Chapter 2 Water Evaluation and Planning System

The text of this chapter first appeared in various chapters of the California Water Plan, Update 2013 document on WEAP (Joyce et al., 2010). Minor edits have been made for consistency with the rest of this document.

This Chapter presents an overview of the WEAP modeling environment that provided the framework for developing both the Statewide Hydrologic Region model, Central Valley Planning Area model (CVPA), and SacWAM. Particular focus is given to the scenario analysis, water allocations, and hydrologic calculations.

2.1 General Description

The WEAP system is a comprehensive, fully integrated river basin analysis tool. It is a simulation model that includes a robust and flexible representation of water demands from different sectors, and the ability to program operating rules for infrastructure elements such as reservoirs, canals, and hydropower projects (Purkey and Huber-Lee, 2006; Purkey et al., 2007; Yates, Purkey et al., 2005; Yates, Sieber et al., 2005; Yates et al., 2008; and Yates et al., 2009). Additionally, it has watershed rainfall-runoff modeling capabilities that allow all portions of the water infrastructure and demand to be dynamically nested within the underlying hydrological processes. This functionality allows the modeler to analyze how specific configurations of infrastructure, operating rules, and operational priorities will affect water uses as diverse as instream flows, irrigated agriculture, and municipal water supply under the umbrella of input weather data and physical watershed conditions.

The WEAP software is organized into five "views":

- Schematic View, in which the spatial layout of the model domain is created, edited and viewed.
- Data View, consisting of a hierarchical tree that organizes modeling data into six major categories: Key Assumptions, Demand Sites and Catchments, Hydrology, Supply and Resources, Water Quality, Other Assumptions and User Defined LP Constraints.
- Results View, which allows detailed and flexible display of all model outputs in customizable charts and tables. Multiple modeling scenarios can be concurrently displayed. It includes a "Favorites" option that saves useful charts, including chart formatting.
- Scenario Explorer View, in which results or data across many scenarios can be grouped together to help show the relative impacts of multiple scenarios.
- Notes View, a word processing tool for making notes or documenting aspects of the modeling analysis.

Information on navigating and using the WEAP "views" can be found in the following documents. For other questions related to the WEAP software, please see the online resources available for download at www.weap21.org.

- WEAP Water Evaluation and Planning System User Guide for WEAP 2015, August 2015

- WEAP Water Evaluation and Planning System Tutorial, January 2015.

2.2 WEAP Approach

The development of all WEAP applications follows a standard approach, as illustrated in Figure 2-1. The first step in this approach is the study definition, wherein the spatial extent and system components of the area of interest are defined and the time horizon of the analysis is set. The user subsequently defines system components (e.g., rivers, agricultural and urban demands) and the network configuration connecting these components. Following the study definition, the "current accounts" are defined, which is a baseline representation of the system – including existing operating rules to manage both supplies and demands. The current accounts serve as the point of departure for developing scenarios, which characterize alternative sets of future assumptions pertaining to policies, costs, demand factors, pollution loads, and supplies. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables. In this context, scenarios represent evaluations of water management response packages under uncertain future conditions. The steps in the analytical sequence are described in greater detail in the following sections.

