APPENDIX C

Draft Drywell Standards Research Needs and Gaps Memorandum, prepared by Geosyntec Consultants

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Memorandum

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To: Matthew Freese, State Water Resources Control Board

From: Geosyntec Consultants

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Task 2.1: Draft Drywell Standards Research Needs and Data Gaps Memorandum
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EXECUTIVE SUMMARY

The purpose of this memorandum is to provide a high-level overview of relevant existing drywell guidance from California and nearby states as well as a summary of the drywell implementation research needs and data gaps that still exist based on a review of relevant drywell literature studies. While there are many topics of interest concerning drywell implementation, this memo narrows its focus based on the priorities identified by this project's Technical Advisory Committee (TAC) and the State Water Board to understanding what scenarios for drywell implementation may present a groundwater contamination risk and whether emerging contaminants present additional contamination risk. This memo also provides a summary of publicly available stormwater datasets that can be used by practitioners to understand influent concentrations to drywells from certain land uses and effluent concentrations expected from certain drywell pretreatment devices. The following summarizes the general findings from this research effort that are explained in more detail in the following sections:

1. **Existing guidance generally has a similar scope and structure, with variability in the details.** This review of guidance informs the current landscape of available guidance, including the structure of recommendations that would be recognizable to users. However, most of the guidance reviewed does not include references for the criteria suggested, therefore consistency among guidance does not necessarily demonstrate protectiveness of groundwater quality.

2. **There are several datasets available to assess stormwater quality**, both at an average level as well as worst case scenarios from various land uses. There are also datasets that can be used to assess the performance of pretreatment systems. However, these datasets tend to be limited to traditionally studied stormwater pollutants.

3. **The effectiveness of pretreatment and vadose zone attenuation to prevent groundwater contamination is a function of several factors**, including:

a. Pretreatment BMP effectiveness (ability to reduce raw stormwater pollutant concentrations for delivery to the drywell);
b. Pollutant concentrations in the drywell discharge relative to groundwater quality objectives and antidegradation requirements; and
c. Physiochemical properties of stormwater pollutants and the vadose zone, which together will dictate pollutant fate and transport between drywell release and arrival at the water table.

4. **When interpreting the findings of field studies and modeling studies found in literature, the case-specific conditions differed between studies and therefore all results cannot be interpreted similarly**. Therefore, it is rarely possible to control enough of the variables to conclusively determine what combinations of conditions led to the study's findings. As a result, this memo focused on summarizing these studies and their conclusions with the intent to understand what additional research is still needed and not necessarily to make conclusive recommendations for drywell implementation.

5. **Monitoring and modeling studies have shown low incidence of groundwater contamination (i.e., concentrations above regulatory levels) resulting from stormwater infiltration**. However, some studies and models have demonstrated that stormwater infiltration can result in increases in pollutant concentrations in the vadose zone or groundwater under certain conditions. While the detected concentrations tend to be below regulatory thresholds, these cases do indicate the potential for issues to arise from typical stormwater loading, particularly in the event of contaminated stormwater and/or sensitive groundwater cases. Therefore, it is important to identify a risk-based framework for drywell implementation guidance so that these high-risk scenarios are property mitigated.

6. **There are many research needs and data gaps remaining.** However, not all of these are of similar importance. A tiered framework is suggested for prioritizing research needs as explained in more detail in the conclusions.

INTRODUCTION

This memorandum summarizes the findings from a review of existing state and municipal drywell design and implementation guidelines as well as a review of literature describing drywell implementation case studies, drywell infiltration modeling studies, and emerging contaminant studies to understand whether and under what conditions stormwater infiltrated through drywells may impact vadose zone and groundwater quality or pose other potential risks to human health. In addition, a summary of publicly available stormwater data collected in California is provided to outline the datasets available to help characterize typical stormwater runoff quality that may drain to drywells and the typical performance of different pretreatment types. The guidance documents and literature, including literature reviews previously conducted by U.C. Davis (Edwards et al., 2016) and the Office of Environmental Health and Hazard Assessment (Hamad et el., 2016), were reviewed to understand trends in drywell siting, design, and implementation guidance and where additional research needs and data gaps exist with respect to this guidance. The conclusions described in this memo will be used to identify future research tasks that may be needed in order to develop recommendations for the siting, design, implementation, and monitoring of drywells as part of potential future California statewide drywell standards. The memorandum is outlined as follows:

- **Section 1. Existing State and Municipal Guidance:** this section provides a summary of existing state and municipal guidance documents and identifies general trends.
- **Section 2. Available Stormwater Data:** this section describes available sources of stormwater data that can be used to characterize stormwater runoff quality and pretreatment performance.
- **Section 3. Literature and Case Studies:** this section summarizes existing literature and case studies on drywell performance to understand the potential risk of groundwater contamination from drywells, treatment of stormwater in the vadose zone, and emerging contaminants in stormwater.
- **Section 4. Conclusion:** this section summarizes the findings from this review and identifies research needs and data gaps that could be filled to support the future California statewide drywell standards.
- **Section 5. Reference Tables:** this section includes table summaries of the guidance and literature documents reviewed.

1. EXISTING STATE AND MUNICIPAL GUIDANCE

Drywells in the United States are regulated as Class V wells under the Underground Injection Control (UIC) program, which is authorized by the Safe Drinking Water Act (SDWA). States and municipalities can further regulate or guide the use of drywells; however, there is currently no statewide regulatory framework in the State of California for drywell permitting, siting, design, construction, or maintenance. To guide the establishment of a statewide framework, thirteen existing guidance documents from various cities, counties, and states in the Western United States were reviewed. Table 1 summarizes the key recommendations and requirements from each source.

The following trends and outliers in the recommendations and requirements were identified through a comparative study:

- **Groundwater separation distance -** Seven of the twelve guidance documents recommend at least 10 feet of separation between the bottom of the drywell and the top of the seasonal high water table. Only one document suggests a separation distance of less than 5 feet. In some cases, evaluation of the potential for mounding is recommended and additional separation distance criteria is provided from the top of the calculated or observed mounded elevation (ranges from 2 – 10 feet).

- **Soil characteristics –** A need to evaluate the infiltration capacity of soil at the target percolation depth was identified in most of the guidance documents. Recommended minimum infiltration rates range from 0.3 to 2 inches/hour and no unanimously acceptable soil type was identified. Some guidance identifies soil chemical properties, such as cation exchange capacity and organic matter, and physical properties (such as an upper limit on permeability) as indicators of the pollutant attenuation capacity of soils (American River Stormwater Resource Plan "ARB SWRP", Washington State Department of Ecology).

- **Setbacks –** The required distance from drinking water wells ranges from 100 to 1,000 feet, with 100-150 feet being the most common. The majority of studies indicate setback requirements for foundations, but distances range from 10 to 100 feet, with 10 feet and 100 feet being equally common. The recommended distance from sources of contamination (e.g., cesspools, animal enclosures, etc.) ranges from 50 feet from sewers and watertight septic tanks (CA DWR Well Design) to 250 feet from auto shops, nurseries and hazardous materials sites (ARB SWRP).

- **Spacing –** The required spacing distance between drywells ranges from less than 20 to 100 feet. The Orange County Guidelines for Use of Drywells in Stormwater Management Applications allows a spacing of less than 20 feet, but an analysis of interference is required in such cases.

- **Pretreatment –** The majority of the guidance documents include pretreatment requirements, but the type of pretreatment and conditions for when pretreatment is required varies. Many require some form of pretreatment such as source controls, biotreatment, or sediment chambers for all drywells (ARB SWRP, City of Fontana, Orange County, Oregon UIC, Riverside County), while others only require pretreatment under conditions more prone to groundwater contamination (Arizona DEQ, Los Angeles County, Nevada DEP). Orange County requires pretreatment for all drywells, but the level of pretreatment increases with increased risk of groundwater contamination. At a minimum, pretreatment to extend the time until clogging is generally required.

- **Monitoring –** Water quality monitoring requirements are included in less than half of the guidance documents. Those that include monitoring requirements generally vary the requirements based on risk potential. For example, the state of Washington only requires water quality monitoring (for nitrate, nitrite, ammonia, or phosphorous) for industrial sites, as these sites were found to pose the greatest risk of groundwater contamination. The ARB SWRP requires monitoring of lead, mercury, chrysene, di(2-ehtylhexyl) phthalate (DEHP), bifenthrin, fipronil, and nitrate entering drywells at all sites not considered an "insignificant risk." Low risk sites only require monitoring during the first two years while high risk sites require annual monitoring.

- **Water quality/fate and transport modeling requirements –** Only two guidance documents include modeling requirements. For example, the ARB SWRP includes risk-based modeling recommendations and requirements where modeling is recommended or required depending on the potential threat to groundwater contamination (i.e., if a maximum contaminant level (MCL) does not exist for a pollutant of concern or if monitored stormwater concentrations exceed criteria values for priority pollutants at the entrance to the drywell for two subsequent years).

- **Requirements based on geology –**The City of Fontana and the state of Washington recommend a separation distance of greater than 5 feet between the bottom of the drywell and bedrock or other impermeable layers. In Orange County, limiting layers, such as bedrock or fine soils, need to be considered when determining the reliable infiltration rate. Additionally, the Oregon UIC program has conducted pollutant fate and transport modeling studies to establish minimum protective vertical and horizontal separation distances based on city and geologic unit. If the location of a UIC matches the city and geologic unit of an existing study, the associated study can be used to demonstrate groundwater protectiveness.
- **Drawdown time –** Required drywell drawdown times range from less than 30 hours to no more than 96 hours.
- **Exclusions –** Exclusions exist for sites with known soil contamination or land uses with high risk of contamination, such as brownfield sites, sites where chemical or hazardous materials are stored, sites with a high risk of sewage effluent mobilization, or sites within a contaminated groundwater plume. Additionally, sites with slopes greater than 15% are sometimes excluded or require professional review.

While the above requirements were summarized due to their prevalence in the guidelines reviewed and the interest of the Technical Advisory Committee (TAC) members, it is important to note that the guidance documents included additional requirements pertaining to other topics such as drywell depth, infiltration rate estimation; sizing calculations/hydrologic modeling, the permitting process, construction details, operation and maintenance provisions, and clogging risk assessments. These are all important factors that should also be considered in any future statewide guidance.

