Colorado Basin
River Forecast Center
National Weather Service

CBRFC Soil Moisture Modeling

The Colorado Basin River Forecast Center (CBRFC) utilizes the Sacramento Soil Moisture Accounting (SAC-SMA) hydrologic model (Burnash et al., 1973) within its operational modeling system. SAC-SMA is a conceptual model that attempts to represent soil moisture characteristics to effectively simulate runoff. A conceptual model uses simplified approximations of natural processes. Parameters in conceptual models must be calibrated and cannot be physically measured.

This document is intended to provide background information about the soil moisture parameters used in operational hydrologic modeling at CBRFC, to describe how SAC-SMA is tailored to the CBRFC's modeling and forecasting environment, and how information generated by SAC-SMA is used by CBRFC hydrologists.

SAC-SMA Model Overview

Types of Runoff Simulated by SAC-SMA

SAC-SMA can simulate six types of runoff, which can be divided into two categories: fast and slow.

In fast-response events, water gets to the channel within hours of the water input event (rainfall and/or snowmelt). Types of fast-response runoff include:

- intensity-dependent surface runoff: generated from unsaturated soils in:
    - pervious areas (areas where water infiltrates into the soil)
    - areas of which a fraction may be impervious
- impervious runoff: generated from areas that are always impervious (e.g., heavily urban areas)
- direct runoff: generated from the saturated portion of an area

SAC-SMA also simulates slow-response processes, in which water takes days or years to reach a stream channel. Within SAC-SMA, these slow-response processes are available only to modeling units that contain pervious areas. The slow-response processes available within SAC-SMA include:

- interflow: drains in days to a week
- supplemental baseflow: drains in weeks to months after a water input event
- primary baseflow: drains in months to years and sustains streams in dry periods

Figure 1 (below) shows a schematic of the SAC-SMA model, including the runoff components described.

