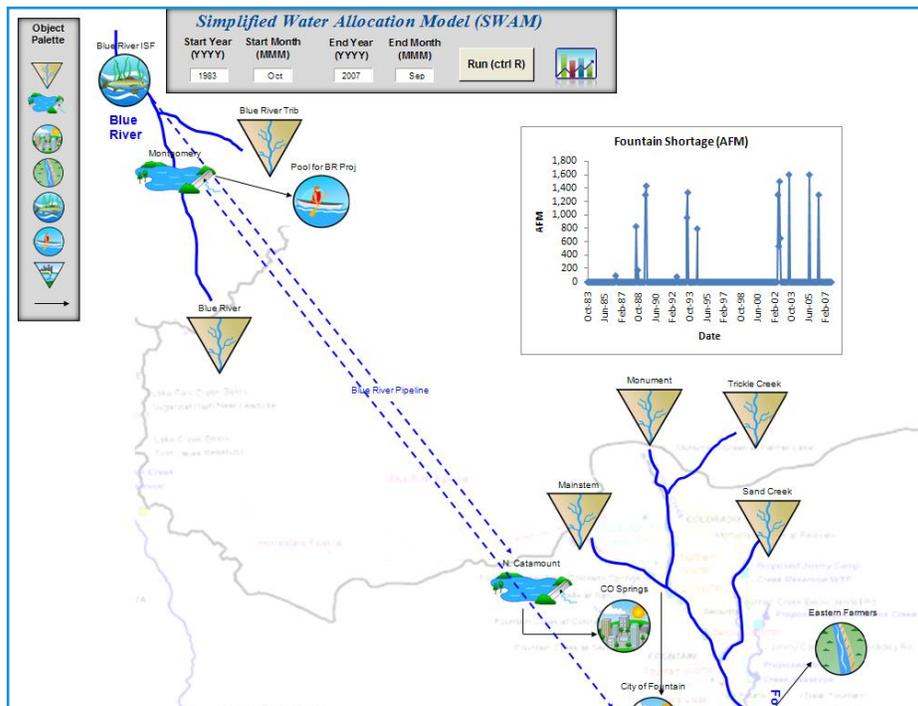


Simplified Water Allocation Model (SWAM)



VERSION 3.0 USER'S MANUAL

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Section 1

Introduction and Overview

CDM's Simplified Water Allocation Model (SWAM) was developed to address an identified need for a networked generalized water allocation modeling tool that could be easily and simply applied for planning studies by a wide range of end-users. Unlike most other water allocation software, SWAM is designed to be intuitive in its use and streamlined in functionality and data requirements, while still maintaining the key elements of water allocation modeling. SWAM was designed to provide efficient planning-level analyses of water supply systems.

Like most water allocation models, SWAM calculates physically and legally available water, diversions, storage, consumption, and return flows at user-defined nodes in a networked river system. A range of water user types can be represented in the model, including municipal water suppliers, agricultural irrigators, and industrial water users, with time-variable demands either prescribed by the user or, in some cases, calculated internally. Legal availability of water is calculated based on prioritized permitted withdrawals or diversions, downstream higher priority demands and physical availability, and anticipated return flows. SWAM has the ability to simulate either a "prior appropriations" system of water rights or a riparian water rights system, as set by the model user. Additional features in the model include easily-parameterized municipal and industrial (M&I) conservation and reuse programs, agricultural land transfers, groundwater pumping, and transbasin diversion projects. Multiple layers of complexity are available as options in SWAM to allow for easy development of a range of systems, from the very simple to the more complex. As an example, SWAM's reservoir object can include only basic hydrology-dependent calculations (storage as a function of inflow, outflow, and evaporation) or can include operational rules of varying complexity: prescribed monthly releases, a set of prioritized monthly releases or storage targets, or a set of conditional release rules (dependent on hydrology). The model user chooses the appropriate level of complexity given the modeling objectives and data availability.

SWAM operates on either a monthly or daily timestep, and the current version of the model is constrained to a total of up to one hundred (100) water user nodes, of varying types. The program is coded in Visual Basic with a Microsoft Excel-based interface.

Section 2

Model Description

2.1 "Main" Worksheet

The SWAM user interface is largely comprised within a single worksheet (Figure 2-1) with drop and drag graphical features for defining and parameterizing a water supply network. On-screen representation of specific model objects, hereafter referred to as "visual objects," are created by clicking on the appropriate button in the "Object Palette" (1.). To drop and drag the created visual objects (2.), the user must first select the object by clicking on the edge of the object (hidden rectangle). Once a visual object is selected, it can be deleted using the "delete" key stroke or by right-clicking with the mouse and selecting "cut." Visual object names can be edited by single-clicking on the object label.

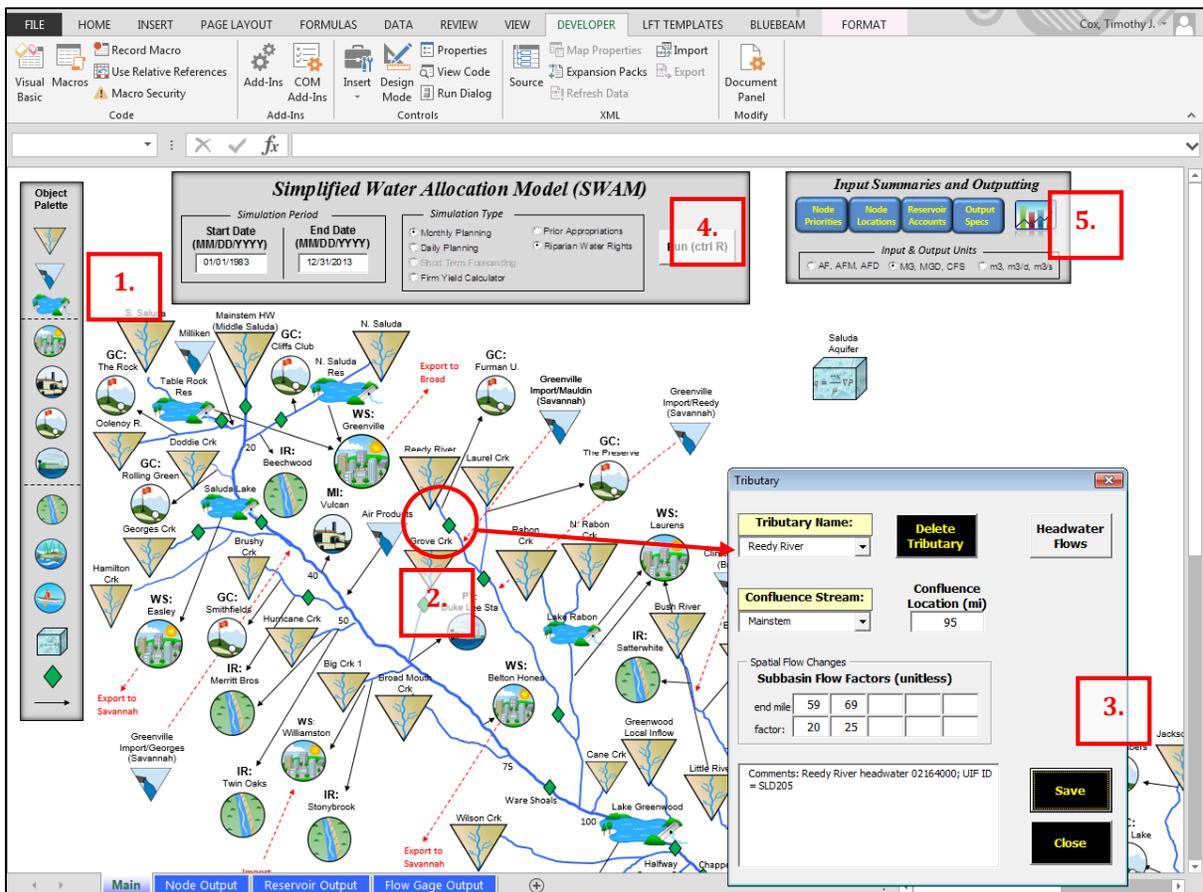


Figure 2-1. SWAM Main Screen

It is important to note that visual objects are merely placeholders and portals to the true model data objects. In other words, the model does not recognize any links between visual objects and simulated model objects (as defined below). **Consequently, deleting the visual object from the white space will not delete the actual model object or the data housed therein.** Similarly, simply creating a visual object, as described above, will not result in inclusion of that object in the model simulation. However, creating a network of visual objects that accurately represents the simulated model objects is usually of great benefit to the user and is strongly advised.

Model objects are created and deleted using the input forms (3.) accessed by clicking on the visual objects. Input forms, specific to the appropriate category of objects, must be populated and saved to create objects that are incorporated into the model simulation. Previously-created model object data are accessed using drop down menus on each of the object forms. The "Save" button must be used each time an update is made to a model object. **Simply closing the input form will not save the updates!** Specific objects and the calculations associated with these objects are described in detail below.

Also on the Main screen is the simulation tool bar (4). Here, the simulation period (start and end dates) and simulation type (monthly planning, daily planning, or firm yield calculations; and simulated water rights program) are specified. Simulation type options are described below. The simulation period can be any continuous period up to a maximum of 100 years. Additionally, inputting and outputting specifications and summaries are accessed via a separate tool bar (5), also at the top of the Main page. Here, preferred input and output units of measurement are specified, the desired level of output detail can be set, and a number of input summary tables can be accessed for review, as described below. Lastly, the simulation "Run" button is clicked to start a simulation. The keystroke "control-R" can also be used to start a simulation.

2.1.1 Simulation Type

SWAM simulations can be performed with either a monthly or daily calculation timestep, as selected by the user. While SWAM was originally designed for a monthly timestep, and a monthly timestep is likely sufficient for most planning applications, the daily option does provide the user with the ability to simulate more detailed hydrology in a targeted basin. Separate sets of input are required for the two timestep options. The model does not automatically aggregate or disaggregate inputs when toggling between the two options. More specifically, daily flow data for each tributary object are required for a daily timestep simulation, prescribed as a separate set of inputs to the monthly datasets (see Section 2.2.1). Additionally, if reservoir evaporation rates are defined with a continuous timeseries (Section 2.2.3), then both monthly and daily rates must be specified to be able to run both timestep options. Lastly, return flow lag times associated with any type of water user object (Sections 2.2.4 and 2.2.5) must be specified with separate inputs for monthly vs. daily timestepping. All other inputs, including water usage values, are the same for either timestep option and do not require separate sets of inputs. Note that, once entered and saved by the user, all input values are retained when toggling between the two timestep options.

In addition to daily and monthly planning simulations, the model can also be used to perform automated firm yield calculations for specific reservoirs or reservoir storage accounts. This simulation option is described in Section 2.4.

Lastly, two types of water rights administration program options are available in SWAM: prior appropriations and riparian. For the former, the "first in time, first in line" principle holds when

determining legally available flow at each model node; with the order of water right priority determined according to user specified appropriation dates. The earlier the appropriation date, the higher the priority of the water right. This type of water rights system can result in legally available flow being less than physically available flow at a given node due to calls on water from downstream senior water users. The calculation of legally available flow is described further in Section 2.2 and Section 3. For riparian water rights, the rights are prioritized in order of upstream to downstream. In other words, each water user is allowed to withdraw or divert as much water as is physically available in the river at the point of withdrawal/diversion, up to their permit limit. Downstream water rights or demands are not considered in the calculation of legally available flow under the riparian system.

