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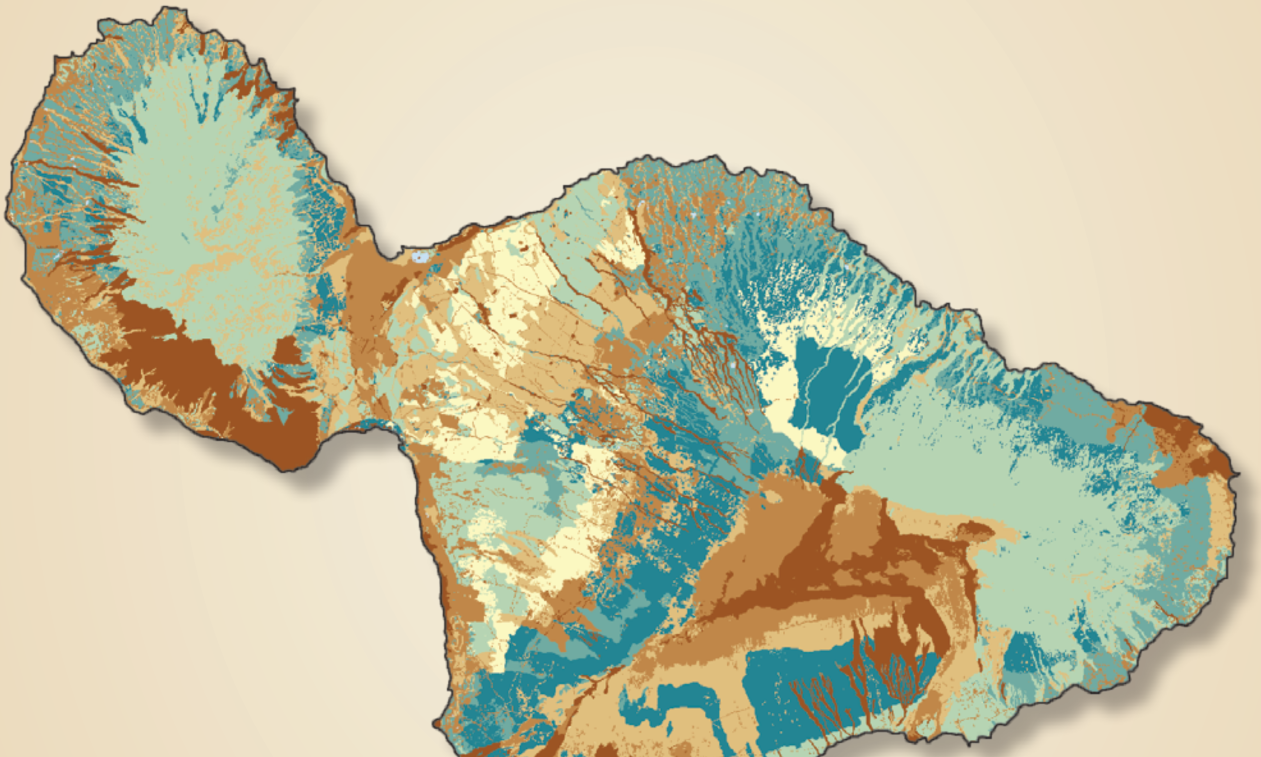
SWB Version 2.0—A Soil-Water-Balance Code for Estimating Net Infiltration and Other Water-Budget Components

Chapter 59 of
Section A, Groundwater
Book 6, Modeling Techniques



Techniques and Methods 6–A59

U.S. Department of the Interior
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Cover: Image of Soil-Water-Balance (SWB) soil-moisture storage grid for the Maui, Hawaii, study area.

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Preface

The Soil-Water-Balance (SWB) version 2.0 code can be downloaded from the U.S. Geological Survey for free. The performance of SWB version 2.0 has been tested in a variety of applications. Future applications, however, might reveal errors that were not detected in the test simulations. Users are requested to send notification of any errors found in this model documentation report or in the model program to the contact listed on the web page (https://doi.org/10.5066/tm6A59).

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Density of heat	
langley (Ly)	0.0171	equivalent water evaporated in millimeters (mm)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Temperature in Fahrenheit (°F) may be converted to Kelvin (K) as follows:

$$K = (°F - 32) / 1.8 + 273.15.$$

Temperature in Kelvin (K) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (K - 273.15) \times 1.8 + 32.$$

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.2808	foot (ft)
kilometer (km)	0.6215	mile (mi)
	Area	
square kilometer (km^2)	0.3862	square mile (mi^2)
	Density of heat	
langley(Ly)	0.673	equivalent water evaporated in inches (in.)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in Celsius (°C) may be converted to Kelvin (K) as follows:

$$K = °C + 273.15.$$

Temperature in Kelvin (K) may be converted to degrees Celsius (°C) as follows:

$$°C = K - 273.15.$$

SWB Version 2.0—A Soil-Water-Balance Code for Estimating Net Infiltration and Other Water-Budget Components

By Stephen M. Westenbroek, John A. Engott, Victor A. Kelson[1], and Randall J. Hunt

Abstract

The U.S. Geological Survey's Soil-Water-Balance (SWB) code was developed as a tool to estimate distribution and timing of net infiltration out of the root zone by means of an approach that uses readily available data and minimizes user effort required to begin a SWB application. SWB calculates other components of the water balance, including soil moisture, reference and actual evapotranspiration, snowfall, snowmelt, canopy interception, and crop-water demand. SWB is based on a modified Thornthwaite-Mather soil-water-balance approach, with components of the soil-water balance calculated at a daily time step. Net-infiltration calculations are computed by means of a rectangular grid of computational elements, which allows the calculated infiltration rates to be imported into grid-based regional groundwater-flow models. SWB makes use of gridded datasets, including datasets describing hydrologic soil groups, moisture-retaining capacity, flow direction, and land use. Climate data may be supplied in gridded or tabular form. The SWB 2.0 code described in this report extends capabilities of the original SWB version 1.0 model by adding new options for representing physical processes and additional data input and output capabilities. New methods included in SWB 2.0 allow for direct gridded input of externally calculated water-budget components (fog, septic, and storm-sewer leakage), simulation of canopy interception by several alternative processes, and a crop-water demand method for estimating irrigation amounts. New input and output capabilities allow for grids with differing spatial extents and projections to be combined without requiring the user to resample and resize the grids before use.

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Introduction

Accurate estimates of the spatial and temporal distribution of groundwater recharge are important for many types of hydrologic assessments, including assessments that concern water availability, water-quality protection, streamflow and riparian-ecosystem management, aquifer replenishment, groundwater-flow modeling, and contaminant transport; these recharge estimates often are key to understanding effects of land-use change in urban, industrial, and agricultural regions. With increasing demand for science-supported hydrologic management comes an increased need for robust and practical methods to quantify groundwater recharge rates (Scanlon and others, 2002).

To fill this need, Dripps and Bradbury (2007) created a spreadsheet code that calculates components of the soil-zone water balance at a daily time step by means of a modified version of the Thornthwaite-Mather soil-moisture-balance approach (Thornthwaite, 1948; Thornthwaite and Mather, 1957). The primary output of the water-balance code is net infiltration out of the root zone. In areas where groundwater is close to the surface (less than 10 meters), net infiltration may be assumed to become recharge. In areas with deeper groundwater tables, or for dynamic models that require simulation of recharge timing, MODFLOW's Unsaturated Zone Flow Package (Niswonger and others, 2006) may be used to simulate the transport of net infiltration to the groundwater table.

Data requirements for the original water-balance code included the following several commonly available tabular and gridded data types: (1) precipitation and temperature, (2) land-use classification, (3) hydrologic soil group, (4) flow direction, and (5) soil-water capacity. The data and required formats were designed to take advantage of widely available geographic information systems (GIS) datasets and file structures. To increase ease of use, reduce reliance on proprietary software, and increase the size of model domain that could be simulated, the U.S. Geological Survey (USGS) translated the original soil-water-balance code from the spreadsheet Visual Basic to modern Fortran 2008; the Fortran version was called the Soil-Water-Balance (SWB) code version 1.0 (Westenbroek and others, 2010). SWB 1.0 was used to estimate net infiltration out of the root zone in a wide variety of environmental settings; for examples, see Feinstein and others (2010) or Hunt and others (2016). The SWB code has evolved since the original release, with the addition of crop-water demand calculations and some of the functionality of the Hawaii water-budget code (Izuka and others, 2010). This report documents version 2.0 of the SWB software, hereafter referred to as SWB.

Background and Terminology

Standard terminology is not available for use in discussions of the water-budget components that result in groundwater recharge. The nomenclature and following definitions from Healy (2010) are used in this report.

Potential recharge.—Water that has infiltrated into the root zone. Potential recharge may leave the bottom of the root zone, eventually becoming recharge. Alternatively, potential recharge may be removed from the soil column by means of evaporation and transpiration.

Net infiltration.—Water that has escaped the evapotranspiration sinks of the root zone, some portion of which will eventually find its way to the groundwater table.

Groundwater recharge.—Water that actually crosses the water table.

This report uses slightly different terminology than Westenbroek and others (2010). In both reports, however, the terms used underscore the fact that SWB does not simulate unsaturated-zone processes beneath the root zone. When the unsaturated zone is sufficiently thick, it can impart appreciable lags between the time when water leaves the bottom of the root zone and the time when water crosses the water table and enters the groundwater system (Healy, 2010; Hunt and others, 2008; Nimmo and others, 2005); under some conditions, separate net-infiltration events coalesce in the unsaturated zone and enter the water table as a single recharge event. Therefore, the output of the SWB code is here referred to as “net infiltration” rather than “groundwater recharge”, in keeping with Healy’s (2010) usage. The distinction between infiltration and recharge has been explored in detail by others; see for example Anderson and others (2015, p. 232–234).

Net infiltration and related groundwater recharge can vary with time and space. Site-specific measurements of net infiltration and recharge, if available, are difficult to upscale for application in regional-scale problems. Yet, in groundwater-modeling problems, application of physically based, spatially variable recharge values to the water table have been determined to improve model performance (Jyrkama and Sykes, 2007; Hunt and others 2008).