2. AVAILABLE STORMWATER DATA

Extensive stormwater quality data have been and continue to be collected throughout California for municipal and industrial stormwater permit compliance and/or research efforts. These data can be used to understand typical runoff concentrations and the performance of certain pretreatment Best Management Practices (BMPs). This section includes a summary of the existing publicly-available databases[1] that can be referenced for future use to support researchers, regulators, and practitioners in estimating or modeling the potential groundwater contamination likelihood from stormwater infiltrated through drywells or other infiltration BMPs. These databases include:

- **The Stormwater Multiple Application and Report Tracking System (SMARTS)**, which serves as a data portal for California's Storm Water General Permits (construction, industrial, and municipal). Data includes permit registration documents, compliance, and monitoring data. The monitoring data in SMARTS can be used to understand the typical stormwater runoff concentrations for certain pollutants from industrial facilities, construction sites, and MS4s.

[1] While the scope of each database is unique, multiple databases may contain some of the same datasets.

- **The California Environmental Data Exchange Network (CEDEN)**, which is a centralized data portal that serves as the State Water Resource Control Board's surface water quality database. Although data are not limited to stormwater data, many entities report stormwater data as required under various National Pollutant Discharge Elimination System (NPDES) permits. Among the many contributing programs include:
  - **The Surface Water Ambient Monitoring Program (SWAMP)**, which was created in order to fulfill Assembly Bill 982 (Ducheny, Statutes of 1999), is intended to provide high-quality data so managers and decision-makers can address management questions regarding the condition of waters in California. SWAMP focuses on biological, chemical, and physical water quality parameters at the statewide and regional level. Similar to CCAMP data, these mostly receiving water data can be used to approximate stormwater concentrations from developed watersheds if needed.
  - **The San Francisco Estuary Institute (SFEI)**, which runs the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP). Through the RMP, SFEI has developed a long-term monitoring program as well as an emerging contaminants strategy to help guide future management and monitoring decisions. RMP datasets can be accessed using the Contaminant Data Display and Download Tool (CD3) as well as through CEDEN.
- **The National Stormwater Quality Database (NSQD)**, which is a national database that includes stormwater monitoring data, mostly collected as part of Phase I NPDES municipal separate storm sewer system (MS4) permits. The most recent version (4.02) contains data from 200 municipalities collected from approximately 600 outfall locations over the course of more than 9,000 events. These data can be used to understand the pollutants present at a specific location as well as to understand the correlation between general land use types and pollutant concentrations.
- **The Bay Area Stormwater Management Agencies Association (BASMAA)**, which is part of the Clean Water for a Clean Bay (CW4CB) Project in San Francisco Bay Area. Monitoring data from source property identification and referral projects, enhanced municipal operation and maintenance projects, and urban runoff treatment retrofit projects is publicly available.
- **The Central Coast Ambient Monitoring Program (CCAMP),** which is the water quality and evaluation program specific to the Central Coast Regional Water Quality Control Board. CCAMP stores water, sediment, habitat, and bioassessment data for the central coast region. While most of these data represent receiving water quality, results from developed watersheds (e.g., urban and agricultural land uses) could be used to approximate stormwater concentrations if needed.

- **The International BMP Database**, which includes influent and effluent data from over 600 BMP study publications. Publications include, but are not limited to, studies, performance analysis results, tools for performance studies, and monitoring guidance. The influent data from this database can be used to understand the typical untreated runoff concentrations and the effluent data can be used to understand how certain BMPs, if implemented as pretreatment for drywells, will reduce pollutant concentrations and what concentrations they will deliver to drywells.
- **The Southern California Coastal Water Research Project (SCCWRP)**, which conducted a study from 2000 to 2005 to understand stormwater pollutant loading from various watersheds and land use types in the greater Los Angeles area (SCCWRP, 2007). The final data from this project can be downloaded from the "Data" page on the SCCWRP website. Additional data from the stormwater research program can be obtained by contacting SCCWRP directly.
- **Ventura Countywide Stormwater Quality Management Program**, which hosts a data query site for stormwater quality data collected from receiving water mass emission monitoring stations and major outfall monitoring stations throughout Ventura County.
- **Land use Event Mean Concentration (EMC) and Mass Emission Monitoring Programs data,** which include, at a minimum, data collected in Los Angeles County, Ventura County, and San Diego County, to understand the pollutant concentrations associated with certain land uses and specific urban discharge locations.
- **The Water Quality Portal (WQP)**, which is sponsored by the United States Geological Survey (USGS), the Environmental Protection Agency (EPA) and the National Water Quality Monitoring Council (NWQMC). The WQP includes water quality data from local, tribal, state, and federal agencies.

3. LITERATURE AND CASE STUDIES

While there are a number of topics of concern with respect to drywell implementation, the review conducted for this memo focused on drywell-specific studies that evaluated potential for groundwater contamination and a review of relevant emerging contaminants based on the Technical Advisory Committee and State Water Board's direction. In addition, each study included multiple variables that could not be controlled therefore conclusively determining the conditions that pose or do not pose a risk to groundwater contamination was not feasible. The purpose of this review was to understand and summarize the relevant studies and the conclusions made to identify additional research needs and data gaps that still exist. Finally, each document's conclusions are subjective based on the case-specific conditions and study goals and therefore the meaning of terminology such as "adequate" or "higher than" may not be explicitly clear. Due to the scope of this review and attempting to comprehensively include a variety of studies, this terminology, taken from the individual study conclusions, is used below to demonstrate general findings and may not result in specific actionable recommendations.

3.1 Groundwater Protection and Vadose Zone Treatment

A common concern regarding the use of drywells for stormwater infiltration is the protection of underlying groundwater quality. In general, most stormwater literature have found low incidences of groundwater contamination from stormwater infiltration. Therefore, the focus of this review was to identify instances where the risk to groundwater contamination may be higher so that a risk-based framework for drywell guidance can be applied in the future and to understand where there is a need for additional research to understand the groundwater contamination risk of certain scenarios. It is also important to note that some studies only evaluated whether certain contaminants were *detected* in groundwater, and if detected, the studies may have concluded that groundwater contamination is a concern. However, it is important to note that thresholds used for determining "contamination" vary depending on the context of an investigation (e.g., were concentrations elevated above ambient or background levels, above applicable water quality objectives, or above human health risk based thresholds?).

Literature on this subject has been extensively reviewed in two literature reviews published in 2016. *Assessing the effectiveness of drywells as tools for stormwater management and aquifer recharge and their groundwater contamination potential* reviewed the available literature on drywell performance as it pertains to stormwater management and groundwater quality (Edwards et al., 2016). *Dry Wells and the Risk of Groundwater Contamination: An Annotated Bibliography* was compiled by staff of the Ecotoxicology Program at the Office of Environmental Health Hazard Assessment to evaluate the impacts of drywells on groundwater quality (Hamad et al., 2016)[2]. Both reviews include a thorough list of peer-reviewed studies, theses and dissertations, and government reports. Table 2 in this memorandum has been adapted from Table 2 in the review conducted by Edwards et al. (2016) and summarizes the studies reviewed in the two literature reviews as well as several additional studies. In addition to reviewing these literature reviews, additional studies were provided by the Technical Advisory Committee (TAC) members as part of this project and other studies were located through internet searches. However, it should be noted that the focus of this review was on extracting general findings and conclusions from the sources that have been commonly referenced in drywell research and that the entirety of studies evaluating potential groundwater risk from stormwater infiltration were not included in this evaluation. The following are key findings from the drywell stormwater infiltration studies that were evaluated. These findings are outlined according to key topics and concerns identified in the literature:

- **Land Use**[3]
    - *Commercial* land use areas contributed to heavy metals, hydrocarbons, oil and grease, semivolatile organic compounds (SVOCs), volatile organic compounds (VOCs), salts, and total dissolved solids (TDS) in stormwater runoff entering

[2] *Elk Grove Dry Well Project: OEHHA Technical Memo* by Washburn and Bennet (2017) was reviewed in conjunction with the annotated bibliography.
[3] It's important to note that the land uses presented here were commonly referenced in the studies reviewed; however, some data may exist for other land uses such as transportation that were not included in these summaries.

drywells, drywell sediments, and the vadose zone. Though one study detected VOCs in groundwater (Wilson et al., 1989) and another detected trace amounts of zinc (Olson, 1987), the majority of studies found no significant degradation of groundwater quality (City of Portland, 2008; Dallman and Spongberg, 2012; Hydrosystems, 2011; Olson, 1987; The Los Angeles and San Gabriel Rivers Watershed Council, 2005, 2008, 2010; Wogsland, 1988). However, contamination from illicit dumping and accidental spills have occurred at commercial sites (US EPA, 1999 a,b). For example, surface spills of gasoline and other contaminants at a commercial site in Los Gatos, CA resulted in groundwater contamination (US EPA, 1999 a,b).

- *Industrial* land use areas contributed to bacteria, heavy metals, hydrocarbons, nitrates, pyrethroids, and SVOCS in stormwater entering drywells. Many of these contaminants were also detected in sediment and the vadose zone. Again, trace amounts of zinc were detected in nearby wells (Olson, 1987), but no significant degradation of groundwater quality was observed (City of Portland, 2008; Nelson et al., 2017; Olson, 1987). Historically, dumping and spills have been observed in industrial land use areas (US EPA, 1999 a,b). An industrial site in Morgan Hill, CA discharged wash water and wastewater containing volatile organic solvents (primarily trichloroethylene or "TCE") into ponds draining to drywells, which resulted in a 2,500 feet wide by 200 feet deep contaminated groundwater plume. TCE concentrations of as high as 2.2 mg/L were detected in the plume. In Mountain View, CA, alleged dumping of solvents into drywells contributed to contamination of nearby drinking water wells (US EPA, 1999 a,b).
- *Residential* land use areas contributed to bacteria, heavy metals, oil and grease, salts, and TDS in stormwater runoff entering drywells and in drywell effluent (Nelson et al., 2017; Pitt et al., 2012; Talebi and Pitt, 2014; Wogsland, 1988). Contaminant concentrations in residential areas were generally low in stormwater runoff, but a study by Olson (1987) concluded that older neighborhoods contributed to higher influent loads and a study by Lindemann (1999) found that neighborhoods near major highways had polycyclic aromatic hydrocarbon (PAH) concentrations in exceedance of MCLs in stormwater and sediment. A study conducted in Missoula, Montana, where deicing salts are commonly used on roadways during the winter, reported that drywell infiltration likely contributed to elevated levels of TDS and salts in groundwater (Wogsland, 1988). In a US EPA study (1999a) on stormwater drainage wells, fewer incidents of dumping and spills were observed in residential areas than commercial and industrial areas; however, in Fairfield, OH people regularly disposed of used motor oil, antifreeze, and other hazardous materials in drywells (US EPA, 1999 a).
- *Agricultural* land use runoff was found to contribute to high nitrate levels in groundwater (Jurgens et al., 2008; Nelson et al., 2017). In historically agricultural

areas where non-agricultural runoff was infiltrated, nitrate levels in groundwater decreased with infiltration.