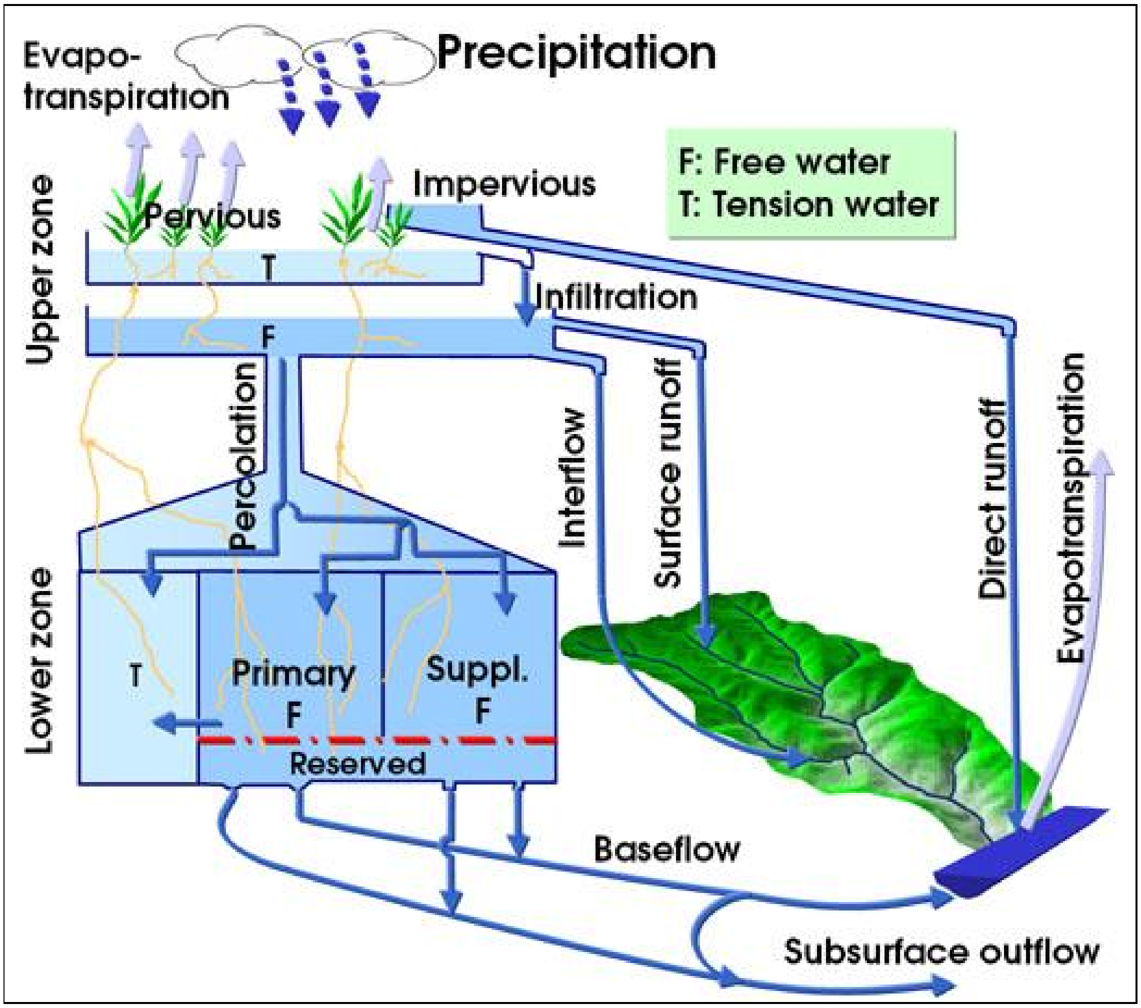

Figure 1: SAC-SMA model components.
https://chrs.web.uci.edu/HP_activities07.php

Soil Layers Modeled by SAC-SMA

Within SAC-SMA, the soil is represented in two layers, or soil zones, to capture soil moisture processes near the surface as well as groundwater processes deeper within the soil column. Generally, the soil moisture within the upper soil layer (soil zone) is influenced by fast-response processes, and the soil moisture within the lower soil layer (soil zone) is influenced by the slow-response processes.

Water may be stored within or exchanged between the two soil layers within SAC-SMA. If the volume of water input to the soil moisture model, either from snowmelt or rainfall, is greater than the available capacity to store water in the two soil layers, or if the rate of water input exceeds defined transport rates, water will be available to the channel as runoff.

SAC-SMA Model Parameters

Model parameters determined through calibration define several quantities in SAC-SMA's conceptual representation of physical soil processes:

- sizes of soil moisture "tanks" for each soil zone
- rates of soil moisture transport between the two soil zones
- percentage of water that goes to deep aquifer recharge
- percentage of modeled area that is impervious
- percentage of area that is covered by riparian vegetation

Simulated soil moisture may exist in several forms within SAC-SMA. Tension water may be removed only by evaporation or evapotranspiration, and it may exist in both the upper and lower soil zones. Free water exists in both the upper and lower soil zones and may be removed by evapotranspiration, percolation (vertical flow), and/or interflow (horizontal flow). The lower soil zone free water is further divided into subcategories of "supplemental" and "primary" free water. "Primary" free water drains very slowly and manifests as baseflow over long periods of time (months to years). "Supplemental" free water drains in weeks to months after a water input event and augments the primary baseflow after the water input event. For each type of soil moisture (tension water, supplemental and primary free water), the SAC-SMA model parameter set includes a maximum capacity value (maximum water volume that the soil can "hold" of that soil moisture type).

Soil moisture transport rates are also included in the SAC-SMA model parameter set and define how quickly soil moisture moves between the upper and lower soil zones and as interflow. In SAC-SMA, the percolation rate is a function of (1) lower soil zone dryness (driving soil moisture movement by capillary suction) and (2) upper soil zone free water content (driving soil moisture movement by gravity). The percolation rate influences the proportion of input water volume that becomes (1) surface runoff and/or interflow generated from the upper soil zone during a storm event and (2) deep soil moisture stored in the lower soil zone to be available at a later time as baseflow.

Other SAC-SMA model parameters influence the amount of water that is generated as outflow from SAC-SMA and ultimately available to the stream channel. A portion of water input to SAC-SMA may go to "deep aquifer recharge" instead of to the stream channel. When water is directed to deep aquifer recharge, it is effectively "lost" and no longer available to SAC-SMA. Parameters that define the amount of impervious area heavily influence the type of runoff response generated by SAC-SMA; impervious runoff is the only source of runoff if the soil is dry. Parameters related to vegetation are also included within SAC-SMA. The percentage of area covered by riparian vegetation as well as evapotranspiration estimates influence soil moisture withdrawal rates.

SAC-SMA at CBRFC

SAC-SMA as a Lumped Model

The SAC-SMA hydrologic model is run in a lumped framework for CBRFC operations over elevation bands (elevation zones) within a watershed. Watersheds modeled by CBRFC are divided into up to three elevation zones, depending on the elevation range within the basin, general vegetation patterns, and snowpack patterns. SAC-SMA model parameters are defined separately for each elevation zone.

SAC-SMA Calibration

At CBRFC, calibration of the hydrologic modeling system (including SAC-SMA as the soil moisture model component) is a manual process executed by staff hydrologists. Streamflow is the criterion variable. Regional consistency among hydrologic model parameters and the minimization of streamflow prediction errors during the critical April-July runoff period is of particular importance.

