Appendix M

Watershed Analysis and Modeling Approaches for the ARB Region

Introduction

Municipal stormwater planners need information to understand infrastructure improvements that can help meet water quality goals and MS4 permit requirements. Modeling and quantitative analysis of watershed processes informs planning activities for new infrastructure, performance assessments of newly installed components such as BMPs, achievable targets for permit compliance, and quantifications of costs for short- and long-term solutions.

Engineers use many types of analysis and models to support stormwater planning and verification needs. To understand the performance of current and future system at the watershed scale, two main types of procedures are followed: mathematical modeling, and performance assessments (Jefferson et al. 2017). *Performance* (*assessments*) use collected data, which can be specific to a single installation or across a watershed, to evaluate the effectiveness of existing installations. *Mathematical modeling* uses data and assumptions to develop mathematical representations of physical processes or variables that correlate with water quality outcomes, which can help to understand current and future performance of stormwater infrastructure.

Other methods of classifying watershed processes and resultant stormwater runoff effects also exist. For decades, geographers, landscape architects and designers, ecologists, and land use planners have used methods to categorize the landscape according to physical characteristics and attributes, such as land use and land cover, geology, topography, urban development, and others (McHarg 1969). Through this approach, stormwater runoff outcomes are assumed to correlate with these landscape and geological characteristics of sites. Attributing stormwater processes and methods for mitigating runoff with particular characteristics of a site can help prioritize actions, such as installing new types of infrastructure, without undertaking complex modeling and field data collection. Instead, such approaches rely on existing research potentially validated through limited fieldwork, to accumulate existing data and scientific understanding for regional watershed classification schemes.

As part of developing a regional stormwater management approach for the American River Basin through the Stormwater Resource Plan (SWRP), this SWRP Appendix will describe and evaluate contemporary methods for watershed-scale analysis and modeling used by municipalities in California. Specifically, it focuses on two of the approaches highlighted above: 1) mathematical modeling techniques, and 2) landscape analysis. These have variously been applied across parts of California in support of watershed-scale plans to help municipalities meet stormwater permit compliance targets.

Mathematical Modeling Approaches

Computer-based watershed models use mathematical relationships to simulate or assess aspects of stormwater system performance, with the goal of modeling water flows and water quality as accurately as possible (Nix 1994). Such models support many types of scientific and decision-making goals, including understanding watershed processes, comparing opportunities and tradeoffs of various management options, assessing effects of water allocation schemes, and identifying well-correlated relationships in landscape characteristics and downstream water quality measurements, to name a few.

Computer-based urban stormwater models were first developed in the 1970’s through initial software such as the Stormwater Management Model Level I, STORM, the Hydrologic Simulation

Program-Fortran in C, and others (Heaney, Nix, and Huber 1976; HEC 1977; Johanson, Imhoff, and Davis 1976). Numerous existing books and sources have documented the many urban stormwater models and modeling approaches that have been developed (Nix 1991; Nix 1994; Zoppou 2001; Obropta and Kardos 2007; Elliott and Trowsdale 2007).

Mathematical stormwater models can be generally classified according to several categories, which are not entirely exclusive and overlap. First, stormwater models can be ***deterministic*** or ***stochastic***. Deterministic models use specified inputs to yield exact outputs based on mathematical relationships. They simulate hydrologic and hydraulic processes. Stochastic models also use mathematical formulas to relate rainfall and runoff processes, but rather than stipulating a direct input and output relationship, stochastic models relate processes using statistical models derived from observations. Since observed relationships in runoff and correlating parameters (climate, rainfall, land cover, etc.) are "noisy", equations derived from statistical observations include estimates of the degree of uncertainty associated with the model and procedures used to identify the best fitting relationship. An example of a stochastic urban runoff model could be a regression equation that details a buildup-wash off relationship, with contaminant concentrations at a downstream discharge point explained by variables such as antecedent (preceding) dry days and volume of runoff. While deterministic models would attribute direct cause and effect, stochastic models demonstrate correlations (not causation) and include inherent randomness. Stochastic models are more likely to have reduced geographic resolution (lumped). As they are derived from observed data, they are best used for planning, making judgements for effective management options rather than simulating outcomes (Tasker and Driver 1988). For both types, the intent of modeling is to inform planning and (potentially) evaluation by relating watershed characteristics, climate, soil, geology, and precipitation with downstream water quality and quantity measurements.