- **Pretreatment**
  - The majority of studies reviewed did not include any form of pretreatment. Those that included pretreatment features generally included sedimentation wells/chambers, at a minimum, in order to improve the functioning of the drywell and remove some contaminants (e.g., floatables, oils, etc.) (Adolfson Associates, 1995; City of Portland, 2008; Dallman and Spongberg, 2012; Nelson et al., 2017; Olson, 1987; Wilson et al., 1990; Wilson et al., 1989).
  - Vegetated pretreatment was found to be effective at removing pollutants. The City of Elk Grove drywell project monitored two types of pretreatment: a grassy swale and a water quality basin. The grassy swale and water quality basin reduced TSS by 63% and 50%, respectively[4]. Both pretreatment devices also contributed to significant reductions in aluminum, bifenthrin and motor oil (Nelson et al., 2017). Another study found that a grassy swale with a sedimentation/oil separation chamber and an infiltration trench was found to remove 45-80% of metals and 83% of total petroleum hydrocarbons (TPH) (Adolfson Associates, 1995).
  - One study found that drywells with pretreatment infiltration facilities (trenches, basins, etc.) and either sedimentation/oil separation chambers or filter fabric lining the drywell did not reduce pollutant loads (Adolfson Associates, 1995).
- **Vadose Zone Characteristics**
  - Pollutants were *not adequately attenuated* at drywell sites with high permeability subsurface soils, especially those with coarse-grained alluvium, sand, and gravel (Adolfson, 1995; Pitt et al., 2012; Talebi and Pitt, 2014; Wilson et al., 1989).
  - One study suggested that the *most pollutant attenuation* occurred in subsurface soil with large amounts of clay below drywell sites (Wilson, 1989). This is exemplified by several other studies, which found that most pollutants, particularly metals, were adequately attenuated at drywell sites with clay in combination with other soil textures (i.e. sand, silt, or caliche) (Bandeen, 1987; Hydrosystems, 2011; Nelson et al., 2017; Olson 1987; The Los Angeles and San Gabriel Rivers Watershed Council, 2005, 2008, 2010; Wilson et al., 1989; Wogsland, 1988). However, TDS and salts were detected in groundwater at drywell sites underlaid by some clay in cases where deicing salts were applied (Wogsland, 1988).

[4] The authors caution that percent removal is often a poor metric of BMP effectiveness and should only be viewed as rough estimates. In general, best practice is to use effluent concentrations as a more robust (e.g., less sensitive to influent concentration) measure of performance (Wright Water Engineers and Geosyntec Consultants, 2007).

- The results from one study suggested that *metal concentrations below the drywell decreased* with depth, while *TDS and salt concentrations increased* with depth at sites where the upper 10-30 feet of the vadose zone consisted of boulders, cobbles, gravel, sand, and silt. Vadose zone water samples were collected using lysimeters at 8 and 13 feet below land surface. The results showed that metal concentrations in samples taken at 8 feet were less than the concentrations in runoff and the concentrations continued to decrease based on the sample collected at 13 feet, indicating that *metal concentrations decreased with depth.* Because metal concentrations in groundwater did not increase, pollutants were believed to be adequately attenuated in the vadose zone. Alternatively, the concentrations of TDS, sodium, chlorine, calcium, magnesium, potassium, nitrate, and bicarbonate increased between the runoff samples, the 8-foot vadose zone samples, and the 13-foot vadose zone samples. This result suggests that *reactions in the vadose zone sequestered ions* (Wogsland, 1988).
- While soil texture is an important vadose zone characteristic to evaluate, Clark and Pitt (2007) suggested that intrinsic permeability, hydraulic conductivity, pH, organic content, and cation exchange capacity also play an influential role in the attenuation and movement of pollutants in the vadose zone.

- **Groundwater Separation**
  - Sites with a groundwater separation of *less than 5 feet* contributed to increases in organic pollutants, nitrogen, and heavy metal concentrations in groundwater (although below the maximum contaminant level) (Barraud et al., 1999) and slow drawdown times leading to standing water (Pitt et al., 2012; Talebi and Pitt, 2014).
  - The importance of groundwater separation is supported by studies that found that concentrations of metals in the vadose zone decreased with greater vadose zone thickness (Pitt et al., 1999; Wogsland, 1988).
  - A drywell modeling study using the One-Dimensional Fate and Transport Tool, which utilizes precipitation patterns and representative soil properties, was conducted to model drywells in Bend, OR. The study found that under average rain conditions for Bend, copper, lead, benzo(a)pyrene, naphthalene, pentachlorophenol (PCP), DEHP, 2,4-dichlorophenoxyacetic acid (2,4-D), and toluene were attenuated to below detection limits within 5 feet of transport and under the "worst-case" scenario all pollutants were attenuated within 37 feet (Brody-Heine et al., 2011).

Needs and Gaps

The studies reviewed provide evidence that with proper siting and design, the use of drywells for stormwater infiltration is unlikely to contribute to significant degradation of groundwater quality. However, there are areas of research that still require further investigation. To identify the pollutants that pose a higher risk to groundwater contamination, an initial screening of publicly available stormwater data (treated and untreated) should be conducted to compare these concentrations with MCLs and typical groundwater objectives to identify the pollutants or land use-pollutant combinations that are expected to exceed these levels, either with or without pre-treatment.

For those pollutant-land use combinations that are potentially problematic (above), the next line of needed investigation is the attenuation of pollutants in the vadose zone. While several studies concluded that pollutants were likely attenuated in the vadose zone, further research is needed to determine the conditions under which adequate attenuation is achieved and if pollutant breakthrough in soil is a concern. Future field and modeling studies could help determine the vadose zone composition and groundwater separation needed to provide sufficient pollutant attenuation to meet applicable water quality requirements. In addition, most studies provided a minimum soil infiltration rate for the drywell to drain properly; however, some studies found that highly permeable soils provided lower pollutant attenuation, suggesting that there is a need to define a maximum infiltration rate under certain circumstances.

The majority of studies occurred under short time scales ranging from one event to several years. Although, one study evaluating groundwater contamination in a city that has relied on drywell infiltration for over 50 years, found no significant degradation of groundwater quality from common urban contaminants[5] (Jurgens et al., 2008), therefore additional long-term studies are needed to better understand the long-term impacts of stormwater infiltration. Some studies suggested that pollutants may accumulate in receiving soils (Weiss, 2008), while others have indicated that accumulation of metals, oil and grease, organic and inorganic compounds, surfactants, perchlorate, and VOCs is unlikely (Dallman and Spongberg, 2012; The Los Angeles and San Gabriel Rivers Watershed Council, 2010). It is difficult to determine definitively whether pollutants have accumulated in receiving soils based primarily on short-term studies.

Maintenance, inspection, and cleaning have been identified as important efforts to delay drywell failure, but drywell lifecycles and proper responses to drywell failure have not been thoroughly developed or investigated. In addition, proper spill control devices or emergency spill response procedures were not present in the literature reviewed and while some municipalities have evaluated spill control and response, further research is needed. Additional research and discussions with cities and counties that have implemented drywells should be carried out to better understand drywell lifecycles and what to do in the event of drywell failure. Furthermore, few studies have attempted to quantify drywell infiltration capacity after installation and compare with typical drywell capacity estimates pre-installation to provide guidance on the most appropriate method for estimating long term drywell capacity. Simple mass balance equations have been used to estimate drywell infiltration, but as these estimates are often oversimplifications, actual drywell infiltration capacity and the flowrate at which drywells infiltrate needs to be better understood.

[5] Contaminants evaluated include conventional water quality parameters, inorganic constituents, pesticides, and volatile organic compounds

Finally, a number of studies included varying levels of pretreatment, but there weren't conclusive results to understand how the inclusion of pretreatment improved water quality and reduced the groundwater contamination risk.

3.2 Emerging Contaminants

There is an increasing awareness and growing concern regarding emerging contaminants – contaminants that are not commonly monitored or regulated but are suspected to have harmful effects on humans or the environment. While there are a variety of emerging contaminants with the potential to occur in stormwater, there is currently a heightened focus on per- and polyfluoroalkyl substances (PFAS)[6] and a growing concern regarding the groundwater impacts of antibiotic resistant genes (ARG). Literature regarding PFASs, ARGs, and other emerging contaminants was reviewed, and the findings are summarized in Table 3 and below.

ARGs can exist in air, soil, and water, and as such, have the potential to be transported in stormwater. ARGs are responsible for antibiotic resistant bacteria and can be transferred between bacteria through horizontal gene transfer. However, the presence of ARGs does not necessarily indicate that antibiotic resistance is present as ARGs are ubiquitous in natural sources and part of natural biological evolution. Two studies investigating antibiotic resistance in urban watersheds found that ARGs in streams and lakes increased during storm events, though in some cases this may have been due to combined sewer overflows (Garner et al., 2017; Zhang et al., 2016). These studies indicated the presence of ARGs in stormwater; however, the sources may be due to combined sewer overflows and not necessarily a result of urban stormwater discharges. As a new emerging contaminant, further research is needed to determine whether ARGs present a groundwater contamination threat in California urban stormwater drywell applications.

