Evaluating Potential Methods to Quantify Stormwater Capture

Elizabeth Fassman-Beck
Ken Schiff
Daniel Apt

Southern California Coastal Water Research Project

SCCWRP Technical Report # 1116

Evaluating Potential Methods to Quantify Stormwater Capture

Elizabeth Fassman-Beck[1], Ken Schiff[1], and Daniel Apt[2]

[1]*Southern California Coastal Water Research Project, Costa Mesa, CA*

[2]*Olaunu, San Clemente, CA*

April 2020
Technical Report 1116

EXECUTIVE SUMMARY

In response to one of the worst droughts in California's modern history, the State Water Resources Control Board (State Water Board) issued the Recycled Water Policy (Resolution 2013-003) asking staff to incorporate stormwater capture and use or reuse into future State Water Board programs. As part of the resolution, staff has been tasked with estimating the total volume of captured stormwater, a fundamentally challenging task in a state as diverse as California. Estimates of stormwater capture have been identified for specific regions, such as Los Angeles County, or by associations of agencies such as the California Urban Water Agencies and the Southern California Water Coalition. The goal of this project is to identify and evaluate methods for how to quantify the potential volume of stormwater captured state-wide.

This document identifies six separate methods that could be used to quantify stormwater capture for different components of water resources infrastructure, which are:

- Stormwater best management practice (BMP) flow monitoring,
- BMP design information from plan submittals,
- Watershed models,
- Large-scale impoundments,
- Measured changes in groundwater levels, and
- Measured changes in Publicly Owned Treatment Works (POTWs) influent flow.

Several of the methods include BMPs that are currently utilized to capture stormwater. The term "BMP" encompasses a suite of technologies from site-scale "green infrastructure" or "low impact development" (GI/LID) techniques to regional stormwater management facilities. The physical methods of water capture in different types of BMPs, and how captured water could contribute to water supply is directly discussed. Methods such as measuring changes in imported water or in site-scale water metering, or where direct capture or industrial use are considered, but not explored in detail. These methods have a relatively small use across the state compared to the six methods listed above. Likewise, since diversions capture predominantly dry-weather runoff, they were excluded from significant consideration in this document.

This document presents a critical evaluation of the six methods for consideration by the State Water Board. The critical evaluation of each method includes:

- Summarizing the overall approach to estimating stormwater capture,
- Defining the necessary data to estimate stormwater capture,
- Identifying other implementation considerations,
- Discussing the advantages and constraints, and
- Identifying added value opportunities.

Concerns raised about the process of quantifying stormwater capture statewide include accuracy, uncertainty, availability of data, and scaling from individual BMPs to a statewide estimate. For example, BMP flow (hydrologic) monitoring is based on empirical data and therefore the most accurate. However, relatively few BMPs are monitored, and assumptions to extrapolate BMP stormwater capture estimates statewide raises concerns about uncertainty. In contrast, watershed models can make estimates of all BMPs of presently known and planned locations. Modeling also introduces accuracy concerns where the underlying assumptions of watershed processes and/or BMP performance have not been compared against true behavior, and because there is vast variation in parameterization and model structures across the state. Several of the methods may trade-off elements of accuracy and uncertainty, or availability of data, but when considered together may provide a viable outcome. Some methods are easier to implement. Using design specifications is perhaps the most easily implemented method, but it suffers from both accuracy and scalability since design specifications typically do not necessarily reflect the final constructed product, or the reality of long-term operation. POTW or groundwater measurement approaches provides indirect estimates of stormwater capture and results may be confounded by multiple factors.

Despite the challenges, it is clear there are many advantages to quantifying stormwater capture statewide. Implementing any of the methods will require data sharing routines for compiling information. These routines and data communication tools will start to remove the silos that surround individual regulated parties or the state agencies regulating them. Moreover, many of the methods will require compiling information on BMPs including where they are located, design and construction details, as well as maintenance and inspection routines. These data are needed to build an effective and interactive asset management program, an approach promoted by the United State Environmental Protection Agency to proactively address stormwater infrastructure needs and reduce overall program implementation costs. Approaches that focus on measurements or models for flow and volume can cost effectively be upgraded for water quality to quantify pollutant reduction as well as stormwater capture.

This document aims to provide the State Water Board with an initial technical resource to explore methods to quantify stormwater capture. It is premature to identify a “best” method due to the complexity of the assessment. More than one method may be required to overcome concerns by State Water Board staff. For some methods, the challenge may be access to information, e.g., data mining records from permitting agencies, or collating information from privately maintained or operated infrastructure. In other cases, the challenge is technical, e.g., feasibility of communicating between different models, or resolving data formats to enable consistent calculations. Conducting pilot scale investigations of multiple methods may assist the State Water Board to evaluate the feasibility and costs of various methods.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1. INTRODUCTION

1.1. Background

Between 2012 and 2016, California experienced one of its worst droughts in modern history (Figure 1). In response, the State Water Resources Control Board (State Water Board) issued the Recycled Water Policy (Resolution 2013-003). One mandate in the Recycled Water Policy was to enhance stormwater capture and use, and to maximize the multiple benefits of stormwater capture. The Recycled Water Policy also created the State Water Board's Strategy to Optimize Resource Management of Stormwater (STORMS) and their Stormwater Planning Unit to implement the strategy by advancing the perspective that stormwater is a valuable resource, supporting policies for collaborative watershed-level stormwater management and pollution prevention. Policies enhancing stormwater capture and use are also found in grant funding requirements, NPDES permits, and Total Maximum Daily Load implementation plans.

The State Water Board also passed the Climate Change Resolution, which, among other mandates, supported the STORMS initiative. Consistent with the Climate Change Resolution was a STORMS priority to establish a methodology for estimating the amount of stormwater captured and used statewide. A summary of information collected on stormwater captured and used was to begin starting in 2017-2018.

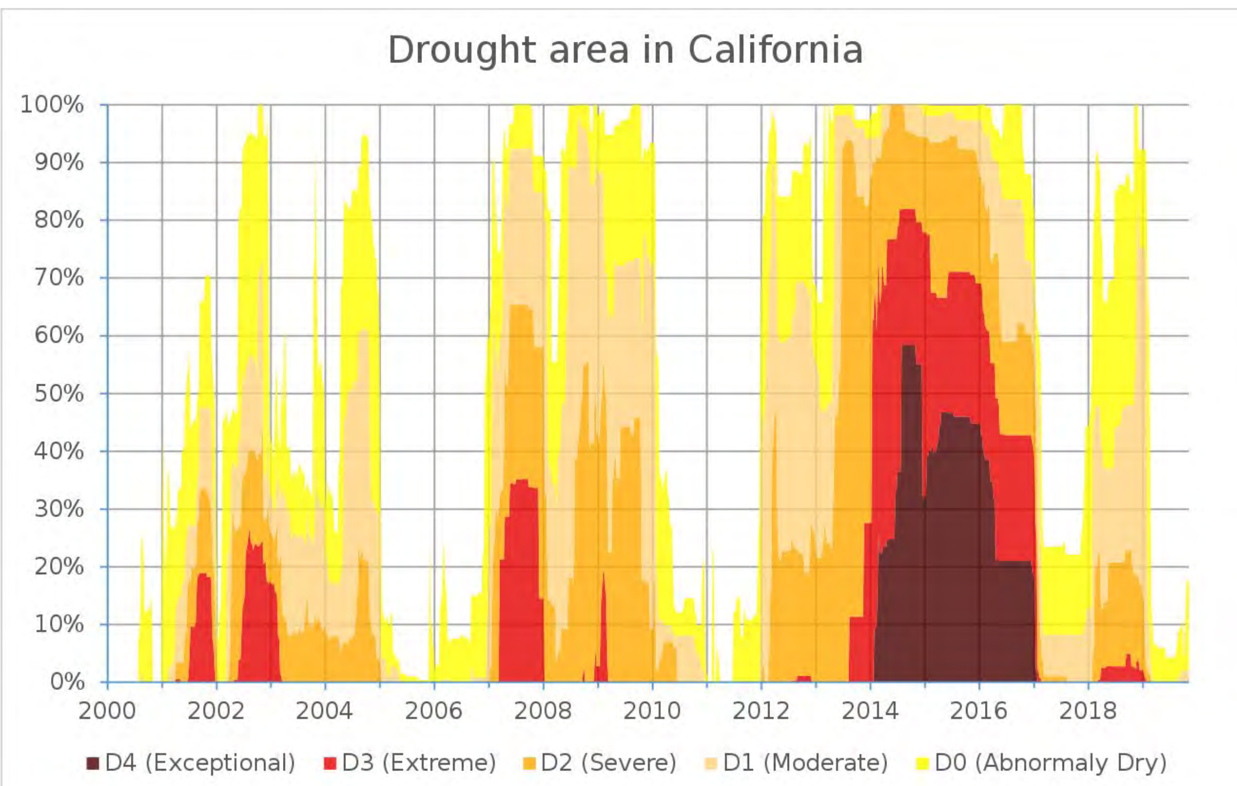


Figure 1. Drought conditions in California 2000-2019.
(source: https://www.drought.gov/drought/states/california)

1.2. Examples of existing stormwater capture estimates in California

Stormwater runoff capture is being quantified by various public entities and associations of agencies around California. Each of these sources of capture estimate is generated by different underlying assumptions (e.g. direct measurement versus models), uses information from different components of water resources infrastructure (e.g. dams versus reservoirs), and presents information in a different context (e.g. public information versus evaluating feasibility). Collectively, the examples demonstrate that collating a state-wide estimate from multiple sources and methods is not likely directly available. The examples herein are not meant to be an exhaustive summary of available information.

Regional examples of estimating stormwater capture are already found in many urbanized areas of California. For example, conditions of the Safe Clean Water program and the MS4 permit commit the Los Angeles County Department of Public Works to calculate the quantity of runoff captured in each storm event throughout their jurisdiction. The capture estimate is generated by a watershed model that incorporates a network of dams, spreading grounds (i.e. regional infiltration basins), and site-scale stormwater best management practices (BMPs). The model is capable of calculating quantities of stormwater discharged to groundwater or reclaimed water, although at present, public announcements share only the total amount of stormwater captured. Elsewhere in urbanized portions of California, including South Coast and San Francisco Bay, watershed models developed for Water Quality Improvement Plans and MS4 permits predict volume capture using a variety of BMPs including low impact development (LID) or green infrastructure-type BMPs.

Associations of agencies including the Southern California Water Coalition and the California Urban Water Agencies compiled estimates of stormwater capture, which were published in white papers in 2016 and 2018, respectively. In either white paper, details on the methodology for quantifying capture were limited, but estimates of stormwater capture are presented. Based on flow monitoring across 32 “stormwater projects” in 6 agencies, the Southern California Water Coalition (2018) estimated that the stormwater capture volume was 13,400 acre-feet per year. As more stormwater projects were built over the 11-yr record of data, the amount of capture increased per inch of rainfall increased. The California Urban Water Agencies (2016) suggests that the majority of stormwater capture across the state occurs via surface water reservoirs. Member agencies collect and use approximately 540,000 acre-feet per year of “local urban stormwater runoff”. The white paper suggests that the urban stormwater capture is not a large portion of the water supply in member agencies, but it could be increased where locally feasible. Since the majority of rainfall occurs in winter, but water demand is largest in summer, feasibility was deemed to be largely dictated by the availability of groundwater storage, which varies substantially across the state. In a subsequent FAQ, “Advancing Water Supply Reliability” (Oct. 2017), the California Urban Water Agencies projected that urban stormwater capture would comprise 1% of the yield in 2035 for its member agencies.