A soil-water-balance modeling approach is currently the preferred method for distributing net infiltration in space and time for use in applied groundwater modeling (Anderson and others, 2015, p. 232). The temporal discretization used in the soil-water-balance model should not be overly coarse. For example, Rushton and Ward (1979) determined that running a soil-water-balance calculation with monthly time steps gave net-infiltration values 25 percent less than soil-water-balance calculations using daily values.

Many soil-water-balance models are described in the literature, most developed for specific applications. Soil-water-balance models have been developed to evaluate crop irrigation requirements and impacts (Boisvert, 1990; Braud and others, 2013; Jensen, 1969; Kendy and others, 2003), crop yield prediction (Akinremi and others, 1996), and landfill cover design (Schroeder and others, 1994), and to estimate net infiltration (Batelaan and De Smedt, 2001; Eilers and others, 2007; Finch, 2001; Fitzsimons and Misstear, 2006; Jyrkama and others, 2002; Lee and others, 2006; Manghi and others, 2009).

Within the USGS, many different water-balance models have been used as a means to estimate net infiltration. The Yucca Mountain Project of the 1980s and 1990s produced the INFIL 3.0 model (U.S. Geological Survey, 2008). The Basin Characterization Model has been applied to significant tracts of the western United States (Flint and others, 2014; Flint and Flint, 2007). A similar model was developed and applied in Montana, Idaho, and Washington State (not shown) (Bauer and Vaccaro, 1987; Bauer and Vaccaro, 1990). A custom water balance model has been applied to the Hawaiian Islands (not shown) for decades (Izuka and others, 2010). Another custom water balance model was applied to the central Midwest regional aquifer system, with special emphasis on estimating consumptive use of water and the resulting impact on recharge (Dugan and Peckenpaugh, 1985). These models have generally been developed with specific environmental settings in mind (Yucca Mountain, Hawaiian Islands) but include processes and algorithms that may be suited for future versions of the SWB code documented in this report.

Scope and Purpose

The purpose of this report is to document version 2.0 of the SWB code. Version 2.0 is designed to estimate components of the water budget, particularly net infiltration, for a model domain represented by a grid of uniformly sized square cells on a daily timescale. Version 1.0 of the code is documented in Westenbroek and others (2010). This report focuses on features and implementations that are part of the version 2.0 code.

An overview of the conceptual basis, data requirements for use, and limitations and assumptions relating to SWB are presented in this report. Additional details are provided in four appendixes in this report; one of the appendixes provides two test cases featuring the SWB code. The first test case (Maui, Hawaii), allows comparison of the performance of the SWB code relative to the Hawaii water-budget code. The second test case (Central Sands, Wisconsin), demonstrates the application of the SWB code to a model domain that includes many irrigated land-use types.

Changes from Previous Versions

The design goals and operation of SWB are similar to the original release documented by Westenbroek and others (2010). The code still performs a modified Thornthwaite-Mather soil-water balance at each grid point within the model domain. However, the scope of recent additions to the process methods and modifications of the input and output file structures are significant enough to warrant a new major SWB release along with new documentation and input instructions.

Many of the SWB code changes will be apparent to users familiar with the original SWB code. These changes pertain to model input and output and include the following list of SWB code changes:

- elimination of **`swbstats`**, (a program to handle post-processing of SWB output);
- elimination of internally generated graphics;
- elimination of the custom **`swb`** binary output files;
- addition of cartographic reprojection and resampling by means of the PROJ4 library that allows SWB to read grids with differing geographic projections;
- upgrading Network Common Data Form (NetCDF) input and output to NetCDF version 4;
- modification of internal structure to make adding new methods easier;
- addition of code to allow for more flexible tabular data and parameter input; and
- rearrangement of internal data structures to more efficiently accommodate blocks of inactive cells within model domains.

Many of the SWB code changes were made in response to user frustrations related to the difficulty of aligning and resampling input grids; SWB 1.0 required that every grid supplied to the code be in exactly the same geographic projection, cover the same extents as the SWB 1.0 project grid, and be discretized at the same grid-cell resolution. This requirement resulted in excessive data management and consumed project time that would have been better spent on other tasks. In addition, SWB 1.0 stored results in a custom-programmed, binary-file format. Following a SWB 1.0 model run, a program called **`swbstats`** could be used to extract daily, monthly, annual, or period grids as well as to generate plots and calculate basic statistics.

With the opportunity to modify and enhance SWB 1.0, the authors decided to standardize model output using an existing file format. SWB now stores all gridded output in the common and widely used format NetCDF (Unidata, 2014). The NetCDF file format is commonly used among climate scientists and meteorologists and is slowly being adopted in other scientific fields. A benefit of switching to a well-known binary-file format is that rather than relying on a single program, **`swbstats`**, to handle post-processing, dozens of actively maintained open-source tools are designed to make post-processing of NetCDF files easier (for example http://www.unidata.ucar.edu/software/netcdf/utilities.html). Other changes made since the initial SWB 1.0 release add or modify the actual hydrologic processes simulated by SWB. These changes include the addition of the methods listed in table 1.

Overview of Data and Input Requirements

Input data requirements for SWB become more demanding as more modules are activated. However, a typical SWB application may be made with a handful of gridded datasets, a daily weather data source, a control file specifying SWB program options, and a lookup table specifying parameter values as a function of land use and soil type. The minimum required data and input files for a typical SWB run are listed in table 2.

Units of Measurement

This report contains units given in a mixture of U.S. customary and International System of Units (SI) units, sometimes in the same equation or paragraph. This dual usage of units of measurement is because many of the early hydrologists and soil scientists worked for the U.S. Federal Government and published using U.S. customary units, whereas most scientific works use SI units. Literature related to irrigation is often in U.S. customary units. The authors have attempted to use SI units where convenient, but have retained the units used originally by the cited authors. Although dual usage of units of measurement may be confusing at times, the dual usage allows SWB users to access some of the original data tables without having to convert units.

Table 1. Summary of new process methods available in Soil-Water-Balance (SWB) code version 2.0.

Process	Method	Description
Irrigation water demand	FAO–56	Simulates addition of water to the soil root zone in an amount necessary to sustain crop growth. FAO is the Food and Agriculture Organization, a branch of the United Nations. FAO–56 is the publication that describes methodology for calculation of crop-water demand and irrigation scheduling (Allen and others, 1998).
Soil-moisture retention	FAO–56	The soil-moisture retention relation in FAO–56 allows plant evapotranspiration to proceed at the rate of potential evapotranspiration until soil moisture drops to some user-defined threshold soil-moisture value; when soil-moisture values drop beneath this threshold evapotranspiration is assumed to proceed at some fraction of potential evapotranspiration.
Crop-coefficient curves	FAO–56	Evapotranspiration by crops and other plants is assumed to be represented as some fraction of potential evapotranspiration; the crop-coefficient curve defines this fraction. FAO–56 represents the crop-coefficient curve as a piecewise linear relation indexed to stages of plant growth.
Interception	Gash, Horton	The Horton (1919) method allows for interception amounts to grow relative to total storm rainfall; the modified Gash (Gash, 1979; Gash and others, 1995) method accounts for partitioning of intercepted water between canopy and stemflow and accounts for canopy density.
Fog interception	Gridded	Fog interception may be specified as some fraction of rainfall to account for capture of fog moisture by vegetation.
Rainfall	Method of fragments	Disaggregates monthly gridded precipitation data using a set of fragments generated from daily observations (Srikanthan and McMahon, 1982).
Runoff	Ratio	Runoff may be simulated as a fraction of rainfall by means of an externally calculated set of runoff ratios.
Direct net infiltration	Gridded or tabular	Direct additions to net infiltration from septic systems, leaky water mains, storage reservoirs, and other diffuse sources.

Table 2. List of minimum required data and input files for a typical Soil-Water-Balance (SWB) run.

[–, unitless; SSURGO, Soil Survey Geographic database; gSSURGO, Gridded Soil Survey Geographic database]

Data or input type	Units	Format	Example source/description
Land use	–	Grid (integer)	National Land Cover Database (Homer and others, 2015).
D8 flow direction	–	Grid (integer)	National Elevation Dataset (Gesch and others, 2002); D8 flow direction must be generated from elevation data using geographic information systems or other such software.
Available water capacity	Inch per foot	Grid (float or real)	SSURGO or gSSURGO (Soil Survey Staff, 2015); typically averaged over the top 0 to 100 centimeters of the soil profile.
Soil hydrologic group	–	Grid (integer)	SSURGO or gSSURGO (Soil Survey Staff, 2015).
Weather data—daily precipitation and minimum and maximum air temperature	Inch; degrees Fahrenheit	Table or grid (float)	Daymet 1 kilometer gridded data (Thornton and others, 2017); many other gridded data sources may be used instead.
SWB control file	–	Text file	SWB control file specifies the location of the data elements listed above, as well as which modules are active during the run.
SWB lookup table	–	Text file (tab delimited)	SWB lookup table contains parameter values for each land use; some parameters are given as a function of the land use and the hydrologic soil group.

Model Description

The SWB code uses a modified Thornthwaite-Mather soil-moisture accounting method (Thornthwaite and Mather, 1955; Thornthwaite and Mather, 1957) to calculate net infiltration; net infiltration is calculated separately for each grid cell in the model domain. Sources and sinks of water within each grid cell are determined on the basis of input climate data and landscape characteristics (fig. 1). Soil moisture is updated on a daily basis as the difference among these sources and sinks as in equation 1. The terms in equation 1 are expressed in units of length; SWB uses units of inches.

$$\theta_t = \theta_{t-1} + rainfall + runon + snowmelt + fog\ interception + irrigation - interception - runoff - ET \quad (1)$$

where

θ_t is the soil moisture for the current simulation day,

θ_{t-1} is the soil moisture on the previous simulation day, and

ET is the actual evapotranspiration.

How the terms from equation 1 relate is shown in figure 1. In addition to the soil-moisture reservoir described by equation 1, two additional storage reservoirs are tracked by SWB—interception and snow. The daily calculation for the interception amounts to new intercepted rainfall and snowfall minus any evaporated interception water. The daily calculation for the snow reservoir is simply the running sum of snowfall minus snowmelt.