PFASs are used in a variety of manufactured products including non-stick coatings and aqueous film-forming foams (AFFF) used for firefighting, as well as some fabrics/textiles and paper products. AFFFs are of particular concern in California with the increased frequency and intensity of wildfires in recent years, noting that their mobility varies based on properties specific to the compound. PFASs with longer perfluoroalkyl tails tend to have more sorption and retardation than those with shorter tails (ITRC, 2018). All the studies regarding PFASs that were reviewed for this memo detected this class of compounds in stormwater samples from urban areas with various land use types (Ahrens, 2011; Houtz, 2013; ITRC, 2018; Lin et al., 2018; Nguyen et al., 2011; Procopio et al., 2017; Xiao et al., 2012). Studies indicated that perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) were the most common PFASs detected (Procopio et al., 2017; Xiao et al., 2012). The US EPA has established health advisory (HA) levels of 70 parts per trillion (ppt) for both PFOS and PFOA. PFOS and PFOA were detected at residential sites below the health advisory level and concentrations at industrial/commercial sites were significantly higher than at the residential sites, with PFOS concentrations exceeding the health advisory level and reaching up to 156 ppt (Xiao et al., 2012). There may be a connection with PFAS concentrations and land use; however, it is important to note that PFASs, specifically perfluoroalkyl acids

[6] Also referred to as perfluoroalkyl compounds (PFCs)

(PFAAs)[7], have been detected in waterbodies worldwide in regions where point sources are not present (Houtz, 2013). In addition to being present in stormwater, two sources found that PFAS in soils leached into the groundwater (Ahrens, 2011; ITRC, 2018). Therefore, stormwater infiltration may have the potential to transport PFASs to groundwater if either the stormwater or the soils contain elevated PFAS concentrations; however, it is unknown whether contamination (i.e., exceedance of health risk-based thresholds) is likely to occur.

In addition to the above, there are a number of other emerging contaminants that are being evaluated and studied to understand their risks of surface water and groundwater contamination such as current use pesticides (e.g., alachlor, atrazine, diazinon, pyrethroids, neonicotinoids, etc.), specifically those with physiochemical properties increasing their mobility, and viruses. For instance, the recent SCCWRP surfer health study[8] demonstrated that highly infective viruses (norovirus) were present in wet weather flows from the highly urban San Diego River watershed, and at health-relevant concentrations, suggesting that viruses in wet weather discharges present a human health risk. However, for all of these emerging contaminants, there is a need for additional studies and research to compare detected concentrations in stormwater to regulatory and health advisory thresholds if they exist.

Needs and Gaps

Certain emerging contaminants, such as ARGs, have only recently become a topic of concern. As such, additional research is needed to understand both the prevalence of ARGs in stormwater and if prevalent, the potential for groundwater contamination from infiltration. PFASs have been better studied and their prevalence in stormwater and potential to transport to groundwater has been observed. Nonetheless, the fate and transport of PFASs infiltrated through drywells and the potential for transported PFASs to contribute to groundwater contamination at levels above health advisory thresholds has not been well-studied. In addition to PFASs and ARGs, future research is also needed for other emerging contaminants such as viruses and current use pesticides. Data on typical urban stormwater concentrations and pretreatment BMP effluent concentrations for these contaminants are lacking, as well as studies of infiltration BMPs and their impacts to groundwater for these pollutants. Once such datasets are developed and a sufficient number of samples are collected, then the stormwater, BMP effluent, and groundwater concentrations should be compared with regulatory and health advisory thresholds where available to make decisions about potential for groundwater contamination from drywells and other infiltration BMPs, along with strategies to mitigate identified risks.

4. CONCLUSION

The existing municipal and statewide drywell guidance documents provide consensus on some siting and design requirements, which are recommended to be included in California's statewide drywell guidance. In addition, existing stormwater and BMP data are available through public datasets and can be used to determine the expected stormwater runoff concentrations from certain

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[7] PFAAs include both PFOS and PFOA.

[8] Acute Illness among Surfers after Exposure to Seawater in Dry- and Wet-Weather Conditions (Arnold et al., 2017)

land uses and to understand the pollutant removal performance of certain pretreatment BMPs. Based on the literature and data reviewed, with proper siting and design, drywells are generally found to pose a low threat to groundwater contamination, at least for commonly studied stormwater pollutants; however, the following additional research needs, and data gaps were identified:

- **Statewide Stormwater Pollutant Groundwater Contamination Risk Analysis:** A statewide analysis of available stormwater runoff data is needed to compare these concentrations with MCLs and typical water quality objectives to identify the pollutants or land use-pollutant combinations that are expected to exceed these levels, thus posing a higher groundwater contamination risk. For the pollutants identified as having a higher risk, they could then be sorted between soluble, posing a higher risk to groundwater contamination due to potential mobility through the vadose zone, and insoluble, potentially posing a lower risk to groundwater contamination. The above analysis could then be used to identify land use-pollutant combinations with varying levels of groundwater contamination risk by comparing average (or higher percentile) concentrations with, for example, drinking water standards and other typical groundwater quality objectives to determine what circumstances may result in elevated contamination risk. If sufficient data are available, the above analyses could be conducted throughout varying geographical regions in the state and assuming different local groundwater conditions to understand whether certain land use-pollutant combinations pose higher groundwater contamination risks in specific regions or for specific groundwater conditions.
- **Vadose Zone Pollutant Attenuation Studies:** Research is needed to identify a method for determining site-specific vadose zone pollutant attenuation potential throughout California for sites classified as having a potential groundwater contamination risk. This could include fate and transport modeling under different scenarios with varying soil composition and depth of vadose zone to appropriately "bin" the possible scenarios that dischargers might be facing and categorize them as "high," "medium," or "low" risk to groundwater contamination. This modeling could also evaluate maximum infiltration rates that should be prescribed to increase pollutant attenuation in the vadose zone. The discharger would then provide site-specific inputs to determine their drywell site's potential groundwater contamination risk.
- **Pretreatment Guidance:** A summary of how potential pretreatment BMPs may reduce groundwater contamination risk is needed, which could be developed by summarizing the BMP performance results from the International BMP Database to provide a summary of how certain BMPs perform under varying influent ranges. In addition, it is important to compare these BMP effluent concentrations with MCLs and typical groundwater quality objectives to understand the BMP types that can reduce certain pollutants to below these levels, thus reducing groundwater contamination risk. This summary could be used to pair BMP types with risk-based scenarios so that the discharger understands what BMP options are appropriate for their site. Then, pretreatment standards and/or specifications could be developed based on target pollutants of concern (i.e., contact time requirements for certain

pollutants) and site characteristics (i.e., spill containment in industrial areas) so that the pretreatment BMPs implemented are adequately protective of groundwater quality.

- **Infiltration Testing Guidance:** Most guidelines and studies do not prescribe the required infiltration testing methods for drywells, therefore an assessment is needed to analyze measured or estimated vs. actual infiltration capacity of drywells to determine the infiltration testing methods that are most reliable and what factor of safety is needed to develop reliable capacity estimates from testing data.
- **Long-term Groundwater Contamination Studies:** An assessment of the long-term groundwater contamination potential of stormwater infiltration through drywells is needed, which could include monitoring dry well field studies in different regions of the state with varying site and geologic conditions. These studies could be conducted on drywells that have previously been installed by evaluating the local groundwater quality to identify elevated concentrations of certain pollutants compared to water quality objectives or upgradient reference groundwater concentrations.
- **Drywell Lifecycle Research:** Additional research and discussion with cities and counties is needed to establish an understanding of drywell lifecycles and reasons for failure through anecdotal evidence. This research and communication could be used to estimate the lifetime of drywells, mitigate potential functionality risks, and plan for drywell deconstruction or abandonment.
- **Emerging Contaminants Stormwater Data Collection:** Stormwater infiltration studies or additional laboratory research is needed to evaluate the transport of emerging contaminants such as PFASs, ARGs, current use pesticides, and viruses to understand the associated groundwater contamination risks. It is important that data be collected from urban stormwater runoff, BMP effluent (representing the concentrations leaving potential pretreatment), and in groundwater and that these concentrations be compared to regulatory and health advisory thresholds to understand whether a potential contamination risk exists.

5. REFERENCE TABLES

Table 1. Comparison of existing state and municipal drywell guidance

Guidance	Monitoring required?	GW separation distance (ft)	Soil characteristics	Setbacks	Spacing (ft)	Pretreatment	Modeling requirements?	Requirements based on geology?	Drawdown time (hr)	Exclusions	Other
Portland Stormwater Management Manual	-	5 (refers to UIC Permit [City if public; State if private])	≥ 2 in/hr Not in dense silt or clay soils.	10 ft on center from foundations; 5 ft from property lines; 500 ft from drinking water well; 200 ft from high/steep slope; 100 ft upslope from any drainfield	-	Protected with sediment control devices	-	-	< 30	Installation in fill material	DTW investigation required if est. seasonal high GW is < 50 ft bls to ensure 5 ft separation is met. Geotechnical evidence required for all slopes >20%; designed for 100 yr. storm event in lieu of escape route.
Oregon UIC (Permit Evaluation Report General Permit for Class V Stormwater UIC Systems, Oregon's Experience with Drywells)	Yes, if UIC drains surface with ≥ 1,000 vehicle trips per day, or if located at facility that handles/stores hazardous substances, toxic materials, or petroleum products. Pollutants: metals, volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), polycyclic aromatic hydrocarbons (PAHs), pesticides/herbicides.	1 - 5 depending on pollutant[a]	-	500 ft from water well or 2 yr travel time of public supply well	-	Source controls or BMPs must be used to treat stormwater prior to discharge to the subsurface	Assess risk to groundwater using the Groundwater Protectiveness Demonstration Tool (GWPD)	Range of vertical (2.5-5ft) and horizontal (NA-335 ft) separation distances based on geologic unit and city		-	Develop robust stormwater management plan for certain types of UICs[b]; Action Levels included for certain scenarios along with Action Level Exceedance requirements; structural spill control required at industrial/commercial facilities where spills are likely.
ARB SWRP Appendix L - Drywell Fact Sheet	Yes for Low to High Risk scenarios. Pollutants: lead, mercury, chrysene, DEHP, bifenthrin, fipronil, and nitrate as N.	10 - 25; include 5 ft treatment zone	Combination of sand, gravel, and clay; no soil contamination	2 yr travel time from public/private drinking water wells or 150 feet; 250 ft from auto shops, nurseries, or hazmat sites; 20 ft downslope/100 ft upslope from foundation; 250 ft from contaminated soils	100	Vegetated stormwater treatment device, sedimentation chamber, and/or a proprietary device.	*Recommended* if (1) no MCL exists for a contaminant, (2) SW quality exceedances for priority pollutants at entrance to drywell 2 years in row, (3) unique chemicals used at site. *Required* if No MADL or if 50% of concentration of pollutant is >MADL.	-	< 48	Roads with ≥ 30,000 AADT[c] without pretreatment; installation on slopes >15% without geotechnical review and avoid slopes >28.5%; within contaminated GW plumes	Contaminant modeling recommended [flow chart guidance included]; Risk-based design requirements including varying separation distances, pretreatment requirements, and shut off valve requirements based on stormwater source, traffic, and upstream land uses
Orange County Technical Guidance Document	-	10 (mounded seasonally high)	0.3 in/hr factored Ksat Borehole methods recommended	Minimum setbacks from foundations and slopes Minimum setbacks from water wells, groundwater clean-up sites, mapped plumes	-	Include robust biotreatment or conventional treatment capable of addressing all potentially generated pollutants and clogging of the drywell	-	Consider limiting layers in determining factored infiltration rate. Consider soil layering in interpreting borehole tests	Needs to be considered in sizing; 96 hours if water is accessible to vectors.	Specific land use areas within industrial sites: fueling areas, etc., except where advanced pre-treatment and isolation are used.	Overflow route required; <25 ft facility depth with geotechnical approval; preferred <10 ft depth and no approval needed; infiltrating should not cause geotechnical concerns related to slope stability, liquefaction, or erosion