Second, models can be ***distributed*** or ***lumped***. Distributed models represent of watersheds as having more than one distinct sub-region of specified geographic boundaries, where runoff outcomes are assessed according to parameters unique to that geographic area. The sub-regions are all connected through a flow routing network that simulates their relative locations in the larger watershed. Alternatively, lumped models treat a study zone as a single region, with predictive inputs and resultant outputs correlated, but lacking any greater geographic resolution. Distributed models tend to be more data intensive but offer greater flexibility for planning and verification purposes.

Third, stormwater models can be ***event-based*** or ***continuous.*** Event-based models focus on particular design storms, such as the 85th percentile storm used in many stormwater planning procedures in California, to model rainfall and associated runoff. Continuous models use a time series record to model flows over a given period of interest with sufficient hydrologic data. Continuous models tend to be more data intensive, but offer greater flexibility for planning and verification purposes.

In practice, many stormwater models are hybrids, continuous features of multiple classification types. Aligning data, planning and verification needs, and available expertise dictates the selection of watershed scale modeling tools appropriate to support stormwater infrastructure assessments (US EPA 2017). Many robust models capable of supporting stormwater planning processes in California are continuous and distributed, or at least pseudo-continuous and pseudo-distributed (Nix 1994). But this does not mean that, for instance, aspects of uncertainty are absent from deterministic models. Moreover, some regions with limited data or established modeling procedures look to more straightforward modeling approaches that rely on less complex empirical methods (Blackwell, Steets, and Schal 2015).

Assembling Watershed-Scale Stormwater Models

Models tend to include one or more water sources or bodies, such as rivers, lakes, groundwater basins, and reservoirs, and use existing data to create a realistic representation of natural and engineered processes. All model results are subject to uncertainties and underlying assumptions. In addition, while increased computing power and better understanding of scientific processes has increased the scale and scope of contemporary models, they are all simplifications. Data availability, resources, and management goals all affect the temporal and spatial resolution of modeling efforts.

For watershed and runoff management, models can simulate the effects of land use changes, infrastructure improvements, and other management actions on watershed processes and contaminant loading. Simulated processes in a watershed model include overland flow, groundwater recharge and infiltration, interflow, evaporation and evapotranspiration, in-stream sediment transfer, bacteria and organic matter growth, and chemical and biological transformations. The simulations use inputs of:

- *Topography*; land use, land cover, and slope,
- *Surface water flows*, based on stream locations, flow volumes and velocities, and in-stream depths,
- *Urban runoff processes* including runoff outfall locations, discharges, and pollutant concentrations,
- *Soil data* such as hydrologic soil groups, and
- *Climate and atmospheric processes* such as historic and predicted precipitation, or estimates of evaporation and evapotranspiration.

Watershed models are typically spatially distributed, whereby they must define how interconnected parts of the watershed interact that include all of the above datasets interconnect and relate. This spatial aspect of watershed processes is most relevant for watershed and runoff management. How do actions in the upper reaches of a watershed affect downstream processes? Where is the best location for reducing impervious surface cover to maximize goals of improving water quality? These and many other questions can be informed by modeling processes.

Stormwater Models for Permit Compliance

Several watershed planning regions around the U.S., as well as many metropolitan areas of California, have developed (or are developing) large scale models of watershed processes, including both water flow and quality, to support watershed-based approaches for managing stormwater and runoff. Several recent models have been developed specifically to assist municipalities in planning and demonstrating compliance with Municipal Separate Storm Sewer Systems (MS4) permits through emerging Alternative Compliance Pathways (ACPs) which use *Reasonable Assurance Analysis* (RAA) and watershed-scale modeling to inform long-term watershed planning activities. The ultimate goal is to inform long-term capital improvement plans en route to achieving receiving water quality goals (US EPA 2017; BASMA 2017; SWRCB 2015).

In developing models, a critical consideration is to identify a good fit for modeling approaches, whereby model outputs yield quantitative estimates useful for evaluating permit compliance. In addition, several modeling procedures also include a method for prioritizing decisions. For instance, models that simulate the functions of various Best Management Practices (BMPs) and the associated reductions in pollutant loads are commonly integrated into stormwater models. In principle, such tools usefully support analysis that identifies prime locations for installing or enhancing BMPs and Low-Impact Development (LID), flood control infrastructure, and habitat restoration. Models help quantify, with some degree of uncertainty, desirable outcomes of such actions including reductions in discharge volumes and pollutant loads, estimated increases in water supply and groundwater recharge, potential reductions in hydromodification effects, and quantified reductions in greenhouse gas emissions.