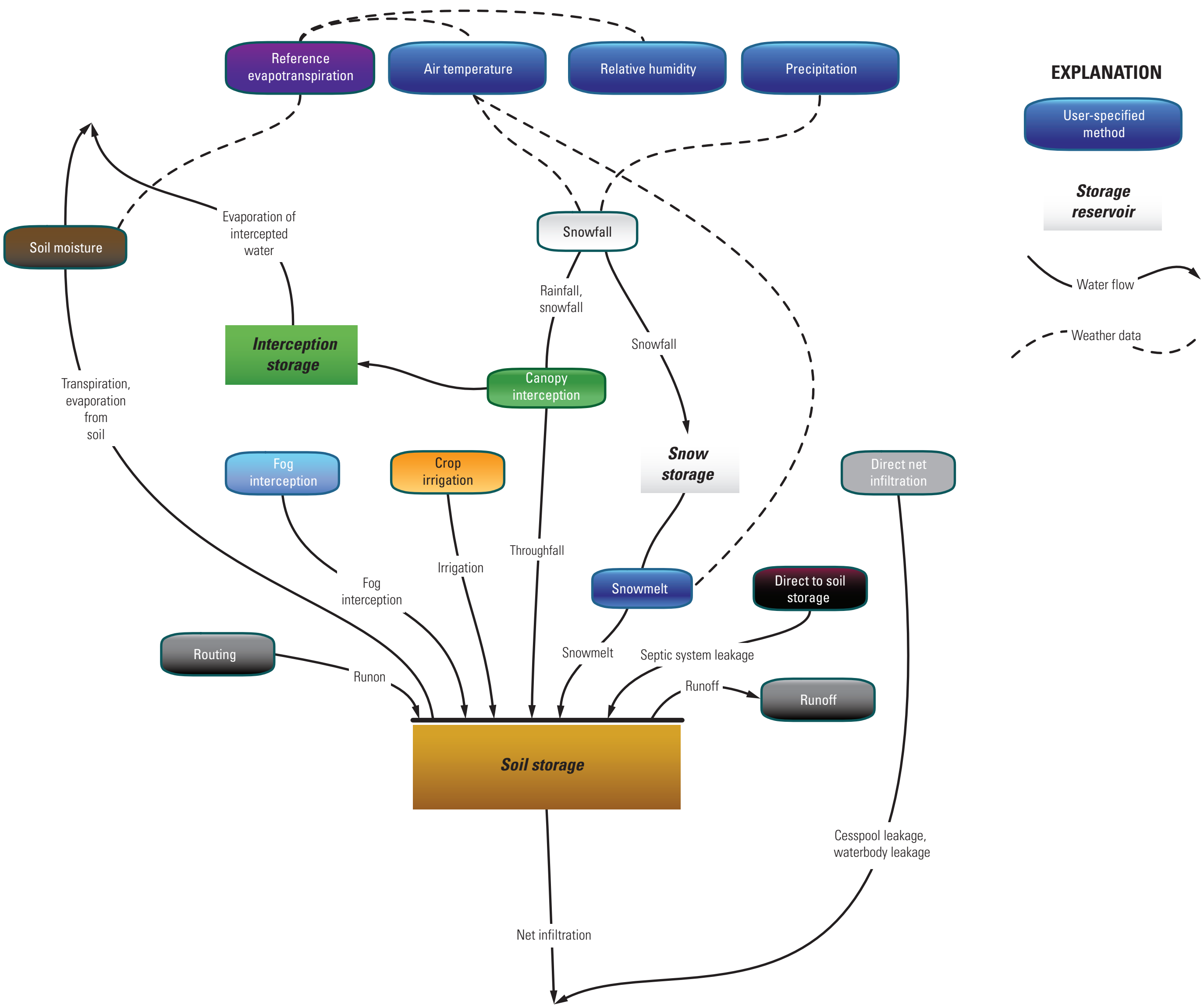

Figure 1. Conceptual diagram of Soil-Water-Balance storage reservoirs and processes.

The range of possible soil-moisture values described by equation 1 is assumed to be bounded by two values—the field capacity and the permanent wilting point. The field capacity of a soil is defined as the amount of moisture remaining in a soil after it has been saturated and allowed to drain freely. The permanent wilting point of a soil is defined as the moisture content at which plants will wilt and fail to recover even when later supplied with sufficient moisture (Barker and others, 2005). The available water capacity—one of the gridded datasets required by SWB—is defined as the difference between a soil's field capacity and its permanent wilting point. The total available water for the soil in a given grid cell is calculated as shown in equation 2.

$$TAW = \left(\theta_{FC} - \theta_{WP}\right) \cdot rooting\ depth \quad (2)$$

where

TAW is total available water, in inches;
θ_{FC} is field capacity, in inches per foot;
θ_{WP} is permanent wilting point, in inches per foot; and
rooting depth is the effective rooting depth of vegetation, in feet.

Net infiltration is assumed to take place any time the soil-moisture value (eq. 1) exceeds the total available water (eq. 2) for the cell.

The following is a list of steps to calculate net infiltration.

1. Precipitation is partitioned into gross rainfall or gross snowfall, or both.
2. Intercepted rain or snow is added to the interception storage reservoir.
3. Net snowfall is added to the snow storage reservoir.
4. Snowmelt (if any) is calculated.
5. Potential evapotranspiration (PET) is calculated.
6. Interim soil moisture is calculated as $\theta_{interim} = \theta_{t-1} + rainfall + snowmelt + runon - runoff$.
7. Direct additions to soil moisture, if any, are added to $\theta_{interim}$.
8. Interim soil-moisture fraction is calculated as $f = \dfrac{\left(\theta_{interim} - \theta_{WP}\right)}{\left(\theta_{FC} - \theta_{WP}\right)}$.
9. Actual evapotranspiration (AET) from the soil storage reservoir is calculated as some function of f and PET.
10. Updated soil moisture is calculated as $\theta_t = \theta_{t-1} + rainfall + snowmelt + runon - runoff - AET$.
11. If the updated soil moisture (θ_t) exceeds the field capacity of the soil, the updated soil moisture is set to θ_{FC}, making the change in soil moisture $\Delta\theta = \theta_{FC} - \theta_{t-1}$.
12. If the updated soil moisture is less than the field capacity, net infiltration is considered to be zero.
13. Otherwise, net infiltration is calculated as $net\ infiltration = \theta_t - \theta_{FC}$.
14. Direct net-infiltration amounts, if any, are added to the *net infiltration* amount calculated in step 13.

Surface runoff from a cell may be routed to the next downslope cell or may be considered to have reached an unmodeled surface-water feature (stream, lake, ditch) and removed from the model domain. In urban areas or in areas with significant impervious surfaces, results of simulating runoff and net infiltration in a more detailed manner might be desirable. This option is triggered in SWB 2.0 when a percent or fraction impervious area grid is supplied to the code. When this option is active, an additional storage reservoir is created—impervious surface storage. In addition, storm drains possibly can be taken into account by supplying the fraction of impervious surface storage that is intercepted by storm drains. The processes referenced in the calculation steps are discussed briefly in the next section and are discussed more fully in appendix 1.

Processes and Methods

The previous section describes the general outline of daily water-budget calculations. At each step in the calculation of the water budget, different methods for estimating hydrologic processes may be specified allowing SWB to be adapted to conditions specific to a particular project area. These methods are described in the following section. SWB control file syntax is indicated in the following section by highlighted capital letters. For example, the precipitation method might be specified in the SWB control file as `PRECIPITATION_METHOD GRIDDED`. The data and parameter requirements, SWB control file syntax, and a description of underlying physical processes and equations for each method are given in the appendixes.

Precipitation and Air Temperature

The following are three methods to specify daily precipitation data for an SWB simulation: `TABULAR`, `GRIDDED`, and `METHOD_OF_FRAGMENTS`. Air temperature data are supplied in `TABULAR` or `GRIDDED` form.

The `TABULAR` method allows a set of tabular daily precipitation and air temperature data to be supplied to all grid cells within the model domain. This method makes the use of tabular data and is suitable for application only to small project areas with dimensions of perhaps 100 square kilometers or less. Of course, the suitability of using a single precipitation and air temperature station in a SWB simulation must be tempered by knowledge of the spatial variability in rainfall, as well as by the project goals. If only annual water-budget components are of interest, a single precipitation gage may be adequate. If, however, SWB output is to be used at a monthly or daily time step, gridded data of some type probably are best if available.

The GRIDDED method instructs SWB to expect further PRECIPITATION or TMIN/TMAX grids to be specified elsewhere in the control file.

The METHOD_OF_FRAGMENTS method creates synthetic sequences of daily rainfall from monthly rainfall by imposing the rainfall pattern from selected rain gages with daily data (Srikanthan and others, 2005; Srikanthan and McMahon, 1999). The synthesized daily rainfall data approximates the long-term (annual) average character of daily rainfall, such as frequency, duration, and intensity, but may not necessarily reproduce the actual historical daily rainfall record.

Interception

The interception of precipitation by crops and other vegetation is sometimes overlooked in hydrological models, but can amount to a significant part of the water budget (Gerrits, 2010; Savenije, 2004). The SWB 1.0 code used a bucket method to estimate the amount of interception; in the bucket interception method, a constant amount of interception is assumed regardless of the total daily precipitation. In an attempt to model this part of the water budget more accurately, two additional interception process formulations have been added. The three methods implemented in SWB are the BUCKET, GASH, and HORTON. The Gash method (Gash, 1979; Gash and others, 1995) models interception by vegetation by simulating canopy storage and flow and evaporation from stems or trunk. The Horton method (Horton, 1919) is an extension of the bucket model that allows for interception values to increase in proportion to the total daily precipitation value.

Snowfall

SWB includes a single method for partitioning precipitation into rainfall and snowfall. This method, SINGLE_TEMPERATURE, is enabled by default; therefore, no control file or lookup-table entries are required to invoke the method. This method makes a comparison between a combination of the minimum and maximum air temperatures and the freezing point of water (32 degrees Fahrenheit) to partition precipitation into rainfall and snowfall.