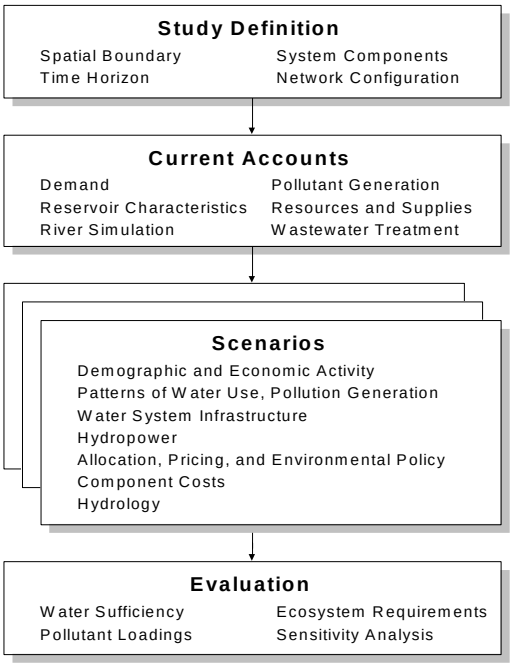

Figure 2-1. Components of a WEAP Application

2.3 Study Definition

Evaluating the implications of diversions and impoundments along a river, and how they are managed, requires consideration of the entire land area that contributes flow to the river, i.e., the river basin. Within WEAP, it is necessary to set the spatial scope of the analysis by defining the boundaries of the river basin. Within these boundaries, there are smaller rivers and streams (or tributaries) that flow into the main river of interest. Because these tributaries determine the distribution of water throughout the

whole basin, it is also necessary to divide the study area into subbasins, or catchments, such that the spatial variability of stream flows can be characterized.

2.3.1 Current Accounts

Current accounts represent the basic definition of the water system as it currently exists. Current accounts include specification of supply and demand infrastructure (e.g., reservoirs, pipelines, treatment plants). *The creation and parameterization of these elements in SacWAM is described in Chapter 3 through Chapter 6*. Establishing current accounts also requires the user to calibrate system data and assumptions so as to accurately mimic the observed operation of the system. This calibration process also includes setting parameters for defined catchments so that WEAP can simulate snowmelt and rainfall-runoff using input climate data (i.e., temperature and precipitation) and also estimate evaporative water demand in the delineated basins. For details on calibration in SacWAM, see Appendices A and B.

2.3.2 Scenarios

At the heart of WEAP is the concept of scenario analysis. Scenarios are story-lines of how a future system might evolve over time. The scenarios can address a broad range of "what if" questions. In this manner, the implications of changes to the system can be evaluated, and subsequently how these changes may be mitigated by policy and/or technical interventions. For example, WEAP may be used to evaluate the water supply and demand changes for a range of future changes in demography, land use, and climate. In the case of SacWAM, the model will be used to study various in stream flow requirement scenarios and their impacts on water storage, water availability, and stream flows.

2.3.3 Evaluation

Once the performance of a set of response packages has been simulated within the context of future scenarios, the response packages can be compared relative to key metrics. Typically, these metrics relate to water supply reliability, water allocation equity, ecosystem sustainability and cost. However, any number of performance metrics can be defined and quantified within WEAP.

2.4 WEAP Water Allocation

Two user-defined priority systems are used to determine allocations of supplies to meet demands (modeled as demand sites and as catchment objects for irrigation), instream flow requirements, and for filling reservoirs. These are: (1) demand priorities, and (2) supply preferences.

A demand priority is attached to a demand site, catchment, reservoir, or flow requirement, and may range from 1 to 99, with 1 being the highest priority and 99 the lowest. Demand sites can share the same priority, which is useful in representing a system of water rights, where water users are defined by their water usage and/or seniority. In cases of water shortage, higher priority users are satisfied as fully as possible before lower priority users are considered. If priorities are the same, shortage will be shared equally (as a percentage of their demands).

When demand sites or catchments are connected to more than one supply source, the order of withdrawal is determined by supply preferences. Similar to demand priorities, supply preferences are assigned a value between 1 and 99, with lower numbers indicating preferred water sources. The

assignment of these preferences usually reflects economic, environmental, historical, legal, and/or political realities. In general, multiple water sources are available when a preferred water source is insufficient to satisfy all of an area's water demands. WEAP treats additional sources as supplemental supplies and will draw from these sources only after it encounters a capacity constraint (expressed as either a maximum flow volume or a maximum percent of demand) associated with a preferred water source.