Guidance	Monitoring required?	GW separation distance (ft)	Soil characteristics	Setbacks	Spacing (ft)	Pretreatment	Modeling requirements?	Requirements based on geology?	Drawdown time (hr)	Exclusions	Other
Draft Orange County (Guidelines for Use of Drywells in Stormwater Management Applications)	-	10	Infiltration testing within test boreholes. Soil lithology should be investigated to at least 10 ft below the drywell. Minimum factor of safety of 2.0 should be applied to the infiltration rate.		If less than 20[d], analysis of potential interference required	Low contamination potential requires grit traps and settling chambers. Moderate contamination potential requires proprietary BMPs with pretreatment certification or biotreatment BMPs. High contamination potential requires the same features as moderate, with the addition of spill isolation features.	Volume/flow modeling may be required where drywells are used to meet hydromodification criteria			Specific land use areas within industrial sites: fueling areas, hazardous material/waste handling, storage, and collection areas.	Must be located somewhere readily accessible for inspection/maintenance. Must include 5 ft deep annular well seal. Well drilling contractors must possess a C-57 contractor's license. Construction must avoid compaction and runoff to the drywell.
Arizona DEQ (Guidance for Design, Installation, Operation, Maintenance, and Inspection of Drywells)	-	10	-	100 ft from water well; 20 ft from UST or fuel loading areas	100[d]	Installation where hazardous or toxic materials are used, handled, stored, loaded or treated (not recommended), Aquifer Protection Permit required, requiring an engineered design to meet Best Available demonstrated Control Technology	-	-		-	May be constructed by an installer licensed by ADWR if perching formation is sealed per ADWR requirements. Include shielding device to enhance separation of petrochemicals, use hydrophobic petrochemical absorbent, include device to screen floating debris
Washington State Department of Ecology	Yes, as part of benchmark monitoring for certain industrial sites. Pollutants: nitrate, nitrite, ammonia, and/or phosphorous	Based on treatment capacity of unsaturated zone and pollutant loading in discharge (5 ft min)	Evaluate infiltration capacity; no soil contamination	100 ft from drinking water well or spring used for drinking water supplies; 20 ft downslope/100 ft upslope from foundation; if upslope or behind top of slope >15% min setback = height of the slope	30[d] or twice the depth, whichever is greater	Source control and treatment based on types and quantities of pollutants expected from contributing land uses and treatment potential of the vadose zone; pretreatment for solids removal to preserve infiltration rates also recommended	-	Bedrock/impermeable layer >5ft below invert of dry well	48 - 72	Slopes >25%; on or above landslide hazard areas or slopes >15% without PE evaluation or geologist/jurisdiction approval; receiving stormwater from land use types with high potential for contamination [e]	Evaluate slope failure potential by PE or geologist; refers to Ecology stormwater management manual for source controls to delay pollutants/sediment from entering UIC wells during construction; high vehicle traffic areas, fueling stations, and facilities with fueling activities or areas where petroleum products are stored/transferred > 1500 gallons per year, must include spill containment structure and spill prevention control and containment plan; high use sites must include spill control device
Nevada DEP	Yes, if moderate risk to GW	5	-	1000 ft from public water system well	-	if moderate risk to GW	-	-		-	-

Guidance	Monitoring required?	GW separation distance (ft)	Soil characteristics	Setbacks	Spacing (ft)	Pretreatment	Modeling requirements?	Requirements based on geology?	Drawdown time (hr)	Exclusions	Other
City of Fontana Water Quality Management Plan Handbook	-	10	Evaluate infiltration capacity at various depths	5 ft vertical from bedrock; 100 ft from well, tank, or spring; 100 ft from building foundation		Required to delay sediment and trash accumulation	-	Bedrock/impermeable layer >5ft below invert of dry well	< 48	-	An overflow system should be constructed
Riverside County Drywell Fact Sheet	-	10	> 0.8 in/hr. factored design infiltration rate	10 ft from buildings; 100 ft from public supply wells	50[d]	Yes, sedimentation well at a minimum	-	-		-	Infiltration should not cause geotechnical concerns related to slope stability, liquefaction, or compromise infrastructure stability
CA DWR Well Design (Bulletin 74-81 and 74-90)	Sample immediately following construction	-	-	50 ft from sewer, watertight septic tank; 100 ft from subsurface sewage leaching field; 150 ft from cesspool/seepage pit; 100 ft from animal or fowl enclosure	-	-	-	-		-	Min depth of seal 20 ft bls to protect against contamination
Los Angeles County LID Standards Manual	-	10	≥ 0.3 in/hr infiltration rate	15 ft and outside 1:1 plane from bottom of adjacent foundations; 100 ft from drinking water wells	-	May be needed if infiltration > 2.4 in/hr	-	-	< 96	Not suitable for brownfield sites, sites where chemicals/hazmat are stored or used, or sites with risk of sewage effluent mobilization. Low permeability soils, high GW levels, slopes >20%	Inlet should be 18 inches bls
Central Coast Low Impact Development Initiative (LIDI)	-	10	Soils should not have >30% clay or >40% silt; conduct facility-specific infiltration testing using standardized methods based on local jurisdiction.	100 ft from public supply wells and septic systems; 250 ft from potential soil or GW contamination (GW flow direction and level of uncertainty may require larger setbacks); Appropriate setbacks from slopes, foundations, and structures	100	Biofiltration BMPs	-	-	-	Avoid infiltration at sites with roads >25,000 ADT; heavy and light industrial pollutant source areas; automotive repair shops; car washes; fleet storage areas; nurseries, agriculture, and landscaped areas using extensive fertilizers; fueling stations	Evaluation of potential groundwater mounding may be needed if hydrogeologic conditions are constrained; drywell should penetrate at least 10 ft into permeable porous soils; apply appropriate factors of safety to address uncertainty in testing methods, long term operational conditions, and potential for clogging; when previous land uses indicate potential for contamination, site assessment for contamination is recommended

Guidance	Monitoring required?	GW separation distance (ft)	Soil characteristics	Setbacks	Spacing (ft)	Pretreatment	Modeling requirements?	Requirements based on geology?	Drawdown time (hr)	Exclusions	Other

[a] may require installation of piezometer or existing nearby GW level data
[b] if UIC drains surface with 1,000 or more vehicle trips per day, or if UIC located at facility that handles/stores hazardous substances, toxic materials, or petroleum products
[c] average annual daily trips
[d] measured center to center
[e] vehicle maintenance, repair, and service; commercial/fleet vehicle washing; airport de-icing activities; storage of treated lumber; storage/handling of hazardous materials and wastes; handling of radioactive materials; recycling facilities (unless only glass, paper, plastic, or cardboard); industrial/commercial areas with outdoor processing, handling, and storage of raw solid materials without management plans; contaminated sites

Table 2. Comparison of existing literature regarding the risk of groundwater contamination from drywells and treatment of stormwater in the vadose zone. Table was adapted from Edwards et al. (2016) Table 2. Information pulled directly from this table is shown in blue.

Source	Land use	Vadose Zone Characteristics	Pretreatment Description	GW Separation	Pollutants Analyzed	Summary	Conclusion
Adolfson Associates, 1995	Commercial	Low permeability till in the north of the county, highly permeable coarse sand and gravel in the south. Deeper subsurface is alternating glacial and non-glacial strata.	(1) Infiltration facility with sedimentation/oil separation chamber and 25-foot drainfield. Riser pipe in chamber with filter fabric to trap sediment. (2) Infiltration facility with manhole that discharges into a dry well lined with filter fabric and filled with drain rock. (3) Grassy swale with sedimentation/oil separation chamber and an infiltration trench.	-	Sediment: metals, TPH, stormwater: in addition to analytes sampled for in sediment, nutrients, fecal coliform, TSS	(1)(2) Did not reduce pollutant loads. This method of pretreatment not recommended where high concentrations of pollutants are present. (3) Effective at removing metals (45-80% reduction) and TPH (83% reduction).	Commercial + infiltration facility = insufficient pollutant reductions
Bandeen, 1987	-	(1) Highly permeable gravelly-sand material , water table at 100 ft bls (2) Same material as 1, but underlain by sandy-clay loam at 30 feet bls, water table at 100 ft bls (3) Gravelly-sand underlain by sandy loam material at 30 feet bls, water table at 100 feet bls	-	~100 feet	-	UNSAT 2 was used to model 3 scenarios. (1) Very little attenuation occurred, stormwater reached water table in 1.5 hours. In 2nd storm event flow rate increased. (2) Lateral movement and slowing at the sandy-clay loam layer. Stormwater reached water table in 130-150 hours. In 2nd storm event flow rate and lateral movement/pollutant attenuation increased (3) Some lateral movement at t the sandy loam layer, but less than scenario 2. Stormwater reached water table in 5-6 hours. In 2nd storm event flow rate and lateral movement/pollutant attenuation increased.	Highly permeable, gravelly-sand material = Inadequate attenuation Multilayered soils with predominant clay= maximum attenuation
Bandeen, 1984	-	Assumes presence of a perched aquifer (1a/2a) Impermeable subsurface (caliche) (1b/2b) finite subsurface permeability	-	-	-	UNSAT 2 was used to model 3 of the 4 scenarios to evaluate lateral movement of perched aquifers. 1a and 1b received 9644 ft3 of runoff and 2a received 0.5 cubic feet per second (cfs) for >24 hr. (1a) 100-yr storm event would result in 100 ft of lateral migration. (1b) 100-yr storm event would result in 50 ft of lateral migration. (2a) 680 ft of lateral migration over 27 hrs.	impermeable subsurface layers = horizontal migration of contaminants
Barraud et el., 1999	Residential/rural	Subsurface is rough alluvia	-	< 3.3 ft	Metals, other organics, (total petroleum hydrocarbons) TPH	Metal and hydrocarbons concentrations elevated directly below dry wells. Organic pollutants, nitrogen, and metals detected in GW during wet weather, but no significant degradation of GW quality.	Residential/rural + rough alluvia + <3.3 ft separation = Organic pollutants, nitrogen, and metals in GW at low levels
Brody-Heine et al., 2011	Commercial, Industrial, residential, and urban	Subsurface composed of thick basaltic lava flows with approximately 3 m thick sedimentary interbeds	-	> 37 ft	Metals, semivolatile organic carbons (SVOCs), volatile organic carbons (VOCs), PAHs, pesticides, other organics	A one-dimensional Fate and Transport Tool was used to estimate pollutant attenuation. Under average rain conditions, all pollutants attenuated within 5 ft. Worst case scenario, toluene and 2,4-D attenuated within 29-37 ft.	Any land use + basaltic subsurface + 37 feet of separation = adequate attenuation under worst case scenario Any land use + basaltic subsurface + 5 feet of separation = adequate attenuation under normal conditions