The Orange County Water District’s method to quantifying stormwater capture and recharge in a groundwater basin underlying north and central Orange County serves as a useful example of the complexity of the calculation challenge. Partially enabled by temporary storage in the Prado Dam, the groundwater basin is recharged by baseflow in the Santa Ana River, stormflow from rivers and additional drainages, imported water, recycled water, and other rainfall and subsurface flow throughout the basin (deemed “incidental recharge” by the Orange County Water District).

The Orange County Water District measures several of these components directly, models the capture and storage in the Prado Dam conservation pool (a large-scale impoundment in the terms of this report), and measures the change in groundwater storage. In an average year, the Orange County Water District estimates that Santa Ana River stormflow and incidental recharge produce a combined 114,000 acre-feet of groundwater recharge.

2. OBJECTIVE AND SCOPE

The primary objective of this project is to identify and evaluate various technical methods for quantifying the potential volume of stormwater capture throughout California. The technical approach, advantages and disadvantages of each method will be highlighted and discussed. Data needs and availability will be included, and data analysis will be described.

This project presents technical approaches to estimating stormwater capture through existing physical infrastructure; the feasibility of constructing new infrastructure to implement runoff capture is not considered. This project is not designed to provide an estimate of stormwater capture; quantifying stormwater capture will require implementation of one or more of the methods described in this report. Finally, this project will not evaluate methods for quantifying captured water use; this may be a goal of a future project.

Stormwater is captured by multiple forms of infrastructure, intentionally or inadvertently. This project includes directly quantifying or indirectly estimating potential volumes of stormwater capture from several broad categories of built infrastructure:

1. Stormwater BMPs, which encompasses a suite of technologies that directly intercept rainfall and stormwater runoff. The potential for runoff capture in BMPs is considered by way of direct measurement, indirect estimation, and modeling (simulation).
2. Large-scale impoundments, such as regional flood control structures, whose water levels are continuously measured.
3. Publicly owned treatment works (POTWs) which inadvertently receive wet weather runoff, and whose operating conditions are continuously monitored.
4. Regional groundwater monitoring networks, which are anticipated to show a response after precipitation events.

3. BEST MANAGEMENT PRACTICES (BMPS) CONSIDERED

Structural stormwater BMPs are broadly defined as built or physical infrastructure designed to capture runoff for water quality improvement and/or hydrologic mitigation. BMPs include a suite of individual technology forms, including, but not limited to, bioretention (rain gardens), infiltration basins and trenches, permeable pavement, cisterns, dry wells, extended detention basins and retention basins. BMPs comprise a rapidly growing, and highly varied category of water resources infrastructure in California. Significant detail is provided in this section to explore the configuration of different BMP types, as it has direct implications for the capture calculation methods presented in Sections 4.1, 4.2, and 4.3.

The method to measure, estimate, or model (re)use potential is directly related to how each BMP type physically captures, stores, and discharges runoff. Likewise, feasibility of stormwater capture and (re)use is directly related to the design features unique to each BMP type. In order to better understand the methods for quantifying capture potential later in this report, physical descriptions of each BMP type and how runoff might be captured for (re)use is described in this section.

There are two broad classifications of structural BMPs presented in this report, according to the method for capture and (re)use:

- Direct (re)use: Rainfall and/or wet-weather surface runoff is captured and stored for direct withdrawal after flowing through a BMP.
- Indirect (re)use: Wet-weather surface runoff is discharged to the subsurface to recharge groundwater after flowing through a BMP.

The BMPs considered in this report are further classified according to the scale of implementation. A strategy to capture stormwater with site-level BMPs distributes capture potential throughout the watershed and might incorporate dozens (or potentially hundreds) of individual BMPs with relatively small drainage areas. Conversely, a neighborhood or regional BMP represents a centralized approach with a few BMPs that treat or retain runoff from relatively large drainage areas.

3.1. Site-level BMPs

Site-level BMPs describe the general category of BMPs which are designed to capture runoff at relatively smaller scales, including individual residential units or small groups of dwellings, commercial or retail space, and parking lots or roadway segments of up to a few acres in size. Large-scale residential developments where the majority of runoff is managed with multiple distributed, site-level BMPs are included in this category. For the purposes of this report, site-level BMPs exclude large-scale residential developments (hundreds to thousands of homes) where runoff is managed in regional BMPs.

In order to estimate the cumulative runoff capture across a region from site-level BMPs, a detailed inventory of site-level BMPs installed or planned across a region must be collated or estimated. It is anticipated that relying on site-level BMPs for direct (re)use supply would require substantial supplemental infrastructure to store or be able to withdraw captured water.

3.1.1. Bioretention including cells and planters

Bioretention systems including cells (a.k.a. rain gardens), bioswales, and planters capture surface runoff from a drainage area typically 10 – 20 times greater than the size of the BMP itself. As it enters the bioretention system, runoff is temporarily captured and stored in a surface layer called the ponding zone. Water subsequently percolates vertically through the underlying engineered media filter bed. The extent to which the ponding zone fills during an individual storm depends on the total volume and rate of runoff compared to the storage capacity of the ponding zone and the capacity for vertical flow through the filter bed. In small storms, surface storage (ponded water) may not occur because runoff percolates quickly into the filter bed. In large storms, some runoff may bypass the system because the ponding zone has become (temporarily) full.

A finite portion of the total inflow volume is stored in the engineered media (filter bed) for subsequent evapotranspiration (moisture loss to the atmosphere through the media surface and plants). This water cannot be extracted for (re)use. Typically, the maximum storage volume in the media is approximately 20-30% of the volume of the media itself (Davis et al. 2012; Fassman-Beck et al. 2015). In vegetated bioretention BMPs, water storage in the media is critical for maintaining vegetative health without irrigation, while possibly reducing the (re)use potential. Conversely, regular BMP irrigation during the rainy season may compromise the media's capacity to store additional inflow, thus potentially allowing more storm flow to pass through the system, and render it available for (re)use (albeit at a cost of irrigation supply).

Overall, the potential stormwater capture volume depends on storm size and frequency relative to BMP water storage and flow characteristics. Runoff potentially available for (re)use is the remaining portion of the inflow that cannot be stored in the engineered media (filter bed). In a typical bioretention system design, this portion of the inflow leaves the bioretention system by either exfiltrating[1] through its bottom and sides to surrounding in-situ soils (Figure 2a), or by flowing through an underdrain for discharge to a specific design point (Figure 2b).

It is assumed that runoff must flow through the filter media for water quality treatment prior to capture for (re)use. Opportunities for capture depend primarily on the discharge configuration of the bioretention system:

- An exfiltrating system provides indirect capture through groundwater recharge. Overflow could potentially be captured in a supplemental storage tank.
- An underdrained bioretention system offers an opportunity for direct (re)use, albeit introducing a need to install supplemental infrastructure (to capture underdrain discharge and overflow).

Storing water for an extended duration and/or depth within bioretention media is not recommended because of the potential to damage plant roots. The design of a typical bioretention system's discharge configuration depends primarily on characteristics of in-situ soils and proximity to other structures. Underdrains are typically installed where in-situ soils exhibit a low hydraulic conductivity (i.e., groundwater recharge is physically inhibited by soil characteristics), in-situ soils are contaminated, or the bioretention system would be installed in close proximity to a building foundation. Underdrains typically discharge to a storm sewer, or directly to a receiving water. Additional infrastructure would be required to harvest discharged, treated stormwater for use. Otherwise, design for exfiltration is the most effective design approach for reducing off-site/downstream discharge of runoff.

Design approaches and alternatives have been studied to enhance exfiltration and groundwater recharge (if it is assumed that exfiltrated water reaches an aquifer). For example, in a side-by-side comparison of equal surface area bioretention systems with unequal media depths, Brown and Hunt (2011) demonstrated that deeper media depth resulted in greater exfiltration, likely due to greater opportunity for exfiltration through the sides of the system. Tu and Traver (2019)

[1] Infiltration is a primary stormwater management objective because of the effect of reducing the volume of runoff discharging off-site or downstream, where in-situ conditions allow. However, to be technically accurate in terminology, runoff that has percolated through a BMP, and seeps out of the BMP into the surrounding soils is said to *exfiltrate* from the BMP. This water *infiltrates* into the surrounding soils.

measured the effectiveness of bioretention planters installed above a subsurface gravel-filled infiltration bed (Section 3.1.4). Over the monitoring period, little overflow was observed in large storm events because of the supplemental storage and exfiltration opportunity. Other design approaches are likely feasible to enhance groundwater recharge.

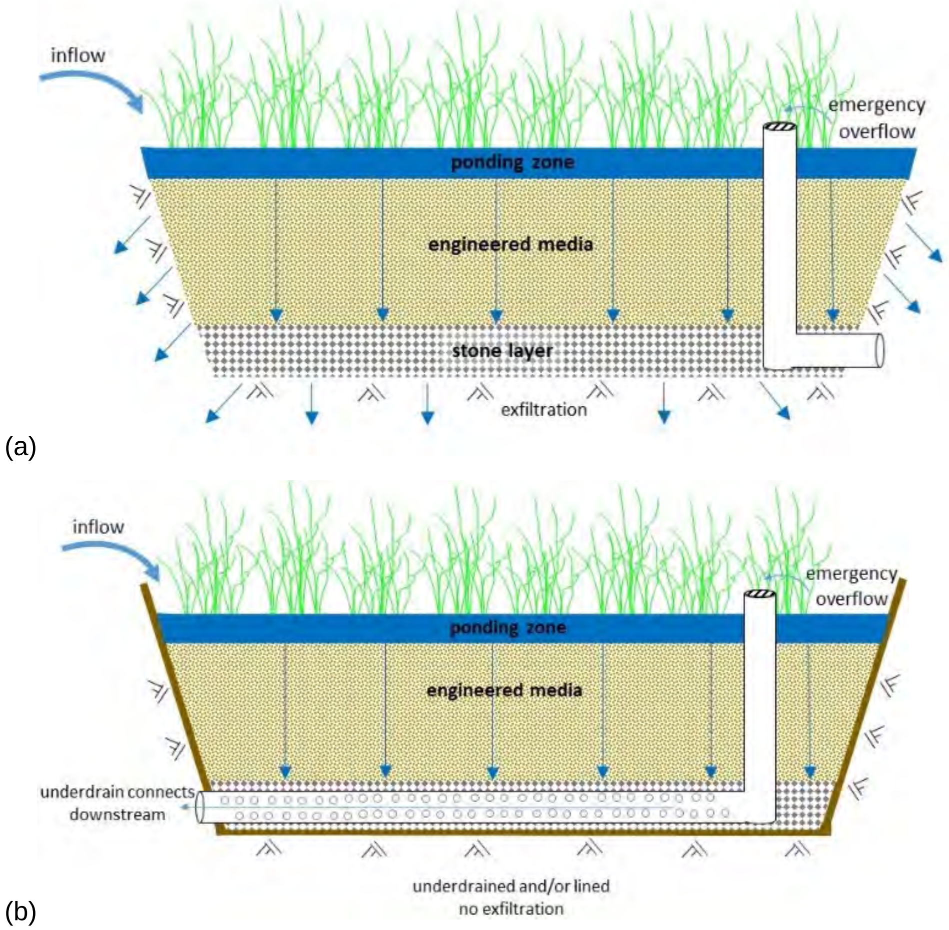


Figure 2. Flow pathways through a bioretention system (adapted from Liu and Fassman-Beck 2017).