Snowmelt

SWB includes a single snowmelt method for determining snowmelt volumes. The TEMPERATURE_INDEX method assumes that 1.5 millimeters (0.059 inch) of water-equivalent snow melts per day per average degrees Celsius that the daily maximum temperature is above freezing. This method also is enabled by default; therefore, no additional control-file or lookup-table entries are required to invoke the method.

Fog Interception

Fog interception is not explicitly modeled within SWB, but estimates of fog interception may be supplied by means of the GRIDDED data method. For pilot application of the new code to Maui, Hawaii (discussed in the appendixes), a set of external grids were developed. These grids express the intercepted fog as a fraction of the monthly observed rainfall. The process relies on external computations using the aspect, elevation, and mean monthly total rainfall grids combined with table values of estimated annual fog-interception rates to yield monthly fog-interception grids expressed as a fraction of monthly rainfall. GRIDDED fog interception is not enabled by default.

Runoff

The following two runoff estimation methods are included: the CURVE_NUMBER method and the RUNOFF_RATIO method.

The CURVE_NUMBER method (Cronshey and others, 1986) defines runoff in relation to the difference between precipitation and an initial abstraction term. User-defined curve numbers are used to describe the tendency for each land use and soil texture to generate runoff. Runoff from frozen ground is simulated by introduction of a continuous frozen ground index, which is used to track frozen ground conditions and modify runoff conditions accordingly.

Grids containing monthly RUNOFF_RATIO relative to precipitation may be used instead of the curve number method. The runoff ratio method relies on external computations to quantify a rainfall-runoff relation for a set of user-defined runoff zones. Details on the mechanics of the runoff ratio method are documented in the appendixes.

Impervious Surface Runoff

Runoff from impervious surfaces may be simulated in a more detailed manner by including a gridded dataset defining the proportion of each grid cell that is comprised of impervious materials. Impervious surfaces, defined as any grid cell with an impervious surface cover greater than zero percent, trigger the creation of a fourth storage reservoir (impervious storage reservoir), with a water balance calculated for the impervious area within the cell.

Runoff Routing

In SWB, two methods are included to implement flow routing from grid cell to grid cell. SWB allows excess water generated on a grid cell to flow to the next downslope cell using a D8 flow-routing scheme to define the linkages between cells.

The simplest method, NO_ROUTING, disables downhill routing altogether. Cell to cell routing becomes increasingly hard to imagine in a meaningful way as grid cell sizes exceed about 1 kilometer; in any system with a well-developed drainage system, overland flow would commonly meet some type of surface-water feature at this scale. With flow routing disabled, all cell runoff is assumed to reach a surface-water feature and leave the model domain.

The DOWNHILL_ROUTING method allows runoff from one or more cells to become runon to downslope cells. All runoff from a cell is assumed to infiltrate in downslope cells or be routed out of the model domain on the same day in which the runoff originated as rainfall or snowmelt.

If runoff routing is active, SWB examines the connectivity between each active cell during model startup. Based on this connectivity, SWB creates a master list of cell identities and sorts them from upslope to downslope. When the model solution is calculated each day, the code begins with the cell furthest upslope, performs all mass-balance calculations, and then proceeds to perform the same calculation on the next cell in the list.

Potential/Reference Evapotranspiration

In SWB, three methods are included to estimate potential or reference evapotranspiration—JENSEN_HAISE, HARGREAVES_SAMANI, and MONTHLY_GRID. Evapotranspiration methods developed with evaporation data from unknown or differing vegetation types are often called potential evapotranspiration methods, whereas methods developed with evaporation data for a specific crop type are often called reference evapotranspiration methods. The Jensen-Haise (1963) method can be called a potential evapotranspiration method; the method was developed using evaporation data from a variety of crops grown in the western United States and is not calibrated to any particular vegetation type. By contrast, the Hargreaves-Samani (Hargreaves and Samani, 1985) method may be called a reference evapotranspiration method; the method was developed using data from weighing lysimeters growing *Festuca altaica* grass.

Evapotranspiration estimation methods can be classified as temperature based or energy based, or both. The reference evapotranspiration method of choice is currently thought to be the FAO–56 Penman-Montieth method, which is a combined temperature and energy-based approach (Allen and others, 1998; Sentelhas and others, 2010); the FAO Penman-Monteith method is not currently included in SWB because application of the method requires gridded datasets for wind speed and relative humidity. Gridded estimates of relative humidity, when available, are often estimated from minimum and maximum air temperatures. The Hargreaves-Samani method included in SWB is a simplified estimation method recommended for use when not enough data are available to support the Penman-Monteith approach. The Jensen-Haise approach may be more applicable to sites in the southwestern United States.

Soil-Moisture Retention/Actual Evapotranspiration

In SWB, three methods are included to implement the estimation of actual evapotranspiration from the soil-moisture reservoir—THORNTHWAITE, FAO-56, and FAO-56_TWO_STAGE. Actual evapotranspiration is the soil moisture that can be extracted from a soil of a given soil-moisture condition; by definition, actual evapotranspiration will be equal to or less than the potential evapotranspiration. In the days following a rainstorm, soil moisture is close to field capacity, and moisture is evaporated from bare soil and transpired by plants at rates close to the maximum rate sustainable given climatic conditions. Assuming no further precipitation, in subsequent days the evaporation and transpiration rates decrease as remaining soil moisture is held more tightly within the soil matrix (Dunne and Leopold, 1978).

A technique to simulate decreasing rates of soil-moisture evapotranspiration is to assume that the actual evapotranspiration is some function of the potential or reference evapotranspiration and the current soil-moisture amount (eq. 3).

$$AET = PET \cdot f\left(\frac{\theta}{\theta_{FC}}\right) \tag{3}$$

where

- AET is the actual evapotranspiration, in inches;
- PET is the potential evapotranspiration, in inches;
- θ is the current soil-moisture amount, in inches; and
- θ_{FC} is the soil field capacity, in inches.

The three soil-moisture retention functions implemented in SWB are discussed in appendix 1. Of the three functions, one function was developed by (Thornthwaite, 1948), and the other two functions were included in the FAO–56 approach (Allen and others, 1998).

Growing Degree Day

Growing degree-day calculations may be enabled, triggering a growing degree-day calculation for each grid cell. SWB allows different base and maximum temperatures to be assigned for each land-use or crop type. Growing degree-day calculations are needed only if crop coefficients are used to modulate actual evapotranspiration rates, and then only if any of the crop-coefficient curves are defined in terms of growing degree days.

Crop Coefficients

The FAO–56 methodology links the estimation of actual evapotranspiration to growth patterns of vegetation and crops by means of a crop-coefficient curve that changes during the course of a growing season. The amount of water required by the vegetation or crop at any point during the growing season is determined by the following crop evapotranspiration equation:

$$ET_c = K_c ET_0 \tag{4}$$

where

- ET_c is the crop evapotranspiration amount, in inches;
- K_c is the crop coefficient (dimensionless); and
- ET_0 is the reference or potential evapotranspiration, in inches.

The crop evapotranspiration equation (eq. 4) is valid for ideal conditions; the equation would remain valid if the soil moisture stayed close to the field capacity regardless of plant water use.

Rooting Depth

Rooting depth either can be assumed static throughout the simulation or can be changed dynamically with the assumption that rooting depth is proportional to the crop-coefficient curve. For purposes of computing the water balance, the maximum root-zone depth is assumed to define the size of the soil-moisture reservoir. Specifying a dynamic rooting depth does not change the size of the soil-moisture reservoir; however, specifying a dynamic rooting depth does change the total available water, which is the amount available for plant growth.

Irrigation Demand and Application

SWB includes a single method for calculating irrigation water demand based on FAO–56 methodology (Allen and others, 1998). Once crop-water requirements have been determined, the next step in the process of simulating irrigation water demand is to apply the water in a realistic manner. The following four rules are included in the module to describe when simulated irrigation events take place.

Restore soil moisture to field capacity.—Complete elimination of soil-moisture deficit on a cell by cell basis. This option calculates the amount of water to be applied as the difference between the maximum soil-moisture value and the soil-moisture value from the previous day. Thus, this amount ignores the current day's water-balance components; the same irrigation amount will be calculated regardless of rainfall conditions.

Restore soil moisture to some fraction of field capacity.—Restore soil moisture to some specified tolerable level of soil-moisture deficit (deficit irrigation). This option calculates the amount of water to be applied as the difference between the soil moisture at some preset deficit amount and the soil-moisture value from the previous day.

Apply fixed amount of irrigation.—Apply the same, constant amount of water once the soil-moisture deficit exceeds the maximum allowable deficit. Many irrigators have sized their equipment to handle application events of average size; for example, a center-pivot irrigation setup may only be capable of delivering water within a narrow range of values. Under this option, a set amount of water is applied to the cell. If the set amount brings the soil moisture to a value in excess of field capacity, a net infiltration event will be triggered.

Apply demand-based amount on a prescribed monthly schedule.—This option is similar to the "restore soil moisture to field capacity" option, except that the calculated irrigation amount accounts for the daily or monthly rainfall and runoff amount and only is applied on a set schedule. This option was extracted from the Hawaii water-budget code and is designed to simulate the unique irrigation conditions in the Pacific Islands; the calculation is dependent on the monthly, rather than daily, datasets that generally are available in the Pacific Islands.

If more control is needed as to which crops receive or do not receive irrigation water, a supplementary irrigation mask may be supplied. This irrigation mask can be helpful if the model domain contains a single crop type, corn, for example, but has areas of irrigated cultivation and areas of dryland farming. Without an irrigation mask, control over the simulation of irrigation water application could be accomplished by including separate land-use codes, one for irrigated corn and another for dryland corn.

Rejected Net Infiltration

Specification of maximum daily net-infiltration amounts is a crude but effective way of preventing SWB from calculating unreasonably high net-infiltration values. With flow routing enabled, downslope cells can have significant amounts of water diverted to them. The resulting calculated net-infiltration values sometimes exceed the values that might be reasonable because of the soils and underlying geology. Setting a maximum daily net-infiltration value will prevent these cells from taking on unrealistic recharge values. Using this method, calculated net infiltration in excess of the maximum net-infiltration rate will be moved to the soil reservoir of the next downslope cell. A control-file directive is not needed, but lookup-table entries defining the maximum net-infiltration rate are required for each combination of land-use and soil type to use this method.