WEAP's allocation routine uses demand priorities and supply preferences to balance water supplies and demands. To do this, WEAP must assess the available water supplies each time step. While total supplies may be sufficient to meet all of the demands within the system, it is often the case that operational considerations prevent the release of water to do so. These rules are usually intended to preserve water in times of shortage so that long-term delivery reliability is maximized for the highest priority water users (often indoor urban demands). WEAP can represent this controlled release of stored water using its built-in reservoir routines.

WEAP uses generic reservoir objects, which divide storage into four zones, or pools, as illustrated in Figure 2-2. These include, from top to bottom, the flood-control zone, conservation zone, buffer zone, and inactive zone. The conservation and buffer pools together constitute a reservoir's active storage. WEAP always evacuates the flood-control zone, so that the volume of water in a reservoir cannot exceed the top of the conservation pool. The size of each of these pools can change throughout the year according to regulatory guidelines, such as flood control rule curves.

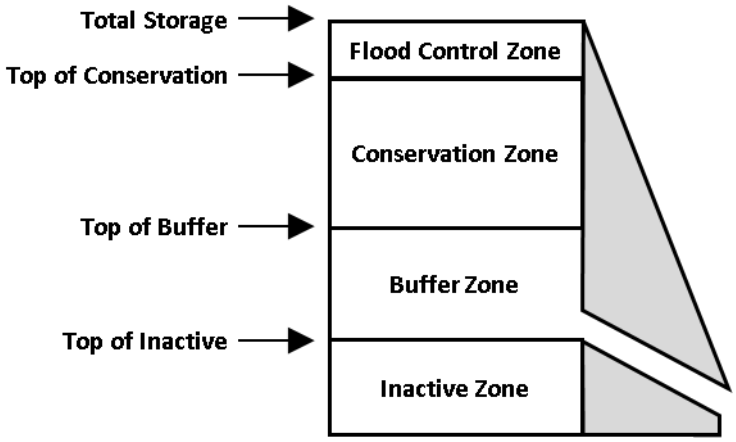

Figure 2-2. WEAP Reservoir Zones

WEAP allows reservoirs to freely release water from the conservation pool to fully meet withdrawal and other downstream requirements. Once the reservoir storage level drops into the buffer pool, the release is restricted according to the buffer coefficient, to conserve the reservoir's dwindling supplies. The buffer coefficient is the fraction of the water in the buffer zone available each month for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully, while rapidly emptying the buffer zone. A coefficient close to zero will leave demands unmet while preserving the storage in the buffer zone. Water in the inactive pool is not available for allocation, although under extreme conditions evaporation may draw the reservoir below the top of the inactive pool.

2.5 WEAP Hydrology

The hydrology module in WEAP is spatially continuous, with a study area configured as a contiguous set of catchments that cover the entire extent of the represented river basin. This continuous representation of the river basin is overlaid with a water management network topology of rivers, canals, reservoirs, demand centers, aquifers, and other features (Yates, Purkey et al., 2005; Yates, Sieber et al., 2005). Each catchment is fractionally subdivided into a unique set of independent land-use or land-cover classes that lack detail regarding their exact location within the catchment, but which sum to 100 percent of the catchment's area. A unique climate data set of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each catchment. *For details on how catchments were developed in SacWAM see Chapter 4 and Chapter 5*.

In the SacWAM application, hydrological processes are represented using two different approaches. In the mountainous upper watersheds the *Soil Moisture* method is used to represent rainfall runoff processes. This method was used in the upper watersheds due to its ability to simulate snow accumulation and melt processes and its relatively small set of input parameters. On the Sacramento Valley floor the *MABIA* method is used to represent agricultural crops and irrigation management. This method was designed for the simulation of irrigated agriculture and allows the model user to specify several irrigation related parameters.

The Soil Moisture method is one-dimensional, quasi-physical water balance model that depicts the hydrologic response of each fractional area within a catchment and partitions water into surface runoff, infiltration, evapotranspiration (ET), interflow, percolation, and baseflow components. Values from each fractional area (fa) within the catchment are then summed to represent the lumped hydrologic response for all land cover classes, with surface runoff, interflow, and baseflow being linked to a river element; deep percolation being linked to a groundwater element where prescribed; and ET being lost from the system.