The extent to which such a model is useful for the ARB in regional planning and permit compliance applications, and if so what would be appropriate temporal and spatial resolutions, is an open question. As a large watershed that spans urban and rural areas, including some areas covered by MS4 permits, a careful survey of available tools and associated data requirements is important in assessing the feasibility of any tool. The ARB SWRP has also devised quantitative procedure for ranking projects proposed by member agencies and stakeholders.

To date, municipalities and entities in charge of watershed-level planning around California have employed a variety of the general modeling approaches described above in support of watershed and stormwater planning. Models were each tailored to address the questions specific to a municipality or group of municipalities in support of permit compliance. Stemming from these efforts, several resources have succinctly summarized watershed modeling options for stormwater planning (US EPA 2017; BASMA 2017; RWQCB-LA 2014).

Generally, the stormwater modeling approaches in California involve:

1) *Simulating watershed processes* that include overland runoff, surface and sub-surface processes, and climate and atmospheric processes, which all support quantifying pollutant loading in receiving waters,
2) *Evaluating Best Management Practices*, which are simulated by models that are either physically-based where BMP processes are mathematically represented, or empirical models where BMP processes are derived from past performance and codified through tools such as statistical analysis and regression,
3) *Prioritizing Decisions* to identify the scale, location, and potential combinations of BMPs that, if implemented as part of a watershed-level program, could meet receiving water goals over the long-term.

The California State Water Resources Control Board is currently exploring how to capture and synthesize lessons learned from parts of the state that have undertaken RAA in permit compliance procedures. In particular, the diversity of California's landscapes significantly influences potential modeling approaches. For instance, the communities that have undertaken large-scale modeling as part of RAA and alternative compliance are highly urbanized and covered by MS4 permits. This does not always align succinctly with watershed-scale planning approaches:

> "While traditional approaches to watershed plans tend to use a holistic approach that considers all point and nonpoint sources that are hydrologically connected (USEPA 2008), the permit-driven approach aims to isolate, quantify, and manage pollutant sources that originate from within the MS4 permit boundary. In some cases, there may be more than one municipal jurisdiction that is addressed by a permit that collectively drain and comingle within a receiving water. Furthermore, areas addressed by separate NPDES permits, federal land, or state-owned land subject to other management that

> fall within the delineated hydrologic boundaries should also be considered and, in some circumstances, removed from the designated planning area." (US EPA 2017, 17)

These considerations are important for the ARB SWRP region, as it includes municipalities with MS4 permit compliance requirements, but also spans to upstream watersheds, which may be driven by goals for meeting TMDLs or promoting aquatic habitat and restoration.

To meet MS4 requirements, permittees in California can undertake a variety of potential actions to be in compliance. First, municipalities can enact programmatic activities such as street sweeping, facility inspections, and source control procedures for key pollutants of concern. Second, municipalities can promote distributed stormwater treatment infrastructure such as LID on public and private property. Finally, municipalities and regional governments can build larger-scale municipal projects, such as green streets, capture and infiltration basins, or other BMPs. These function at larger scales and may require collaboration across jurisdictions. Models may, in principle, help municipalities and utilities in deciding efficient and cost-effective collections of these treatments as part of long-term planning and monitoring.

Models developed as part of RAA and permit compliance processes must offer capabilities for long-term simulations capable of predicting the extent of BMPs and new infrastructure required in a watershed for meeting water quality goals. As noted, most municipalities to date have developed continuous simulation models of flows (surface and groundwater) and pollutant discharges to receiving waters of interest, including simulating potential engineering infrastructure to mitigate effects of intensive land use and urbanization. They generally consider three categories of pollutants (single or combinations):

1) TMDL-identified pollutants
2) Pollutants included on the 303(d) list
3) Pollutants with noted exceedances in receiving waters specific to permits.

Quantifications are performed by calibrating models with existing flow measurement and constituent monitoring data. Generally, the watershed models and associated estimated pollutant loads are highly sensitive to changes in hydrologic flows. Calibrating watershed-scale models for both quantity and constituent concentrations is an iterative and complicated process.

The existing models incorporate one or more core models to perform hydrology and water quality calculations, calibrated to local conditions. Models are region-specific, incorporating core hydrology sub-models, GIS, and other software to perform continuity calculations (preserving flow and pollutants) across the watershed(s) of interest. As part of RAA and permit compliance actions in Southern California and the Bay Area, summary documentation was developed that describes the capabilities of core models and integrative modeling frameworks. The documents provide general guidance for available modeling options a community may undertake if seeking the develop watershed models in support of stormwater planning (RWQCB-LA 2014; US EPA 2017; BASMA 2017).