Summary

This report documents the U.S. Geological Survey Soil-Water-Balance (SWB) code, version 2.0. SWB is designed to estimate net infiltration and other water-budget components by using readily available geographic information systems (GIS) and gridded climate datasets. SWB is based on a modified Thornthwaite-Mather soil-water-balance approach, with components of the soil-water balance calculated at a daily time step. Net-infiltration calculations are computed by means of a rectangular grid of computational elements, which allows the calculated infiltration rates to be imported into grid-based regional groundwater-flow models. The code can include canopy interception, runoff, evaporation, transpiration, rainfall, and snowmelt in a basic water budget. Additional hydrologic components may be added to the simulation as needed, including fog interception, crop-water demand and irrigation, and direct additions to soil moisture and net infiltration. Version 2.0 of SWB is written so that additional process methods may be added more easily and with minimal impact on the workflow of existing SWB 1.0 users.

Appendixes to this report contain additional detail on the methods incorporated into SWB as well as a basic user's guide and detail on the format of required input grids and tables. The following is a list of the appendixes.

- Appendix 1. Method Documentation
- Appendix 2. User Guide
- Appendix 3. Input Data, Lookup-Table Entries, and Control-File Directives by Method
- Appendix 4. Example Applications

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Appendixes 1–4

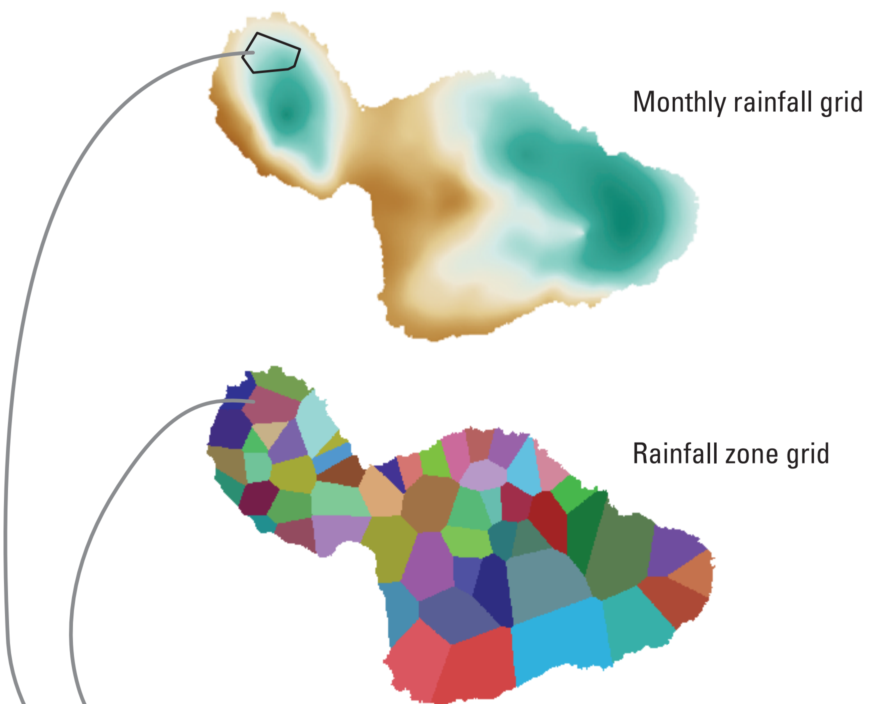
Appendix 1. Method Documentation

Each of the hydrologic processes that are part of the water budget can be simulated in one or more ways; Soil-Water-Balance (SWB) has a collection of methods that implement the processes included in the water budget. The user may select which method to use depending on which is most applicable to the problem at hand. The approach and implementation of the SWB methods are described in appendix 1. Methods that read in tabular or gridded datasets are not described in appendix 1; use of tabular or gridded data with SWB is discussed in the user guide (appendix 2).

Precipitation

Precipitation data may be supplied to SWB in gridded or tabular form or may be estimated using the method of fragments. Only the method of fragments is discussed in appendix 1.

In the method of fragments module, daily rainfall for each grid cell is generated by use of a combination of monthly gridded rainfall datasets and a set of discrete point observations. First, fragments are generated by dividing each daily rainfall observation at a point for a particular month by the total rainfall measured at the gage for that month. This method results in a set of fragments for that particular month in which the total number of fragments is equal to the number of days in the month, and for which the sum of the fragment values equals one. Thiessen polygons are developed from the network of viable rainfall gages within the model domain and are used to develop a set of rainfall zones (fig. 1–1). Thus, for each of the rainfall zones, a set of monthly fragment values is developed; the number of distinct fragment sets at a gage is about equal to the number of years the gage has been in operation. A partial set of fragments that might be generated for an arbitrary month is listed in table 1–1. A similar set of tables must be generated for each month in the year.



0	0.03	0.01	0.09	0.02	0	0.04	0.07	Rainfall fragment sequence
4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	Monthly rainfall
0	0.13	0.04	0.39	0.09	0	0.17	0.30	Synthetic daily rainfall

Figure 1–1. Example of synthetic daily rainfall generation for a specific rainfall zone.

Table 1–1. Example of fragment sets for an arbitrary month associated with a rainfall gage.

[n, the number of complete months for which daily rainfall data are available; * * *, omitted values]

Fragment set	Day of the month				
	1	2	3	* * *	31
1	0.01	0.07	0.03		0.04
2	0.02	0.05	0.02		0.02
* * *	* * *	* * *	* * *	* * *	* * *
n	0.03	0.06	0.04		0.03

Daily rainfall for a particular cell within a given month is synthesized by multiplying total gridded-rainfall amount for that month by the daily fragment value. The daily fragment values are extracted from one of the available fragment sets associated with a rainfall gage; the particular fragment set is chosen at random at the beginning of each month of the simulation (fig. 1–1).

The SWB model grid is divided into rainfall zones, and an integer-grid file that contains the rainfall zone numbers is loaded into the model during initialization. An example of this integer-grid file is in the set of digital files associated with appendix 4. Each rainfall zone represents an area in which a rainfall gage has operated for several consecutive years; at each zone, the observed daily values possibly can be used to create a rainfall-fragment set. The calculated rainfall supplied to SWB takes on the correct total monthly rainfall amount (from the grid), whereas the timing and magnitude of daily events is taken from an actual sequence of events as contained in the fragment set.

Interception

Interception of rain or snow by vegetation is an important part of the water budget; estimates of interception as a percentage of total precipitation range from 20 to 50 percent in some forested areas (Savenije, 2004). The three interception methods included in SWB are bucket, Gash, and Horton.

Bucket

The bucket method of interception is the original interception process method that was coded into SWB. The bucket method assumes that a constant, user-defined amount of rainfall or snowfall must fall before the soil will receive any precipitation.

Gash

Another option in SWB for calculating canopy interception is a modified version of the method described by Gash (1979). Using this approach, canopy evaporation for a given day and location depends on forest structure and the mean rates of evaporation and precipitation. The Gash method was modified so that (1) precipitation includes rainfall and fog interception, instead of rain only and (2) water cannot be stored on the forest canopy for more than a day (Izuka and others, 2010). The forest structure is characterized in terms of canopy cover, canopy capacity, trunk-storage capacity, and the proportion of precipitation diverted to stemflow. Canopy cover, c, is the fraction of a forested area that is covered by leaves, stems, and branches of trees. Canopy capacity, S, is the depth of water left on the canopy when rainfall and throughfall have ceased (Gash and Morton, 1978). Evaporation of water from tree trunks is accounted for using the fraction of precipitation that is diverted to stemflow, p, and trunk-storage capacity, k, which is considered in terms of an equivalent depth of precipitation. The last parameter needed for the Gash model is the ratio of the mean evaporation rate to the mean precipitation rate during saturated conditions, V.

To calculate canopy interception, the first step is to determine the minimum depth of precipitation necessary to saturate the forest canopy, P_{sat}.

$$P_{sat} = -\frac{S}{c \cdot V} \ln\left(1 - V\right) \quad (1\text{–}1)$$

where

P_{sat} is precipitation necessary to saturate the canopy, in inches;

S is canopy storage capacity, in inches (a constant);

c is fraction of ground area covered by canopy (dimensionless);

V is ratio of mean evaporation rate to mean precipitation rate during saturated conditions (dimensionless).

On the basis of the revised analytical form of the Gash model presented in table 1 of Gash and others (1995), canopy interception for a given day, I, is calculated for three canopy conditions as listed in table 1–2.

Advantages of the Gash method are as follows: (1) the method accounts for gaps in the forest canopy, which allows for a sparse canopy to be differentiated from a dense canopy; (2) the canopy interception during a period of precipitation is dependent on the amount of precipitation during that period; and (3) the method can account for spatial differences in climate. Disadvantages of the Gash model are that the method is theoretical and may be difficult to parameterize.

Horton

Robert Horton made countless observations of various hydrological processes at his hydrologic laboratory in the early 1900s, including observations of canopy interception. The Horton model begins with a bucket that must be filled regardless of total storm volume and adds a linear relation that produces an increasing canopy interception value proportional to increasing storm volume (Horton, 1919). Some of Horton's working equations that are based on his analysis of rainfall and interception are listed in table 1–3. These relations represent an improvement from the bucket model approach, which does not consider the total daily precipitation.

To use Horton's working equations in an SWB simulation, the user must supply the constant, slope, and exponent as given in table 1–3. No attempt is made to incorporate plant height; the user must modify the equation with the approximate plant height. Thus, the equation for 8-foot corn would be $I = (0.005 + 0.08 P_s) \cdot 8 = 0.04 + 0.04 P_s$; the constant, slope, and exponent supplied to SWB would be 0.04, 0.04, and 1.0, respectively.