3.1.2. Cisterns and rain barrels

A rain barrel is a small, above-ground storage tank (e.g., a 55-gallon drum) used for collecting stormwater runoff from a roof via roof downspouts (Figure 3a). Rain barrels are typically installed at residential locations, where a homeowner uses captured runoff for outdoor irrigation.

A cistern is a larger storage tank, which can be above or below ground (Figure 3b). A subsurface stormwater detention system (another form of BMP) can be configured as a cistern. A cistern's potentially substantial capture volume supplies typically non-potable indoor (re)use, such as toilet flushing or laundry, as well as outdoor irrigation or vehicle washing. For example, a combination of above-ground cisterns and subsurface detention systems were designed to capture roof and parking lot runoff for up to a 77 mm storm event in North Carolina (Wilson et al. 2015). Field monitoring indicated that over 47 storm events, a median of 98% of the stormwater was harvested for toilet flushing and outdoor irrigation, or allowed to recharge groundwater via a large subsurface infiltration gallery.

The primary stormwater management objective for cisterns and rain barrels is to reduce or delay the volume of off-site discharge. In either case, multiple cisterns or rain barrels may be connected to increase capture capacity (Figure 3c). For continued effectiveness to manage stormwater, cisterns and rain barrels must be emptied between storm events.

Neither system is likely to provide significant water quality treatment of incoming runoff for conventional stormwater pollutants (e.g., suspended solids and nutrients). Heavy metals can be significant in roof runoff where metal building materials are used, e.g., copper guttering or galvanized aluminum or zinc roofs. There may be some concern for pathogen contamination (e.g., from bird droppings), but research is inconclusive on the scale of the issue.

(a) (b) (c)

Figure 3. (a) Residential rain barrel; (b) Cistern; (c) Hydraulically connected cisterns to maximize capture potential. All photos taken in North Carolina by E. Fassman-Beck.

3.1.3. Permeable/Pervious/Porous Pavement

A typical permeable pavement has a permeable surface (allows water to pass through) and an underlying gravel-filled storage bed (Figure 4). Typical permeable pavement installations capture rain that falls directly over the surface area of the pavement itself, which means the capacity of the BMP to provide stormwater capture is likely limited to the surface area of a given installation, and the rainfall that occurs. Permeable pavements may also be designed to manage runoff from adjacent impervious surfaces. Typically, the extent of supplemental drainage area is limited to 5 times the extent of the permeable pavement and impervious surfaces (e.g., roofs, additional street or parking lot area). Local design guidelines may differ.

The gravel bed under the permeable surface stores water in the pore space, almost all of which eventually drains by gravity. As with bioretention systems, typical permeable pavement BMPs may be designed to exfiltrate excess treated water, or discharge via an underdrain.

An exfiltrating permeable pavement creates opportunity for indirect runoff capture via groundwater recharge. For direct runoff (re)use, a permeable pavement system that is lined to prevent exfiltration, or is installed over impermeable in-situ soils, may provide a self-contained storage facility. A subsurface cistern to enhance storage capacity could be introduced as per Winston et al. (2020). Treated runoff would be withdrawn via an underdrain or other supplemental infrastructure. The permeable pavement's gravel storage bed must be emptied between storm events to allow effective stormwater management.

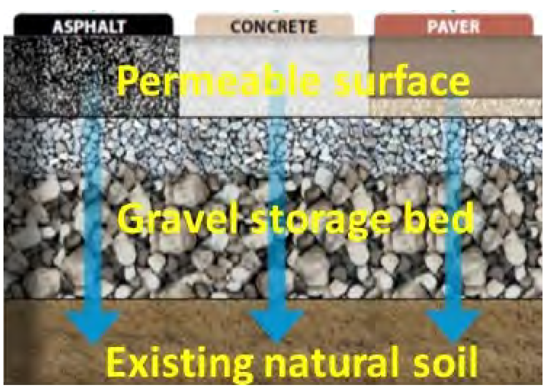


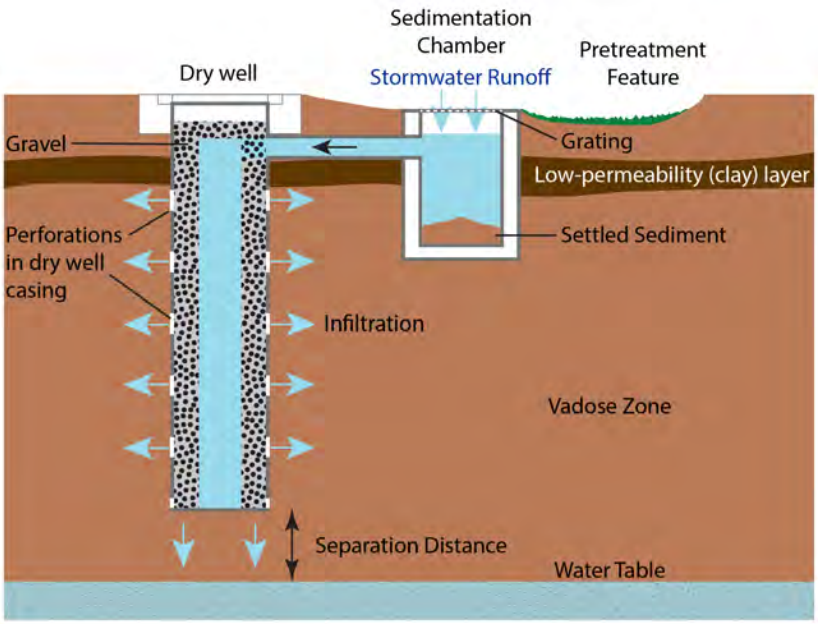
Figure 4. Exfiltrating permeable pavement cross section (underdrained configuration not shown). Adapted from ASCE/EWRI Permeable Pavement Task Committee Report (Eisenberg et al. 2015).

3.1.4. Infiltration basins, trenches and dry wells

A typical infiltration basin, trench or dry well provides temporary runoff storage for subsequent exfiltration to recharge groundwater (Figure 5). Dry wells usually capture runoff in a subsurface vault, managing runoff from a small drainage area. Infiltration trenches or basins are usually configured with a surface ponding zone which provides temporary storage of runoff from a large drainage area. The ponding zone may be created directly over rapidly draining in-situ soils, or a gravel bed may be installed for supplemental subsurface storage.

Infiltration basins, trenches, and dry well BMPs are typically designed specifically to exfiltrate all runoff that enters the BMP, creating opportunity for indirect runoff (re)use via groundwater recharge. These BMPs are rarely designed with underdrains. It is generally assumed that water quality treatment occurs as water discharges through the in-situ soils in the immediate vicinity of the BMP, rather than within the BMP itself. Few studies have quantified the potential for contaminant migration through the subsurface near an exfiltrating BMP.

(a)



(b)

Figure 5. (a) Infiltration basin in North Carolina and (b) dry well (https://www.americangeosciences.org/geoscience-currents/dry-wells-stormwater-management).

3.2. Neighborhood scale or regional BMPs

Neighborhood or regional scale BMPs collect runoff from a larger drainage area than a site-scale BMP, and usually also serve a flood control or hydromodification management purpose. Regional BMPs might include residential subdivisions or office parks where 10 or more acres drain into a single basin.

Because regional BMPs, by design, are generally large surface impoundments with significant storage, it is anticipated that less supplemental infrastructure would be needed to capture runoff for meaningful (re)use supply.

3.2.1. Recharge basins and spreading grounds

A recharge basin is similar to the infiltration basin described in Section 3.1.4, but larger in scale. In some areas, such as the Los Angeles region, these systems are known as spreading grounds. By definition, a recharge basin is designed to recharge groundwater by directing captured runoff into the subsurface. In the terminology of this report, recharge basins provide indirect (re)use.

There are at least 30 spreading grounds in the Los Angeles region, occupying hundreds of acres of land. The spreading grounds are part of the region's flood control system and conservation program. Information on the locations, capacity, and monthly volume of water conserved in 26 of these basins operated by the Los Angeles County Department of Public Works are published online. These data are also incorporated into the regional watershed model described in Section 1.2.

3.2.2. Retention basins

A retention basin captures runoff in a surface impoundment with a permanent pool. Downstream discharge from a retention basin is through an outlet designed to restrict (or enable) flow rate. While most retention basins have passive outlets, introducing real-time controls into field monitoring systems enables active manipulation of stored water release (basin emptying). Changing outlet structures and release rates could contribute surface storage and supply for direct (re)use. For continued effectiveness to manage stormwater, the retention basin's active storage above the permanent pool must be emptied between storm events.

3.2.3. Detention basins and flood control impoundments

A detention basin captures runoff in a surface impoundment that empties completely between runoff events. Downstream discharge is typically through a passive outlet designed to restrict (or enable) flow rate, but real-time controls can be introduced to help optimize BMP performance.

Flood control impoundments are similar to detention basins in that they capture surface runoff but are specifically designed for flood control purposes. Changing outlet structures and release rates could enhance surface storage and supply for direct (re)use. For continued effectiveness to manage stormwater, a detention basin (or flood control impoundment) must be emptied between storm events.

3.3. Runoff Diversions

Dry weather runoff diversions from the storm drain system to the sanitary sewer are frequently used for sites upstream of sensitive receiving water bodies where complete water quality treatment is necessary. Many runoff diversions are located at or near high use recreational beaches where complete treatment of runoff is required to maintain bacteria standards. Many examples exist throughout California including Mission Bay in San Diego, CA where more than 100 storm drains around the circumference of the bay are diverted to the sanitary sewer system. Most runoff diversions occur during dry weather, but sometimes first flush during wet weather is also targeted. Once diverted, the captured runoff can then be used by the POTW for wastewater recycling and (re)use.