The hydrologic response of each catchment is depicted by a "two-bucket" water balance model as shown in Figure 2-3. The model tracks soil water storage, in the upper bucket, z_{fa}, and in the lower bucket, Z. Effective precipitation, Pe, and applied water, AW, are partitioned into evapotranspiration (ET), surface runoff/return flow, interflow, percolation and baseflow. Effective precipitation is the combination of direct precipitation (P_{obs}) and snowmelt (which is controlled by the temperatures at which snow freezes, T_s, and melts, T_l). Soil water storage in the shallow soil profile (or upper bucket) is tracked within each fractional area, fa, and is influenced by the following parameters: a plant/crop coefficient (kc_{fa}); a conceptual runoff resistance factor (RRF_{fa}); water holding capacity (WC_{fa}); hydraulic conductivity (HC_{fa}); upper and lower soil water irrigation thresholds (U_{fa} and L_{fa}); and a partitioning fraction, f, which determines whether water moves horizontally or vertically. Percolation from each of these fractional areas contributes to soil water storage (Z) in the deep soil zone (or lower bucket) and is influenced by the following parameters: water holding capacity (WC_{fa}), hydraulic conductivity (HC_{fa}), and the partitioning fraction, f.

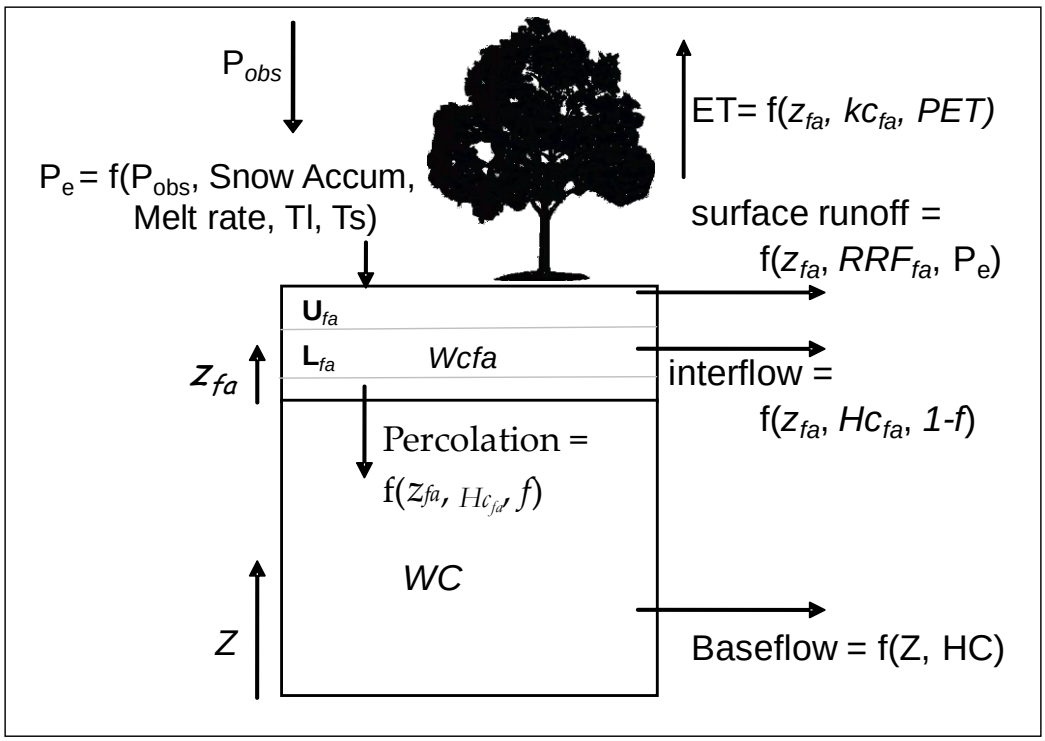

Figure 2-3. Two-Bucket Soil Moisture Method Model

The MABIA method is a daily simulation of transpiration, evaporation, irrigation requirements and scheduling, crop growth and yields, and includes modules for estimating reference evapotranspiration and soil water capacity. It was derived from the MABIA suite of software tools, developed at the Institut National Agronomique de Tunisie by Dr. Ali Sahli and Mohamed Jabloun. For more information about MABIA and to download standalone versions of the software, visit http://mabia-agrosoftware.co. The algorithms and descriptions contained here are for the combined MABIA-WEAP calculation procedure.