2.1.2 Simulation Units

Three options for units of measure are available in SWAM: 1) acre-feet (AF) and acre-feet per month/day (AFM or AFD); 2) million gallons (MG), million gallons per month/day (MGM or MGD) and cubic feet per second (CFS); and 3) cubic meters (m³), cubic meters per day (m³/d) and cubic meters per second (m³/s). The first set of units are widely used in the western U.S., while the second set are more common in the east. The third set (metric) are more typical internationally. The units preference refers to inputting and outputting only. All internal model calculations remain unchanged and use the first set of units. Users will be prompted for inputs in the selected set of units, via the various input forms, and output will be generated in the same set of units. **It is important to note that the model does not automatically convert input values when toggling between the units options!** It is left to the user to properly convert and change all input values manually if the units preference is changed. For this reason, the units preference should ideally be set at the beginning of a SWAM modeling study and maintained throughout the study.

2.1.3 Output Specifications

For each simulation run, output can be generated for all nodes in the system, for a single selected node, or for flow gage objects only (see Section 2.3). Reducing the amount of written output data can greatly reduce model run times. This may be a desirable option for some simulations where only specific nodes or water users are of interest or where the user is primarily interested in calculated stream and river flows (captured by flow gage objects).

Additionally, SWAM output can be generated in separate text files (in user specified file locations) rather than directly in the model Excel workbook. This option is also provided to reduce model run times.

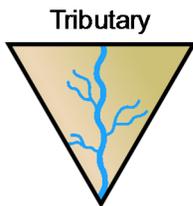
2.1.4 Input Summary Tables

Input summary tables are generated by clicking on the buttons labeled “Node Priorities”, “Node Locations”, or “Reservoir Accounts”. Summary tables provide a useful snapshot, across all model nodes, of these key inputs and can also serve as a more convenient option for reviewing and/or changing these inputs (rather than via the specific object forms, described below). Note that changes made to these summary tables are saved to the model database, and made permanent, when the “Update Table” buttons are clicked on the respective forms. These same input changes will then be seen when the user accesses the inputs via the individual water user input forms.

2.2 Model Objects

SWAM requires a user-constructed network of streams, water use nodes, and reservoirs. Each element in a constructed network is referred to as a model “object”. Each object has its own set of equations

and calculations in the underlying SWAM Visual Basic program (often referred to as “object-oriented” code) and its own set of user inputs (described below). In SWAM, relationships between objects are specified through the individual objects themselves, as described below. Spatial locations of objects, and the available flows associated with the objects, are set in SWAM based on user-specified relative mile markers for each object. SWAM calculates stream flows at each node based on this positioning. Details of individual model objects are provided below.



2.2.1 Tributaries

Tributary objects provide the hydrologic drivers for the entire water allocation system. Tributaries can be represented either explicitly or implicitly in SWAM. Explicit tributary objects in SWAM are tributaries that include any number of water user nodes and/or reservoir objects with operations and water use explicitly simulated in the model. Conversely, implicit tributary objects are treated as simple point inflows to receiving streams in the model, without any simulated water use or operations. SWAM requires at least one tributary object (“Mainstem”) for a simulated system. The Mainstem tributary object cannot be renamed or deleted. A timeseries of monthly or daily “headwater” flows (flows at the top of the simulated tributary reach) is specified for each explicit tributary object in the system, while downstream confluence flows are required for implicit tributary objects. In order to establish spatial positioning and stream order in the model, tributary objects also require, as inputs, the downstream confluence stream name and the relative location (on the receiving stream) of the confluence (Table 2-1). The downstream confluence stream for the Mainstem object is set as “none”.

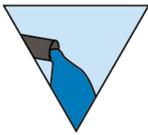
In SWAM, reach gain/loss factors capture unengaged flow gains and losses associated with increasing drainage area with distance downstream and/or interaction with subsurface flow (leakage, seepage). Reach gain/loss factors are often the primary parameters adjusted during model calibration. The gain/loss factors are only applied to the input headwater flows (tributary and mainstem) and represent a steady and uniform gain/loss volume, proportional to stream length, along the length of the designated reach. The mainstem gain/loss factor is specified on a per unit mile basis. For example, if the mainstem headwater flow is 10 cfs in a given timestep with a gain factor of 0.1 per mile specified for the entire mainstem reach, then the model applies a rate of gain of 1 cfs/mile throughout the length of the mainstem. At the end of a 5 mile reach with no other inflows or outflow, the flow would be 15 cfs. For all other tributary objects, the gain/loss factor is specified as a total subbasin flow gain factor, used to calculate total natural (unimpaired) flow at the end of the designated reach. For example, if a tributary flow is 10 cfs in a given timestep, with a gain factor of 5, then the end-of-reach flow (with no other inflows or outflows) is 50 cfs. The model linearly interpolates when calculating the unimpaired flow at intermediary points in the reach. Both mainstem and tributary flow factors can be spatially variable in the model for up to five (5) different sub-reaches.

Table 2-1. Tributary Input Parameters

Parameter Name	Units	Description
Tributary name	NA	A unique name must be assigned to each object; “Mainstem” name cannot be modified
Headwater flows	AFM, CFS, m3/s	Monthly timeseries of inflows to the top of the stream
Confluence stream	NA	Name of confluence receiving stream immediately downstream of tributary (specified via a drop-down list of previously-created tributaries)
Confluence location	miles	Relative mile marker, on the receiving stream, of tributary confluence
Mainstem gain/loss factors	fractional gain/loss per unit stream length	Spatially variable (up to 5 sub-reaches) mainstem gain or loss coefficient; applied to headwater flows to increase or decrease flows with distance downstream
Tributary subbasin flow factors	unitless	Spatially variable (up to 5 sub-reaches) tributary (non-mainstem) flow amplification factor; applied to headwater flows to increase flows with distance downstream and increasing drainage area

2.2.2 Discharges

Discharge

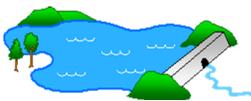


Discharge objects are intended to represent any type of piped discharge to the modeled river basin and might include wastewater treatment facility discharges or industrial discharges. Note that the user should be careful not to duplicate discharges already captured, more explicitly, by calculated water user return flows. There may be situations, however, where discharges are not explicitly included in a water user node in the basin model, such as the case of water

sourced outside of the modeled basin but discharged as return flow inside the basin. Discharge objects behave exactly as tributary objects (above) in the model except that they aren't subject to any gains or losses, and thus don't require these specific inputs. Otherwise, the input requirements and internal calculations are exactly the same as those described above for tributary objects (prescribed monthly and/or daily flows).

2.2.3 Reservoirs

Reservoir



Reservoir objects provide for the physical storage of water. The total storage of a reservoir is generally comprised of multiple storage “accounts” associated with various water users (described below and less applicable for riparian water rights). However, the reservoir object is used to define only the physical characteristics of the total reservoir (Table 2-2), including spatial location, storage capacity, surface area, dead pool storage, and evaporative (and/or seepage) losses. Monthly reservoir operating release requirements can also be specified in this object.

Evaporative losses can be specified using monthly average seasonal rates (inches per day or percent volume) or with a user-specified timeseries of daily or monthly rates (inches per day or inches per month). Calculated evaporative losses are distributed to individual accounts based on relative volumes of storage in each account at the given timestep. In other words, accounts with larger stored water will realize a greater evaporative loss than accounts with less stored water. Note that

evaporation rates should be input as *net* evaporation (gross open water evaporation minus direct precipitation), with a minimum rate of 0. Negative net evaporation rates (precip > evap) are not allowed in the current version of SWAM. For such cases, it is recommended that gross evaporation rates be specified for the reservoir object and direct precipitation included as a local inflow to the reservoir using a tributary object.

There are two options for defining reservoir release operations in SWAM: simple and advanced. Simple reservoir release rules consist of twelve prescribed mandatory monthly minimum releases. These releases are prioritized ahead of all water user withdrawals. Advanced reservoir release rules can be defined by the user to include up to five (5) different sets of rules governing release operations. Each of these five rules, implemented in order of priority, can consist of either prescribed minimum monthly release values (see simple rules), “conditional” rules based on hydrologic parameter values associated with other objects in the system, or monthly storage targets. Conditional rules can be specified based on storage values (AF) in either individual water user accounts or entire reservoirs, or based on headwater flow rates (AFM). For conditional releases, the user defines the targeted release volume and the conditions (e.g. >, <, = a prescribed value) that must be satisfied for the release to occur. Note that due to the numerical approach utilized in SWAM (see Section 3), for any given timestep (t), conditional releases are determined as a function of the start-of-timestep storage or the previous timestep’s (t-1) headwater flow. Prescribed storage targets establish end-of-month (or end-of-day) total reservoir storage volumes that the model attempts to meet by adjusting release volumes in the given timestep. There is no “ramping” (up or down over time) associated with the storage targets in the model; rather it releases or stores all available water, to the extent possible, required to meet the target at the end of the given timestep. Note that the assessment of storage targets is performed in the model at the start of every timestep, based on start-of-timestep storage. If starting storage is greater than the specified target, water is released during the timestep. Conversely, if starting storage is less than the target, that release for that timestep is set to zero. This approach is analogous to a reservoir operator making operational decisions at the start of a month or day. The uncertainty associated with subsequent hydrologic and climatic conditions results in storage targets not being achieved exactly in the model (but general monthly patterns are usually well achieved).

Reservoir releases are distributed across individual accounts based on storage permit priority (lowest to highest priority). SWAM attempts to assign all of a regulated release to the lowest priority account. If this account is unable to meet the total release volume required (due to lack of physical availability), the model moves on to the next lowest priority account, and so on.

Reservoirs can be defined in SWAM as either “offline” or “online”. There are effectively only subtle calculation differences between the two in the model. For online reservoirs, a “flood control pool” is automatically created and handled as a water user, with unlimited physical and legal diversion capacity, in internal model calculations. This ensures that all upstream water is available for routing through the online reservoir at each timestep. The size of the flood control pool is calculated internally as the difference between total reservoir capacity and the sum of individual water user accounts. When creating an online reservoir object in SWAM, the user must define how flows are released from the flood control pool via an outflow-capacity table, if applicable. This type of table would typically express a direct relationship between the magnitude of monthly outflow and the reservoir volume (greater storage equates to greater outflow). In this way, by providing temporary storage and gradual release, an online reservoir smooths out downstream hydrographs during periods of high flow.

Note that offline reservoir inflows can only be created via the “diversions” of various account-holder objects (water users, agricultural users, and recreational pools) (described below). Without user accounts with specified stream diversions, offline reservoirs will not fill with water. Stream diversions for filling offline reservoirs can be located anywhere in the modeled basin. Conversely, for online reservoirs, associated storage account “diversions” are not applicable and not required as model inputs.