4. PROPOSED METHODS TO QUANTIFY STORMWATER CAPTURE VOLUME

For site or regional-scale BMPs and large-scale impoundments, several methods are proposed to estimate the potential volume of stormwater capture, each of which relies on calculating or estimating a BMP's *water balance*. A water balance is also known as a *water budget* or *hydrologic budget.* In a water balance calculation, the sum of the inputs of water must balance with the sum of the outputs of water (Figure 6). During the time scale of a storm event, all inflow (runoff) into the BMP is distributed amongst all water flowing out of the BMP and water stored inside the BMP. These elements may include:

- downstream discharge, potentially comprised of treated and untreated flow,
- water stored in the BMP's tank, basin, or pore space (media-filled BMPs),
- water lost to evaporation (BMPs open to atmosphere),
- water lost to evapotranspiration (vegetated BMPs only), and/or
- exfiltration (where site conditions and BMP design allow).

Each of these elements is quantitatively represented in the water balance calculation. The potential capture volume is estimated, where:

- Indirect (re)use BMPs: Potential capture volume is the result of a water balance calculation for exfiltration.
- Direct (re)use BMPs: Potential capture volume is the result of a water balance calculation for withdrawal.

Sections 4.1 to 4.3 present different approaches to quantifying water balance elements. The methods differ in varying levels of accuracy, ease of data access, and additional work required for scaling from single BMPs to regional or statewide estimates. To develop a statewide assessment, each of the approaches in Sections 4.1 to 4.3 relies on the development of a statewide inventory of existing and planned BMPs. The "data needs" section of each method details the actual data that would need to be collected to calculate the water balance according to that method, as well as basic information required to extrapolate to additional BMP sites and/or to develop a state-wide inventory of BMPs and their attributes. Additional information may be required to develop methods for extrapolation from site- to regional- to state-wide estimation of stormwater capture, but such a methodology has not been explicitly considered in this report.

A critical condition for stormwater to be captured for potential (re)use is the comparison between the influent runoff volume and the BMP's available storage volume in any given storm. The potential to generate (re)use volume from media-filled BMPs depends on whether a storm produces enough runoff to exceed the storage capacity of the BMP's media layer. The potential (re)use volume generated by BMPs that store water in a tank or reservoir (either surface, or subsurface, and including large scale impoundments) is determined by the dimensions of that storage chamber, and the extent to which it is filled during a given storm. In all cases, the BMP related elements may be manipulated by design, which suggests that it may be feasible to enhance (re)use potential from BMPs by reconsidering the current typical design approach.

The methods proposed in Sections 4.1 to 4.6 rely on analysis of historic measurements of large scale water management infrastructure. Each of these methods would create regional estimates of stormwater capture potential.

For a comprehensive estimate of the potential to capture stormwater runoff, it is likely necessary to combine several of the approaches discussed herein; however, the feasibility of and resources required to implement methods varies, particularly for site-level BMPs. Therefore, the following discussion includes considerations such as logistics of data collection, feasibility and resource implications for implementing methods, and opportunities for added value.

The California Department of Water Resources released a draft "Handbook for Water Budget Development: With or Without Models" in Feb. 2020. The intent of the technical reference is to compile and organize existing information on various methods and data sources for developing water balances (a.k.a. water budgets). Motivation for developing the manual is primarily to support preparation of groundwater sustainability plans under California's Sustainable Groundwater Management Act. As such, the methods and examples are in a context of large-spatial scale systems (e.g. regional impoundments or groundwater basins). The draft technical reference is open for public comment at the time of writing of this report.

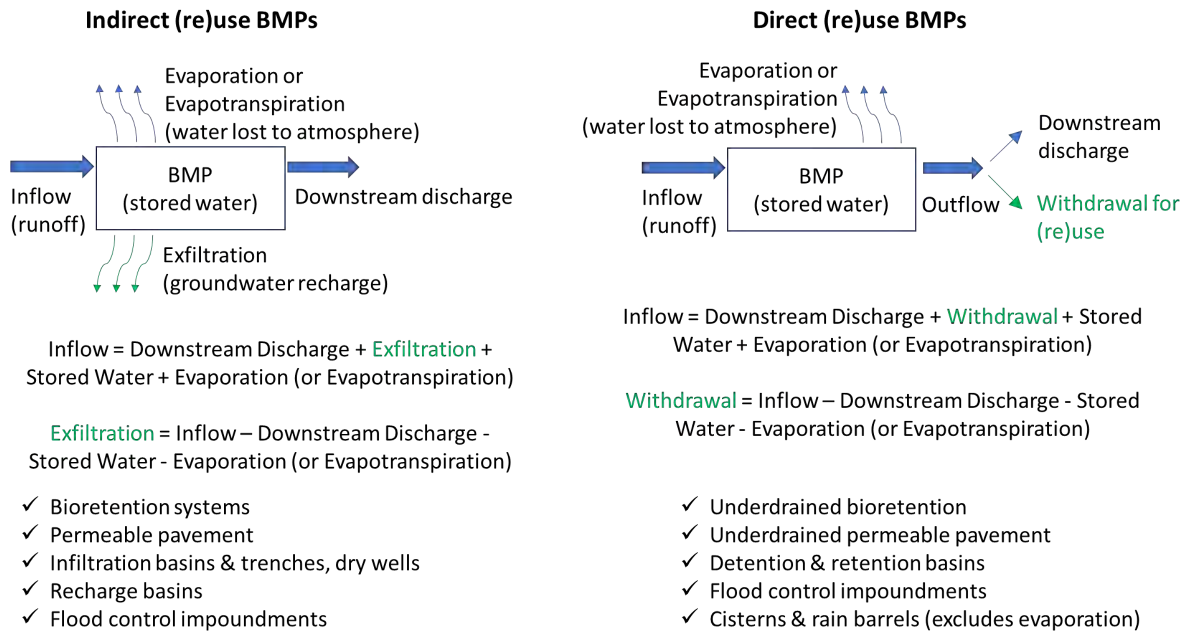


Figure 6. Conceptual BMP water balance for indirect (re)use BMPs (left) and direct (re)use BMPs (right).

4.1. BMP Hydrologic (Flow) Monitoring

4.1.1. Approach

The premise of a hydrologic (flow) monitoring approach is to directly quantify water balance elements (Figure 6) for individual BMPs via empirical data collection through direct field measurement.

4.1.2. Data needs

Table 1 summarizes typical approaches for the types of data collected during field monitoring campaigns to measure BMP hydrology. In practical application, how the sensors used and configured are site-specific. While rainfall measurement is not directly incorporated into a water balance calculation for a site-scale BMP, the data is essential to provide context, and enable extrapolation of results to non-measured storm events and/or unmonitored sites.

BMP design information such as construction drawings documenting BMP configuration and the size of the contributing drainage area are needed to develop methods to scale results from site-level to regional or statewide estimation. If design documentation is not available, parameters of interest can often be measured in the field.

Table 1. Typical data collection objectives for BMP flow monitoring

Element	Typical Measurement Technique
Water Balance	
Rainfall	Directly measured on-site, or obtained from public gauges nearby
Inflow	Directly measured using a sensor in each inflow channel or pipe
Discharge	Directly measured using a sensor in each discharge mechanism (pipe, channel, weir, pump)
Stored Water	• In media-filled BMPs (e.g., bioretention systems) soil moisture sensors may be used to directly measure water content in the media. • In BMPs where ponded (standing) water occurs (on a surface, inside a tank, or within the pore space of a gravel bed), measurements of ponded water level may be coupled with BMP geometry to calculate stored water.
Evaporation	Can be modeled or measured
Evapotranspiration	Applies only to vegetated systems. Can be modeled or measured.
BMP Drainage Area	
Location	Each point of inflow and outflow (preferably defined by latitude/longitude coordinates)
Drainage Area Size	Extent of direct tributary drainage area
Land Use	All major land uses and extents thereof
BMP Design	
BMP Dimensions	3D extents, including footprint and full depth
BMP Components	BMP characteristics (e.g., engineered fill media depth, if present, and water storage characteristics)

4.1.3. Other implementation considerations

Intensive resources are typically necessary to execute a field monitoring program and subsequent data analysis. Multi-year monitoring periods are required to generate data sets that reflect a range of expected operating conditions (e.g., storm sizes, durations, frequency and inter-event timing, BMP condition, presence/absence of vegetation and irrigation). Ideally, monitoring programs will also account for equipment malfunction or complete failure. Methods must be developed to extrapolate performance from a relatively small number of site-level BMPs to a regional scale, watershed scale, and/or statewide scale. It is anticipated that statewide estimation of capture volume will require collation of a statewide inventory of existing and planned BMPs. Some jurisdictions are currently developing this kind of asset resource, e.g., Orange County Public Works' "OC Stormwater Tools" (https://www.ocstormwatertools.org/). Given that at this time, stormwater asset management is a tool being voluntarily adopted, gaps will likely exist in a compiled inventory. The accuracy of the scaled-up statewide model will be a function of the inventory.

A cost-effective approach to estimating stormwater capture across California may arise from coupling BMP field monitoring data with watershed modeling techniques (Section 4.3). Criteria would need to be established to prioritize BMP sites for field monitoring. Factors to consider might include, but are not limited to:

- How well a particular BMP site represents the range of actual installations, including drainage area characteristics, BMP type, BMP design, BMP age, and/or maintenance condition;
- Logistical feasibility of monitoring, including installing and maintaining equipment, and conducting monitoring;
- Legal access; and
- Safety for monitoring personnel and equipment.

Fit-for-purpose monitoring guidance (data collection and field quality assurance), data analysis methods (calculation methods and quality assurance) and submission protocol (prescribed digital formats) must be developed. These guidance documents will help streamline collating data from a large number of monitoring sites, and to ensure a consistent and reliable approach is used when calculating stormwater capture potential. A digital repository must be developed to store the data. This could be accomplished through:

- Construction of a new volume estimation tool and database,
- Expansion and modification of existing State Water Board electronic reporting systems (e.g., SMARTS),
- Expansion of the existing database supporting the California BMP Effectiveness Calculator (https://sccwrp.shinyapps.io/bmp_eval/) (Afrooz et al. 2019), developed with funding from the State Water Board,
- Application of another readily-available (preferably open-source) platform.

While many agencies across the state are currently engaged in BMP monitoring, site- or permit-specific approaches are commonly found, compromising the potential to compile and leverage information currently being gathered. These existing data nonetheless provide a useful starting point for initial evaluation of the overall feasibility of implementing a statewide field monitoring approach for stormwater capture calculation. In addition to generating estimates of the potential capture volume from some types of BMPs, these data and monitoring programs would be useful to identify sites that could or should be revisited for additional monitoring, consolidating monitoring guidance, and/or documenting lessons learned for future monitoring efforts. For example, accurately measuring rainfall, BMP inflow, and BMP outflow are fundamental and essential steps for water quality monitoring.