The MABIA Method is a one-dimensional water balance model that depicts the hydrological response within each fractional area within a catchment and partitions rainfall (P) into surface runoff (SR), infiltration (I), evapotranspiration (E and T), and deep percolation (DP) (Figure 2-4). For the calculation of evapotranspiration it uses the 'dual' Kc method, as described in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998), whereby the Kc value is divided into a 'basal' crop coefficient, Kcb, and a separate component, Ke, representing evaporation from a shallow soil surface layer. The basal crop coefficient represents actual ET conditions when the soil surface is dry but sufficient root zone moisture is present to support full transpiration. This method also provides parameters for the user to specify irrigation efficiency and effective rainfall. This method can be used to model both agricultural crops as wells as non-agricultural land classes, such as forests and grasslands.

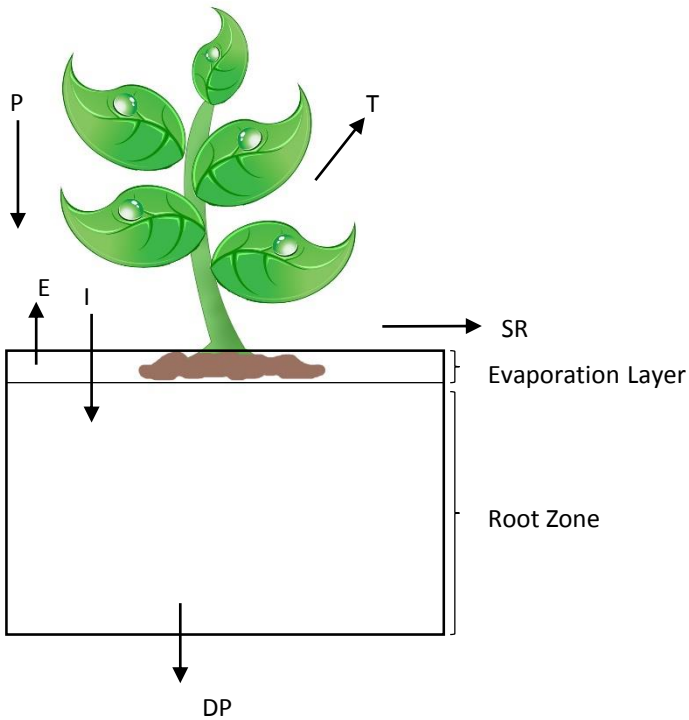

Figure 2-4. MABIA Soil Moisture Model

Although the timestep for MABIA is daily, the timestep for the rest of the WEAP analysis does not need to be daily (although it can be daily). For each WEAP timestep (e.g., monthly), MABIA would run for every day in that timestep and aggregate its results (evaporation, transpiration, irrigation requirements, runoff, and infiltration) to that timestep. For example, in January, MABIA would run from January 1 to 31, and sum up its results as January totals, including the supply requirement for irrigation. WEAP would then solve its supply allocations, using this monthly irrigation requirement from the MABIA catchments. In the case where the supply delivered to the catchments was less than the requirement, MABIA would rerun its daily simulation, this time using only the reduced amount of irrigation to determine actual evaporation, transpiration, irrigation requirements, runoff, and infiltration.