Table 2-2. Reservoir Input Parameters

Parameter Name	Units	Description
Reservoir name	NA	A unique name must be assigned to each object;
Reservoir type	NA	Offline or online
Storage capacity	AF, MG, m3	Total physical storage capacity of reservoir
Dead pool storage	AF	Total dead pool (inactive) storage capacity of reservoir; when volumes drop below this level, withdrawals are not possible in the model
Initial storage	AF, MG, m3	Start of simulation initial volume of water in reservoir
Evaporation input type	NA	Monthly rates of inches per day (option 1) or percent of total volume (option 2), or user-specified timeseries of rates (option 3)
Evaporation rates, option 1	in. day ⁻¹	Seasonal rates of evaporation (multiplied by calculated surface area, via area-capacity table, to get volumetric losses)
Evaporation rates, option 2	%	Seasonal rates of evaporation (multiplied by calculated volume to get volumetric losses)
Evaporation rates, option 3	in. day ⁻¹ , in. mo ⁻¹	User-defined continuous timeseries of evaporation rates
Area-Capacity table, option 1	AF / Ac, MG / Ac, m3 / m2	Surface area vs. storage volume based on bathymetry of reservoir
Reservoir release receiving stream	NA	Name of receiving stream for mandatory reservoir releases
Release location	mi	Relative mile marker (on receiving stream) of reservoir releases
Monthly minimum releases	AFM, CFS, m3/s	Required (regulated) minimum releases for reservoir (if applicable)
Outflow-Capacity table	AFM, CFS, m3/s / % capacity	For online reservoirs only, defines outflows from flood control pool as a function of reservoir storage (percent capacity)

Advanced Release Rules:		
Advanced rules option	NA	Option button for user-specified advanced release rules, rather than simple method; allows for up to 5 different condition release rules that model attempts to meet in order of priority
User-prescribed monthly release targets	AFM, CFS, m3/s	If selected, monthly minimum release targets that model attempts to satisfy at each timestep, in order of release rule priority (1 – 5)
User-prescribed monthly storage targets	AF, MG, m3	If selected, monthly end-of-timestep storage targets that dictate reservoir releases for each timestep, in order of release rule priority (1 – 5)
Conditional release rules	NA	If selected, reservoir release rules that are internally determined and conditional on user-specified storage or flow conditions. Storage conditions can be associated with either total reservoir storage or a specific user account storage. Flow conditions are based on headwater flows associated with a specified tributary object. The actual release flow targets, if conditions are met, are specified by the user (AFM).
Conditional object	NA	Name of the object (water user, reservoir, or tributary) whose conditions dictate whether given release occurs
Criteria	NA	<, >, or =
Trigger value	AF, MG, m3; or AFM, CFS, m3/s	Storage or flow value threshold that triggers or activates the given release
Release target	AFM, CFS, m3/s	Monthly reservoir release that is targeted if prescribed conditions are met
Release accounts	NA	Name of user account from which release is apportioned; if “all users” is selected then monthly release is apportioned across all user accounts associated with the reservoir in reverse order of storage permit priority (i.e. lowest priority loses water first)

Water User



2.2.4 Water Users

The water user object is the most generalized and versatile of the available demand node objects. It is primarily intended to represent single or aggregated municipal and/or industrial (M&I) water users, but, given its flexibility, can be used to represent a multitude of water user types, including agricultural irrigation (although a separate agricultural object, described below, is also available). Separate visual object icons, all under the same water user umbrella, are available in SWAM specifically for golf courses, thermal power plants, and industry,

in addition to the generic M&I water user icon (left) Note that the alternative water user icons differ visually only. They all access the same water user input form with the same input requirements.

On the demand side, water users are parameterized by either monthly mean water usage requirements or a continuous timeseries of monthly demands. The latter is particularly well suited for hind cast (e.g. calibration) simulations with time variable demands, while the former is better suited to simulating static demands across a range of hydrologic conditions. The monthly mean option requires specification of indoor vs. outdoor use and consumptive vs. non-consumptive portions of each (Table 2-3). To simplify the parameterization process for this option, preset patterns of seasonal usage, including indoor/outdoor and consumptive/non-consumptive components, are available for typical M&I (or agricultural) users. For the timeseries option, only total usage values and final net consumptive use percentages are required.

Reuse and conservation demand management options are available that reduce the net demands on water. The reuse option in SWAM assumes a one-time use only of recaptured indoor use return flows (effluent) that can only be applied toward outdoor (irrigation) demands. For conservation, SWAM allows for the use of manual monthly reductions in water use or combinations of previously-parameterized conservation program initiatives. For the latter, SWAM calculates the net final reductions in monthly usage expected for any given combination of conservation programs. The assumed reduction parameters associated with the preset option were derived based on independent analyses and experience and may not be entirely accurate for any site-specific application. However, they are included to provide for quick and easy “what if” simulations of the potential impacts of conservation.

On the supply side, multiple sources of supply (up to five) are available for each water user object, including direct diversions, storage account withdrawals, and groundwater pumping. This is an appealing feature in the model if, for example, the user desires to simulate a single set of municipal demands (e.g. a city) that can be met by a portfolio of water supply options. In many other water allocation models, the total demand would need to be disaggregated (outside of the model) into multiple “demand nodes”. SWAM simulates the use of water from multiple sources according to the preference order (1 – 5) of each source. In other words, if the entire monthly demand can be met with water from source water 1, then no water is used from other available sources (although there still may be accrual in storage accounts). For some situations, this modeling logic may not be valid – for example, water users that attempt to maintain a certain ratio of supply sources, rather than following a preference order. For these situations, model users may want to either disaggregate demands into multiple nodes in the model or “artificially” constrain source account usage using, for example, permit or infrastructure limits on supply accounts. Storage accounts are defined through the water user object with reference to specific reservoir objects. Groundwater pumping as a source of supply can be specified according to monthly pumping rates and an aquifer source (Aquifer object, see Section 2.2.8). Groundwater pumping is applied to meet water user demands at the full prescribed pumping rates, subject to aquifer storage availability (see Section 2.2.8).

The ability to divert water (for direct use or into a storage account) is dependent on calculated physical and legal availability of the water at the point of diversion. Legal availability is one of the key calculations in SWAM and is based on specified permitted withdrawals/diversions, downstream higher priority demands and physical availability (if applicable), and anticipated return flows. SWAM has the ability to simulate either a “prior appropriations” system or a “riparian water rights” system, as set by the model user.

The prior appropriations doctrine, often referred to as “first in time, first in line”, recognizes earlier priority dates as higher priority in the water allocation scheme. Under this system, SWAM attempts to meet the water demands of water users in order of their priority, regardless of location in the basin. The order of priority is set based on user defined “priority dates” (Table 2-3) for each source of supply (direct diversion or storage withdrawal), with earlier priority dates equating to higher priority water rights. Legal availability at a given node is calculated precisely in the model as the maximum amount of water that can be diverted without impairing a downstream priority water user’s ability to meet their own demands. Return flows, available to downstream users, are a key consideration in this calculation.

Alternatively, for the riparian water rights option, water rights are prioritized in order of upstream to downstream. In other words, each water user is allowed to withdraw or divert as much water as is physically available in the river at the point of withdrawal/diversion, up to their permit limit and subject to a minimum instream flow requirement (if applicable). For the latter, minimum instream flow requirements, at the point of diversion, can be specified by the user for individual nodes. These instream flow requirements impact legally available flows during low flow periods. Note that downstream water rights or demands are not considered in the calculation of legally available flow under the riparian system and priority dates are not a required input. Further details of the legal availability algorithm in SWAM are provided in Section 3.

For both types of water rights administration, water use is governed by water permits or “rights”. These permits can be specified as either a constant value or as seasonal (monthly) values. For reservoir permits, the limits can either refer to the allowable diversion amount *into* storage or the allowable withdrawal *from* storage (storage withdrawal permit). The former is generally more applicable for prior appropriations systems, while the latter is more applicable for riparian water rights. Additionally, water user storage “accounts” are generally only applicable for prior appropriations systems with diversion limits. For storage withdrawal permits (riparian water rights), the entire reservoir active storage content is considered to be legally available to a given water user. For such cases, water user storage account capacities should be set by the user equal to the total reservoir conservation pool.

Supplemental water supplies can also be specified for the given water user, namely agricultural land transfers and transbasin imports. Agricultural land transfers are simulated as steady seasonal supplies available for direct use or storage augmentation. Transbasin imports provide the user with the ability to move water from a reservoir in one river basin (source) to an account in another river basin (destination). Monthly target inflows are prescribed which define the amount of water transferred, subject to physical availability. Transbasin exchanges can be either explicitly or implicitly represented in the model. For the former, a source reservoir (and stream system) must be explicitly constructed in the model and is included in the model simulation calculations. Alternatively, the source water could be implicitly included in the model as an assumed steady (monthly variable) supply that is assumed to be always available.

Note that, with respect to transbasin imports, SWAM also has the ability to directly divert (no source-side storage) from a stream in a different basin as one of the standard sources of supply for a given water user. In this case, the “transbasin import” option is not needed and the user can simply specify an out-of-basin stream as one of its sources of diverted water. However, if it is desired to move water across basins reservoir to reservoir, then the transbasin import option must be used.

Water exchange programs can be established between two water user supply accounts. Because it requires two supply accounts acting in concert, water exchanges are only available if the “multiple sources of supply” checkbox is selected. A water exchange is defined in SWAM as an agreement whereby an upstream diversion account can only divert water if a downstream partner account releases water from storage of the same amount and in the same timestep. Practically, this allows for diversion and storage to occur at the downstream location during wet periods and direct diversion to occur at the upstream location during dry periods, with no impact on downstream users (since the diversion is offset by releases from the downstream stored water). In SWAM, the downstream storage account in an exchange program can only store and release water to the stream. Water can’t be used for consumption from this storage account. Diversion to the downstream storage account can only occur in timesteps where there is no release requirement (i.e. no upstream diversion) and as allowed according to standard water user supply account calculations of physically and legally available flow. For the upstream direct diversion in an exchange program, the model calculates legally and physically available flow at the node following the standard algorithms but then constrains the legally available flow to less than or equal to the total available for release from the downstream partner account. When the seasonality flag is selected (under “Water Exchange” tab), the user can specify the months in which the exchange program is active. For the selected months, upstream diversions and downstream releases can occur as described above. For months when the exchange program is not active (unselected checkboxes), no diversions to the upstream account are allowed even if downstream storage is available for releases. Note that the downstream account in an exchange program must be assigned to the #5 preference supply account and thus is forced to be the less preferred account in the exchange partnership.

Finally, water user return flows are calculated in the model as a function of water usage and consumptive vs. non-consumptive fractions of this usage. The user must specify where these returns take place (single location or multiple locations) and whether or not the returns are lagged. Time lags on return flows are generally only applicable for outdoor irrigation uses and daily timestep simulations (where lags can be expressed as days rather than months).

Table 2-3. Water User Input Parameters

Parameter Name	Units	Description
User name	NA	A unique name must be assigned to each object;
Multiple sources flag	NA	Flag specifying whether multiple sources of water are to be defined
Water Usage:		
Monthly mean vs. timeseries option	NA	Option for defining water usage values with either static mean monthly values or a time variable monthly series
Monthly use distribution	NA	Options for populating monthly usage values: with either an annual total use and preset distribution patterns (M&I or Agricultural) or manually by month (monthly mean option only)
Total annual use	AFY, MGY, m3/yr	If either of the automated monthly distribution options are selected, then this annual total gets distributed across

Parameter Name	Units	Description
		months according to preset distribution patterns (monthly mean option only)
Monthly usage	AFM, MGM, m3/mo	Monthly water usage (before conservation or reuse) (monthly mean or timeseries)
% Indoor use	%	Percent of total monthly usage that is indoor (outdoor usage is calculated internally as the difference) (monthly mean option only)
% CU indoor	%	Percent of total monthly indoor usage that is consumptive (no return flows) (the non-consumptive fraction is calculated internally as the difference) (monthly mean option only)
% CU outdoor	%	Percent of total monthly outdoor usage that is consumptive (no return flows) (the non-consumptive fraction is calculated internally as the difference) (monthly mean option only)
net %CU	%	net total percent consumptive use associated with prescribed monthly usage values (timeseries option only)
Source Water:		
Source stream	NA	Name of stream from which water is diverted
Source type	NA	Either direct diversion, via reservoir storage account, or groundwater pumping
Diversion location	mi	Relative location of withdrawal or diversion on source stream
Priority date	dd/mm/yyyy	Date of withdrawal permit (Priori Appropriations option only)
Diversion capacity	AFM, CFS, m3/s	Physical capacity of diversion ditch or withdrawal
Permit limit	AFM, MGD, m3/s	Constant or monthly-varying direct diversion or reservoir withdrawal water right
Minimum instream flow requirement	AFM, CFS, m3/s	Instream minimum flow requirements at the point of diversion; used to curb diversions/withdrawals during low flow periods (Riparian Water Rights only)
Storage withdrawal permit flag	NA	Flag indicating that the specified permit refers to a reservoir withdrawal limit (rather than a limit on a diversion into a reservoir account) (usually only applicable for riparian water rights)
Reservoir name (if applicable)	NA	Name of physical reservoir in which storage account is held