4.1.4. Discussion

A well-designed and executed field monitoring plan provides the best opportunity for generating accurate estimates of potential (re)use volume from BMPs. Monitoring data measures the dynamic operation of a BMP, as well as changes in BMP performance, including inter- and intraevent behavior. Because many BMPs fill and drain concurrently, either by exfiltration to groundwater or discharge via underdrains, they typically process more water during individual events than anticipated during the planning process. Better-than-expected performance has been documented by monitoring studies of GI/LID type BMPs (e.g., rain gardens [several citations within Traver and Ebrahimian 2017] and permeable pavement [Fassman and Blackbourn 2010]), particularly when compared to the "on paper" estimates from design calculations (Section 4.2). The typical design approach assumes a fixed maximum storage capacity, regardless of operating conditions. This fixed maximum is based on BMP characteristics such as basin geometry and measurements of an engineered media's capacity to store water. Figure 7 provides a conceptual diagram of an "on paper" estimate derived from design information compared to the dynamic operation that is quantified by field measurements. Similarly, many existing computer models used to predict BMP performance incorporate the idea that there is a fixed maximum storage capacity in a BMP. Furthermore, the accuracy of these models often has not been widely validated against "real" data (Section 4.3).

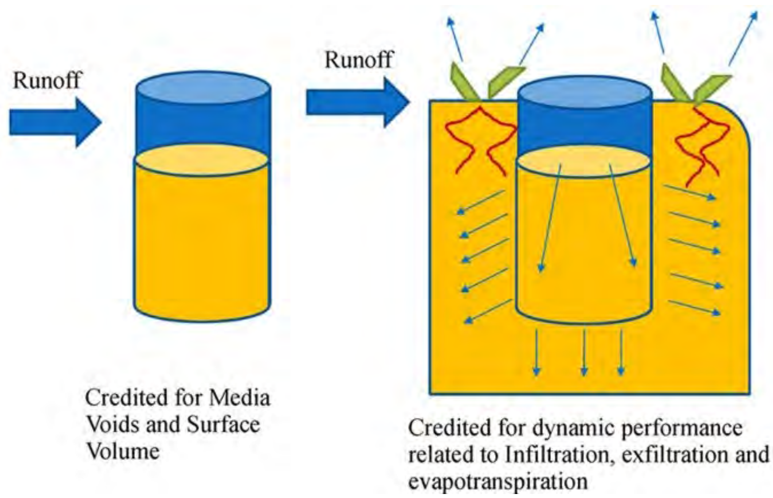


Figure 7. Conceptual comparison of capture estimates: "on paper" estimate from design information (left) and dynamic operation measured in the field (right). Source: Traver and Ebrahimian 2017

4.1.5. Added Value

BMP monitoring is notoriously difficult. As such, many water quality compliance-oriented monitoring campaigns emerge with less data than ideal for performance analysis. While some excellent monitoring guidance is readily available, existing guidance tends to present high-level descriptions rather than targeted information that a monitoring crew can directly translate into practice, such as sensor selection, calibration, and installation techniques. Development of guidance for BMP hydrologic monitoring and calculating components of the water balance using field data would improve compliance monitoring outcomes through standardization and dissemination of best practices. As measuring BMP hydrology is the critical first step in any BMP effectiveness assessment, including hydromodification mitigation or water quality treatment, this guidance could contribute substantially to the general body of knowledge on BMP performance in California.

Likewise, data analysis guidance could be extended beyond water balance calculations to include indicators for asset management and long-term maintenance. For example, continuous hydrologic monitoring (when subject to active data analysis) provides a reasonably easy indicator of clogging or short-circuiting.[2] Resulting changes in data patterns can alert managers that water is not flowing through the BMP as intended and treatment effect has been compromised – in other words, when there is a deterioration in operating conditions induced by changes in the physical condition of the BMP. These data could be used to schedule emergency maintenance activities to restore acceptable levels of service. Tracking these data over time in a shared database would eventually generate a critical mass of information to extract performance-driven indicators that could be used to optimize scheduling of routine BMP maintenance. This could be done by building or populating asset management models discussed in Section 4.1.3.

Advances in sensor technology, remote communication and access, and the Internet-of-Things is rapidly advancing the ability to actively manage stormwater. BMPs are typically designed as passive operations, but the introduction of "real time controls" (i.e., hardware and software) integrated into field monitoring systems can be used to actively manage (maximize) capture volume. An opportunity arises to configure some BMP monitoring sites to explore the cost-benefit of implementing these technologies.

4.2. BMP Design Information from Plan Submittals and As-Builts

4.2.1. Approach

In all cases, the potential for BMPs to contribute to stormwater capture depends on quantifying elements of the system's water balance. Section 4.1 directly quantified the water balance under dynamic field conditions. This section estimates the water balance using static estimates of a BMP's maximum storage volume determined during BMP planning and design.

The total volume of storage in a BMP is the sum of the estimated maximum potential storage provided by each component or layer within the system. These calculations, and the assumptions contributing thereto are typically included in plan submittals and "as-builts."[3] Therefore, this approach to estimating BMP capture potential develops a site-scale model from data mined for BMP design. When coupled with estimates of daily rainfall (inflow), a water balance may be calculated. The specific calculations depend on BMP type.

4.2.1.1. Tank or reservoir-type BMPs, including cisterns, rain barrels, retention basins, dry wells, infiltration basins and trenches, and permeable pavement

The potential for capture is determined as the minimum of either the inflow volume or the water storage volume in the tank or reservoir-style BMP in any given storm. Inflow volume exceeding the BMP's water storage capacity is assumed to bypass the system, and is unable to be harvested.

---

[2] Short-circuiting is when flow intended to enter a BMP follows a quicker and/or easier path to the outlet (BMP discharge point). Short-circuiting may occur because of a design flaw, installation flaw, or heterogeneity in the media used. As a result, treatment provided by the BMP is minimized and flow mitigation may be reduced or completely eliminated.

[3] As-builts typically refer to construction drawings that have been edited to reflect how a BMP was actually constructed. Often, modifications are required due to unanticipated site conditions encountered during construction.

4.2.1.2. Media filled BMPs, such as bioretention systems and sand filters

The fill media in many BMPs can provide substantial stormwater storage. In theory, the maximum volume of water a soil-filled system can retain is known as its "*field capacity*." According to soil scientists and geotechnical engineers, field capacity measures the quantity of water stored by a medium against gravity drainage. Because of field capacity, all runoff entering a media-filled BMP is held in the media during most small storm events. No flow out of the system occurs through exfiltration or through underdrains. In theory, significant quantities of water should not begin to be released from any soil-filled system until the field capacity of the media is filled. Field capacity is typically less than "*porosity*," which corresponds to the total volume of pore space. A "*saturated*" soil will temporarily hold a volume of water equivalent to the porosity, but gravity will cause water to drain (i.e., to empty until the field capacity is reached). At the opposite end of the moisture spectrum, in temperate and humid climates, a soil media will only naturally dry to its "*wilting point*," which means there is a small, but measurable amount of moisture present. In semi-arid to arid regions, soils will naturally dry completely (e.g., to "oven-dry"). The difference between the maximum (field capacity) and minimum values (wilting point or oven-dry) is used to estimate runoff storage potential under ideal conditions. In practice, deviations from the theory occur regularly.

Estimating the stormwater capture potential for media-filled BMPs must consider multiple flow conditions:

- <u>If a storm produces less runoff than the media's water storage capacity</u>, no water will be available for (re)use.
- <u>If a storm produces runoff that exceeds the media's storage capacity, but is less than the system's capture capacity</u> (including temporary storage in a ponding zone), all runoff will be captured in the BMP. Some of the runoff will be stored in the media for subsequent evaporation or evapotranspiration, while the remainder will eventually discharge via exfiltration (indirect [re]use] potential) or through underdrains (direct [re]use potential).
- <u>If a storm produces runoff that exceeds the entire BMP's capture capacity</u> (including media storage and ponding zone), that portion of the inflow will bypass the system (direct downstream discharge) and will not be available for (re)use. Likewise, a portion of the inflow equal to the media's storage capacity will not be available for capture. The remainder of the inflow is assumed to be available for direct or indirect (re)use.

4.2.2. Data needs

Most of the elements of a BMP's water balance can be estimated using information from plan submittals and/or "as-builts," but may also require supplemental information from the literature, particularly with respect to the water storage characteristics of media-filled BMPs.

Table 2 summarizes information that would need to be extracted from plan submittals, as-builts, or estimated based on best available information such as literature sources.

Table 2. Data needs from plan submittals and as-builts

Element	Typical Measurement Technique
Water Balance	
Rainfall	Historic records (data mining), future prediction, or design storms
Inflow	Calculated using standard engineering methods from drainage area size, land use characterization, precipitation depths of interest, and appropriate rainfall-runoff transformation (e.g., TR-55, Rational Method, watershed hydrologic model, etc.)
Stored Water	• In media-filled BMPs (e.g., bioretention systems, sand filters), estimated from media characteristics including porosity, field capacity and wilting point (Davis et al. 2012, Fassman and Simcock 2012, Fassman-Beck et al. 2015) and BMP dimensions. • In aggregate-filled BMPs (permeable pavement, infiltration basins & trenches), estimated from media porosity and BMP dimensions. • In BMPs where ponded (standing) water occurs (either on a surface, or stored inside a cisterns or dry wells), calculated from BMP dimensions.
Evaporation	Can be modeled or measured
Evapotranspiration	Applies only to vegetated systems. Can be modeled or measured
BMP Drainage Area	
Location	Each point of inflow and outflow (preferably defined by latitude/longitude coordinates)
Drainage Area Size	Extent of direct tributary drainage area
Land Use	All major land uses and extents thereof
BMP Design	
BMP Dimensions	3D extents, including footprint and full depth
BMP Components	BMP characteristics (e.g., engineered fill media depth, if present, and water storage characteristics)

4.2.3. Other implementation considerations

To estimate potential stormwater capture over a long time period, a range of scenarios representing varying rainfall depths and their frequency of occurrence must be developed for each BMP. The potential volume of stormwater capture relies on the varying relationship between storm size (and hence inflow) and available storage capacity within the BMP. Small storms that do not fill up available storage tend to occur more frequently than large storms, which might bypass flow. With the BMP monitoring approach in Section 4.1, this variability is quantified through direct measurement. When using information from plan submittals, each condition must be modeled to develop a spectrum of potential capture volume. This could be accomplished through discrete calculations of individual storm events (e.g., design storms), or by developing a site-scale spreadsheet model that accounts for alternating periods of wet and dry weather on a daily time step. A finer temporal resolution is not warranted because the overall method does not account for the dynamic flow processes through the BMP (i.e., time varying filling and draining).

To ensure consistent and reliable application of the water balance calculation, and interpretation of its results, spreadsheet templates or an online calculator should be developed for each BMP type and configuration (Section 3.1). Likewise, a common digital repository should be created to streamline the challenge of collating and storing data from contributing agencies across the state.

Similar to Section 4.1, the BMP site-scale model to estimate stormwater capture proposed in this section must be scaled to a watershed, region, or statewide. Fortunately, the BMP inventory needed to scale site-level estimates is concurrently developed during the data mining step. It is anticipated that collating these data from municipal and/or county records is a time-consuming activity, but it is limited to a desktop procedure.