Source	Land use	Vadose Zone Characteristics	Pretreatment Description	GW Separation	Pollutants Analyzed	Summary	Conclusion
Chen et al., 2007	Commercial, industrial, and residential	Varied	-	-	Metals, VOCs, TPH	Soils near soakaways in industrial and commercial areas may contain hydrocarbons and heavy metals. In industrial areas, hydrocarbons were also present in water in the soakaways. No observed contamination in residential areas. Recommend oil receptors in areas draining industrial and/or commercial areas.	Commercial = hydrocarbons and metals in soils Industrial = hydrocarbons and metals in soils and water in soakaways Residential = no contamination in soils
City of Portland Bureau of Environmental Services, 2008	Commercial, industrial, residential, and urban	subsurface is coarse and fine grained sedimentary deposits, cemented gravel mixed with sand and silt.	Catch basin followed by a sedimentation manhole	-	Metals, SVOCs, VOCs, PAHs, pesticides, other organics	Benzo[a]pyrene, PCP, and lead exceeded MADL requirements in stormwater at entry to UIC; however, modeling suggested that all pollutants modeled would be adequately attenuated before reaching the water table. Recommend separation distance > 5 ft.	Coarse and fine sediment/cemented gravel/sand and silt + 5 feet separation = Adequate attenuation
Clark and Pitt, 2007	Commercial, industrial, and residential	-	-	-	Nutrients, pesticides, other organics, pathogens, heavy metals, salts	The following were identified as having a high potential to impact GW: (1) mobility in vadose zone, (2) abundance in stormwater, and (3) high soluble fractions. Pollutants of most concern: nutrients, pesticides, other organics, pathogens, heavy metals, and salts. Soil characteristics that need to be identified: soil texture, intrinsic permeability, hydraulic conductivity, pH, organic content, and cation exchange capacity.	High mobility in the vadose zone + high abundance in stormwater + high soluble fractions = high potential for degradation of GW quality Residential = GW contamination rare Commercial/Industrial = GW contamination more common
Dallman and Spongberg, 2012	Commercial and residential	Aquifer below commercial site at 32 ft bls and 60+ meters bls at the residential site.	Structural pretreatment to remove sediment, oil and grease installed at residential site only	-	Metals, SVOCs, VOCs, other organics, minerals, E. coli, pathogens, TPH	Contaminants were detected at high levels in most stormwater samples, but only detected at very low levels in the vadose zone and groundwater samples. In some cases, stormwater infiltration diluted contaminant concentrations already in the GW. No evidence of contaminant buildup in the soil.	Commercial/Residential + water table >9.75 ft bls = low levels of contaminants in vadose and GW
Hydrosystems, 2011	Commercial	Mostly silt and clay as well as calcium carbonate cement to 52 ft bls. >52 ft bls is uncemented sand and gravel with interbedded silt and clay.	Dual settling chambers		Field measurements, inorganic compounds, metals, TPH, VOCs, herbicides, pesticides	Monitored 3.8 million gallons of stormwater recharge infiltrated through the MaxWell Plus Drainage System over 3 years. 9/118 target parameters were detected above the minimum reporting level (MRL) and none of the ambient groundwater samples exceeded MCLs.	Commercial + dual settling chamber + silt/clay/calcium carbonate underlain by sand/gravel/silt/clay = No MCL exceedances in GW
Izuka, 2011	Commercial, Industrial, residential, and urban	High porosity volcanic rock layers	-	-	Hypothetical, non-reactive contaminant	Used SEAWAT to simulate groundwater flow and solute transport. Contaminant concentrations in GW decreased with greater vadose zone thicknesses. Gradual recharge and low hydraulic conductivity also resulted in lower concentrations. Too many generalizations made - better predictions can be made with a site-specific model.	Any land use + porous volcanic rock + thick vadose zone = pollutant attenuation
Jurgens et al., 2008	Agricultural and urban	Unconfined aquifer composed of sand and gravel layers with discontinuous clay layers. Perched (28-28 ft), shallow (95-115 ft), intermediate (166-215 ft), and deep (328-347 ft) aquifers.	No pretreatment	-	Metals, VOCs, other organics, pesticides, organics, nutrients, minerals	Uranium and nitrate were the only contaminants to exceed their MCLs, neither were associated with urban land use. However, highly alkaline waters, urban and agricultural, were found to increase desorption of uranium and arsenic. Urban stormwater could dilute nitrate concentrations in GW.	Urban + sand/gravel/discontinuous clay = potential for mobilization of uranium and arsenic agricultural + sand/gravel/discontinuous clay = elevated nitrate in GW and potential for mobilization of uranium and arsenic

Source	Land use	Vadose Zone Characteristics	Pretreatment Description	GW Separation	Pollutants Analyzed	Summary	Conclusion
Lindemann, 1999	Residential	Shallow subsurface consists of gravel and sand deposits overlying bedrock.	No pretreatment	-	Water samples analyzed for metals, VOCs, PAHs, nutrients, minerals	In sediment samples PAH concentrations were elevated. In groundwater, PAH, VOC, and metals concentrations were below MCLs. This suggests that there was no degradation of GW quality.	Residential + gravel/sand = PAH, VOCs, and metals below MCLs in GW.
Nelson et al., 2017	Industrial and residential	Subsurface is stratified with layers of sand, clay, and silt	Vegetated pretreatment and sedimentation wells	10-30 ft	Metals, fecal coliform, nutrients, VOCs, SVOCs, PAHs, TSS, TPH, pesticides/herbicides, and other organics	VOCs, SVOCs, PAHs, and chlorophenoxyl herbicides were rarely detected in stormwater. Aluminum, manganese, and bifenthrin were detected in stormwater but not in groundwater monitoring wells, indicating capture/attenuation by pretreatment or in the vadose zone. Arsenic and chromium were found in higher concentrations in groundwater than in stormwater. Nitrate present in groundwater from agricultural activities may be diluted by stormwater infiltration.	Industrial/residential + sand/clay/silt + 10-30 ft separation = attenuation of metals and pyrethroids and dilution of nitrate in GW
Olson, 1987	Commercial, industrial, and residential areas	Subsurface is caliche layers with sand and clay interbeddings.	Pretreatment sedimentation chambers	> 75 ft	Sediment samples: metals, VOCs, SVOCs, pesticides, other organics. Water samples: VOCs, SVOCs, PAHs, pesticides, other organics, TPH	Pollutants accumulate over time in the source area and in the settling chamber, so older neighborhoods and older dry wells have high concentrations of contaminants. Only trace amounts of zinc were detected in nearby public supply wells, suggesting that metals were attenuated in the vadose zone and there was no degradation of groundwater quality.	any land use + caliche/sand/clay + GW separation >75 ft = Only trace amounts of Zn in nearby GW wells Older developments + caliche/sand/clay + GW separation >75ft = higher influent loads
Pitt et al., 1999	Commercial, industrial, and residential	-	-	-	Nutrients, pesticides, other organics, pathogens, heavy metals, salts	*Nitrate* is highly soluble and mobile *Pesticides* are mobile in coarse-grained soils if pH is similar to the soil's pH. Risk of groundwater contamination decreases with greater vadose zone thickness. *Organics* were found to be most likely to cause contamination in pervious soil s (i.e. high percentage of sand and gravel) and areas with a shallow water table *Pathogens* were found at the highest concentrations where the water table is shallow *Metals* most metals adsorb to soils at neutral pHs *Salts* are common in runoff where de-icing is needed. Chlorides have a high groundwater contamination potential.	Chloride = high GW contamination potential Nitrate, pesticides, organics + coarse-grained soils = high GW contamination potential
Pitt et al., 2012; Talebi and Pitt, 2014	Residential	Low permeability surface soils above high permeability subsurface layers.	-	> 2 ft	Metals, pesticides, nutrients, organics, bacteria	The dry wells were in their first year of use and did not attenuate contaminants, indicating a need for pretreatment. Roof runoff had the best water quality and was therefore least likely to degrade groundwater quality. High water tables and low permeability subsurface soils were not suitable for dry wells.	Residential + 2ft separation = no pollutant attenuation