Snowfall

Snow is allowed to accumulate or melt, or both on a daily basis. The daily mean, maximum, and minimum air temperatures are used to determine whether precipitation takes the form of rain or snow. Precipitation that falls on a day when the mean temperature minus one-third the difference between the daily high and low temperatures is less than or equal to the freezing point of water is considered to fall as snow (Westenbroek and others, 2010):

$$snow: T_{mean} - \frac{1}{3}\left(T_{\max} - T_{\min}\right) \le 32 \qquad (1\text{–}2)$$

$$rain: T_{mean} - \frac{1}{3}\left(T_{\max} - T_{\min}\right) > 32$$

where

T_{mean} is the mean daily air temperature, in degrees Fahrenheit;

T_{max} is the daily maximum air temperature, in degrees Fahrenheit; and

T_{min} is the daily minimum air temperature, in degrees Fahrenheit.

Snowmelt

Snowmelt is based on a temperature-index method. In the SWB code, the assumption is that 1.5 millimeters (0.059 inch) of water-equivalent snow melts per day per degree Celsius that the daily maximum temperature is above the freezing point (Dripps and Bradbury, 2007):

$$potential\,snowmelt = 0.059 \cdot \left(T_{\max} - 32\right) \qquad (1\text{–}3)$$

where

T_{max} is the daily maximum air temperature, in degrees Fahrenheit.

Table 1–2. Equations for calculating canopy interception for various precipitation conditions.

[k, trunk storage capacity [L] (a constant); p, proportion of precipitation diverted to stemflow (dimensionless); c, fraction of ground surface covered by vegetative canopy (dimensionless); V, ratio of mean evaporation rate to mean precipitation rate (dimensionless); P, total daily precipitation (inches); P_{sat}, precipitation amount required to fully saturate the forest canopy; I, canopy interception (inches)]

Condition	Interception calculation
$P < P_{sat}$	$I = c \cdot P$
$P \ge P_{sat}$ and $P \le \frac{k}{p}$	$I = c \cdot P_{sat} + c \cdot V \cdot \left(P - P_{sat}\right) + p \cdot P$
$P \ge P_{sat}$ and $P > \frac{k}{p}$	$I = c \cdot P_{sat} + c \cdot V \cdot \left(P - P_{sat}\right) + k$

Table 1–3. Horton's working equations for estimating intercepted rainfall.

[I, interception, in inches; P_s, precipitation received during a storm event, in inches; h, plant height, in feet]

Vegetation type	Working equation
Orchard	$I = 0.04 + 0.18P_s$
Chestnut, hedge and open	$I = 0.04 + 0.20P_s$
Chestnut, in woods	$I = 0.06 + 0.15P_s$
Ash, hedges and open	$I = 0.015 + 0.23P_s$
Ash, in woods	$I = 0.02 + 0.18P_s$
Beech, hedges and open	$I = 0.03 + 0.23P_s$
Beech, woods	$I = 0.04 + 0.18P_s$
Oak, hedges and open	$I = 0.03 + 0.22P_s$
Oak, woods	$I = 0.05 + 0.18P_s$
Maple, hedges and open	$I = 0.03 + 0.23P_s$
Maple, woods	$I = 0.04 + 0.18P_s$
Willow shrubs	$I = 0.02 + 0.4P_s$
Elm, hedges and open	$I = 0.03 + 0.23P_S^{0.5}$
Elm, woods	$I = 0.04 + 0.18P_S^{0.5}$
Basswood, hedges and open	$I = 0.03 + 0.13P_S^{0.5}$
Basswood, woods	$I = 0.05 + 0.1P_S^{0.5}$
Hemlock and pine, hedges and open	$I = 0.03 + 0.2P_S^{0.5}$
Hemlock and pine, woods	$I = 0.05 + 0.2P_S^{0.5}$
Clover and meadow grass	$I = \left(0.005 + 0.08P_s\right)h$
Forage, alfalfa, vetch, millet, etc.	$I = \left(0.01 + 0.1P_s\right)h$
Beans, potatoes, cabbage, and other small-hilled crops	$I = \left(0.02 + 0.15P_s\right)h$
Tobacco	$I = \left(0.01 + 0.08P_s\right)h$
Cotton	$I = \left(0.015 + 0.1P_s\right)h$
Buckwheat	$I = \left(0.01 + 0.12P_s\right)h$
Corn, planted in hills or rows	$I = \left(0.005 + 0.005P_s\right)h$
Fodder corn, sorghum, Kaffir corn, etc., sowed in drills	$I = \left(0.007 + 0.006P_s\right)h$

Fog Interception

Fog interception is not explicitly modeled within SWB, but estimates of fog interception may be supplied by means of externally generated grid files. For pilot application of SWB to Maui, Hawaii, a set of external grids were developed. These grids express the intercepted fog amounts as a fraction of the monthly observed rainfall amounts. The process involves computation using aspect, elevation, and monthly total rainfall grids combined with table values of estimated annual fog-interception rates to yield monthly fog-interception grids expressed as a fraction of monthly rainfall amounts. More details on this external fog calculation are in appendix 4, along with example input files.

Runoff

Runoff may be calculated by means of the Natural Resources Conservation Service curve number method or may be related to precipitation values as a set of user-defined ratios. This section describes both methods.

Curve Number

The curve number method defines runoff in relation to the difference between precipitation and an initial abstraction term. Conceptually, this initial abstraction term represents the summation of all processes that might act to reduce runoff, including interception by plants and fallen leaves, depression storage, and infiltration (Woodward and others, 2003). Equation 1–4 is used to calculate runoff volumes (Woodward and others, 2003):

$$R = \frac{(P - I_a)^2}{\left(P + \left[S_{max} - I_a\right]\right)} \qquad (1–4)$$

where

- R is runoff, in inches;
- P is daily precipitation, in inches;
- I_a is initial abstraction, in inches, the amount of precipitation that must fall before runoff is generated; and
- S_{max} is the maximum soil-moisture holding capacity, in inches.

In the original curve number methodology, the initial abstraction term is assumed to be $I_a = 0.2S_{max}$; SWB modifies the initial abstraction term to that indicated in equation 1–5. The initial abstraction (I_a) term is related to a maximum storage term (S_{max}) as follows:

$$I_a = 0.05S_{max} \qquad (1–5)$$

where

- I_a is initial abstraction, in langleys, the amount of precipitation that must fall before runoff is generated; and
- S_{max} is the maximum soil-moisture holding capacity, in langleys.

This modification implies that runoff will begin for smaller precipitation events than with the original method; this change has been determined to result in more realistic continuous simulations (Woodward and others, 2003).

The maximum storage term, in inches, is defined by the curve number for the land cover and infiltration capacity that is being considered:

$$S_{max} = \left(\frac{1{,}000}{CN}\right) - 10 \qquad (1–6)$$

where

- S_{max} is the maximum soil-moisture holding capacity, in inches; and
- CN is the curve number.

For convenience, the curve number method assigns all soils surveyed in the United States into one of four groups (A, B, C, D) on a continuum ranging from A soils, which represent porous soils of high infiltration capacity, to D soils, which represent fine textured soils of low infiltration capacity (Hawkins and others, 2009). Assumed characteristics of the four standard hydrologic soil groups are listed in table 1–4.

Curve numbers are user-defined; a separate curve number is supplied in the SWB lookup table for each combination of land use and hydrologic soil group. Curve numbers can range from 0 to 100, but the useful range of curve numbers is far less depending on the hydrologic soil group. The range of typical curve numbers for the four hydrologic soil groups are listed in table 1–5; these values should be considered when assigning curve numbers to the various land-use categories included in an SWB lookup table.

Equations 1–5 and 1–6 can be used to back calculate the implied initial abstraction values associated with the curve number ranges listed in table 1–5. For a D soil, the maximum storage term (S_{max}) ranges from about 0.63 to 3.7 inches. Use of an initial abstraction term of $0.05S_{max}$ as suggested by Woodward and others (2003) implies that between 0.03 and 0.18 inch of precipitation must fall before runoff begins. For an A soil, the maximum storage term ranges from 3.0 to 30 inches, which implies that between 0.15 and 1.5 inches of precipitation must fall before runoff begins.

Published Curve Numbers

An attractive feature of the curve number method is that published tables of curve numbers exist that serve as useful starting values for use in the SWB lookup tables. A subset of the values published with one of the curve number method publications (Cronshey and others, 1986) is listed in table 1–6; curve numbers for more land uses are given in the original publication along with details regarding appropriate choice and application of those curve numbers. Other researchers may have published curve numbers applicable to vegetation types not included in the official publications; researchers have published curve numbers intended for application to specific areas such as rangelands of the northern plains of the United States (Hanson and others, 1981), croplands in the southern plains of the United States (Hauser and Jones, 1991), and pineapple and sugarcane fields in Hawaii (Cooley and Lane, 1982).

Table 1–4. Characteristic and texture classes for the hydrologic soil groups.

[From Hawkins and others (2009). >, greater than; <, less than]

Hydrologic soil group	Characteristics	Texture	Infiltration rate (inches per hour)
A	Low runoff potential and high infiltration rates, consisting primarily of deep, well- to excessively-drained sand or gravel.	Sand, loamy sand, sandy loam	>0.30
B	Moderate infiltration rates when wetted consisting of moderately deep to deep, moderately well-drained to well-drained soils of moderately fine to coarse texture.	Silt loam or loam	0.15–0.30
C	Low infiltration rates when wetted consisting primarily of (1) soils that have an underlying layer impeding downward movement of water and (2) soils with moderately fine to fine texture.	Sandy clay loam	0.05–0.15
D	Very low infiltration rates and high runoff potential when wetted, consisting primarily of clay soils with (1) high swelling potential, (2) high permanent water table, (3) clay or claypan near the surface, or (4) shallow soils over nearly impervious material.	Clay loam, silty clay loam, sandy clay, silty clay, or clay	<0.05

Table 1–5. Range of typical curve numbers for the hydrologic soil groups.

[From Hawkins and others (2009)]

Hydrologic soil group	Minimum	Central	Maximum
A	25	51–68	77
B	48	62–77	86
C	65	70–84	91
D	73	77–88	94

Table 1–6. Recommended initial curve numbers for select land uses and hydrologic soil groups.