Parameter Name	Units	Description
Storage capacity	AF, MG, m3	Capacity of storage account (legal allotment for prior appropriations systems; total reservoir conservation pool for riparian water rights)
Storage right (if applicable)	AFY, MGY, m3/yr	Annual total cumulative diversion right associated with storage account
Water year start month (if applicable)	NA	Starting month for tracking annual storage right
Carry over rule (if applicable)	NA	Flag indicating whether stored water remaining in account at the end of the previous year counts toward the annual storage right of the following year
Monthly groundwater pumping rates	AFM, MGD, m3/d	If selected, monthly groundwater pumping rates used to meet demands (subject to aquifer storage availability)
Aquifer name	NA	if selected, name of Aquifer Object that groundwater pumping draws from
Return Flows:		
Locations option	NA	All return flows to a single location or return flows spread out over multiple locations
Receiving stream	NA	Name of receiving stream for return flows
Location	mi	Relative mile marker on receiving stream for location(s) of return flow discharge to the stream
Lag	months or days	Lag (if any) associated with return flows, relative to month/day of water use
% of Return flow (for multiple locations only)	%	Percent of total return flow, for given month, that is discharged at each location (sum across locations must equal 100% for each month)
Conservation: (optional)		
Manual vs. preset option	NA	Manual option requires user inputs of monthly water usage reductions (indoor and outdoor), while preset option uses assumed parameters associated with various selected conservation mechanisms to calculate net monthly usage reductions
Indoor/outdoor reduction	%	Percent reduction in water use, by month
% CU indoor/outdoor	%	Percent of indoor/outdoor reduction that is consumptive; these parameters are used for internal calculations of adjustments to overall consumptive use after conservation is applied

Parameter Name	Units	Description
Drought-only flag	NA	Flag indicating whether conservation is activated only during user-defined drought conditions
Min-res volume (for drought-only conservation)	%	Percentage of water user storage capacity (for each source water account) that, when reached, triggers conservation
% of pop. (preset option only)	%	Percentage of service area population that is participating in given conservation activity
Reuse: (optional)		
% recapture	%	Percentage of indoor use effluent that gets recaptured for outdoor reuse
Graywater recycling flag	NA	Flag indicating whether to simulate graywater recycling
Ag Transfer: (optional)		
Ag lands retired	acres	Total area of agricultural land involved in transfer
Annual CU	AF/acre	Average annual consumptive use of crops in retired ag lands
Irrigation efficiency	%	Amount of water consumed divided by amount of water diverted at farm headgate, expressed as %
Monthly distribution of supply	%	Percentage of annual total water delivery provided by month
Transbasin import: (optional)		
Implicit vs. explicit option	NA	Implicit transbasin imports do not simulate water at the source. Rather, the specified monthly volumes are assumed to be available at every timestep and are simply added to the specified water user account. Explicit transbasin imports explicitly simulate diversions and storage within the source basin and require specification of the source reservoir and account. For explicit imports, the monthly targeted imports may not always be met as they are subject to water availability.
Source reservoir (explicit only)	NA	Name of reservoir in source basin that imports draw from
Source account (explicit only)	NA	Name of account in source reservoir that imports draw from
Target inflow	AFM, CFS, m3/s	Desired monthly import flow for transbasin project
Conveyance loss (explicit only)	%	Percent loss associated with transbasin import
Destination account	NA	Source water account number that transbasin import water is placed (augments existing source water)

Parameter Name	Units	Description
Water exchange: (optional)		
Upstream diversion account	NA	Account number associated with the upstream diversion component of the exchange program
Downstream release account	NA	Account number associated with the downstream storage and release component of the exchange program. Note that currently the model requires that this be Source Water 5 account)
Seasonal water exchange flag	NA	Flag indicating that exchange program is seasonal (as specified by monthly on/off flags). Note that for months where the exchange is not allowed (monthly flag unchecked), no diversions are permitted by upstream diversion account, but downstream storage account can divert and fill storage according to associated withdrawal permit.

Agricultural User



2.2.5 Agricultural Users

The primary difference between this object and the water user object (described above) is the way in which water usage (demand) is calculated or input. The agricultural user object allows for explicit calculation of water demands associated with crop agriculture. Monthly stream demands are calculated as a function of calculated monthly evapo-transpiration (ET) rates, irrigated acreage, and irrigation and conveyance efficiencies (Table 2-4). ET rates are calculated using the well-known Blaney Criddle (or Modified Blaney Criddle) equations as a function of crop type, effective mean monthly precipitation, monthly mean temperature, field elevation, latitude, and crop-specific coefficients. Details of these calculations are provided in Section 3. Crop coefficients for seven crop types (corn, wheat, alfalfa, pasture, potatoes, grain, and beans) have been pre-set in the model. However, these coefficients are easily modified by the user. Additionally, a user-defined crop type is available.

Agricultural user demands can also be hard-entered by the modeler as a monthly or daily timeseries. These need to be entered for the full period of simulation. This feature may be useful when historical diversion flows are known at a particular node and no changes to that node are simulated.

As with the generalized water user object, up to five different source water accounts may be utilized for any given agricultural user. Each of these can either use water directly from the source stream (direct diversion), from a reservoir account, or from groundwater pumping. These sources of water are modeled in the same manner described above for the Water User object. Transbasin imports are also available to supplement an agricultural user's local sources.

Return flow percentages are either calculated within the model interface (if demands are calculated) as a function of irrigation efficiency and ditch loss, or are directly input by the user (if demands are input). If calculated, water returned to the stream is equal to the water lost during conveyance (ditch loss) plus the water lost due to irrigation inefficiencies and over-watering. Return flow locations (up

to five different locations) are specified by the user in the same manner as the water user object (above).

Table 2-4. Agricultural User Input Parameters

Parameter Name	Units	Description
User name	NA	A unique name must be assigned to each object;
Multiple sources flag	NA	Flag specifying whether multiple sources of water are to be defined
Water Usage:		
Blaney Criddle ET option	NA	Original Blaney Criddle ($U = KF$) or SCS modified equation (includes extra climatic factor)
Irrigated acres	acres	Area of land to be irrigated associated with given node
Ditch loss	%	Percent of headgate diversion water that gets lost (e.g. via leakage) during conveyance to fields
Irrigation efficiency	%	Represents all on-field losses of water, including excess application, leakage, and evaporation
Elevation	ft (absl)	Approximate elevation of irrigated acreage
Latitude	degrees	Approximate latitude of irrigated acreage (used for calculating daylight hours in given month)
Crop factors (Kc)	unitless	Empirical factors used in Blaney Criddle equations specific to crop type and growth stage
Duration of growth stage	days	User-defined (or pre-set) number of days in given growth stage; used for applying the crop factors (Kc)
% of total acreage	%	For each crop type, the percent of the total node irrigated acreage used for growing given crop
Start month	NA	Growing season starting month for given crop (note that duration of growing season is defined by growth stage durations described above)
Temp	°F	mean monthly temperature (for Blaney Criddle ET calculations)
Precip	inches	mean monthly precipitation (for Blaney Criddle ET calculations)
Source Water:		
(see water user object)		

Instream Flow



2.2.6 Instream Flow Objects

Instream flow objects allow for the prioritization of stream flows to meet environmental or recreational goals (Table 2-5). Monthly flow rights or requirements are specified along with a priority date associated with those rights (prior appropriations only). Under a prior appropriations system, maintaining the target instream flows is prioritized over junior diversion rights. If flow targets are not achieved, a “shortage” is calculated and reported by the model.

Table 2-5. Instream Flow Object Input Parameters

Parameter Name	Units	Description
Instream Flow name	NA	A unique name must be assigned to each object;
Target stream	NA	Name of stream associated with instream flow target
Downstream location	mi	Relative location of instream flow on source stream
Priority date (prior appropriations only)	dd/mm/yyyy	Date of withdrawal permit
Flow right	AFM, CFS, m3/s	Monthly-variable or constant instream flow right

Recreation Pool



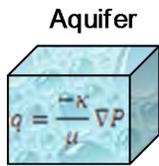
2.2.7 Recreation Pool Objects

Recreation pool objects are used to prioritize the maintenance of a reservoir pool. In other words, water is diverted and/or retained as needed and as available to maintain a user-specified volume of water in a given reservoir. Often this water might be for recreational purposes, such as boating, fishing, or swimming. The pool target might also be for hydropower purposes. Generally, the only losses associated with a recreation pool are evaporative. In some cases, regulated reservoir releases are also drawn from the recreation pool, depending on the assigned priority of the pool. See discussion on the distribution of reservoir evaporative losses and regulated releases in Section 2.2.3. Note that a recreation pool can only be created for an existing reservoir (which needs to be created first). Object parameters are listed in Table 2-6.

Table 2-6. Recreation Pool Object Input Parameters

Parameter Name	Units	Description
Reservoir name	NA	A rec pool may only be added for an existing reservoir (only 1 rec pool per reservoir allowed)
Source stream	NA	Name of stream from which water is diverted
Downstream location	mi	Relative location of rec pool diversion on source stream

Priority date (prior appropriations only)	dd/mm/yyyy	Date of withdrawal permit
Pool volume	AF, MG, m3	Target volume of recreation pool



2.2.8 Aquifers

Aquifer objects are used to track groundwater storage as subject to pumping by single or multiple users (water users and/or ag users). Storage calculations are performed at each timestep as a function of: total groundwater pumping associated with the aquifer (calculated), monthly aquifer recharge rates (prescribed), and initial aquifer storage (prescribed). Aquifer objects are simulated as a fully contained and lumped storage vessel. Any upgradient or lateral inflows or downgradient lateral outflows are neglected.

In addition to tracking groundwater storage, aquifer objects can be used to estimate water table drawdown, at up to five (5) different monitoring well locations, as a function of aggregate pumping rates and aquifer hydraulic properties. Drawdown calculations are only available for confined aquifers. Aquifer drawdown is calculated using a polynomial approximation to the Theis Equation (Abramowitz and Stegun, 1968). Application of the equation has been extended in SWAM to handle time-variable pumping rates. The equation assumes a homogeneous isotropic confined aquifer and fully penetrating wells. It also assumes that the aquifer is infinite in radial extent. Aquifer hydraulic properties are defined according to user-prescribed storativity and transmissivity values. Drawdown is calculated at each simulation timestep for up to five specified “monitoring well” locations. The locations are parameterized according to a table of user-defined radial distances between monitoring well and pumping well (or wellfield). The impacts of each water user or ag user pumping well /wellfield are included in the cumulative drawdown calculations.

2.2.9 Flow Gages

Flow Gage



Model flow gage objects provide for streamflow output at specific locations in a modeled river basin. They are designed for outputting purposes only and do not prompt any internal calculations or impact any other components of the modeled system. The only required inputs associated with a flow gage object are the name of the gage, the associated tributary object (“target stream”) and mile marker location (“downstream location”).

2.3 Model Output

Monthly output for all model nodes are written to the “Node Output” worksheet in SWAM. Brief descriptions of each output parameter are provided below. For water user or agricultural user objects with multiple sources of water, SWAM provides detailed output for each source account as well as the totals for the object.