Source	Land use	Vadose Zone Characteristics	Pretreatment Description	GW Separation	Pollutants Analyzed	Summary	Conclusion
The Los Angeles and San Gabriel Rivers Watershed Council, 2005, 2008, 2011	Commercial and residential	Soil types range from hydrologic soil groups (HSG) A-D. Aquifer depths were 32 ft and greater than 200 ft bls. Residential site had silt and some sand and clay in upper 6 ft of sediment.	(1) No pretreatment (2) Trench drain and swale	-	Stormwater, vadose zone and groundwater samples: minerals, metals, oil and grease, perchlorate, pesticides, VOCs, SVOCs, surfactants, and bacteria	Pollutant concentrations in stormwater runoff, vadose zone, and groundwater samples were below MCLs. VOCs were detected in groundwater but were different contaminants than those detected in runoff samples. Variable and negative pollutant concentration trends for groundwater and vadose zone samples suggests that pollutant concentrations are unlikely to build up over time.	Commercial/Residential + water table >9.75 ft bls = low levels of contaminants in vadose (arsenic) and GW
US EPA, 1999 a,b	Commercial, industrial, residential, and urban	-	Vegetated and structural pretreatment	-	TSS, nutrients, metals, pesticides, bacteria, viruses	Passive treatment is effective at removing sediments and metals, but less effective at removing water soluble pollutants. The majority of groundwater contamination incidents were caused by spills and dumping. Steps to reduce risk: following recommended design specifications, including the use of pretreatment, proper siting, monitoring. providing BMP recommendations, developing spill prevention plans, understanding the local geology, and educating the public on groundwater contamination risks.	Any land use + Dumping/spills = groundwater contamination
Wilson at al., 1990	Commercial, industrial, and residential	Subsurface is predominantly coarse sand and gravel with low percentages of silt and clay. Water table depth range between 130 and 250 ft bls.	Sedimentation chamber	> 100 ft	Metals, VOCs, PAHs, pesticides, organics	Contaminant results were inconclusive due to lack of instrument sensitivity. Sedimentation chambers were effective at containing sediments.	Results inconclusive
Wilson et al., 1989	Commercial, industrial, and residential	Subsurface is predominantly coarse sand and gravel with low percentages of silt and clay. Varied from site to site. Perched aquifers present at some sites. Water table depths range between 110 - 250 ft bls.	Sediment/settling chamber	> 95 ft	Metals, oil and grease, VOCs, and other organics	Pollutants were detected at low levels or not at all in the groundwater samples, suggesting that drywells did not significantly degrade groundwater quality. Results suggest that vadose zone lithology affects pollutant attenuation, with large amounts of clay resulting in the most attenuation.	Industrial + clay + separation 95 ft =metals and organics detected at low levels Commercial + coarse alluvium + 100 ft separation = 2 VOCs detected in GW Residential + clay/caliche/silt/sand/gravel + perched aquifer + 200ft separation from water table = metals in perched aquifer and toluene in GW (all at low levels)
Wogsland, 1988	Commercial and residential	Unconfined aquifer extending to 100 to 200 ft bls composed of layers of boulders, cobbles, gravel, sand, and silt (10-30 ft thick); silty sand, coarse sand and gravel (40 ft thick); interbedded gravel, sand, silt, and clay (50-100 ft thick).[a]	No pretreatment	-	Metals, VOCs, PAHs, nutrients, TPH, salts, and other USEPA organic priority pollutants[a]	Infiltration likely increased concentrations of particulates and salts in groundwater and reactions in the vadose zone have the potential to increase concentrations of TDS, Cl, Ca, Mg, Na, K, nitrate, and bicarbonate. Metal concentrations decreased with depth in the vadose zone and were not elevated in groundwater. Oil and grease were detected in runoff but not in the vadose zone or groundwater.	Commercial/residential + coarse materials underlain by silt/clay = attenuation of metals but elevated salts and particulates in GW

a Cell contains information in addition to that provided in Edwards et al. (2016)

Table 3. Comparison of existing literature regarding emerging contaminants detected in stormwater.

Source	Description of Study	Contaminant(s)	Detections in Stormwater	Risk to Groundwater Quality	Identified Gaps and Research Needs
Garner et al., 2017	Five ARGs were quantified over three storm events in an urban inland stream	ARGs	Storm events showed higher ARG loads than background events.	-	Further research on seasonal and geographic variation in ARGs in stormwater runoff -identify “indicator” ARGs associated with risk of downstream transfer to pathogens and antibiotic resistance.
Zhang et al., 2016	Antibiotic resistance was investigated in two urban lakes before and after a storm event	ARGs	After the storm event, antibiotic concentrations, antibiotic resistance and ARGs increased in lake water and surface sediments. It should be noted that this is partially the result of CSO overflows.	-	-
Houtz, 2013	Investigated the extent to which PFAAs in runoff could affect drinking water supplies. Utilized new analytical techniques to indirectly measure PFAA precursors.	PFAS/PFC	Previous studies found existing measurement techniques could not detect precursors. Used a new method and found that PFAA precursors were present in SF Bay Area runoff.	Storage of stormwater may contribute to increased concentrations of PFAAs, individual PFAA precursors, and total precursors.	Many PFAA precursors are not currently included in HPLC-MS/MS protocols -No understanding of transformation potential of fluoropolymers -Insufficient investigation of toxicity of PFAA precursors and non-C8 PFAA compounds
Nguyen et al., 2011	Case study in an urban watershed in Singapore to characterize occurrence and sources of PFC compounds in surface waters.	PFAS/PFC	13 of the 19 targeted PFCs were detected. Results suggested that rain water contributed to 12-25% of total PFC loads from non-point sources. Reservoir concentrations were below precautionary levels, but may increase with increased urbanization.	PFOS concentrations were relatively low in groundwater, likely because of its ability to sorb to sediments.	-
Procopio et al., 2017	Sampled for PFAAs in surface water, groundwater, stormwater, sanitary/sewer water, and commercial/industrial process water in a 7.5 km2 area of the Metedeconk River watershed.	PFAS/PFC	PFOA was identified as the primary contaminant. PFAAs were primarily coming from a contaminated groundwater plume rather than surface runoff.	In this study, PFAAs were released directly to the soil and groundwater.	Emphasizes importance of source tracking
Ahrens, 2011	Review on existing knowledge of occurrence, fate, and processes of PFCs	PFAS/PFC	PFCs were ubiquitous in aquatic environments, with concentrations ranging from pg/L to ng/L. In Albany, NY, snowfall was identified as a significant pathway for PFCs into lakes. High PFOA concentrations in precipitation were correlated with air masses in a study in North America. PFCs were found to be associated with surface runoff from agricultural lands and one study found PFCAs to be associated with runoff from streets.	High PFC concentrations were found in groundwater where water infiltrated through contaminated soil. PFCs are very persistent, so high levels were detected near a fire-training location 7-10 years after training activities were halted.	Key loss processes and deposition -Relationship between sources and aqueous env. Concentrations -Solid-water partitioning and air-water exchange -Extent of long-range transport -Investigations of seasonality and long-term changes

Source	Description of Study	Contaminant(s)	Detections in Stormwater	Risk to Groundwater Quality	Identified Gaps and Research Needs
ITRC, 2018	Fact sheet on fate and transport of PFAS	PFAS/PFC	Several sources showed that stormwater runoff may contribute significant loads of PFAS. Concentrations are affected by proximity to the source.	PFCAs and PFSAs are relatively mobile in groundwater but tend to associate with the organic carbon fraction in soil. PFAS in soils can leach into groundwater.	-
Xiao et al., 2012	Six PFAAs were monitored in stormwater over seven storm events in the Twin Cities	PFAS/PFC	PFOS and PFOA were the most abundant PFAAs in stormwater. PFOS were detected at higher levels in industrial and commercial areas.	-	-
Pitt et al., 2013	Literature review and sampling results focused on identifying and treating emerging contaminants in wet weather flows.	Multiple Contaminants	Average PPCP and PAH concentrations nearly doubled during wet weather flows. Only one runoff sample detected pesticides.	Pesticides have moderate to high GW contamination potential due to high mobility in the vadose zone	-
Fairbairn et al., 2018	Investigates 384 emerging contaminants in stormwater samples in Minneapolis-St. Paul	Multiple Contaminants	31 of the 384 emerging contaminants were detected in more than half of the samples. Significant variability due to seasonal site differences.	-	-
Wicke et al., 2016	An event-based one-year monitoring program, which analyzed for 100 micropollutants in separate storm sewers	Multiple Contaminants	Found catchment-specific differences in concentrations. Benzothiazoles and PAH were highest in areas with road runoff, whereas organophosphates were highest in areas with older buildings.	-	-
Lin et al., 2018	A "living document" that guides special studies on emerging contaminants in the San Francisco Bay	Multiple Contaminants, including PFAS/PFC	Stormwater is a significant pathway for the following: PFOS, PFOA, long-chain perfluorocarboxylates, fipronil, alkylphenols, alkylphenol ethoxylates, PFBEs, pyrethroids. Some detections: HBCD	PFASs are mobile in groundwater, so treatments relying on sorption are ineffective	-
Pal et al., 2014	Investigates anthropogenic sources of emerging organic compounds in the urban water cycle	Multiple Contaminants	A recent study showed evidence of "first flush" effect for PFC concentrations.	-	-

6. References

Adolfson Associates, 1995. Pilot Evaluation Subsurface Stormwater Disposal Facilities. Tacoma-Pierce County Health Department, Tacoma-Pierce County Washington.

Ahrens, L., 2011. Polyfluoroalkyl compounds in the aquatic environment: a review of their occurrence and fate. Journal of Environmental Monitoring, 13(1), pp.20-31.

American River Basin Stormwater Resource Plan (ARB SWRP), 2018. Appendix L – Drywell Fact Sheet: Guidance for the ARB Region.

Arizona Department of Environmental Quality (ADEQ), 2000. Guidance for Design, Installation, operation, Maintenance & Inspection of Drywells. Arizona Department of Environmental Quality, Water Quality Division.

Arnold, B.F., Schiff, K.C., Ercumen, A., Benjamin-Chung, J., Steele, J.A., Griffith, J.F., Steinberg, S.J., Smith, P., McGee, C.D., Wilson, R., Nelsen, C., Weisberg, S.B., Colford, J.M., 2017. Acute Illness among Surfers after Exposure to Seawater in Dry- and Wet-Weather Conditions. American Journal of Epidemiology, Volume 186, Issue 7, 1 October 2017. Pages 866-875.

Bandeen, R.F., 1987. Additional Case Study Simulations of Dry Well Drainage in the Tucson Basin. Pima County Transportation and Flood Control District, Tucson, AZ.

Bandeen, R.F., 1984. Case Study Simulations of Drywell Drainage in the Tucson Basin. Pima County Transportation and Flood Control District, Tucson, AZ.