[From Cronshey and others, 1986. <, less than; >, greater than; –, no data]

Cover description			Curve numbers for hydrologic soil group			
Land use	**Specifics**	**Hydrologic condition**	**A**	**B**	**C**	**D**
Open space	Lawns, parks, golf courses, cemeteries	Poor (grass cover <50 percent)	68	79	86	89
		Fair (grass cover 50 percent to 75 percent)	49	69	79	84
		Good (grass cover >75 percent)	39	61	74	80
Impervious areas	Paved parking lots, rooftops, driveways	–	98	98	98	98
	Paved streets and roads—with curb and gutter	–	98	98	98	98
	Paved streets and roads—with open ditches	–	83	89	92	93
	Gravel road	–	76	85	89	91
Urban	Commercial and business	–	89	92	94	95
	Industrial	–	81	88	91	93
Residential	Lot size is < 1/8 acre	–	77	85	90	92
	Lot size is 1/8 to 1/4 acre	–	61	75	83	87
	Lot size is 1/4 to 1/3 acre	–	57	72	81	86
	Lot size is 1/3 to 1/2 acre	–	54	70	80	85
	Lot size is 1/2 to 1 acre	–	51	68	79	84
	Lot size is 1 to 2 acres	–	46	65	77	82
Newly graded areas	Pervious areas only, no vegetation	–	77	86	91	94
Fallow	Bare soil	–	77	86	91	94
	Crop residue cover	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row plus crop residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured plus crop residue cover	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured and terraced	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured and terraced plus crop residue cover	Good	65	73	79	81
			61	70	77	80

Table 1–6. Recommended initial curve numbers for select land uses and hydrologic soil groups.—Continued

Cover description			Curve numbers for hydrologic soil group			
Land use	**Specifics**	**Hydrologic condition**	**A**	**B**	**C**	**D**
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row plus crop residue	Poor	64	75	83	86
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured plus crop residue cover	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured and terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured and terraced plus crop residue cover	Poor	60	71	78	81
		Good	58	69	77	80
Pasture, grassland	Continuous forage for grazing	Poor (<50 percent ground cover or heavily grazed with no mulch)	68	79	86	89
		Fair (50 percent to 75 percent ground cover and not heavily grazed)	49	69	79	84
		Good (>75 percent ground cover and only lightly grazed)	39	61	74	80
Meadow	Continuous grass, protected from grazing, mowed for hay	–	30	58	71	78
Brush	Brush-weed-grass mixture, with brush the major element	Poor (<50 percent ground cover)	48	67	77	83
		Fair (50 percent to 75 percent ground cover)	35	56	70	77
		Good (>75 percent ground cover)	30	48	65	73
Woods	–	Poor (litter, small trees and brush destroyed by grazing or regular burning)	45	66	77	83
		Fair (woods are grazed but not burned; some forest litter present)	36	60	73	79
		Good (woods protected from grazing; liter and brush adequately cover soil)	30	55	70	77

Antecedent Runoff Conditions

SWB adjusts the user-specified curve numbers upward or downward depending on how much precipitation has fallen in the previous 5-day period. The amount of precipitation that has fallen in the previous 5-day period is used to describe soil-moisture conditions; three classes of moisture conditions are defined and are called antecedent runoff condition I, II, and III (table 1–7). The base (user-defined) curve numbers are assumed to represent antecedent runoff condition II.

For example, assume that in the previous 5 days 1 inch of precipitation fell on a grid cell; the runoff condition number would be I, and the runoff curve number would be adjusted down from the base (user-supplied) value. As another example, if a 5-day total of 1.5 inches of precipitation were to fall on a grid cell, the antecedent runoff condition would be III, and the curve number would be adjusted upwards from the base (user-supplied) value.

If the soils are nearly saturated, as in antecedent runoff condition III, the curve number for a grid cell is adjusted upward from antecedent runoff condition II (eq. 1–7) to account for generally higher runoff amounts observed when precipitation falls on saturated soil (Mishra and Singh, 2003):

$$CN_{ARC(III)} = \frac{CN_{ARC(II)}}{\left(0.427 + 0.00573 \times CN_{ARC(II)}\right)} \quad (1\text{–}7)$$

where

CN is the curve number,
ARC(III) is the antecedent runoff condition III, and
ARCII is the antecedent runoff condition II.

Conversely, when soils are dry, as in antecedent runoff condition I, curve numbers are adjusted downward from antecedent runoff condition II (eq. 1–8) in an attempt to reflect the increased infiltration rates of dry soils (Mishra and Singh, 2003).

$$CN_{ARC(I)} = \frac{CN_{ARC(II)}}{\left(2.281 - 0.01281 \times CN_{ARC(II)}\right)} \quad (1\text{–}8)$$

where

CN is the curve number,
ARC(I) is the antecedent runoff condition I, and
ARCII is the antecedent runoff condition II.

Between dry and nearly saturated conditions is antecedent runoff condition II, which represents an average rainfall-runoff relation for moderate soil-moisture conditions.

Continuous Frozen Ground Index (CFGI)

Runoff from frozen ground is simulated by adjusting the base curve numbers toward antecedent runoff condition III when frozen ground conditions exist. Frozen ground conditions are tracked by use of a continuous frozen ground index (CFGI; Molnau and Bissell, 1983):

$$CFGI_i = A \cdot CFGI_{i=1} - T \cdot e^{(-0.4K \cdot D)} \geq 0 \quad (1\text{–}9)$$

where

$CFGI_i$ is continuous frozen ground index on the current day, in Celsius degree days;
A is daily decay coefficient, unitless;
$CFGI_{i\text{-}1}$ is continuous frozen ground index on the previous day, in Celsius degree days;
T is daily mean air temperature, in degrees Celsius;
K is snow reduction coefficient, per centimeter; and
D is depth of snow on ground, in centimeters.

The values for the coefficients A and K are defined in the same manner as described by Molnau and Bissel (1983): K=0.5-$^{\text{centimeter}}$ for above-freezing periods, K=0.08-$^{\text{centimeter}}$ for below-freezing periods, and A=0.97. During conditions of no snow cover, the CFGI represents the running sum by which the average air temperature deviates from the freezing point of water; snow conditions cause the CFGI to grow or shrink at a slower rate.

Table 1–7. Antecedent runoff conditions.

[Nongrowing season and growing season antecedent runoff conditions are given in inches]

Runoff condition number	Description	Nongrowing season	Growing season
I	Dry	0.05	1.4
II	Average	0.5–1.1	1.4–2.1
III	Near saturation	1.1	2.1

The CFGI is applied by allowing for a transition range to be applied through which runoff enhancement ranges from negligible to strong (Molnau and Bissell, 1983).

In the SWB code, a probability of runoff enhancement factor, P_f, is used to linearly interpolate between the curve numbers at antecedent runoff condition II and antecedent runoff condition III; P_f is defined as given in equation 1–10.

$$P_f = \frac{CFGI - LL}{UL - LL} \tag{1–10}$$

where

- P_f is the probability that runoff will be enhanced by frozen ground conditions;
- $CFGI$ is continuous frozen ground index, in Celsius degree days;
- UL is the upper limit of the *CFGI*, above which frozen ground conditions exist, in Celsius degree days; and
- LL is the lower limit of the *CFGI*, below which frozen ground conditions do not exist, in Celsius degree days.

If no values are assigned for *LL* and *UL*, default values of 9999 are assigned to both, effectively disabling the CFGI option; this behavior is unchanged from SWB version 1.0. If the CFGI option is used, Molnau and Bissel (1983) recommend starting with a value of 83 Celsius degree days for the upper limit and a value of 56 Celsius degree days for the lower limit. These values were developed for the Pacific Northwestern United States and may not be applicable elsewhere.

Monthly Runoff Fraction Grid

Grids containing monthly runoff ratios relative to precipitation may be used instead of the curve number approach. A series of grids may be supplied as discussed in the user guide in appendix 2.

Impervious Surface Runoff

Runoff from impervious surfaces may be simulated in a more detailed manner by including a gridded dataset defining the proportion of each grid cell that is comprised of impervious materials. Data may be supplied as either a fraction (0.0–1.0) or percentage (0–100 percent) of either pervious or impervious surface area.

Any cell that is assigned an impervious surface fraction or percent that is greater than zero will operate in a fundamentally different way than in original SWB code; in these cells, mass-balance calculations will be performed on an additional impervious surface storage reservoir (fig. 1–2), the capacity of which is determined by the impervious surface rainfall-retention depth.

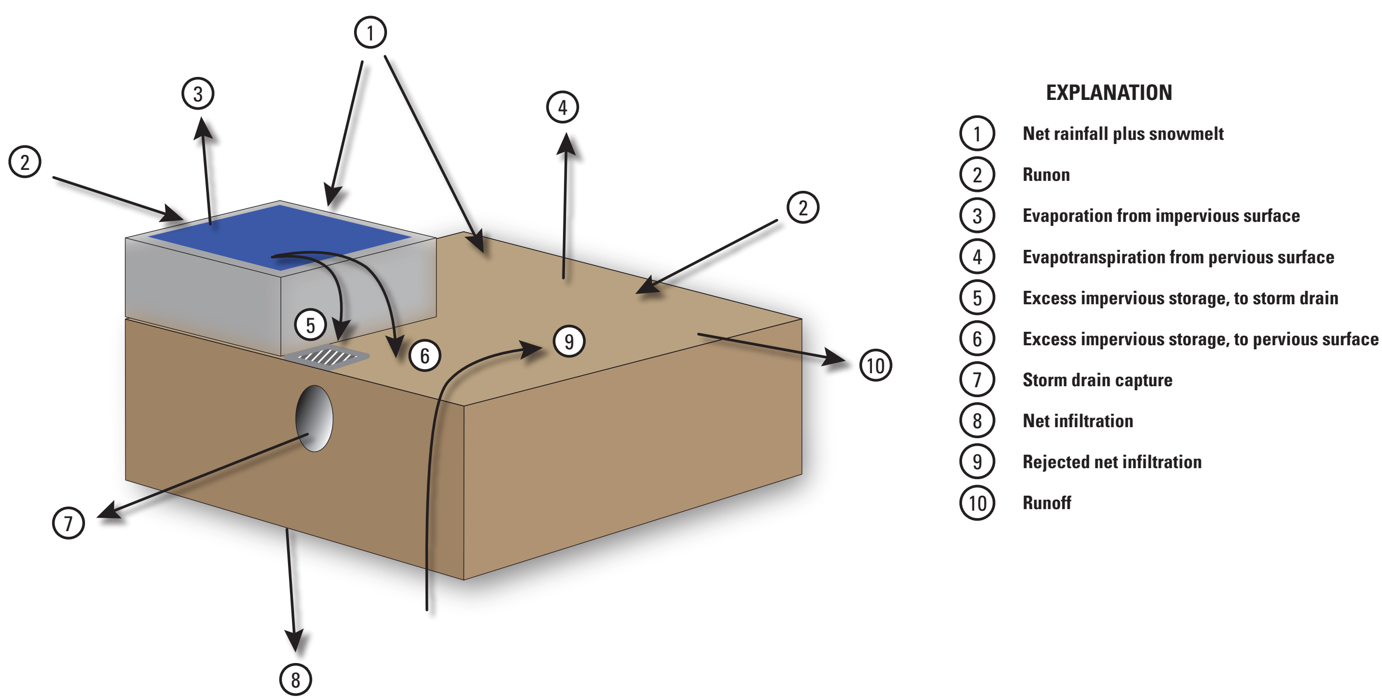


Figure 1–2. Conceptual diagram showing treatment of impervious surface runoff.