- **Physically available (AFM, MGD, m3/s):** This is the physical stream flow just upstream of the point of diversion. Physical availability is calculated as a function of upstream headwater flows, node diversions, and node return flows.
- **Legally available (AFM, MGD, m3/s):** This is the total flow that can legally be diverted at the point of diversion. As discussed elsewhere, legal availability is calculated in SWAM as a function of downstream priority demands (prior appropriations only), node monthly diversion and/or

withdrawal rights, annual storage rights, and physical flows in the system (prior appropriations only). Note that in times of surplus water, SWAM reports the non-limiting legal availability as the physical availability + node return flow.

- Diverted (AFM, MGD, m3/s): This is the actual amount diverted for the given node. It is generally the smaller of physical availability, legal availability, and desired diversion total. Note that the “desired diversion total” here refers to the net usage demand plus any storage make-up water to fill available capacity (e.g. make-up for evaporative or release losses).
- Storage Withdrawal (AFM, MGD, m3/d): This is the monthly, or daily, withdrawal from storage by the given water user to meet demands (if applicable).
- Storage (AF, MG, m3): This is the node storage account volume (if applicable) at the end of the given timestep. This value is calculated as a function of diverted flow (inflow) and demand withdrawals, account evaporative losses, and account regulated releases (outflows). The actual volume resides in the associated “parent” reservoir.
- GW Pumping (AFM, MGD, m3/d): Monthly groundwater pumping rates by the user associated with the given node (if applicable).
- Demand (AFM, MGD, m3/d): This is the net water usage demand on the stream for the given node at the given timestep. Demand is calculated as a function of user-input (or calculated) monthly usage values and reuse and conservation impacts (if applicable).
- Shortage (AFM, MGD, m3/d): This is the monthly shortfall in water supply and represents the difference between demand and demand met. Demands are met through both direct diversion water and storage account withdrawals. In the case of instream flow objects, shortages are simply the difference between the instream flow target and the actual physical flow at the node. For recreation pools, the reported shortage reflects the difference between targeted rec pool volume and actual pool volume.
- Return Flow (AFM, MGD, m3/s): This is the monthly returns to the stream after node usage. These are calculated in SWAM as a function of user-input consumptive use percentages, actual demand met, and reuse considerations (if applicable). Note that if the node return flow lag is > 0, then reported return flows reflect the calculations associated with the timestep at $t - \text{lag}$.
- Release (AFM, MGD, m3/s): This is the monthly storage regulated release associated with the node storage account (if applicable). As discussed in Section 2.2.3, total reservoir regulated releases are distributed by the model across individual storage accounts according to permitted withdrawal priority (lowest to highest priority). These releases decrease storage account volume and are unavailable for node use.
- Evap Loss (AFM, MGD, m3/d): This is the monthly or daily evaporative loss associated with the water user storage account (if applicable). As discussed in Section 2.2.3, this evaporative loss may only be a portion of the total reservoir evaporative loss, as total evaporation may be distributed across multiple user accounts in a reservoir.

Output specific to reservoir objects are provided in the “Reservoir Output” worksheet. These output are described below.

- **Storage (AF, MG, m3):** This is the total volume of water in the physical reservoir at the end of the given timestep. This volume is inclusive of all of the individual user accounts and, if applicable, the recreation pool associated with the reservoir. This value is calculated as a function of total inflows to the reservoir (“diversions” to storage by various accounts) and total outflows from the reservoir (evaporation + regulated releases + user withdrawals).
- **Excess Volume (AF, MG, m3):** Currently, this output variable only reflects the result of specifying an initial reservoir volume that exceeds the sum of all account capacities held by the reservoir. It is water that is not “owned” by any of the child accounts of the reservoir and is included in the output only to provide for complete water balances during the early timesteps of a simulation (when initial conditions are impacting calculations).
- **Overflow (AFM, MGD, m3/s):** Reservoir overflows can only occur in the model This in the case of the sum of individual account storage capacities exceeding total reservoir physical storage capacity or if prescribed transbasin imports exceed the demand + storage capacity of the user. In both cases, non-zero reservoir overflows suggest potential problems with inputs. Note that in the case of true hydrologic overflows associated with online reservoirs during flooding periods, SWAM considers excess flows to directly bypass the reservoir rather than reporting as “overflows”. This can be seen in the output when online reservoir inflow is less than the total river flow at the top of the reservoir.
- **Total Inflow (AFM, MGD, m3/s):** This output reflects the total inflow to the reservoir during the given timestep. For offline reservoirs, total inflows are the sum of diversions to individual user accounts. For online reservoirs, total inflow represents the total river flow entering the reservoir, minus any amounts in excess of the reservoir capacity (see note above, these flows are treated as bypass flows in the model).
- **Total Withdrawal (AFM, MGD, m3/s):** This is the total amount of water withdrawn from the reservoir by individual water users.
- **Release (AFM, MGD, m3/s):** This is the total reservoir regulated release for the given timestep. In most cases (unless there is excess volume) this value will be the sum of the individual account releases provided in the “Node Output” worksheet.
- **Outflow (AFM, MGD, m3/s):** This is the outflow from the reservoir flood control pool (if applicable, online reservoirs only), as calculated based on the user defined outflow-capacity table.
- **Evap (AFM, MGD, m3/d):** This is the total evaporative loss from the reservoir during the given timestep.

Output specific to aquifer objects are provided in the “Aquifer Output” worksheet. These output are described below.

- **Storage (AF, MG, m3):** This is the total volume of water stored in the aquifer at the end of the given timestep. This value is calculated as a function of aggregate groundwater pumping rates by all users associated with the aquifer, specified aquifer recharge rates, and a specified initial storage value.

- Recharge (AFM, MGD, m3/d): This is an output of the input values specified by the user on the aquifer input form and represents total monthly recharge to the aquifer.
- Total Pumping (AFM, MGD, m3/d): These are the total pumping withdrawals from the aquifer, representing the sum of all water user and ag user pumping for the given timestep.
- Drawdown 1 – 5 (ft): Water table drawdown levels at given timestep for monitoring well locations 1 – 5 (defined by user), calculated as a function of pumping rates and aquifer hydraulics using the Theis analytical solution.

Note that none of the output worksheets should ever be deleted by the user (the model won't know where to place output)!

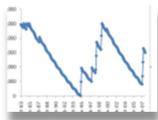
In addition to the raw timeseries output data described above, graphical output summaries can easily be created on the “Main” page using the “Output Plotting” control button (below). Both timeseries and percentile plots can be generating using this tool. The intent of this functionality is to provide for quick graphical results summaries that are dynamically updated for each simulation run.



Lastly, an option (button shown below) is available in SWAM to specify various output specifications. Included here is an option to output raw timeseries data to an external text file rather than to the output worksheets. This is provided as a means of greatly reducing simulation run times for larger, more complex models. Text file outputting can only be for a single user-specified node. Therefore the model must be run multiple times to generate text file output for all nodes (still may save simulation time for larger models). Normal worksheet outputting can be done for all nodes during a single simulation or, for improved efficiency, for flow gages only (if the user is only interested in river flows) or for a single targeted node.



2.4 Reservoir Firm Yield Calculations



In addition to the normal water allocation simulation mode described above, SWAM contains an alternative simulation option whereby automated firm yield calculations are performed for a specified reservoir object. Under this simulation, full outputting of network parameters is not provided. Instead, only final firm yield values are provided. Firm yields are calculated through internal simulation iterations of the full networked system with adjustments made to targeted reservoir water user demands until the firm yield is identified. For these purposes, firm yield is defined as the minimum annual reservoir demand that can be sustained throughout the period of simulation. The model iterates until zero storage in the targeted reservoir account is exactly achieved during the simulated critical drought period. Firm yields are calculated for a specified reservoir user account and are a

function of tributary flows, monthly demand patterns, reservoir evaporation rates, and higher priority demands (either upstream or downstream) in the simulated system.

Firm yield calculations can be performed in SWAM for multiple “alternative hydrology” input data sets. Users can prescribe multiple monthly timeseries sets of upstream tributary flows with the model calculating, in “batch” mode, firm yields for each hydrologic scenario. These alternative hydrologies might represent, for example, various climate change forecasts derived from Global Climate Model (GCM) projections. Two sets of hydrology projections can be prescribed, each with up to ten (10) different data sets. This format was implemented in recognition of a common approach to climate change modeling whereby separation is maintained between groups of projections specific to assumed greenhouse gas emission scenarios. For example, a user might prescribe a set of ten hydrologic projections developed for the A2 (worst case) greenhouse gas emission scenario and another ten for the B1 (best case) emission scenario. Model simulations are performed independently for each group. Output from the batch mode simulation are provided in the form of a table of firm yield values. Output can also be summarized by the model in probability (normal) distribution functions fitted to the output data. This type of summary provides quantification of the levels of model consensus across scenarios and is often useful for planning decision-making.

Section 3

Technical Documentation

This section provides detailed descriptions of the fundamental equations and algorithms employed by SWAM.

3.1 Tributary Hydrology

Unimpaired, or naturalized, flows form the building block of hydrologic calculations in SWAM. However, in contrast to many other water allocation models, SWAM calculates these flows internally rather than requiring extensive naturalized flow inputs. As described in Section 2, model explicit tributary objects require as input a timeseries of *headwater* flows. These are recorded or estimated flows upstream of any modeled impairment and are generally quantified with flow gage data. To extend these flows downstream through the modeled river basin network, SWAM requires user-defined flow gain/loss factors (see Section 2.2.1).

For the mainstem object, these factors (which can be spatially variable) are defined according to a percent gain or loss with unit stream length (percent per mile). For calculating the unimpaired flow at any node or location along the mainstem, the gain/loss percentage is multiplied by the node mile marker and the mainstem headwater flow. These flows typically represent localized inflows to the mainstem (diffuse runoff or groundwater inputs) or seepage losses from the mainstem to groundwater. Unimpaired flows are calculated at any node, i , along the mainstem according to the following equation:

$$Q_{i,t}^{UIF} = Q_{HW} + \sum_{j=1}^n \text{Upstream}Q_j + GLF * \text{location}_i * Q_{HW}$$

where $Q_{i,t}^{UIF}$ = the calculated unimpaired flow at any mainstem location i ; Q_{HW} = the mainstem headwater flow for timestep t ; $\text{Upstream}Q_j$ = the contributing upstream flow from tributary j ; n = the number of upstream tributaries; location_i = the downstream mile marker associated with node i ; and GLF = the mainstem gain/loss factor (%/mile).

For all other tributary objects, the factors are specified in terms of an overall sub-basin flow gain (or loss) factor. In other words, the ratio of flows at the tributary confluence (or any intermediate location) to the prescribed headwater flows. In many cases, this can be set based on the ratios of drainage areas, following a common ungaged flow estimation technique (area weighting). The sub-basin flow factors are multiplied by headwater flows at each timestep to estimate flows at specific locations along the tributary reach, including the confluence. Linear interpolation is used to estimate flows at any other location along the tributary reach. Unimpaired flows are calculated at any node i , along a non-mainstem tributary reach, according to the following equation:

$$Q_{i,t}^{UIF} = Q_{HW} + \sum_{j=1}^n \text{Upstream}Q_j + GLF * \frac{\text{location}_i}{\text{reach_length}} * Q_{HW}$$

where GLF = the tributary sub-basin flow factor (unitless); reach_length = the total length of the tributary reach (miles) and all other variables are defined as above.

Note that mainstem and tributary flow gain/loss factor values are typically refined as part of the model calibration exercise, as described in Appendix A.

3.2 Diversions/Withdrawals

For every timestep, t, diversions are calculated for each node as a function of physical availability, legal availability, net user demand, and physical diversion capacity. Within each timestep, these calculations are performed in order of node ranking by withdrawal permit (highest priority to lowest priority). The overall equation for calculating node diversions can be written as:

$$Q_{div} = \min(Q_{phys}, Q_{avail}, demand, capacity) \quad (3-1)$$

Where Q_{phys} = physically available water at point of diversion, Q_{avail} = legally available water at point of diversion, demand = net demand on stream by node, and capacity = physical (ditch) capacity of diversion.