4.2.4. Discussion

A static estimate of capture volume as described in this section essentially conceptualizes a BMP as a bucket that fills up and overflows once its capacity is exceeded. While this approach is somewhat easily applied, is has been shown to underestimate runoff capture potential compared to field measurements of real behavior (Davis et al. 2012, Fassman and Simcock 2012, Traver and Ebrahimian 2017). As described in Section 4.1.4, many BMPs fill and drain concurrently, either by exfiltration to groundwater or discharge via underdrains. This enables the system to process more water than is estimated by a fixed capacity (maximum “bucket”). The benefit of applying the proposed static capture approach is that it would likely create a more conservative estimate of (re)use volume. The drawback is knowingly misrepresenting the potential supply, and therefore creating bias in a potential cost-benefit analysis.

Other than oversimplifying a BMP’s water balance, additional uncertainty arises from the methods used to estimate water storage characteristics of a BMP’s components, particularly for media filled systems. Each media’s retention capability is unique (Fassman-Beck et al. 2015, Liu and Fassman-Beck 2016a and b) and can be manipulated by design. Measurements of an engineered media’s water storage characteristics are typically obtained under ideal conditions in a laboratory setting, or reference values are substituted. Laboratory measurements introduce some uncertainty as the methods do not truly reflect actual field conditions. For example, preferential flow paths or overall storage capacity could be impacted by the presence of plants and plant roots, media heterogeneity/abnormality can be introduced by the construction process, or characteristics (clogging, compaction or settling) can change due to system age or maintenance. Reference values may introduce even more uncertainty simply due to a lack of easily accessible information. Porosity and saturation measures are more easily obtained than field capacity and wilting points.

4.2.5. Added Value

As mentioned, the majority effort in implementing this approach is exerted in data mining municipal and county records. A significant added value opportunity is concurrently offered for creating and/or populating a statewide asset management inventory or database, similar to the database suggested in Section 4.1.3. A myriad of future applications potentially emerge, for example, work in compliance assessment, audits, budgeting, and performance assessments from monitoring campaigns and/or operations and maintenance activities.

4.3. Watershed Models

4.3.1. Approach

A watershed modeling approach to determine potential stormwater capture relies on simulations to predict catchment runoff generation, stormwater capture and BMP behavior. A BMP's water balance remains at the core of a watershed modeling approach; however, in this case, it is estimated based on mathematical representations of the underlying natural processes.

4.3.2. Data needs

Feasibility of a modeling approach is predicated on the existence and availability of watershed models, or the ability to create a model should one not exist. A preliminary step would create an inventory of existing jurisdictional models and their spatial extent, thereby identifying where new models might need to be created. As discussed previously, a detailed georeferenced inventory of existing and planned BMPs, and their drainage area and design characteristics is required.

With reliance on existing models, regionally appropriate rainfall data are the primary inputs needed to run simulations. Typically, a multi-year historic precipitation record is the driver for a continuous simulation. An event-based model is typically driven by a design storm, or set of design storms. Design storms are prescribed by the local jurisdictional hydrology manual and other design manuals.

To simulate site-level BMPs in a watershed model, information from plan submittals (Section 4.2.2) either directly contributes to model formulation (where models explicitly represent these BMPs), or the overall method in Section 4.1 or 4.2 can be used as a separate calculation, and coupled with the watershed simulation.

Data needs for modeling regional BMPs or large-scale impoundments are described in Section 4.4.2.

4.3.3. Other implementation considerations

Several factors contribute quantifiable uncertainty in (re)use volume predictions using hydrologic models. For example:

- A plethora of watershed models are available to predict catchment hydrology (runoff generation); however, only a subset of these models incorporates explicit representation of BMP behavior. Where a jurisdiction's existing model does not explicitly incorporate BMP simulations – such as flood control models - methods must be developed to approximate the BMP's effect; however, it is likely these methods are limited to coarse approximations.

- It is anticipated that each jurisdiction across the state has developed a unique model, using different platforms. To generate a consistent statewide estimate of (re)use potential, methods must be developed to track and evaluate the influence of model assumptions, and temporal and spatial resolution.
- All hydrologic models are mathematical representations of natural processes. There does not (yet) exist a model that precisely simulates hydrologic behavior under all storm conditions.

Altogether, performing an uncertainty analysis on predictions of (re)use potential is considered an essential component of using a watershed approach.

4.3.4. Discussion

There are many different types of models used throughout California, ranging from very simple spreadsheet models to complex, linked watershed-receiving water-groundwater models. Each of these models have various positive and negative attributes, including accuracy, ability to recreate BMP function, efficacy for estimating volume capture, and cost to create and run. Some are public domain models allowing for transparency in estimation techniques. Other models are private and confidential, restricting access and interoperability with other models. Models for flood control are not optimum for estimating stormwater capture; models to estimate stormwater capture need to incorporate site-scale and regional-scale BMPs, and to consider small storms that are unlikely to pose flood risk but would contribute to potential (re)use supply. Multiple models may be found within the same Regional Water Quality Control Board, or different parameterizations of the same model.

Few models are able to directly communicate across applications. For example, to cover the geographic extent of Los Angeles County into a consolidated regional model, the Department of Public Works' Watershed Management Modeling System was compiled from multiple unique, watershed-specific models. In addition to differing model packages (i.e., software type and/or version), variations among the individual watershed models included differing assumptions and inputs such as subwatershed delineation, source data describing land uses, and model parameterization. In some cases, the existing watershed models were abandoned completely because the effort involved in converting from one model package to another exceeded the effort required to build a new model in the selected platform (Tetra Tech 2010).

The ability to model regional BMPs or large-scale surface impoundments is readily available in most common surface hydrology models. Depending on the particular model, representing site-level BMPs may be substantially more complicated. Models with coarser resolution may be limited to simulation of regional-scale BMPs, and/or a pre-processing method may be developed to aggregate site-scale effects across a larger geographical range (e.g., incorporating site-scale BMP models from Section 4.2). Finer resolution models may operate at hourly to minute time scales enabling simultaneous filling and draining of BMPs (this dynamic operation has been identified as the reason BMPs typically provide better than anticipated flow control in empirical studies (Fassman and Blackbourn 2010, Traver and Ebrahimian 2017). In any case, some adjustment to each existing model is likely required to reflect actual or planned BMP implementation. In all cases, significant expertise is required for model development and interpretation. Despite the complexity of developing methods to compare results across watershed models, employing a modeling approach facilitates extrapolation across spatial and temporal scales, ultimately providing a pseudo-direct watershed scale assessment, even with site-level BMPs. In other words, watershed models overcome one of the main limitations of the BMP flow monitoring or design information approach, which is the ability to scale up from individual BMPs to entire watersheds by linking flow and capture across many BMPs of varying types, sizes, and storm conditions.

Potential stormwater capture volume predictions depend in part on whether the model is limited to simulating isolated storm events (i.e., an "event-based" model), or whether the model performs a "continuous simulation." Substantial differences emerge between continuous simulation and event-based models, with respect to the level of effort required to develop the model(s), run simulations, and interpret results. A continuous simulation is generally considered to provide a more realistic prediction of BMP behavior because it incorporates a sequence of alternating wet and dry weather, and therefore accounts for antecedent conditions in the BMP (e.g., the extent to which a BMP's storage is already full because of a recent storm that has not yet fully drained or dried). The multi-year simulation produces stormwater capture estimates over a range of precipitation patterns and climate conditions, thereby explicitly quantifying performance variability. Conversely, an event-based model produces a single result, typically based on a hypothetical, conservative rainfall pattern developed for the design of drainage infrastructure (not treatment BMPs), and which does not directly represent an actual storm, a.k.a. "design storm." An event-based simulation approach rarely accounts for variable conditions of the BMP, i.e., available storage at the onset of an event. Were an event-based modeling approach to be adopted, a range of scenarios would need to be expressly identified and simulated (similarly to the approach suggested in Section 4.2.3 for site-scale BMPs), and methods to compare outputs across regions would need to be developed.

Prediction uncertainty emerges as a significant concern with a modeling approach to stormwater capture prediction. While traditional open reservoir-style BMPs such as retention basins and cisterns are confidently simulated with existing hydrologic models, the accuracy of simulating GI/LID type BMPs (e.g., any form of bioretention or permeable pavement) is largely unverified in the literature. Likewise, few (if any) of the existing watershed models in California have been calibrated for site-scale BMPs. It is widely recognized amongst the stormwater industry that few California-specific BMP data sets are available to perform calibration, particularly when climatic differences across the state are considered. As a first-generation attempt to quantify stormwater capture potential, it could be assumed that model calibration is outside of the scope. However, it is recommended for future study, and likely the most significant factor that would improve accuracy (decrease uncertainty) of the estimate.

4.3.5. Added value

Modeling and simulation of BMP performance is an increasingly important component of stormwater planning and assessment across a range of regulations in California. A good example is Reasonable Assurance Analysis to support Alternative Compliance, which is based almost exclusively on watershed modeling. As a result, many California Phase I municipalities have invested in advanced watershed modeling because of their primary goals to reduce runoff volume, pollutant concentrations and loads. Investing in the model development necessary for improving the accuracy of estimating stormwater (re)use volume could also improve the accuracy, reduce (or at least quantify) uncertainty, and promote consistency across the state for these other watershed modeling applications. With appropriate guidance, the data generated by BMP flow monitoring campaigns (Section 4.1) would contribute towards advancing models.

4.4. Large-Scale Impoundments

4.4.1. Approach

Multiple approaches to quantifying the potential for stormwater capture in large scale impoundments, such as regional flood control facilities, can be explored individually, or in combination. Large scale impoundments are considered direct capture opportunities, where the water stored in the impoundment provides the supply and may be manipulated through restricting the downstream discharge. Each of the following proposed methods to quantify stormwater capture and (re)use potential fundamentally relies on a water balance calculation:

- <u>Use historic data</u>. Across the state, there are likely existing data sets that can be mined, thereby offering an immediate opportunity for estimating capture potential and/or informing development of future monitoring programs. These data can be manipulated with a spreadsheet type approach to estimate the potential for capture under existing or historic conditions, or could potentially be applied to develop a more sophisticated hydrologic model to simulate future potential capture and (re)use volume under a range of scenarios.
- <u>Conduct field measurement</u> (i.e., field monitoring) similarly to the approach described for site-level BMPs (Section 4.1). The primary distinction is that monitoring large-scale impoundments gives a direct measure of regional scale potential for stormwater capture. These data would be compiled into a (re)use volume estimate using a spreadsheet type approach under existing conditions. Likewise, these data could also be used to calibrate a hydrologic model, thereby improving accuracy of predicting future (re)use volume.
- <u>Develop hydrologic models</u> for individual impoundments. The hydrology of reservoirs with open water discharges (i.e., via open channels or non-pressurized pipes) is well understood. A calculation procedure known as hydrologic routing yields time-varying quantification of the water balance. For a known inflow hydrograph (i.e., time variable inflow) into an impoundment with known geometry and outlet configuration, the calculation procedure yields the amount of storage in the impoundment and the downstream discharge at any time. The impoundment’s storage volume is directly related to the potential for direct (re)use supply. A hydrologic routing procedure can be applied to individual storm events, or in a continuous simulation (see Section 4.3.1) to predict future potential (re)use volume.

