 56 influent data points. The FC data for media filters were obtained from the international BMP database.

EPM is regarded as the most comprehensive BMP evaluation tool that presents the "whole picture" of BMP performance[3]. EPM treats all storms equally and demonstrates the overall variability in water quality data related to a stormwater BMP. The EPM approach makes use of the influent data that do not have corresponding effluent value (vice versa) and presents a visual comparison among multiple BMPs in terms of their performances.

The primary challenge for using EPM as a BMP effectiveness evaluation method is its inability to offer any quantitative or numeric performance measure for volumetric, pollutant concentration, or pollutant load reduction in a BMP. Moreover, due to the presence of non-paired data points, the EPM method cannot capture the effect of the size of the storm or antecedent conditions on BMP performance.

One way to determine BMP efficiency is to develop an effluent probability plot for a BMP, and then exclusively use effluent concentrations corresponding to a given percentile on the EPM plot. The value of the effluent concentration corresponding to a certain probability percentile then can be compared with its influent concentration (again, corresponding to a certain probability percentile) to determine the BMP efficiency using Equation 1. However, efficiencies calculated using such an approach are significantly influenced by managers' choices regarding what percentile effluent (and influent) should be used. Table 3 shows the fecal removal efficiency of media filters in California for a median influent concentration (240 MPN/100mL) estimated using EPM plots (Figure 3) and Equation 1. Table 3 also summarizes the fecal removal efficiency of media filters calculated using other approaches discussed earlier.

Table 3: Influence of efficiency evaluation approach on fecal coliform removal (%) in media filters

| Approach | | Efficiency equation/effluent value for effluent fecal coliform (MPN/100 mL) (Y and X are effluent and influent concentrations, respectively) | Removal efficiency (%) (assuming X = 240 MPN/100 mL) |
|---|---|---|---|
| Average concentration reduction | | - | -34.8 |
| Regression | Least Square | Y = 26.7+0.9*X | -0.01 |
| | KTRL | Log Y = -0.04+0.9*Log X | 45 |
| Effluent Probability | 25th percentile | 8 | 96.7 |
| | 50th percentile | 90 | 62.5 |
| | 75th percentile | 700 | -192 |
| | 100th percentile | 240000 | -99900 |

[3] Strecker, E., et al. Urban stormwater BMP performance monitoring. Vol. 1. EPA-821-B-02, 2002.

## Recommended approach for estimating BMP effectiveness

In light of the above discussion on various BMP effectiveness assessment approaches, we recommend using the regression analysis approach. However, instead of the OLS or KTRL approach, we recommend using quantile regression to fit the influent and effluent data for a stormwater BMP to estimate its effectiveness. Quantile regression, which is a robust regression method that focuses on achieving least absolute deviation, offers the following advantages over existing BMP effectiveness evaluation methods:

a) Offers a statistical range for the expected removal. (For example, for a given BMP type, the calculated removal efficiencies from various BMP locations could be plotted, allowing the median efficiency to be reported as the design efficiency for that BMP type.)
b) Is less susceptible to non-normal errors and outliers or extreme data points.
c) Provides a direct measure of uncertainties involved in the effectiveness estimation.

Figure 4 presents quantile regression lines ($25^{th}$, $50^{th}$, $75^{th}$ and $100^{th}$ percentile) using influent and effluent fecal coliform concentrations data from media filters in California. The equations for the lines and corresponding estimated media filter efficiencies are shown in Table 4. We recommend using $50^{th}$ percentile efficiency for RAA in evaluating the effectiveness of a watershed management plan for runoff control (i.e., 19.8% removal of fecal coliform in media filters). A similar approach using influent and effluent flow data pairs could be used to calculate volumetric reduction efficiency of a media filter.