The models used in California used in California (both core models and watershed-specific models) are summarized below. Note that this list details the most commonly used models in support of watershed-scale planning and permit compliance, but is not a comprehensive list. Other sources detail the models that have been developed over decades in support of urban stormwater planning (Zoppou 2001; Nix 1991; Nix 1994; Elliott and Trowsdale 2007).

Core Numerical Simulation Models

Several core models of hydrologic processes are used directly or incorporated into integrative modeling frameworks. These are capable of continuous simulation based on inputs, derived from observations, statistical analysis of observations, and national parameters. These include the:

- *Stormwater Management Model (SWMM)*. First developed by the US Environmental Protection Agency, SWMM is now on its 5 iteration. SWMM is tailored to urban stormwater management and simulates overland and pipe flow, and performs water flow and pollutant loading calculations. It also has associated modules for simulating various BMPs. SWMM can be used as a standalone desktop platform, but it has also been incorporated numerous commercial and open-source software platforms.
- *Loading Simulation Module in C++ (LSPC)*. LSPC is a watershed modeling system that incorporates an underlying model, the Hydrological Simulation Program- Fortran, to simulate water quality and quantity in watersheds. LSPC can perform calculations for pollutant and nutrient loading, and it provides continuous simulation capabilities for modeling surface, sub-surface, and climate processes. LSPC and HSPF are underlying models for Los Angeles County's *Watershed Management Modeling System*, which is open-source and has been used in analyses to optimize existing stormwater capture basins and understand future water supply management options in the LA Basin (County of Los Angeles 2009).
- *Soil and Water Assessment Tool (SWAT)*. SWAT was developed by the US Department of Agriculture and Texas A&M to simulate water quantity and quality processes for small watersheds and river systems. It is widely used for these purposes, but in the context of urban and watershed runoff management, must be coupled with additional models that provide additional capacities for modeling BMPs or performing prioritization.

Integrative Software for Watershed Modeling

Several software products integrate the above core models to provide flexible platforms that can be applied to many problems. Examples of popular models include:

- *EPA SUSTAIN*. The SUSTAIN model was developed by US EPA to support watershed-scale stormwater planning and optimization. SUSTAIN combines SWMM and HSPF to simulate flow, pollutant loading, and sediment loading, along with BMP processes. It also incorporates capacity for multi-objective optimization across cost, locations, and receiving water quality using an evolutionary algorithm. EPA SUSTAIN was developed to be incorporated into ArcGIS. It was first released in 2013 but is no longer being supported (U.S. EPA 2009).
- *GreenPlanIT*. GreenPlanIT was developed by the San Francisco Estuary Institute (SFEI) to support regional urban stormwater planning with BMPs and green infrastructure. It has been used in several communities throughout the San Francisco Bay Area. Similar to SUSTAIN, GreenPlanIT uses SWMM and an evolutionary algorithm to help communities in identifying priority actions through multi-objective optimization. It also support site-level planning and project tracking to assist utilities in implementing long-term infrastructure plans. GreenPlanIT is only appropriately used in urban areas due to using SWMM for core hydrology and pollutant loading calculations.
- *Watershed Management Optimization Support Tool (WMOST)*. WMOST was developed by researchers for the US EPA to support watershed-scale planning and decision-making. WMOST is capable of simulating entire watershed-scale processes, including both urban

hydrology and engineering operations such as wastewater treatment, as well as environmental processes including precipitation and groundwater recharge. WMOST incorporates SWMM, SWAT, and HSPF for simulating water quality and quantity, along with potential BMPs. It was released in 2013.

Region-Specific Models

Many regional models for California watersheds have been built and calibrated to simulate watershed processes for specified regions. Many have used one or more of the core models and frameworks above to provide regional water agencies and watershed planners with empirical tools for evaluating short- and long-term decisions. Some examples of relevant models include:

- *Watershed Management Modeling System (WMMS)*. WMMS was developed by LA County and consultants to support watershed planning and stormwater permit compliance. It uses LSPC and a geospatial interface (*MapWindow)* to perform continuous water quality and quantity simulations for a 25-year time horizon and optimize locations for potential BMPs. WMMS has supported multiple water planning processes in LA, including permit compliance, re-optimization of existing LA County stormwater infrastructure, infrastructure investments needs, and countywide water planning goals for future water supply portfolios (LACDPW 2013).
- *Structure BMP Prioritization and Analysis Tool (SBPAT)*. SBPAT was developed by Geosyntec to support watershed planning and permit compliance for the City of Los Angeles. It provides similar functionality and output support as WMMS and has been used for multiple applications in Los Angeles, San Diego, and other coastal areas. It uses SWMM and also draws on the International BMP database for empirical parameters to support BMP planning (Geosyntec Consultants 2013).
- *Sacramento Area Hydrology Model (SAHM).* SAHM is a model to analyze effects of hydromodification in the Sacramento region and supports analysis and sizing of potential projects to reduce effects of land use changes. It was developed by adapting the *Western Washington Hydrology Model* that uses HSPF for continuous simulation of hydrology. SAHM is closely related to several regional models in other parts of Northern California (Clear Creek Solutions, Inc. 2013).

Data Requirements

Watershed models that support RAA and stormwater permits are data intensive. Data must be collected on: 1) geography, topography, land use and land cover, 2) Climate and precipitation patterns, 3) Soils and sub-surface geology, 4) Hydrology, 5) Water quality and contaminant loads, and 6) Municipal and water utility jurisdictions.

High-resolution hydrology and water quality data are critical in calibrating the model to meet performance criteria. The Los Angeles Regional Water Quality Board, as part of the RAA process in LA County, outlined criteria for evaluating model performance. In creating a model, key parameters such as runoff ratios and flow are iteratively refined so as to improve the model results as compared to historical data. Documented materials provide detailed guidance on the ranges for sensitivity analysis used to evaluate model performance in that region (RWQCB-LA 2014). Regional water quality boards throughout California have published documentation with guidance on developing useful watershed modeling tools in support of RAA and stormwater permits.

Table 1: Data requirements for watershed modeling in support of stormwater planning and RAA permit processes (adapted from documentation from the Los Angeles Regional Water Quality Control Board)

Watershed Model Data Requirements	
Geography and Topography	**Climate**
Imagery and satellite data Topography (Digital Elevation Models) Land use and land cover Stream and channel network Drainage areas and outfalls	Precipitation Evaporation and evapotranspiration
Soil and Geology	**Hydrology**
Soil groups Distribution and composition of soils Sub-surface geology Groundwater basins Average slope Vegetative cover of soil	In-stream flows In-stream depth Water storage infrastructure
Water Quality	**Jurisdictions**
Point source location Point source discharges Point source concentrations	Water utility boundaries Municipal boundaries Watershed planning areas

Managing Uncertainty

In any analysis with modeling, both stochastic and deterministic, uncertainty exists in results. Uncertainty in urban stormwater models can be characterized as resulting from random variability in hydrologic and environmental processes, challenges in translating real-world conditions into a model with inherent simplifications, and uncertainty associated with specific parameters (Zoppou 2001). Sources of uncertainty can also be grouped into categories (Montalto, Behr, and Yu 2012; Behr and Montalto 2008; Sample et al. 2003; Gold et al. 2015; EPA 2007):

- **Variable costs** across BMPs and management alternatives, which can have wide ranges,
- **Variable performance** of traditional and new stormwater infrastructure,
- **Human factors** such as installation rate of new on-site infrastructure by property owners or behavior for certain activities related to contaminants such as littering,
- **Modeling simplifications,** and
- **Analysis assumptions** that simplify or make judgements about environmental conditions that influence runoff such as build-up and washoff rates or land cover.

Urban stormwater models have incorporated a variety of procedures to characterize uncertainty. First, sensitivity analyses can quantify the parameters that, when changed, have the greatest effect on outcomes. Sensitivity analysis is typically used in model calibration but can also provide insights into actual model outcomes for a verified model if assumptions or new data provide additional details for parameter ranges. Second, while input parameters are generally included in models as a single value representing a mean of observed data, the inputs could also include variance values that provides confidence intervals for the output distributions. Finally, Monte Carlo techniques can be used to generate a large number of outcome scenarios from many (typically thousands) of model runs with randomly sampled input parameters. The output estimates distributions of output variables that can give an indication of the relative likelihood of real-world outcomes given reasonable assumptions of quantified system uncertainties (Zoppou 2001).