An adjustment to the water balance calculation should be performed to account for direct rainfall onto the surface of the impoundment due to the size and the time scale of operation of a large-scale impoundment, while evaporation should be included as a loss from the system. Unlike site-scale BMP water balance calculations, direct rainfall and evaporation may not be negligible inputs and losses.

4.4.2. Data needs

Across the state, an inventory of large-scale impoundments and watersheds served must be generated. For each individual impoundment, the data in Table 3 are needed for water balance calculations, either to perform spreadsheet-type calculations, or to configure and run a model.

Table 3. Data needs for large scale impoundment assessments

Element	Typical Measurement Technique
Water Balance	
Rainfall	Directly measure on-site, or accessed from public gauges near the study site
Inflow	• Directly measure using a sensor in each inflow channel or pipe, or • Estimate using a watershed model, based on drainage area characteristics and rainfall
Discharge	• Configuration of outlet works (pipe and/or channel dimensions and elevations relative to the bottom of the impoundment), in order to: o Directly measure using a sensor in each discharge mechanism (pipe or channel), or o Calculate using hydrologic routing procedure Minimum required sustained downstream discharge, if applicable
Stored Water	• Measure water level in impoundment coupled with impoundment dimensions (surface area vs. depth) • Minimum water level in impoundment/water surface elevation of permanent pool
Evaporation	Can be modeled or measured
Evapotranspiration	Applies to vegetated systems only. Can be modeled or measured

4.4.3. Other implementation considerations

In terms of implementing a strategy for using large-scale impoundments for stormwater capture, a risk assessment would need to be conducted to ensure public safety if/when any deviations from the intended operating conditions were introduced – i.e., flood protection functions cannot be compromised. For example, for capture and (re)use, it may be beneficial to maintain more water in an impoundment for longer, to allow for additional time for water extraction or exfiltration; however, this could compromise flood storage potential in a near-term subsequent event.

4.4.4. Discussion

To ensure consistent and reliable application of the proposed method, and interpretation of its results, spreadsheet templates or an online calculator could be developed. It is anticipated that extensive records are reasonability readily available. Being regional systems, these impoundments also present an analytical benefit in that they each serve reasonably large areas of land or watersheds, thus directly generating stormwater capture estimates at a regional scale.

Relying solely or even predominantly on capture estimates generated based on large-scale impoundments would potentially underestimate the supply potential in catchments with significant site-scale BMP implementation. On the other hand, without the BMP inventory discussed in Sections 4.1 to 4.3, it is infeasible to quantify the magnitude of this potential discrepancy.

4.4.5. Added value

Collating data to support analysis of large-scale impoundments across the state generates another opportunity for creating a state-wide database of stormwater capture assets for this subset of BMP types.

Should the use of large-scale impoundments emerge as a viable option, there is likely opportunity to enhance stormwater capture through introducing real-time controls, or real-time adaptive management. For example, if/when water levels and risk assessment allow (e.g., low or acceptable risk of subsequent precipitation events), operators could maintain more (or less) water in the impoundment to allow for additional time for water extraction or exfiltration.

4.5. Measured Changes in Groundwater Levels

Infiltration of stormwater to the subsurface, and the assumed subsequent aquifer recharge, is the underlying process driving capture for indirect (re)use supply. Infiltration may occur from distributed, site-level BMPs, or from regional infiltration galleries. Infiltration also occurs directly through vegetated or permeable surfaces.

4.5.1. Approach

California benefits from an extensive network of groundwater monitoring wells. The potential for quantifying stormwater capture through this indirect method can be achieved by comparing to historic groundwater level data. The estimation is predicated on an assumption that for some post-storm period of time (to be determined through data analysis), a measurable increase in groundwater levels will be detected.

4.5.2. Data needs

Historic records from groundwater wells and concurrent precipitation coupled with the areal extent of aquifers are the primary data needs to implement this estimation approach. These data need to be geo-referenced, i.e., stored in a GIS or other spatially organized format, and geo-located somewhere near capture structures. California has a network of groundwater monitoring wells through the state’s Sustainable Groundwater Management Act (SGMA), which could supply some, but not all of the necessary information. Also, the amount of historical record necessary for detecting current or future increases in groundwater levels resulting from stormwater capture is unknown.

4.5.3. Other implementation considerations

A series of confounding factors will also need to be quantified to help interpret changing groundwater levels. One example is quantifying groundwater use, which simultaneously draws down groundwater levels and may underestimate stormwater capture. Another example is groundwater injection, typically from treated wastewater, which can raise or sustain groundwater levels and may overestimate stormwater capture. The third example is advancing saltwater intrusion due to sea level rise, particularly on the urbanized coastal floodplains where many LID/GI BMPs are being implemented.

4.5.4. Discussion

The existing extent of BMP implementation is low compared to the extent of subsurface area occupied by aquifers across the state. Depending on the locations of groundwater wells compared to locations and numbers of exfiltrating BMPs, well data may not detect localized incidents of recharge, such as beneath a site-scale rain garden.

As site-level BMP implementation increases, the reliability or accuracy of using historic groundwater records to predict future capture decreases. Watersheds with BMPs designed to exfiltrate water should see an overall increase in groundwater levels, whereas groundwater recharge will not be seen in catchments where significant surface storage BMPs are introduced, yet capture is actually occurring.

One issue that has not been resolved is the transfer of infiltrated stormwater from shallow to deep groundwater. This vertical movement of water will be an important factor when translating stormwater capture to (re)use, particularly with site-scale BMPs. Shallow groundwater may exfiltrate back into stream baseflow or be used by tap-rooted plants. Deep groundwater will serve as a long-term water supply and resource.

While there are many groundwater wells in California, and many wells that are monitored, the preponderance of useful data may come from private wells. Collecting and accessing the data from private wells may be programmatically difficult.

4.6. Measured Changes in POTW Inflow

Sanitary sewer collection systems inevitably accumulate unintended flow from stormwater either via illicit connections (unintended or otherwise) or through inflow and infiltration (I&I) into the underground sewer pipes. Frequently, the I&I seeps through imperfections in the sewer collection system (i.e., cracks, joints, etc.), but can also occur through manholes or connected downspouts. During and immediately following precipitation events, flow into POTWs can increase as much as 30% or more. If/when there is increased inflow due to I&I, there is an opportunity to increase stormwater capture for reclaiming or recycling treated wastewater for (re)use. Alternatively, if/where a POTW does not currently reclaim or recycle water, long term changes in inflow patterns can be used to estimate the volume of stormflow potentially captured, should additional infrastructure be introduced.

4.6.1. Approach

Over the long-term, statistical changes in patterns of influent flows to the POTWs that are not attributed to changes in service areas or population may be attributed to infiltrating stormwater. POTWs also maintain records of reclaimed or recycled water production, and downstream discharge on an hourly basis. The outcome of coupling these data are an estimate of the fraction of reclaimed or recycled water potentially available from POTWs due to stormwater-enhanced inflow to the plant.

When supplemented with analysis of precipitation records, statistical patterns may emerge to enable prediction of stormwater capture and potentially future capture for (re)use supply. As these data are collected in real-time, the capture estimates can be continually updated.

4.6.2. Data needs

For each POTW analyzed, data required includes:

- Historic influent flow and treated effluent discharges (downstream and reclaimed/recycled, where applicable);
- Minimum flow requirements through the plant and/or downstream discharges;
- Delineation of service area, including dates and extent of service area expansion and/or major changes in flows through or from a plant;
- Precipitation records concurrent with flow data. Precipitation data should be collected within the collection system service area.

4.6.3. Other implementation considerations

Generating real-time estimates of capture depends on developing a centralized data repository, data submission/upload protocol and dashboard to consolidate and report results.

4.6.4. Discussion

Analysis of POTW flows provides indirect estimates of regional capture potential and may be particularly useful for an initial screening of POTWs that could introduce or increase capacity for reclaiming or recycling water. Omitted from the estimate would be volumes of runoff infiltrated through site-level and regional BMPs, the implementation of which is anticipated to continually increase for the foreseeable future across California. As with all methods other than BMP hydrologic monitoring (Section 4.1), quantifying accuracy or uncertainty of the method is an important component of the analysis.

4.6.5. Added value

For the most part, POTW and stormwater agencies do not interact closely throughout the state. A project like this could be justification for initiating continuing interactions, to better integrate the one-water concepts. For example, this could help overcome both technical, regulatory, and jurisdictional hurdles to additional stormwater capture in both dry and wet weather.

4.7. Other Potential Sources

Several other sources of information may contribute to estimating the potential for stormwater capture but are considered peripheral estimates. The stormwater capture volume estimates from the facilities/methods listed below would likely be small relative to the other methods across all of California. Moreover, these estimation methods would likely be difficult to scale up across the state with acceptable levels of certainty. However, if or where the previously described methods are unavailable or infeasible in specific regions, or to supplement those estimates if/where there is a known large facility, the following methods may warrant further investigation:

- Measured volumes of direct capture or industrial use: Limited installations of direct capture and industrial uses of stormwater are found in California. An inventory of these facilities would need to be collated. It is anticipated the volumes of capture would be readily available from these facilities.

- Measured changes in imported water: Imported water estimates are quantified daily. As more stormwater is captured locally, it is presumed that less imported water will be required to meet the needs of water-starved areas. Historic records of imported water can be reviewed to identify occurrences of periodic decreases in import demand and coupled with precipitation records and records of BMP implementation. There are a number of competing and confounding factors to this approach, making uncertainty and applicability questionable.

- Measured changes in water metering: Rain barrels and cisterns are site-scale BMP technologies typically installed specifically to capture and enable stormwater (re)use. Rain barrels are typically used for irrigation, whereas cisterns can also be used for non-potable indoor use (e.g., toilets or laundry) after some level of treatment. A comparison of potable water demand via water meter records, at sites with and without either of these BMPs, may be used to quantify site-scale capture and (re)use volumes.

5. Discussion

5.1. Selecting the best method

This report evaluated the technical approach of six uniquely different methods for quantifying stormwater capture. Each method represents differing levels of effort, complexity in implementation, and potential accuracy. A simplistic comparison between methods is illustrated in Table 4.

Ultimately, every stormwater capture method evaluated presents positive and negative attributes. For example, measuring BMP hydrology was the most accurate because this method focused on empirical field monitoring measurements. Unfortunately, so few BMPs are monitored at present that the extrapolation to unmonitored BMPs introduces potentially unquantifiable uncertainty. However, there are emerging opportunities to leverage resources, such as the Southern California Stormwater Monitoring Coalition’s newly approved initiative to develop a regional BMP monitoring network. On the other hand, using BMP design information to estimate capture could be initiated state-wide in the near term. While the design information method is technically the easiest to implement, it has been well-documented that BMPs are not always built to original design specifications, nor are changes fully documented in as-built drawings. BMP performance may erode with age, and this deterioration is exasperated when maintenance is neglected. Little data is available to quantify, or reliably estimate the performance variation over the lifespan of any type of BMP. In either case, using watershed models provides the ability to extrapolate site- or individual BMP capture to regional scales, either in their present configuration or in future implementation scenarios, with predictions potentially calibrated from monitoring data or estimated from design information, but there are many assumptions about the accuracy of how well each BMP performs and how it is simulated.