Table 4: Fecal removal efficiency of media filter using quantile regression

| Percentile | Efficiency equation (Y and X are effluent and influent concentrations, respectively) | Removal Efficiency (%) (assuming X = 240 MPN/100 mL) |
|---|---|---|
| $25^{th}$ percentile | Y = 8.0 +0.002*X | 99.8 |
| **$50^{th}$ percentile** | **Y = 0.4+0.8*X** | **19.8** |
| $75^{th}$ percentile | Y = -1.7+1.8*X | -80.7 |
| $100^{th}$ percentile | Y = 1856.2+1.8*X | -853 |

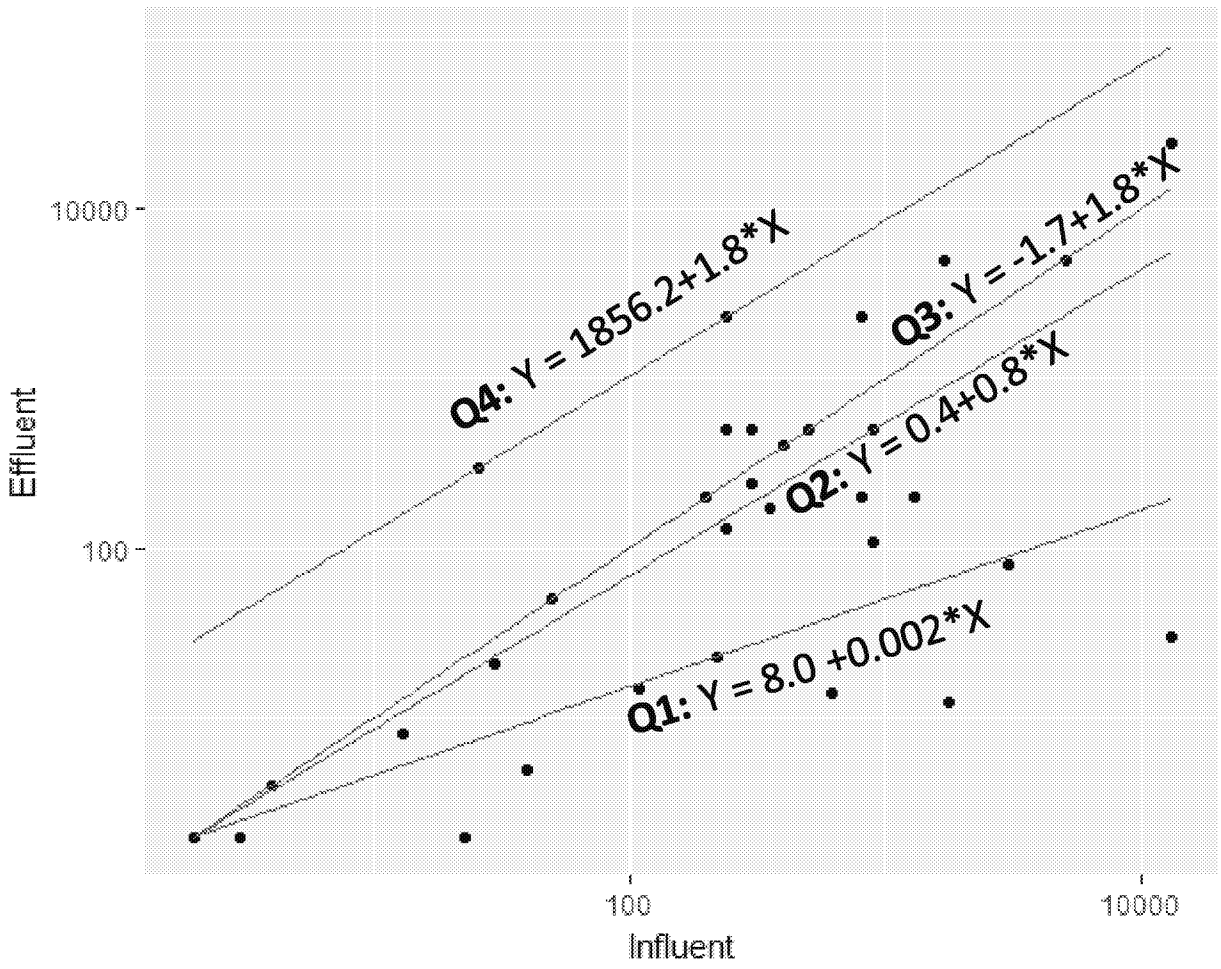


Figure 4: Quantile regression analysis using 30 influent and effluent data pairs for fecal coliform (FC) concentrations. The FC data for media filters were obtained from the international BMP database.