Landscape and Watershed Classification Approaches

In additional to hydrologic modeling, other approaches have been developed to inform watershed-level planning related to stormwater and hydromodification goals. Such approaches have long roots in landscape planning and analysis. For instance, in 1969, Ian McHarg characterized the relationship between landscape characteristics and function, using typologies to classify regions and understand what land use planning and mitigation actions could be taken to responsibly grow cities while preserving natural systems (McHarg 1969). In the 1970's, the U.S. Geological Survey developed the first nationwide classification system for land use and land cover, which serves as a basis today for properly-used to categorizations of land area, based on the function and cover of the land surface in that zone (Anderson et al. 1976).

Extending this approach to stormwater planning can assist in categorizing boundaries of watershed zones that relate to assumed or measured characteristics of runoff (Huang and Ferng 1990). For this task, multiple data sets (layers of surface, sub-surface, and climate characteristics) must be collected and integrated to understand the effects that processes have on stormwater runoff outcomes. In this view, natural hydrologic processes, which are influenced by many factors such as slope, geology, land cover, and others, are altered by urbanization and documented effects of increasing the velocity and volume of runoff from precipitation (Leopold 1968).

In California, such approaches using watershed categorizations have been applied for stormwater planning and hydromodification mitigation as part of recent permit compliance processes. For instance, in the Central Coast of California, researchers developed a framework for identifying watershed management zones and associated strategies based on a broader collection of characteristics (Booth et al. 2012). The method first created *physical landscape zones* (PLZs) based on topography and geologic characteristics. Then within each of these PLZs, key watershed processes were identified, including:

1. Overland flow
2. Infiltration and groundwater recharge
3. Groundwater interflow
4. Evaporation and evapotranspiration
5. Sediment transport and organic matter delivery
6. Chemical and biological processes and transformations

The geology, slope, land cover, and level of urbanization all affect which of the above processes are dominant in an identified watershed management zone. Additionally, zones were organized according to the type of receiving water body they contribute to, including surface streams, lakes, rivers, wetlands, and groundwater basins. The combination of understanding surface and sub-surface characteristics, associated watershed processes, and ultimate downstream receiving waters helps inform what types of BMPs and control measures are most appropriate.

The method is detailed and requires significant knowledge, but does offer from a "snapshot"-style approach that is not reliant on the high-resolution temporal and spatial data that typically feeds watershed models. The method was applied as part of a regional plan for controlling hydromodification in the Central Coast. The diversity of landscapes and geology in the Central Coast region made this type of approach highly applicable. It has also been applied to other parts of California.

As part of the SWRP development process, a similar inventory of watershed characteristics and associated processes is being developed to inform regional managers developing BMPs and stormwater infrastructure upgrades. As part of the effort, the applicability of each stage of the process – watershed inventory, classification of zones, identification of watershed processes, and assessment of relevant BMP strategies – to the ARB will be assessed and recommendations made for integrating this understanding into SWRP processes.

RAA and Modeling

Modeling and watershed analysis approaches developed in support of stormwater planning and RAA all have core needs for data collection and integration. RAA efforts with modeling tend to use one of a core group of models to simulate watershed processes, tailored to regional specifics. Most models, especially models with continuous simulation over time, have significant data requirements and are intensive to develop. To date, a cadre of experts and regulators have led in developing standards and guidelines for implementing modeling in the RAA process.

Many of the planning efforts that undertook modeling as part of RAA did so at the outset. The efforts helped to collect data from scattered sources and create watershed-scale understandings of the scope of BMP interventions necessary for achieving permit compliance. Model results provided empirical context for building support across government agencies and regional stakeholders, as well as feeding into long-term capital planning processes. Many of the models have also been employed for other purposes, including applications beyond stormwater planning and permitting.

At the same time, the models have generally not been used to identify specific projects sites due to a number of reasons. Identifying exact locations for a project is subject to many factors external to model workings, including other existing infrastructure and upgrade needs, financing, interest and advocacy, and site requirements. In addition, once new BMP installations are operating, the capacity for post-installation monitoring to capture predicted improvements in flow and contaminant loads is limited. Implemented projects may not be reinstated into existing models as part of adaptive management. Further, even if such models are developed and become useful repositories for disparate datasets, the agencies that create them may not reap benefits or returns from the effort and resources that went into developing a regional tool.

For future planning processes, regional stormwater and water quality agencies can seek to build broader partnerships with other water utilities in developing models that serve multiple purposes. Underlying model data, as well as model results, can feed into efforts to create open-source repositories for municipal data. State agencies such as the California State Water Resources Control Board are currently developing guidelines and long-term projects to support improved stormwater planning processes using RAA. Such efforts may offer future opportunities for more efficient development of models in support of watershed planning, water supply management, and stormwater permit compliance.