The steps in the MABIA calculations are as follows:

1. Reference Evapotranspiration (ETref)
2. Soil Water Capacity
3. Basal Crop Coefficient (K_{cb})
4. Evaporation Coefficient (K_e)
5. Potential and Actual Crop Evapotranspiration (ET_c)
6. Water Balance of the Root Zone
7. Irrigation
8. Yield

2.6 WEAP Solution Methodology

At each time step, WEAP first computes the horizontal and vertical fluxes using the catchment objects, which it passes to each river and groundwater object. Next, water allocations are made for the given time step by passing constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, and the priorities and preferences assigned to demand sites to a linear programming optimization routine that maximizes demand "satisfaction" to the greatest extent possible (Yates, Sieber et al., 2005). All flows are assumed to occur instantaneously; thus, demand sites can withdraw water from the river, use some of the water consumptively, and optionally return the remainder to a receiving water body in the same time step. As constrained by the network topology, the model can also allocate water to meet any specific demand in the system, without regard to travel time. Thus, the model time step should be at least as long as the residence time of water within the study area.

A form of linear programming known as mixed integer programming (MIP) is used to solve the water allocation problem whose objective is to maximize satisfaction of demand, subject to supply priorities, demand site preferences, mass balances, and other constraints. The constraint set is iteratively defined at each time step to sequentially consider the ranking of the demand priorities and supply preferences. The approach has some attributes of a more traditional dynamic programming algorithm, where the model is solved in sequence based on the knowledge of values derived from the previous variables and equations. Individual demand sites, reservoirs, and in-stream flow requirements are assigned a unique priority number, which are integers that range from 1 (highest priority) to 99 (lowest priority). Those entities with a Priority 1 ranking are members of Equity Group 1, those with a Priority 2 ranking are members of Equity Group 2, and so on. The MIP constraint set is written to supply an equal percentage of water to the members of each Equity Group. This is done by adding to the MIP for each demand site:

- a percent coverage variable, which is the percent of the total demand satisfied at the given time step.
- an equity constraint that equally satisfies all demands within each Equity Group in terms of percentage of satisfied demand.
- a coverage constraint which ensure the appropriate amountof water supplied to a demand site or the meeting of an instream flow requirement.

The MIP is solved at least once for each Equity Group that maximizes coverage to demand sites within that Equity Group. When solving for Priority 1, WEAP will suspend (in the MIP) allocations to demands with Priority 2 and lower. Then, after Priority 1 allocations have been made that ensure equity among all Priority 1 members, Priority 2 demands are activated (but 3 and lower are still not set). Similar to demand priorities, supply preferences apply an integer ranking scheme to define which sources will supply a single demand site. Often, irrigation districts and municipalities will rely on multiple sources to meet their demands, so there is a need for a mechanism in the allocation scheme to handle these choices. To achieve this effect in the allocation algorithm, each supply to the same demand site is assigned a preference rank, and within the given priority, the MIP algorithm iterates across each supply preference to maximize coverage at each demand site. In addition, the user can constrain the flow through any transmission link to a maximum volume or a percent of demand, to reflect physical (e.g.,

pipe or pump capacities) or contractual limits, or preferences on mixing of supplies. These constraints, if they exist, are added to the MIP.

Upon solution of the MIP, the shadow prices on the equity constraints are examined and if non-zero for a demand site, then the water supplied for this demand site is optimal for the current constraint set. The supply set from the optimal solution of the current MIP, its equity constraint removed, and the LP is solved again for the current Equity Group and the equity constraints re-examined. This is repeated until the equity constraint for each demand site returns a positive shadow price, and their supplies set.

The MIP then iterates across the supply preferences, and this too is repeated until all the demand sites have an assigned water supply for the given Equity Group. The algorithm then proceeds to the next Equity Group. Once all Equity Groups are solved at the current time step, the algorithm proceeds to the next time step where time dependent demands and constraints are updated, and the procedure repeats.

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