We note here that the accuracy of a BMP effectiveness estimate with quantile regression analysis is likely to increase with increasing volume of monitoring data. Therefore, we recommend periodic updates to effectiveness values for various BMPs as additional data become available via annual MS4 monitoring efforts throughout California. Additionally, it should be noted that the quantile regression approach is a novel approach for computing BMP effectiveness. Unlike the methods presented in the review section of this document, quantile regression has not widely applied in the stormwater literature for reporting BMP effectiveness. However, our comparative assessment of BMP effectiveness evaluation methods suggests that quantile regression has the most potential for improving RAA by eliminating uncertainties associated with BMP effectiveness.

# Attachment A

Glossary of Terms

**Distributed BMP:** Neighborhood scale stormwater BMP that receives, retains, and treats runoff on site. Typically, these are vegetated systems receiving runoff from a drainage area less than an acre. Stormwater captured in these BMPs are generally used for groundwater recharge. However, non-potable reuse of the treated water is also common. Some systems may also discharge water to the storm sewer systems after treatment.

**Regional BMP:** Stormwater BMP that captures runoff from an engineered drainage system with a large drainage area (up to 100 acres). Stormwater retained in these systems can be used for managed aquifer recharge or direct non-potable reuse.

**Household BMP:** Stormwater BMP installed at the household level primarily for capture and reuse.

**Infiltration:** Stormwater movement to subsurface or the soil surrounding the BMP.

**Filtration:** For this document, all processes involved in contaminant removal in a packed bed via chemical straining, sorption, precipitation, attachment, or ion exchange.

**Detention:** Stormwater storage for a limited period (<72 hr).

**Retention:** Storage for an extended period, sometimes throughout the year.

**Conveyance:** Stormwater flow.

**Infiltration Basin:** Shallow, earthen depression that captures and infiltrates stormwater.

**Infiltration Trench:** Long, narrow, stone-filled BMP without outlet designed to store and infiltrate stormwater runoff.

**Media Filters:** Sand filters with a pre-treatment chamber for filtering or infiltrating stormwater. The filter may or may not have engineered amendments.

**Dry Pond:** Stormwater basin that detains runoff. Also known as detention basin, detention pond, and extended detention basin.

**Wet Pond:** Stormwater basin that has a permanent pool of water for a long period of time, i.e., throughout the season or during the wet season. Also known as retention basin, retention pond, wet extended detention pond, and wet basin.

**Constructed Wetland:** Shallower wet pond (<4 ft) with greater vegetation coverage.

**Vegetated Buffer Strip:** Flat vegetated area that receives sheet flow. Also known as biofiltration strip, grassed strip, filter strip, grassed filter, and grass buffer.

**Vegetated Swale:** Open, shallow, mild sloped, vegetated channel for conveying runoff downstream. Also known as grass swale.

**Bioretention:** Engineered, small-scale, vegetated, depressed area that captures, reduces, and infiltrates or filters stormwater runoff from the surrounding area. Also known as biofilter, rain garden, and porous landscape detention area.

**Pervious Pavement:** Permeable load bearing concrete or asphalt surface overlying detention basins. Also known as porous pavement, porous concrete, and permeable pavement.

**Dry Well:** Excavation lined with perforated casing and backfilled with gravel or stone that receives water from the roof.

**Rain Barrel:** Plastic (or concrete) water tank used to collect and store rainwater from a roof.

**Green Roof:** Soil media with vegetation overlying a traditional roof. Also known as living roof, vegetated roof, and eco-roof.