Synopsis: Managing Runoff at the Watershed-Scale in the ARB

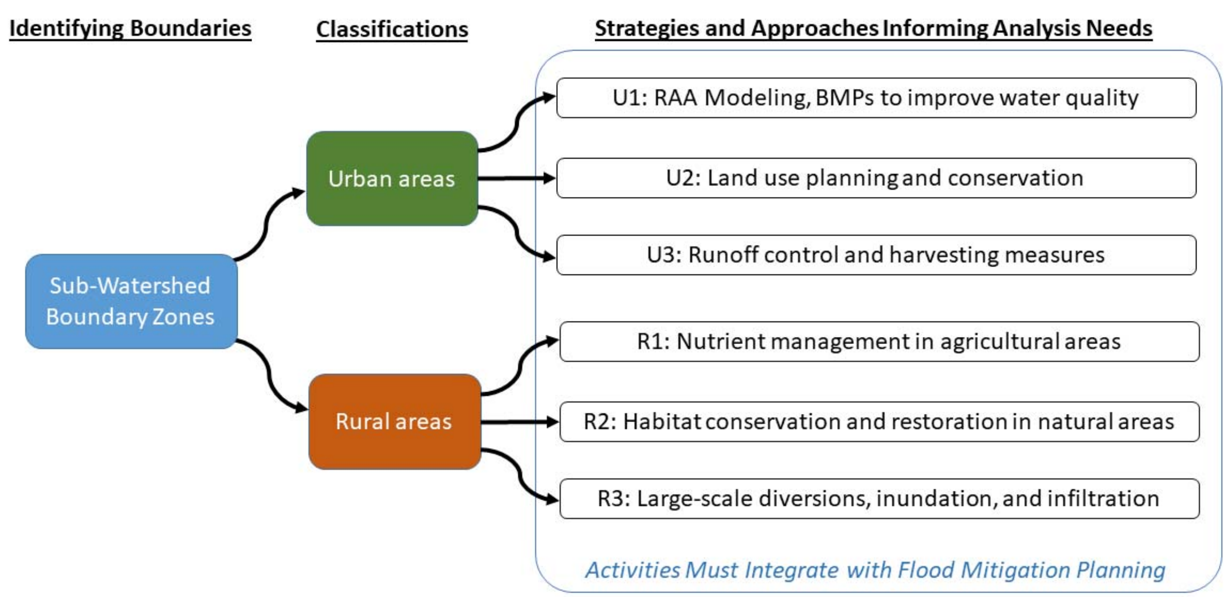
The ARB combines urban and rural areas. It is also an upstream basin, situated in the middle of the state. Runoff and urban system discharges that exit the basin flow downstream to the Sacramento-San Joaquin Delta, where a portion is diverted to users throughout the state. Combined, these factors influence the strategies and scale of water management in the basin.

The mix of land uses and associated regulatory tools and planning approaches, in particular, is a critical consideration for developing watershed-scale analytical tools. In the ARB's urban regions, municipalities must develop long-term stormwater infrastructure improvement plans to comply with MS4 permits. In agricultural and rural areas, statewide policy development is moving towards optimizing capture and diversion of runoff, especially for recharging groundwater basins in either dedicated Managed Aquifer Recharge areas or on agricultural fields. Finally, many areas of the ARB are important critical habitat zones for fish spawning and other aquatic species.

Given the mix of regulatory and policy drivers, a regional approach would look to use the appropriate tools in the appropriate locations, with the overall goal of increasing water quality and aquatic habitat, along with opportunities for capture runoff and infiltrating it directly on favorable land uses or through diversion to recharge basins. Given the continued growth and land development of the region, an integrated approach that considers land conservation and easements would be timely.

The graphic below provides a general framework for such a watershed-scale approach to managing runoff. As a first step, watershed zones can be delineated according to characteristics of geology, slope, land use and cover, receiving water processes, and any other factors deemed relevant. Next, the sub-watershed zones (potentially equivalent to watershed management zones or physical landscape zones discussed above) can be separated generally into urban and rural areas. Urban areas would include municipalities principally subject to managing stormwater runoff through MS4 permits. Alternatively, rural areas, which could include agricultural lands and natural areas such as forests or open-space, would be areas to consider multi-benefit land use planning for conservation, and increasingly watershed-scale efforts to boost Managed Aquifer Recharge (MAR).