Since no single method emerges as superior, the State Water Board may choose to use a variety of approaches to estimate stormwater capture. If multiple methods provide similar estimates of stormwater capture, then managers will have additional confidence in the final estimate. Similarly, multiple methods may be necessary to encapsulate the range of techniques that capture stormwater around the state. The State Water Board may need one approach for site-scale BMPs, another method for regional-scale BMPs, and a third method for interoperability with POTWs.

Conducting pilot scale investigations may assist the State Water Board to evaluate the feasibility and costs of various methods. For some methods, the challenge may be access to information (e.g. data mining records from permitting agencies, or collating information from privately maintained or operated infrastructure). In other cases, the challenge is technical, e.g., feasibility of communicating between different models, or resolving data formats to enable consistent calculations. Testing stormwater capture estimates at regional or county scales at different locations around the state will ground-truth the efficacy of any method, and create opportunity for adaptive management. A phased implementation approach will provide managers with lessons learned to help ensure success of full-scale implementation.

5.2. Added Value

For each method evaluated, the added value of attempting the approach was discussed. There were some recurring themes in added value amongst the different methods. One important added value was the need to share data. Currently, very limited information is shared by municipalities or regulatory agencies about stormwater capture or BMPs. The California Department of Water Resources provides an online dataset of stormwater projects that involve groundwater recharge and direct use. The dataset is limited to systems to be constructed post 2014. Other BMP databases or management systems have been newly introduced for isolated jurisdictions.

Collating information such as the location of every stormwater BMP, design characteristics, and performance is fundamental to implementing methods 4.1 (hydrologic measurements), 4.2 (design information), or 4.3 (watershed modeling). In addition to the primary objective of estimating stormwater capture, each of these approaches enable the State Water Board to concurrently develop and populate a statewide BMP asset management system. Initiating a long-term BMP performance measurement and assessment program contributes to optimizing BMP construction, maintenance, and placement on the landscape. This would increase stormwater capture and simultaneously improve stormwater pollutant treatment and/or removal. Additional attributes including construction cost, and operation and maintenance activities, among others, would also enable evaluation of BMP cost-effectiveness for stormwater capture and/or pollutant mitigation.

Another added value of implementing the various methods was creating a procedure to compare and link surface water models across the statewide landscape. The value may be particularly useful for jurisdictions that share watersheds. A procedure to compare and contrast accuracy and precision among models would build confidence and reduce uncertainty in stormwater capture estimates. It may also contribute to advancing a consistent statewide approach to Reasonable Assurance Analysis.

5.3. Thinking about next steps

This report evaluates the technical aspects of different methods to capture stormwater using present day infrastructure. However, BMP infrastructure is being implemented at a rapid rate. Any method selected will need to evolve and upgrade as the new infrastructure is built, as existing infrastructure is maintained, and as old infrastructure is renovated. Likewise, there may be opportunity to adjust the design of individual BMPs to maximize capture potential for (re)use supply, for example, incorporating supplemental storage components in BMPs.

A second important consideration for the future is stormwater use or reuse. This report was specifically aimed at estimating stormwater capture, rather than estimating the (re)use of the captured stormwater. Several areas within the report address the importance of linking (re)use estimation methods, but the capture methods were not evaluated based on their ability to estimate (re)use. Clearly, (re)use will be an important next question for the State Water Board and the success of their Climate Change Resolution. Stormwater use can take on many forms; additional potable or non-potable water, more industrial or agricultural use, or enhancing environmental flows are all viable outcomes. However, none of these considerations were part of the algorithms presented herein.

Part of the next step thinking on stormwater capture for (re)use is water quality. This takes on two equally important considerations: treatment requirements for (re)use and contamination of groundwater. This report focused on the technical feasibility of capturing stormwater, but not what treatment would be required for its intended use. For example, site-scale bioretention BMPs with underdrains clearly provide some level of water quality treatment, but the level of treatment necessary for direct use is unlikely. In contrast, not using underdrains allows for infiltration and storage in shallow groundwater. This water can potentially be stored prior to use, and the indirect (re)use provides some level of water quality treatment. However, the remaining pollutants may contaminate groundwater supplies or the vadose zone in the immediate vicinity of the BMP, leading to unintended consequences. Studies on surface water to groundwater contamination using GI/LID BMPs are few, particularly in California (Dallman and Spongberg 2012). Thus, further work into surface water-groundwater interactions is likely called for, since this linkage may limit the amount of stormwater that can either be captured in or extracted from groundwater.

Finally, little is known on flood risk potential induced by rising groundwater levels. The only example identified to date is a calibrated, coupled surface water - groundwater modeling study in Perth, Australia. Locatelli et al. (2017) demonstrated that widespread infiltration in an urban catchment increased groundwater levels, thereby increasing risk of surface flooding. At the site-scale, Machusick et al. (2011) concluded that groundwater mounding was isolated to the immediate vicinity of an exfiltrating bioretention system. Comparable studies have not yet been identified in California.

Table 4. Summary of attributes amongst stormwater capture methods based on approach, spatial scale, data availability, accuracy, and prevalence. Checkmarks indicate the method uses the designated attribute.

Method	Approach		Scale of Estimate*		Data Availability			Relative Accuracy at Scale			Prevalence/ # Installations	
	Field Measurement	Modeled Estimate	Site	Regional	New Field Measurements	New Modeling	Data Mining	Unknown at present	Low	High	Wide-spread	Limited
BMP Monitoring	✓		✓		✓		✓			✓		✓
BMP Design Information		✓	✓				✓		✓		✓	
Watershed Models		✓	✓	✓		✓	✓	✓			✓	
Large-Scale Impoundments	✓			✓	✓		✓			✓		✓
Groundwater Level Change	✓			✓			✓		✓		✓	
POTW Flow Change	✓			✓			✓	✓			✓	

* Methods must be developed to scale from site to regional-level estimates, while direct regional estimates may omit site-scale opportunity for stormwater capture.

6. References

Afrooz, N., M. Beck, T. Hale, L. McKee, and K. Schiff. 2019. BMP Performance Monitoring Data Compilation to Support Reasonable Assurance Analysis. SCCWRP Technical Report 1081.

California Department of Water Resources. 2020. Draft Handbook for Water Budget Development: With or Without Models. Accessed online 03/28/2020 from

Brown, R.A, and W.F Hunt. 2011. "Impact of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells." *Journal of Irrigation and Drainage Engineering* 137 (3): 132–43.

Dallman, S. and M. Spongberg. 2012. Expanding local water supplies: Assessing the impacts of stormwater infiltration on groundwater quality. The Professional Geographer, 64: 1–18.

Davis, A.P, J.M. Olszewski, R.G. Traver, R.A. Brown, W.F. Hunt, and R. Lee. 2012. "Hydrologic Performance of Bioretention Storm-Water Control Measures." *Journal of Hydrologic Engineering* 17 (5): 604–14. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000467.

Eisenberg, B., K. Collins Lindow, D. Smith, D. (eds.). 2015. *Permeable Pavements*. American Society of Civil Engineers Task Committee Report https://doi.org/10.1061/9780784413784.

Emerson, C.H, and R.G. Traver. 2008. "Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices." *Journal of Irrigation and Drainage Engineering* 134 (5): 598–605. https://doi.org/10.1061/(ASCE)0733-9437(2008)134:5(598)

Fassman, E.A., and S. Blackbourn. 2010. "Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils." *Journal of Hydrologic Engineering* 15(6):475-485.

Fassman, E., and R. Simcock. 2012. "Moisture Measurements as Performance Criteria for Extensive Living Roof Substrates." *Journal of Environmental Engineering (United States)* 138 (8): 841–51. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000532.

Fassman-Beck, E., S. Wang, R. Simcock, and R. Liu. 2015. "Assessing the Effects Assessing the Effects of Bioretention's Engineered Media Composition and Compaction on Hydraulic Conductivity and Water Holding Capacity." *Journal of Sustainable Water in the Built Environment* 04015003-1, DOI: 10.1061/JSWBAY.0000799.

Locatelli, L., O. Mark, P.S. Mikkelsen, K. Arnbjerg-Nielsen, A. Deletic, M. Roldin, and P.J. Binning. 2017. "Hydrologic Impact of Urbanization with Extensive Stormwater Infiltration." *Journal of Hydrology* 544: 524–37. https://doi.org/10.1016/j.jhydrol.2016.11.030.

Liu, R. and E. Fassman-Beck. 2017. "Hydrologic Experiments and Modeling of Two Laboratory Bioretention Systems under Different Boundary Conditions." *Frontiers of Environmental Science and Engineering* 11(4): 1-10.

Liu, R., and E. Fassman-Beck. 2016a. Hydrologic response of engineered media in living roofs and bioretention to large rainfalls: experiments and modeling. *Hydrological Processes* 31(3): 556-572 https://doi.org/10.1002/hyp.11044.

Liu, R. and E. Fassman-Beck. 2016b. "Effect of Composition on Basic Properties of Engineered Media for Living Roofs and Bioretention." *Journal of Hydrologic Engineering* 21 (6). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001373.

Machusick M., A. Welker, and R. Traver. 2011. "Groundwater Mounding at a Storm-Water Infiltration Bmp." *Journal of Irrigation and Drainage Engineering* 137 (3): 154–60. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000184.

Tetra Tech, Inc. (2010). Los Angeles County Watershed Model Configuration and Calibration – Part I: Hydrology. https://pw.lacounty.gov/wmd/wmms/docs/Final_Phase_I_Modeling_Report_Part_I.pdf Accessed online 03/23/2020

Traver, R.G., and A. Ebrahimian. 2017. "Dynamic design of green stormwater infrastructure." *Front. Environ. Sci. Eng*. 11, 15 (2017). https://doi.org/10.1007/s11783-017-0973-z.

Tu, M. and R. Traver. 2019. "Performance of a Hydraulically Linked and Physically Decoupled Stormwater Control Measure (SCM) System with Potentially Heterogeneous Native Soil." *Water* 2019, 11(7), 1472; https://doi.org/10.3390/w11071472.

Wilson C. E., W.F. Hunt, R.J. Winston, and P. Smith. 2015. Comparison of Runoff Quality and Quantity from a Commercial Low-Impact and Conventional Development in Raleigh, North Carolina. *Journal of Environmental Engineering* 141(2):05014005.

Winston, R.J., K. Arend, J.D. Dorsey, J.P. Johnson, and W.F. Hunt. 2020. "Hydrologic Performance of a Permeable Pavement and Stormwater Harvesting Treatment Train Stormwater Control Measure." *Journal of Sustainable Water in the Built Environment* 6(1):04019011. https://doi.org/10.1061/JSWBAY.0000889.