In the manual model calibration process used at CBRFC, historical data (temperature, precipitation, diversions, reservoir information, etc.) are input to the hydrologic modeling system, and a streamflow simulation is produced for each watershed modeled and forecasted by CBRFC. CBRFC hydrologists then manually tune model parameters so that the historical simulated streamflow matches the historical observed streamflow as closely as possible. Model parameters determined in the calibration process define the size of several soil moisture “tanks” for the upper and lower soil zones, the rates of soil moisture transport between the two soil zones, and other parameters within each modeled zone. The derived model parameters are then implemented into the operational hydrologic modeling system used in real-time at CBRFC.

CBRFC’s hydrologic model calibration period is 1981-2020. Model parameters are updated via manual recalibration by CBRFC hydrologists generally every 5 to 10 years, but may be updated more frequently if circumstances warrant (e.g., watersheds impacted by wildfires).

Soil Moisture Considerations in Operational CBRFC Forecasting

Soil moisture conditions influence the efficiency and volume of streamflow that occurs when rainfall and/or snowmelt occurs. One of the influences on efficiency and volume of runoff during the critical spring and summer months is the amount of soil moisture in the lower soil zone, which is best indicated to CBRFC by antecedent, stable baseflow streamflow patterns during dry periods in the fall. While forecast accuracy is important to CBRFC throughout the entire year, CBRFC particularly scrutinizes the simulated soil moisture conditions in the lower soil zone during dry periods in the fall, prior to the full onset of winter. CBRFC uses dry periods in the fall to make adjustments to simulated soil moisture in the lower soil zone because doing so reduces the complexity of the soil moisture simulation to the processes related to baseflow. Specifically:

● Two of the major seasonal types of water inputs in CBRFC's area of responsibility, spring/summer snowmelt runoff and the summer monsoon, have concluded by the late fall.

● Fall rain events may have a significant effect on simulated soil moisture in the lower soil zone. Waiting to adjust simulated soil moisture in the lower soil zone until dry baseflow periods just before the full onset of winter allows CBRFC hydrologists to more carefully consider impacts of such events on the soil moisture simulations.

Secondly, observations from many stream gages within CBRFC's area of responsibility are heavily impacted by ice in the winter. Adjustments to simulated lower zone soil moisture content must be completed before ice eliminates the streamflow observations as a reliable source of information.

Once dry weather and baseflow are dominant, SAC-SMA model states related to soil moisture content in the lower soil zone are adjusted by CBRFC hydrologists to make the simulated baseflow match observed baseflow as closely as possible. By comparing simulated and observed streamflow patterns during fall baseflow periods with dry weather, CBRFC hydrologists can better estimate the simulated soil moisture content of the lower soil zone.

After CBRFC hydrologists make their final adjustments to simulated soil moisture content in the lower soil zones during dry periods in the fall, CBRFC publishes a map that indicates how CBRFC's estimates of lower soil zone moisture content compare to normal conditions. The map gives CBRFC hydrologists and others a sense of how spring and summer runoff might be influenced by antecedent soil moisture conditions in the lower soil zone. The maps are available online at https://www.cbrfc.noaa.gov/rmap/grid800/index_soil.php.

These maps show lower soil zone soil moisture content as a percent of normal as of the date on the map. "Normal" values for the date shown on the map are computed by averaging 40 years (1981-2020) of lower soil zone soil moisture model states for that date. The 40 years of soil moisture model states are generated during the CBRFC manual calibration process.

The maps show areas where the lower soil zone moisture content is greater than one inch (25 mm) of water. These areas are typically at high elevations and contribute the majority of snowmelt-driven runoff. While other areas (primarily at lower elevations) can contribute to streamflow during rain events, the lower-elevation areas do not normally accumulate sufficient snow that, when it melts, contributes significantly to spring and summer snowmelt-driven runoff.

Note that operational CBRFC streamflow forecasts do not currently incorporate soil moisture observations from the Natural Resource Conservation Service's soil moisture sensors, which are part of the SNOTEL (http://www.wcc.nrcs.usda.gov/scan/) and SCAN (http://www.wcc.nrcs.usda.gov/snow/) networks. CBRFC also does not currently consider soil moisture or groundwater measurements from remote sensing platforms in its hydrologic modeling or forecasts.

References

Burnash, R. J., R. L. Ferral, and R. A. McGuire (1973), A generalized streamflow simulation system conceptual modeling for digital computers, U.S. Department of Commerce National Weather Service and State of California Department of Water Resources.