Figure AM-1: Framework for managing runoff across a watershed. The principles for strategies in both urban and rural areas overlap, but are often implemented at much different geographic scales.



In highly urbanized watersheds, where municipalities span most of the watershed, MS4 permits would drive modeling, analysis, and compliance actions. Outside of municipalities, multiple policy and regulatory drivers can apply. For both cases, however, strategies and associated approaches that shape resulting analysis can be grouped into categorizations for: 1) **Water Quality**, 2) **Habitat**, conservation, and land use planning, and 3) **Mitigating floods and promoting recharge** in managing excess water as a resource. The general principles for both cities and rural areas are similar, including mitigating effects of intensive human land uses, promoting watershed ecosystems, and thinking about runoff management more broadly than just flood protection, but the scale at which actions are taken can vary significantly. Municipalities will likely consider smaller scale implementations and planning. Across a large watershed, the volumes of runoff to manage are much larger and more potential critical habitat likely exists. Thus, planning for watershed-scale activities such as stream restoration or large-scale recharge operations requires data and modeling for a much broader area, though perhaps with not as high of temporal or spatial resolution. From Figure 1 above, the strategies and approaches for the ARB in relation to scale and land use are discussed below in more depth.

Urban Areas

Urban areas must manage runoff to reduce contaminant loading, improve water quality, mitigate flood hazards, and promote integrated planning. These can be generally categorized as:

- *U1: RAA Modeling and BMP Planning*. These actions are taken as part of stormwater permit compliance and, more recently, undertaking Reasonable Assurance Analysis in support of long-term planning efforts. Urban BMPs would include small and large infrastructure improvements that provide treatment, infiltration, and retention capacity throughout the urban watershed.
- *U2*: *Land Use Planning and Conservation.* Protecting areas from intense development in and near cities can have many benefits for habitat and recreation. But such areas can also potentially provide flood mitigation or other services when, for instance, undeveloped land along regional rivers remains undeveloped or is able to be inundated during floods.
- *U3: Stormwater Capture and Use.* Cities throughout California increasing look to utilize stormwater as a resource, especially in drier areas. To this extent, capturing and infiltrating stormwater can help augment regional water supplies or provide excess supplies that can be swapped through conjunctive use agreements.

Rural Areas

Rural areas spanning agricultural, protected, forest, and open-space lands consider runoff management challenges somewhat differently. The actions taken to improve water quality often involve reducing nutrient loading from fertilizers and similar sources, along with promoting natural processes for filtration and treatment of runoff that reaches less-disturbed creeks and streams with habitat value. Such actions can again be generally categorized as:

- *R1: Nutrient and Runoff Management for Water Quality*. Agricultural areas in California's Central Valley can affect surface and groundwater quality, especially in regards to fertilizers and pesticides. Reducing or changing fertilizer applications, adapting agricultural BMPs, and adjusting plowing techniques are some of the available options for addressing water quality issues in rural areas. Additionally, while rural roads often have fewer transportation-related contaminants such as metals and oils, they can contribute as much or more sediment to local watersheds during storm events. Locating larger BMPs such as a buffer strip, which are capable of managing larger runoff volumes in sparsely populated areas, is a cost-effective tactic for addressing pollutant loading.

- *R2*: *Habitat Conservation and Restoration.* Similar to urban areas, actions to protect key habitat can be informed by overall watershed planning. But habitat conservation in rural areas often includes much larger land areas, as well as habitat corridors that better connect discontinuous protected land areas.
- *R3: Large-Scale Diversions, Inundation, and Infiltration.* The state of California has conducted watershed-scale planning for flood mitigation and water supply management from decades. Stemming from recent drought and groundwater overdraft, however, researchers and policy experts throughout the state are re-examining the potential to significantly scale up Managed Aquifer Recharge. While cities and rural areas have used MAR for decades, the scale currently being discussed, along with the tactics, are novel. Peak runoff can be diverted from rivers and channels into recharge basins or for flooding open-space and agricultural areas. In the ARB, scientific studies of soils, geology, infiltration, and groundwater flows must inform land-use planning and help agencies assemble watershed-scale projects that promote aquifer recharge.

The framework above presents a roadmap for municipalities and water agencies to assemble projects for managing runoff, which also provide other benefits for habitat, water supply, and flood control. In particular, using the framework to consider project scale and scope can assist regional planning efforts in the ARB to understand policy and regulatory drivers, available funding, and analysis needs across the region's diverse landscapes.

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