Physical availability at any given node is calculated as a function of upstream tributary flows, node diversions and return flows, and reservoir regulated releases. This calculation can be written as:

$$Q_{phys}^i = \sum_{j=i-1}^{j=0} Q_{HW}^j - Q_{div}^j + Q_{RF}^j + Q_{release}^j \quad (3-2)$$

Where index i designates the relative downstream position of the node and j designates the upstream locations of tributary inflows, node diversions, node return flows, and reservoir releases.

For a prior appropriations system simulation, legal availability is calculated for each node, again in descending order of priority, as a function of monthly diversion right, annual storage right (if applicable), downstream priority demands, return flows, and downstream physical availability. This calculation follows the algorithm used in the State of Colorado's StateMod model ("Direct Solution Algorithm"). The first step in the algorithm is calculating the minimum flow left in the river at all downstream nodes after priority water users have diverted their allowable amount. This step can be written as:

$$Q_{avail}^i = \min([Q_{phys}^{i+1} - Q_{div}^{i+1}], [Q_{phys}^{i+2} - Q_{div}^{i+2}], [Q_{phys}^{i+3} - Q_{div}^{i+3}], \dots [Q_{phys}^{i+n} - Q_{div}^{i+n}]) \quad (3-3)$$

Where i refers to the relative downstream position of the node and n = number of downstream nodes. Because of the order of node calculations, only higher priority downstream users will have non-zero Q_{div} values in this equation.

The second step in the calculation of legally available flow is the recognition of the availability of return flow from the given node to downstream users. An adjustment is made to the previously calculated Q_{avail} to account for these return flow "credits":

$$Q_{avail}''^i = \frac{Q_{avail}^i}{1 - \%RF_i} \quad (3-4)$$

Where % RF_i = percent return flow at node i . This step essentially allows for the diversion of additional water due to recognition of the return flows on that diversion that can then be used to satisfy downstream priority users.

The final steps in the calculation of legally available flow, applicable for either prior appropriations or riparian water rights, are checks against the node's monthly diversion right, annual storage right, and minimum instream flow requirement – all of which are user input. The model constrains the legally available flow to the lesser of the monthly diversion right and the previously calculated Q_{avail} . It also ensures that the total cumulative diversion for the given water year does not exceed the user-specified annual storage right (if applicable) and that the required minimum instream flow is retained in the river. This can be written as:

$$Q_{avail}^i = \min(Q_{avail}^i, \text{diversion right}, \Delta\text{storage right}, (Q_{phys} - Q_{min})) \quad (3-5)$$

Where $\Delta\text{storage right}$ = the remaining “cap” space in the annual storage right allotment (annual storage right – total water year cumulative diversion to-date), Q_{phys} = physically available flow in stream at the point of diversion and Q_{min} = minimum instream flow requirement at the point of diversion.

For riparian water rights calculations, Equations 3-3 and 3-4 do not apply. The model only checks on the diversion and storage rights and the minimum instream flow requirement in determining Q_{avail}^i . Additionally, in contrast to a prior appropriations simulations, node calculations simply proceed from upstream to downstream rather than based on priority dates.

The demand at each node is calculated as a function of the available storage space in a reservoir account (if applicable) and the actual water usage for a given timestep. For a water user or agricultural user with a storage account, the model first attempts to meet water usage demands with stored water, then looks to the available stream water to make up the difference and replenish storage. This can be written as:

$$\text{demand}^i = \text{storage gap} + \Delta S^i \quad (3-6)$$

Where demand = the demand on source stream at given timestep for node i , storage gap = timestep demand - storage water withdrawal (see Section 3.2), and ΔS = available storage space (capacity – S) in account for node i after withdrawals.

Finally, as described in Equation 3-1, the model considers the physical capacity of the diversion structure, i.e. ditch or pipeline. This is simply a user-specified value that may or may not be constraining, depending on the other terms in the equation.

3.3 Water Users

The water user calculation module (WaterUserCalc) is called twice within each simulation timestep. The first call is prior to the calculation of diversions (described above). During this call, initial storage calculations are performed with all available storage used to meet node demands as needed. If there is not enough storage to meet the total demand, the “storage gap” is carried over to the calculation of stream diversion demands (Equation 3-6, above). The available storage space (ΔS) is also calculated in this first iteration and carried through to the stream diversion demand calculations. The second call to the water user calculation module incorporates the stream diversion and updates storage values, node shortages, and return flows. WaterUserCalc also includes calculation of various optional supply and

demand management alternatives, including conservation, reuse, agricultural transfers, transbasin imports, and water exchanges.

Key equations associated with the water user object include calculations of storage, shortages, return flows, and the dynamics of multiple source accounts with a single water user (and single set of demands). Water user storage is calculated as a function of diversions, withdrawals, evaporation, and releases using the standard water balance equation:

$$\frac{dS}{dt} = inflow - outflow \quad (3-7)$$

In SWAM, the numerical solution to this equation looks like:

$$S_i^t = S_i^{t-1} + diversion_i^t - demand_i^t - evap_i^t - release_i^t \quad (3-8)$$

where S_i^t = storage volume at time t , diversion = stream diversion (= 0 for first call to WaterUserCalc), demand = demand for storage water to meet water user needs, evap = reservoir evaporation credited to storage account (see Section 3.4), and release = mandatory storage account release to fulfill reservoir release obligations or exchange program offset requirement.

In SWAM, Equation 3-8 is first applied using the full water user demand. If the demand exceeds the available storage (after mandatory releases and evaporation), then the result will be a negative storage value ($S_i^t < 0$). In this case, the model sets the storage to 0 and assigns the difference (the negative storage) to the “storage gap” variable used in Equation 3-6, for the 1st call to WaterUserCalc, or to the final node shortage, for the 2nd call to WaterUserCalc.

Water user return flows are calculated according to:

$$RF_i^t = (1 - \%CU) * demandMet \quad (3-9)$$

Where RF_i^t = return flow volume for given timestep, $\%CU$ = percent consumptive use associated with the water user demand, and $demandMet$ = the actual demand met by storage water + diversion water.

When a water user includes multiple sources of water (see Section 2.2.4), SWAM calculates each account as if a stand-alone water user object. These calculations proceed in order of source account preference. SWAM attempts to meet all water user demands using the 1st preference source account, before moving to the 2nd, and so on. Residual demands (shortages) are carried over from one account to the next account by setting the demand variable of the next preferred account to the residual demand (shortage) of the previous account. The distribution of demands across multiple accounts for a water user occurs during an initial iteration in each timestep. During this initial iteration, the model assesses the potential yield (capacity) of each account to meet the prescribed demand, in order of account preference. Residual (unmet) demands are carried from first preference account to second preference account and so on, based on the source yield capacity. This is accomplished, conceptually, by imparting artificial demands, equal to the total water user demand, on each of the source accounts and performing normal yield calculations to meet these demands. Following these calculations, “surplus” yield is calculated based on the difference between the total account yields and the true water user demand. Account demands are then reduced, in reverse order of preference, to eliminate the supply surplus. These new account demands (the sum of which are now equal to the total water user demand) are carried over to the second iteration. During the second iteration, the final supply/demand water balance calculations are performed for each account. See the example provided below for an illustration of this sequence of calculations. . An illustrative example is provided below.

Example of Multiple Source Account Distribution of Demands, For Timestep t:

Original total demand = 100 AF

Iteration 1:

Account #1 demand = 100 AF

Account #2 demand = 100 AF (temporary and artificial, just to invoke supply/yield calculation)

Account #3 demand = 100 AF ("")

Account #1 yield (storage + diversion) = 50 AF

Account #2 yield = 100 AF

Account #3 yield = 75 AF

Total Yield = 225 AF

Total Surplus = 225 - 100 = 125 AF

Account demand adjustments (for next iteration):

Account #3 demand = $\min(0, \text{yield} - \text{surplus}) = \min(0, 75 - 125) = 0$ AF

Remaining surplus = 125 - 75 = 50 AF

Account #2 demand = $\text{yield} - \text{surplus} = 100 - 50 = 50$ AF

Remaining surplus = 50 - 50 = 0 AF

Account #1 demand = $\text{yield} - \text{surplus} = 50 - 0 = 50$ AF

Iteration 2:

Account #1 demand = 50 AF

Account #2 demand = 50 AF

Account #3 demand = 0 AF

Account #1 yield = 50 AF

Account #2 yield = 50 AF

Account #3 yield = 0 AF

Total Shortage = 0 AF.

3.4 Agricultural Users

Agricultural users are handled as water users in SWAM and utilize the same code. Differences compared to standard (M&I) water users are:

- Ag User return flow percentages are used directly within the WaterUserCalc module, rather than percent consumptive use (see Equation 3-9). As described in Section 2.2.5, these percentages are either user-defined or calculated within the user-interface as a function of irrigation efficiency and ditch losses.
- Demands can either be user-specified (full timeseries) or calculated within the user-interface according to the Blaney-Criddle equation (modified or original) for crop ET.

Return flow calculation:

$$\%RF = \%ditchLoss + (100 - \%ditchLoss) * \%irrEffic \quad (3-10)$$

where $\%ditchLoss$ = ditch loss percentage and $\%irrEffic$ = irrigation efficiency.

Ag demand calculation (Blaney Criddle):

$$u = kt * kc * f \quad (3-11)$$

$$kt = \max(0.0173 * T - 0.314, 0.3); \text{Modified Blaney Criddle} \quad (3-12)$$

or

$$kt = 1; \text{Original Blaney - Criddle}$$

$$kc = WF_1 * kc_1(t) + WF_2 * kc_2(t) + WF_3 * kc_3(t) + \dots \quad (3-13)$$

$$WF_i = \frac{A_i}{A} \quad (3-14)$$

and

$$demand = \frac{u}{12} * A - \frac{P_{eff}}{12} * A \quad (3-15)$$

where u = crop ET (inches), kt = climate factor for modified Blaney-Criddle equation, kc = aggregate crop factor that is calculated as a weighted average of user-defined crop-specific factors that vary according to growing season stage, T = mean air temperature, f = temperature and daylight factor, A = total irrigated acreage, A_i = irrigated acreage for crop type i , and P_{eff} = effective precipitation (inches).

3.5 Reservoirs

Reservoir objects are comprised of single or multiple water user storage accounts. The primary purposes of the reservoir object calculations are to calculate total reservoir storage values as a function of inflows (account and flood control pool inflows), water use (withdrawals), evaporative loss, and releases and to distribute evaporative losses and released volume across appropriate user accounts. Specific account storage calculations are described in Section 2.2. Reservoir object calculations are performed at the start of each simulation timestep (in the sub-routine "ResCalc"). Start of month total reservoir storage is calculated as the sum of all relevant user account storage values calculated in the previous timestep (see Equations 3-7 and 3-8). Evaporation and release calculations are linearized in SWAM by formulating as a function of start-of-timestep reservoir storage only. This is an approximation, but is deemed adequate for this planning level model.

Evaporation losses are calculated as a function of user-defined monthly rates (in mo⁻¹) and start-of-month surface area, or as a function of user-defined monthly percent volumetric losses and start-of-

month storage. Alternatively a timeseries of monthly evaporation losses (AFM) can be prescribed by the user. As an example, the former can be written as:

$$evap^t = evapRate^t * area^{t-1} \quad , \quad (3-16)$$

where $evap^t$ = evaporation loss (AFM) at timestep t, $evapRate^t$ = prescribed monthly loss rate corresponding to timestep t, and $area^{t-1}$ = reservoir surface area at start of timestep t (or end of timestep t-1).