Barraud, S., Gautier, A., Bardin, J.P., Riou, V., 1999. The impact of intentional stormwater infiltration on soil and groundwater. Water Sci. Technol. 39 (2), 185–192.

Brody-Heine, B., Kohlbecker, M., Peavler, R., 2011. Pollutant Fate and Transport Model Results in Support of the City of Bend UIC WPCF Permit-Groundwater Protectiveness Demonstration and Proposed EDLs. Tech. N.p.: GSI.

California Department of Water Resources (CA DWR), 1991. California Well Standards. Bulletin 74-90, supplement to Bulletin 74-81.

California Department of Water Resources (CA DWR), 1981. Water Well Standards: State of California. Bulletin 74-81.

Chen, H.-P., Stevenson, M.W., Li, C.-Q., 2007. Assessment of existing soakaways for reuse. Water Manage. 161 (WM3).

City of Fontana, 2016. Water Quality Management Plan Handbook. Prepared by CWE Corp.

City of Portland Bureau of Environmental Services, 2008. Framework for Groundwater Protectiveness Demonstrations: Underground Injection Control System Evaluation and Response.

City of Portland, 2016. Stormwater Management Manual.

Clark, S.E., Pitt, R., 2007. Influencing factors and a proposed evaluation methodology for predicting groundwater contamination potential from stormwater infiltration activities. Water Environ. Res. 79 (1), 29–36.

County of Los Angeles Department of Public Works, 2014. Low Impact Development Standards Manual.

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

Edwards, E.C., T. Harter, G. E. Fogg, B. Washburn, H. Hamad, 2016. Assessing the effectiveness of drywells as tools for stormwater management and aquifer recharge and their groundwater contamination potential. Journal of Hydrology 539 (2016) 539–553

Environmental Protection Agency (US EPA), 1999a. The class V underground injection control study. Volume 3: storm water drainage wells. In: Office of Ground Water and Drinking Water, pp. 1–4.

Environmental Protection Agency (US EPA), 1999b. The Class V Underground Injection Control Study. Volume 3: Storm Water Drainage Wells. Appendix E. Office of Ground Water and Drinking Water.

Fairbairn, D.J., Elliott, S.M., Kiesling, R.L., Schoenfuss, H.L., Ferrey, M.L. and Westerhoff, B.M., 2018. Contaminants of emerging concern in urban stormwater: Spatiotemporal patterns and removal by iron-enhanced sand filters (IESFs). Water research, 145, pp.332-345.

Garner, E., Benitez, R., von Wagoner, E., Sawyer, R., Schaberg, E., Hession, W.C., Krometis, L.A.H., Badgley, B.D. and Pruden, A., 2017. Stormwater loadings of antibiotic resistance genes in an urban stream. Water research, 123, pp.144-152.

Hamad, H., Lock, B.H., Ashoor, A., Pi, N., Green, R., Edwards, E., Washburn, B., 2016. Dry Wells and the Risk of Groundwater Contamination: An Annotated Bibliography. Ecotoxicology Program, Pesticide & Environmental Toxicology Branch, Office of Environmental Health Hazard Assessment, California Environmental Protection Agency. Originally published December, 2014.

Houtz, E.F., 2013. Oxidative Measurement of Perfluoroalkyl Acid Precursors: Implications for urban runoff management and remediation of AFFF-contaminated groundwater and soil (Doctoral dissertation, UC Berkeley).

Hydrosystems, 2011. Advances in Stormwater Drainage – The Maxwell PlusTM Drywell A Case Study in Phoenix Arizona. Prepared for Torrent Resources.

Interstate Technology Regulatory Council (ITRC), 2018. Environmental Fate and Transport for Per- and Polyfluoroalkyl Substances.

Izuka, S.K., 2011. Potential effects of roadside dry wells on groundwater quality on the Island of Hawai'i – Assessment using numerical groundwater models. In: U.S.G.S. Scientific Investigations Report 2011-5072, pp. 1–30.

Jurgens, B.C., Burow, K.R., Dalgish, B.A., Shelton, J.L., 2008. Hydrogeology, water chemistry, and factors affecting the transport of contaminants in the zone of contribution of a public supply well in Modesto, eastern San Joaquin Valley, California. USGS Scientific Investigations Report 2008-5156. 78 p.

Lin, D., Sutton, R., Shimabuku, I. and Sedlak, M., 2018. Contaminants of Emerging Concern in San Francisco Bay: A Strategy for Future Investigations 2018 Update.

Lindemann, J., 1999. Evaluation of Urban Runoff Infiltration and Impact to Groundwater Quality in Park Ridge, Wisconsin Master's Thesis. College of Natural Resources, University of Wisconsin, Stevens Point, Wisconsin.

Nelson, C., Washburn, B., Lock, B., 2017. Separating Fact from Fiction: Assessing the Use of Dry Wells as an Integrated Low Impact Development (LID) Tool for Reducing Stormwater Runoff while Protecting Groundwater Quality in Urban Watersheds. City of Elk Grove, California.

Nguyen, V.T., Reinhard, M. and Karina, G.Y.H., 2011. Occurrence and source characterization of perfluorochemicals in an urban watershed. Chemosphere, 82(9), pp.1277-1285.

Olson, K.L., 1987. Urban Stormwater Injection via dry Wells in Tucson, Arizona and its Effect on Groundwater Quality Master's Thesis. Department of Hydrology and Water Resources, University of Arizona.

Orange County, 2011. Technical Guidance Document Appendices: INF-5: Drywell, pp. XIV-37 – XIV-38.

Oregon Department of Environmental Quality (ODEQ), 2015. General Permit: Water Pollution Control Facilities Permit for Class V Stormwater Underground Injection Control Systems.

Pal, A., He, Y., Jekel, M., Reinhard, M. and Gin, K.Y.H., 2014. Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle. Environment international, 71, pp.46-62.

Pitt, R., Clark, S., Field, R., 1999. Groundwater contamination potential from stormwater infiltration practices. Urban Water 1 (3), 217–236, Journal of Hydrology 539 (2016) 539–553.

Pitt, R., Goodson, K., Ogburn, O., Eppakayala, V., Veeravalli, S., Bathi, J., Wilson, B., Subramaniam, S., Clark, S., 2013. Identification And Treatment Of Emerging Contaminants In Wet Weather Flows. Urban Watershed Management Branch and Office of Research and Development, U.S. Environmental Protection Agency.

Pitt, R., Telebi, L., Raghavan, R., Singer, M., Annoi, M., Watkinson, T., 2012. Evaluation and Demonstration of Stormwater Dry Wells and Cisterns in Millburn Township, New Jersey. PARS Environmental, Inc., Robbinsville, NJ 08691, pp.1–296.

Procopio, N.A., Karl, R., Goodrow, S.M., Maggio, J., Louis, J.B. and Atherholt, T.B., 2017. Occurrence and source identification of perfluoroalkyl acids (PFAAs) in the Metedeconk River Watershed, New Jersey. Environmental Science and Pollution Research, 24(35), pp.27125-27135.

Riverside County, N.D. Drywell Factsheet.

Southern California Coastal Water Research Project (SCCWRP), 2007. Watershed and Land Use Storm Water Pollutant Loading Data for the Greater Los Angeles Area, California, USA, 2007. Available from http://www.sccwrp.org/Data/SearchAndMapData/DataCatalog/2007StormWaterLoading.aspx.

Talebi, L., Pitt, R., 2014. Evaluation and Demonstration of Stormwater Dry Wells and Cisterns in Millburn Township, New Jersey. Journal of Water Management Modeling.

The Los Angeles and San Gabriel Rivers Watershed Council, 2005. Phase II Final Report. The Los Angeles and San Gabriel Rivers Water Augmentation Study.

The Los Angeles and San Gabriel Rivers Watershed Council, 2008. Phase II Monitoring Report Update. The Los Angeles and San Gabriel Rivers Water Augmentation Study.

The Los Angeles and San Gabriel Rivers Watershed Council, 2010. Ground Water Augmentation Model Demonstration Report. The Los Angeles and San Gabriel Rivers Water Augmentation Study.

Washburn, B., Bennett, L., 2017. Elk Grove Dry Well Project: OEHHA Technical Memo.

Washington State Department of Ecology, 2006. Guidance for UIC Wells that Manage Stormwater. Publication Number 05-10-067.

Weiss, P.T., LeFevre, G., Gulliver, J.S., 2008. Contamination of soil and groundwater due to stormwater infiltration practices – A literature review. *University of Minnesota, Stormwater Assessment Project.* Project Report No. 515.

Wicke, D., Matzinger, A., Caradot, N., Sonnenberg, H., Schubert, R.L., Von Seggern, D., Heinzmann, B. and Rouault, P., 2016. Extent and dynamics of classic and emerging contaminants in stormwater of urban catchment types. Pollution des rejets urbains de temps de pluie/Pollution of wet weather flow-Modélisation/Models.

Wilson, L.G., Osborn, M.D., Olson, K.L., Maida, S.M., Katz, L.T., 1990. The groundwater recharge potential of dry wells in Pima County, Arizona. Monit. Remed.,pp. 114–121.

Wilson, L.G., Osborn, M.D., Olson, K.L., Maida, S.M., Katz, L.T., 1989. The groundwater pollution potential of dry wells in Pima County, Arizona. The Water Resources Research Center, University of Arizona.

Wogsland, K.L., 1988. Effect of Urban Storm Water Injection by Class V Wells on the Missoula Aquifer, Missoula, Montana. University of Montana, pp. 1–33.

Wright Water Engineers and Geosyntec Consultants, 2007. Frequently Asked Questions Fact Sheet for the International Stormwater BMP Database: Why does the International Stormwater BMP Database Project omit percent removal as a measure of BMP performance? (as posted on www.bmpdatabase.org)

Xiao, F., Simcik, M.F. and Gulliver, J.S., 2012. Perfluoroalkyl acids in urban stormwater runoff: influence of land use. Water research, 46(20), pp.6601-6608.

Zhang, S., Pang, S., Wang, P., Wang, C., Han, N., Liu, B., Han, B., Li, Y. and Anim-Larbi, K., 2016. Antibiotic concentration and antibiotic-resistant bacteria in two shallow urban lakes after stormwater event. Environmental Science and Pollution Research, 23(10), pp.9984-9992.