As described previously (Section 2.2), calculated evaporative losses are distributed to individual accounts based on relative volumes of storage in each account at the given timestep. In other words, accounts with larger stored water will realize a greater evaporative loss than accounts with less stored water. This distribution occurs within the Reservoir object module at the start of the given timestep.

Similar to evaporation losses, reservoir releases are either calculated as a function of start-of-timestep hydrologic conditions or are prescribed by the user as mandatory monthly release volumes. For the latter, the model releases the prescribed amount as available in storage (after evaporation losses). For the former (“advanced” reservoir release rules), the model calculates release requirements based on a set of user-defined rules. These rules might include any combination of minimum monthly release requirements, monthly variable storage targets, and/or “conditional” release rules conditioned on hydrologic thresholds elsewhere in the basin.

For storage targets, if start-of-timestep storage is greater than the given storage target, then the model releases water in an attempt to meet the target at the end of the timestep. As an estimate of the required release volume to meet the intended target, the release volume is set simply to the difference between the target and start-of-timestep storage volume. Alternatively, if start-of-timestep storage is less than the target, then the release is set to zero (subject to other rules).

For conditional release rules, prescribed “conditions” can refer to flow or storage associated with any tributary object or reservoir in the modeled system. Hydrologic thresholds (flow or storage) are prescribed that trigger a release requirement in the model when the threshold criteria are met. Model users have flexibility in defining the criteria (<, >, =). Note that the hydrologic conditions used in this assessment are those at the start of the given timestep.

Reservoir releases are distributed across individual accounts based on storage permit priority (lowest to highest priority). SWAM attempts to assign all of a regulated release to the lowest priority account. If this account is unable to meet the total release volume required (due to lack of physical availability), the model moves on to the next lowest priority account, and so on. Note that flood control pool outflows (described below) and “bypass” flows are included in the total release volume required to satisfy prescribed monthly release requirements. Bypass flows (online reservoirs only) are flows that, for the sake of model calculations, are technically never diverted into the reservoir and can be considered to either go straight through or around the reservoir. As an example, if a prescribed mandatory monthly release is 10,000 AFM, and the total river flow at the top of the reservoir is 15,000 AFM, but only 10,000 AFM is diverted to fill up reservoir available capacity, then only an additional 5,000 AFM is required to satisfy the release requirement.

Since allocation of evaporation and release losses to individual user accounts is performed at the start of each timestep, these values are incorporated into subsequent water user water balance calculations.

For online reservoirs, flood control pool outflows are calculated as a function of start-of-month reservoir storage and user-defined outflow-capacity tables. Flood control pool outflows are calculated after evaporation calculations for each timestep. Therefore storage volumes used to calculate outflows equate to start-of-month values minus evaporation losses for the current month.

3.6 Instream Flow Objects

Instream flow objects are handled as non-consumptive water user objects (Section 3.3) in the model. Instream flow objects impart a monthly demand on the system, parameterized according to a permit and priority date, but all allocated flows are 100% immediately returned to the system and no water storage occurs. In this way, no flow depletions occur while still imparting a flow demand. Internally, calculations follow those described for water user objects above but with storage set to zero, return flow percentages set to 100%, and return flow location set to the same as the point of diversion.

3.7 Recreation Pools

As above, recreation pools are included in the model calculations as non-consumptive water user objects. Reservoir recreation pool object demands are calculated as the difference between the specified rec pool target volume and the actual pool volume at the start of the timestep. Water usage for the rec pool object is set to zero. Consequently, the only losses of water for a rec pool object are evaporation. As with any water user object, rec pools are parameterized with a storage permit priority date. The rec pool permitted withdrawal volume is set internally so that it is non-limiting (106 AFY). Water therefore gets allocated to a rec pool based on its priority date and the pool demand (difference between target and beginning of timestep volume).

3.8 Aquifer Objects

Aquifer storage is calculated via a standard storage water balance:

$$\frac{dS}{dt} = inflow - outflow \quad (3-7)$$

In SWAM, the numerical solution to this equation looks like:

$$S_i^t = S_i^{t-1} + recharge_i^t - \sum_{j=1}^n GWpumping^t$$

where i = aquifer index, S = storage at end of given timestep, $recharge$ = monthly aquifer recharge rate, j = index for all water users that pump from aquifer i , n = number of water users that pump from aquifer i . Groundwater pumping rates are calculated internally for each water user or ag user object as a function of demands and availability and priority of other sources of supply.

Aquifer drawdown is calculated using a polynomial expansion of the Theis equation. The Theis equation can be written as:

$$s = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

where s = drawdown (change in hydraulic head at a point in space as a function of cumulative impacts from pumping since the start of pumping), u = dimensionless time parameter, Q = pumping rate, T = aquifer transmissivity (L^2/t), S = aquifer storativity (unitless), r = distance from the pumping well to the drawdown observation point, t = time since pumping began, and $W(u)$ is the well function. In SWAM, the well function ($W(u)$) is approximated by a multi-term polynomial presented in Abramowitz and Stegun (1968). SWAM applies convolution principles to calculate the combined impacts of multiple pumping wells, in different locations, with time-variable pumping rates.

3.9 Reuse

Reuse is a demand management option for water user objects. In SWAM, the only form of reuse explicitly available under this option is direct recapture of indoor usage return flows (wastewater treatment plant effluent). When this option is selected by the user, net monthly water demand is adjusted at each timestep according to:

$$demand^t = total_usage^t - total_indoor_usage^t * (1 - \%CU) * \%reuse$$

where $\%reuse$ = a user-specified percentage of indoor return flows that gets recaptured for reuse and $\%CU$ = percent consumptive use associated with the indoor usage. Return flows from a water user implementing reuse are also reduced accordingly.

3.10 Conservation

A net monthly conservation percentage is calculated at each timestep as parameterized by the model user. This percentage corresponds to a percent reduction in water usage. Different percentages are calculated for indoor use versus outdoor use. The percentages are applied according to:

$$totalUsage^t = indoor_usage^t * (1 - \%Cons^{in}) + outdoor_usage^t * (1 - \%Cons^{out})$$

where $\%Cons^{in}$ = monthly percent conservation reduction in indoor water usage at timestep t , and $\%Cons^{out}$ = monthly percent conservation reduction in outdoor water usage at timestep t .

3.11 Transbasin Imports

Transbasin import water gets added to the total supply portfolio of a water user at each timestep. Import water is calculated as a function of specified transbasin delivery targets, source water availability, and conveyance losses (if any). In SWAM, transbasin water automatically gets added to the total supply of the assigned water user, regardless of demand. If a surplus in supply in a given month results, the surplus is returned to the river. In other words, transbasin import water, if designated by the water user, represents a continuous additional water source for a modeled basin.

3.12 Agricultural Transfers

As with transbasin imports, agricultural transfers are simulated in SWAM as supplemental sources of supply for a given water user. Ag transfer water deliveries are calculated as a function of user-defined irrigated acreage that gets retired, the irrigation consumptive use associated with the acreage, irrigation efficiency, and a monthly distribution of irrigation demands. As above, ag transfer water,

when selected by the user, represents a continuous source of supply to the water user, and ultimately the modeled surface water basin, independent of demand.

3.13 Groundwater Pumping

Groundwater pumping is available as a source of supply for water user and agricultural user objects in SWAM. Groundwater supply is calculated in the model as a function of user-specified target pumping rates, net demand for groundwater, and aquifer storage availability. A key difference between groundwater as a source of supply and the supplemental supplies described above is that groundwater pumping is constrained by demand at each timestep. In other words, groundwater will not be pumped if there is not a need for it in a given simulation month.

Groundwater pumping return flows are included in the calculation of total surface water returns from a given water user.

3.14 Water Exchanges

Water exchange programs can be established between two water user supply accounts. Because it requires two supply accounts acting in concert, water exchanges are only available if the “multiple sources of supply” checkbox is selected. A water exchange is defined in SWAM as an agreement whereby an upstream diversion account can only divert water if a downstream partner account releases water from storage of the same amount and in the same timestep. Practically, this allows for diversion and storage to occur at the downstream location during wet periods and direct diversion to occur at the upstream location during dry periods, with no impact on downstream users (since the diversion is offset by releases from the downstream stored water). In SWAM, the downstream storage account in an exchange program can only store and release water to the stream. Water can’t be used for consumption from this storage account. Diversion to the downstream storage account can only occur in timesteps where there is no release requirement (i.e. no upstream diversion) and as allowed according to standard water user supply account calculations of physically and legally available flow. For the upstream direct diversion in an exchange program, the model calculates legally and physically available flow at the node following the standard algorithms but then constrains the legally available flow to less than or equal to the total available for release from the downstream partner account. When the seasonality flag is selected (under “Water Exchange” tab), the user can specify the months in which the exchange program is active. For the selected months, upstream diversions and downstream releases can occur as described above. For months when the exchange program is not active (unselected checkboxes), no diversions to the upstream account are allowed even if downstream storage is available for releases. Note that the downstream account in an exchange program must be assigned to the #5 preference supply account and thus is forced to be the less preferred account in the exchange partnership.

Section 4

References

Abramowitz and Stegun 1968. Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables. 7th Edition. United States Department of Commerce.

Appendix A

Notes on Model Calibration/Verification

Philosophy and Objectives

SWAM is a water allocation model that moves simulated water from upstream to downstream, combines flows at confluence points, routes water through reservoirs, and allocates water to a series of water user nodes. It is designed for applications at a river basin scale. In common with all water allocation models, neither rainfall-runoff, nor reach routing, are performed in SWAM. As such, the “calibration” process should be viewed differently compared to catchment or river hydrologic modeling.

The overriding objective of the SWAM calibration process is to verify that the model is generally accurately representing water availability in the basin; i.e. that ungaged flow estimates are roughly accurate, that flows are being combined correctly, and that basin operations and water use are well captured. More specifically, the objectives include:

- extending the hydrologic input drivers of the model (headwater flows) spatially downstream to adequately represent the unimpaired (naturalized) hydrology of the entire basin by incorporating hydrologic gains and losses below the headwaters;
- refining, as necessary and appropriate, a small number of other model parameter estimates within appropriate ranges of uncertainty, potentially including: reservoir operational rules, consumptive use percentages, and nonpoint (outdoor use) return flow locations; and
- gaining confidence in the model as a predictive tool by demonstrating its ability to adequately replicate past hydrologic conditions, operations, and water use.

In many ways, the exercise described here is more about model verification than true model calibration. The model parameterization is supported by a large set of known information and data – including tributary flows, drainage areas, water use and return data, and reservoir operating rules. These primary inputs are not changed during model calibration. In fact, only a small number of parameters are modified as part of this process. This is a key difference compared to hydrologic model calibration exercises, where a large number of parameters can be adjusted to achieve a desired modeled vs. measured fit. Because SWAM is a data-driven model and not a parametric reproduction of the physics that govern streamflow dynamics, care is taken so that observed data used to create model inputs are not altered. In calibrating SWAM, generally the primary parameters adjusted are reach gain/loss factors for select tributary objects. These factors capture ungaged flow gains associated with increasing drainage area with distance downstream. Flow gains through a sub-basin are initially assumed to be linearly proportional to drainage area, in line with common ungaged flow estimation techniques. However, there is significant uncertainty in this assumption and it is therefore appropriate to adjust these factors, within a small range, as part of the model calibration process. These are often the only parameters changed in the model during calibration, though adjustments can also be made if needed to reservoir operating rules, consumptive use rates, and flow estimates in ungaged headwater basins. It is important to note that reservoir operating rules are simulated in the verification of the model in lieu of prescribing actual historic data on reservoir usage. This is to help

ensure that the model has predictive strength for simulating the continuation of prescribed rules into the future, by demonstrating that the rules adequately reproduce historic reservoir dynamics.

Consideration also needs to be given to the accuracy of the measured or reported data that serve as key inputs to the model and are not adjusted as part of the calibration exercise. For example, historical water withdrawals reported by individual water users are based on imperfect measurement or estimation techniques. Even larger errors may exist in the USGS flow gage data used to characterize headwater flows in the model. These errors are known to be upwards of 20% at some gages and under some conditions (USGS, <http://wdr.water.usgs.gov/current/documentation.html>). The uncertainty of model inputs merits consideration in the evaluation of model output accuracy.

Lastly, in considering the model calibration and verification, it is also important to keep in mind the ultimate objectives of the models. The final models are generally intended to support planning and permitting decision making. Planners will use the models to quantify impacts of future demand increases on water availability. For example, if basin municipal demands increase by 50%, how will that generally impact river flows and is there enough water to sustain that growth? Planners might also use the models to analyze alternative solutions to meeting projected growth, such as conservation, reservoir enlargement projects, and transbasin imports. With respect to permitting, regulators might look to the model to identify any potential water availability problems with new permit requests and to quantify the impacts of new or modified permits on downstream river flows. In other words, they will look to the model to answer the question of: if a new permit is granted, how will it impact downstream critical river flows and downstream existing users?

Given the methods and objectives described above, there is no expectation that downstream gaged flows, on a monthly or daily basis, will be replicated exactly. The lack of reach routing, in particular, limits the accuracy of the models at a daily timestep. Rather, the questions are only whether the representation of downstream flows is adequate for the model's intended purposes, key dynamics and operations of the river basin are generally captured (as measured by the frequency of various flow thresholds and reasonable representation of the timing and magnitude of the rise and fall of hydrographs), and whether the models will ultimately be useful as supporting tools for the planning and/or permitting studies.

Methods

For any model calibration exercise, an appropriate historical period should be selected for hindcast simulations. Attempts should be made to capture as great a range of hydrologic conditions as possible, but with consideration for the reliability of supporting data. Model inputs should reflect historical conditions rather than "current" conditions. For example, actual reported time-variable historical water use records should be used in the calibration model, to the extent possible. Selected historical periods should also be relatively steady in terms of river operations (e.g. reservoirs) (which are simulated with a constant set of operating rules to test their stability and efficacy over a broad range of hydrologic conditions), but not necessarily water usage (which can be characterized with time variable values, as noted above). Alternatively, if operations do change at a known point in time, modelers could consider breaking up the period into two separate models.

Guided by the principles described above, the following specific steps should generally be followed (in order) as part of the SWAM calibration/verification process:

1. Extend tributary headwater flows to the tributary confluence points using drainage area ratios to calculate tributary object subbasin flow factors.
2. Add new implicit tributary objects, as needed and based on visual inspection of GIS mapping, to capture ungaged drainage areas and tributary inputs not included in the original model construction.
3. Adjust intermediary subbasin flow factors for non-mainstem tributary objects to achieve adequate modeled vs. measured comparisons at selected tributary gage targets, based on monthly timestep modeling.
4. Adjust mainstem reach gain/loss factors (per unit length) to better achieve calibration at mainstem gage locations. This factor can be varied in up to 5 locations along the main stem, which allows modelers to account for general variations in runoff and groundwater interaction, but does not result in so many degrees of freedom that the model can be almost perfectly fit to historical observations but loses its predictive strength.
5. Review simulated reservoir operating rules and outflows based on reservoir level modeled vs. measured comparisons. Adjust and/or change operating rules or flood control outflows as appropriate.
6. If applicable, verify daily timestepping by reviewing daily output once the monthly model is calibrated.

All USGS flow gages at downstream locations in the basin with reasonable records within the targeted simulation period should be used to assess model performance and guide the model calibration steps described above. Note that in order to minimize the uncertainty in chosen calibration targets, ideally only gaged (i.e. measured) flow records should be used to assess model performance as part of this exercise. Ungaged flow estimates or record filling techniques should be used with caution to supplement the available data set (ideally not at all). Note also that all upstream basin water use and operations are implicitly represented in these gaged data, thereby providing an ideal target to which model output can be compared. In addition to the flow gages, reported historical reservoir levels (where available) should also be used as calibration/verification targets. Lastly, all water users in the model should be checked to ensure that historical demands were being fully met in the model or, alternatively, if demands were not being met during certain periods, that there was a sensible explanation for the modeled shortfalls.

As indicated above, options for model calibration parameters (i.e. those that are adjusted to achieve better modeled vs. measured matches) should generally be limited to a very small group of inputs with relatively high associated uncertainty. In general, and for future basin models, these might include any of the following: mainstem and/or tributary reach hydrologic gain/loss factors, reservoir operational rules, assumed consumptive use percentages, and return flow locations and/or lag times associated with outdoor use. However, the primary calibration parameters in SWAM are the reach gain/loss factors. Adjustments to other parameters are secondary and often not required.

A number of performance metrics should be used to assess the model's ability to reproduce past basin hydrology and operations. These may include, but not limited to, monthly and daily water user supply delivery and/or shortfalls, monthly and daily timeseries plots of both river flow and reservoir levels, annual and monthly mean flow values, monthly and daily percentile plots of river flow values,

regulatory low flows (e.g. annual 7-day low flows with a 10 year recurrence interval, 7Q10), and mean flow values averaged over the entire period of record.

The reliability of historical water supply to meet specific water user demands is an important consideration in the calibration process to ensure that water user historical demands and supply portfolios are properly represented in the model, as well as providing checks on supply availability at specific points of withdrawal. Timeseries plots, both monthly and daily, are used to assess the model's ability to simulate observed temporal variation and patterns in flow and storage data and to capture an appropriate range of high and low flow values. Percentile plots are useful for assessing the model's ability to reproduce the range of flows, including extreme events, observed in the past (and are particularly important when considering that the value of a long-term planning model like this is its ability to predict the frequency at which future flow thresholds might be exceeded, or the frequency that various amounts of water will be available). Monthly statistics provide valuable information on the model's ability to generally reproduce seasonal patterns, while annual totals and period of record mean flows help confirm the overall water balance represented in the model. Lastly, regulatory low flows (e.g. 7Q10) may be of specific interest if, for example, the model might be used to predict such low flows as a function of future impairment. However, the limitations of the daily model and supporting data should be properly considered in assessing model performance on this particular metric.

It is recommended that the assessment of performance and adequacy of calibration be primarily based on graphical comparisons (modeled vs. measured) of the metrics described above and subject to the professional judgement of the modeler. It is our opinion that graphical results, in combination with appropriate modeling expertise, provide the most comprehensive view of model performance for this type of model. Reliance on specific statistical metrics can result in a skewed and/or shortsighted assessments of model performance. Tabular comparisons (e.g. period of record average flow values) should also be used. Ultimately, keeping in mind the philosophies and objectives described above, consideration should be given as to whether the model calibration could be significantly improved with further parameter adjustments, given the limited calibration "knobs" available in the process. In actuality, a clear point of "diminishing returns" may quickly be reached whereby no significant improvements in performance can be achieved without either: 1) adjusting parameters outside of their range of uncertainty or, 2) constructing an overly prescriptive historical model that then becomes less useful for future predictive simulations. At this point, the calibration exercise should be considered completed.

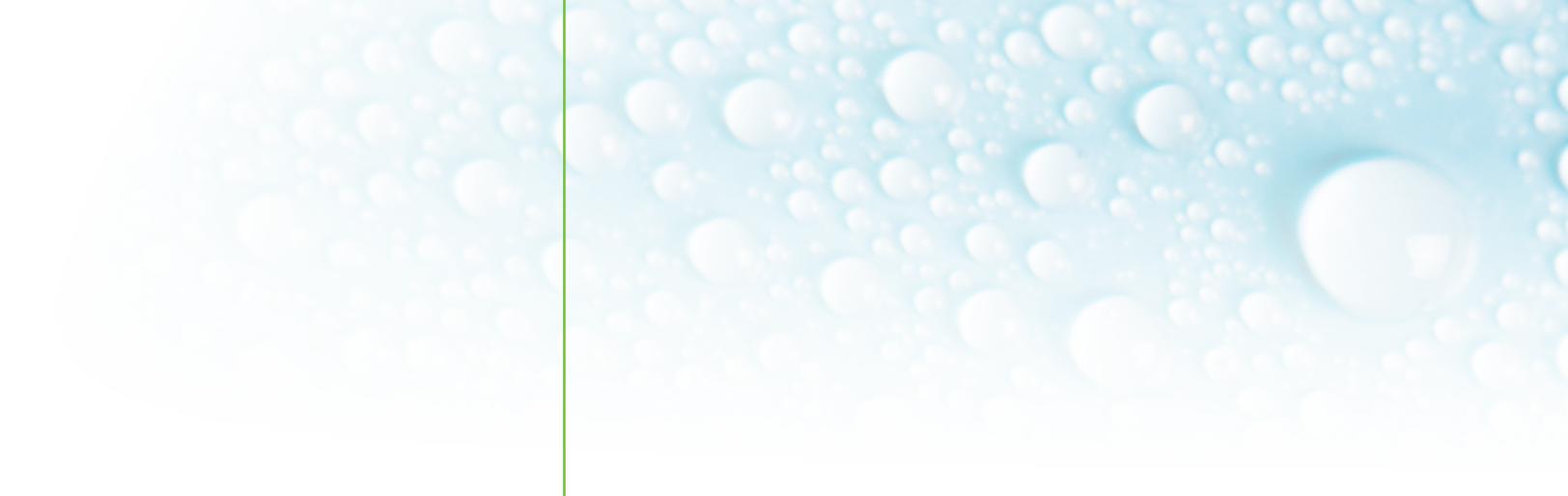
Appendix B

Guidelines for Representing Multi-Basin Water Users in SWAM

There are many examples in South Carolina of water users that access source waters in multiple river basins and/or discharge return flows to multiple basins. Since SWAM models for each major river basin are being developed, it is important to represent the multi-basin users concisely and clearly in the models. The following provides a recommended set of consistent guidelines to follow as each river basin model is developed. In all cases, the constructs should be documented in the basin reports and described in the model itself using the Comment boxes.

1. If a water user's primary source of supply and discharge locations are located within the given river basin, then this user should be explicitly included as a Water User object in that basin model.
 - a. If secondary sources are from outside of the basin, then these should be included using the "transbasin import" option in SWAM.
 - b. If a portion of the return flows are discharged to a different basin, then this should be incorporated by using the multiple return flow location option, with the exported portion represented by a specified location far downstream of the end of the basin mainstem (e.g. mile "999"). This is not affiliated with a physical place, but rather, ensures that the water balance is maintained within the basin while properly accounting for water that does not return to the river.
2. If only a water user's secondary source of supply (i.e., not the largest portion of overall supply) is located outside the river basin being modeled, then this should be represented as a water user with an "Export" identifier in the name (e.g. "Greenville Export") in the river basin model where the source is located.
 - a. For this object, set the usage values based only on the amount sourced from inside the basin (i.e. only that portion of demand met by in-basin water).
 - b. Set the return flow location for this use to a location outside of the basin (e.g. mainstem mile "999").
 - c. For future demand projection simulations, the in-basin portion of overall demand will need to be disaggregated from the total demand projection, likely by assuming a uniform percent increase.
3. If a portion of a water user's return flow discharges to a different basin than the primary source basin, then this portion of return flow should be represented as a Discharge object (e.g. named "Greenville Import") in the appropriate basin model.
 - a. Reported discharge data can be used to easily quantify this discharge for historical calibration simulations.

- b. For future demand projection simulations, this discharge can be easily quantified by analyzing the return flow output for the primary (source water basin). See 1b. above. However, the user will need to manually make the changes to the prescribed Discharge object flows in the model.



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