For grid cells with impervious surfaces, a temporary impervious storage amount is determined using the following conditions:

$$imperv\_stor_{temp} = rainfall + snowmelt + imperv\_stor_{t-1} - evap\_imperv \quad (1\text{–}11)$$

where

$imperv\_stor_{temp}$ is the temporary impervious storage amount,
$rainfall$ is the daily rainfall amount,
$snowmelt$ is the daily snowmelt amount,
$imperv\_stor_{t-1}$ is the previous days' impervious storage amount, and
$evap\_imperv$ is the daily evaporation of water from the impervious surface.

The final amount of water stored in the impervious storage reservoir is dependent on the value of $imperv\_stor_{temp}$. The values of the daily ending impervious storage amount and the impervious storage excess are calculated as listed in table 1–8 depending on whether the temporary impervious storage amount is less than or greater than the maximum impervious storage amount.

The resulting impervious surface excess is distributed to the pervious fraction of the cell or is directed to a storm sewer for immediate removal of the surface excess from the model domain. Specifying a storm-drain capture fraction greater than zero will result in that fraction of impervious surface excess being diverted and extracted from the model domain. The model default is zero, or no, storm-drain capture and zero, or no, fraction impervious surface. The storm-drain capture fraction may be supplied in a lookup table or in gridded form.

Runoff Routing

SWB allows excess water generated at a grid cell to flow to the next downslope cell using a D8 flow-routing scheme to define the linkages between cells. Activation of the overland flow-routing method within SWB allows runoff from one or more cells to become runon to downslope cells. All runoff from a cell is assumed to infiltrate in downslope cells or be routed out of the model domain on the same day in which the runoff originated as rainfall or snowmelt. Runoff flow routing may be disabled and also may be configured such that only some fraction of runoff is routed to the downslope cell.

During model initialization, SWB examines the connectivity between each active cell. Based on this connectivity, SWB creates a master list of cell identifications and sorts them from upslope to downslope. When the model solution is calculated each day, the code begins with the cell furthest upslope, performs all mass-balance calculations, and then proceeds to perform the same calculation on the next cell in the list.

Connectivity is defined on the basis of an input D8 flow-direction grid; this is a scheme by which connections between cells are encoded as an integer value within the flow-direction grid (O'Callaghan and Mark, 1984), with flow directions defined as shown in figure 1–3*B*. The original algorithm assigns a unique flow direction to each grid cell by determining the steepest slope between the central cell and its eight neighboring cells. For the cells shown in figure 1–3*A*, the steepest descent algorithm results in flow from the central cell to the southwest; the corresponding cell figure 1–3*B*, located to the southwest of the central cell, contains the number 8. By convention, therefore, the D8 flow direction for the cell shown in figure 1–3*A* is 8.

Table 1–8. Equations for determining impervious surface storage and impervious surface storage excess.

[$imperv\_stor_t$, daily ending impervious storage amount, in inches; $imperv\_store_{excess}$, excess impervious storage amount in inches; $imperv\_stor_{temp}$, temporary impervious storage amount, in inches; $imperv\_stor_{max}$, maximum impervious storage amount in inches; *f*, ratio of impervious surface fraction to the pervious surface fraction (dimensionless); *imperv_frac*, fraction of the grid cell covered by impervious surfaces (dimensionless)]

Condition	Value of $imperv\_stor_t$	Value of $imperv\_stor_{excess}$
$imperv\_stor_{temp} \leq imperv\_stor_{max}$	$imperv\_stor_{temp}$	Zero
$imperv\_stor_{temp} > imperv\_stor_{max}$	$imperv\_stor_{max}$	$\left(imperv\_stor_{temp} - imperv\_stor_{max}\right) \cdot f$ where $f = \left(\frac{imperv\_frac}{1 - imperv\_frac}\right)$

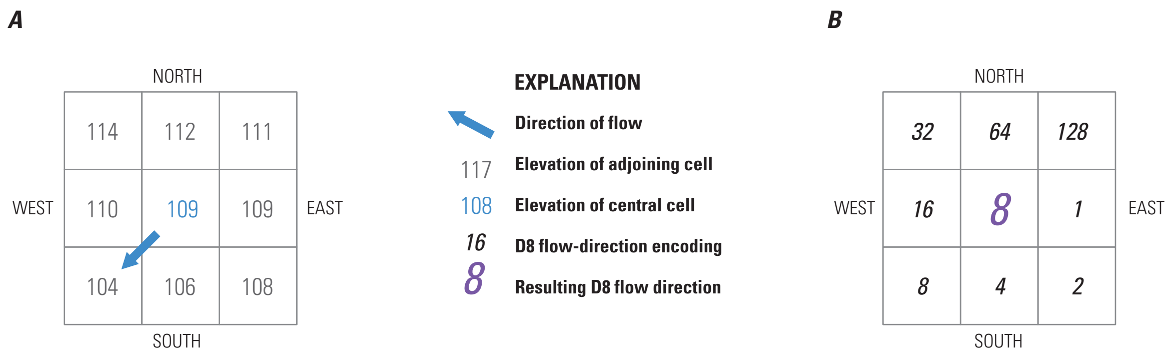


Figure 1–3. Examples of *A*, elevation grid values, in meters and *B*, resulting D8 flow-direction encoding.

Once water is routed to a closed surface depression and evapotranspiration and soil-moisture demands are met, the only loss mechanism is net infiltration. The simplified nature of the flow routing results in cases where maximum net-infiltration values of hundreds or thousands of inches per year are calculated. These values are unrealistic and likely result from the simplified treatment of overland flow routing. SWB allows the user to enter a maximum recharge rate for each land cover and soil group combination. This feature offers a way to restrict the estimated net-infiltration values to a more reasonable range; however, the rejected net infiltration, nonetheless, is removed from the model domain on the same day in which the net infiltration originated as precipitation or snowmelt.

If desired, only a fraction of the calculated runoff can be routed downslope. A user-specified routing fraction grid may be specified in order to split runoff between RUNOFF_OUTSIDE (in other words, assumed to join a surface-water feature and exit the model grid) and inflow to the next downslope cell. For cases in which flow routing is undesirable, the runoff flow routing routine may be disabled altogether.

Potential/Reference Evapotranspiration

Thornthwaite (1948) classified the world's climate and observed that "* * *there is a distinction* * *between the amount of water that actually transpires and evaporates and that which would transpire and evaporate if it were available. When water supply increases, as in a desert irrigation project, evapotranspiration rises to a maximum that depends only on the climate. This we may call 'potential evapotranspiration,' as distinct from actual evapotranspiration."

At about the same time that Thornthwaite (1948) was making climate observations, agronomists were struggling with the notion of plant evapotranspiration. The Blaney-Criddle and Hargreaves-Samani methods attempt to link a method to a specific vegetation type and condition or reference crop. The potential evapotranspiration associated with a specific crop may be considered to be a reference evapotranspiration amount. The Blaney-Criddle method, for example, links the potential evapotranspiration to an 80–150 millimeters tall actively growing green-grass cover, "completely shading the ground and not short of water" (Allen and Pruitt, 1986).

SWB provides the Jensen-Haise (Jensen and Haise, 1963) and the Hargreaves-Samani (Hargreaves and Samani, 1985) methods for estimating potential or reference evapotranspiration. The Jensen-Haise method for estimating potential evapotranspiration (ET) was developed with evapotranspiration data for several crop types common to the southwestern United States. The Hargreaves-Samani method for estimating reference evapotranspiration (ET0) was developed with evapotranspiration data pertaining to a reference crop of fescue grass of known length. In SWB, both of these methods rely on air temperature observations (table 1–9) to estimate the amount of extraterrestrial solar radiation that reaches the crop surface. Both methods will likely return similar values. The Jensen-Haise method may be more appropriate for sites in the southwestern United States. Users should examine the SWB-estimated potential evapotranspiration amounts and compare them to estimates published by university agricultural extension services and others.

Table 1–9. Data requirements for the reference/potential evapotranspiration estimation methods included in SWB.

Method	Minimum air temperature (degrees Fahrenheit)	Maximum air temperature (degrees Fahrenheit)	Gridded monthly estimates (inches per month)
Jensen-Haise	Yes	Yes	No
Hargreaves-Samani	Yes	Yes	No
Monthly gridded	No	No	Yes

The distinction between potential ET and reference ET0 is more important if the FAO–56 crop coefficients are to be applied as modifiers to the potential or reference evapotranspiration values. Crop coefficients are often determined and published with a particular reference crop in mind. The crop coefficients published in Allen and others (1998) are developed with the same reference crop *Festuca altaica* (Alta fescue) grass that was used to develop the Hargreaves-Samani method. Solar radiation at the top of the atmosphere (extraterrestrial solar radiation) is calculated for both the Jensen-Haise and the Hargreaves-Samani methods by making use of standard estimation equations that take into account Earth's position and tilt relative to the sun and the position of the grid cell upon the Earth. The equations are applied by using the latitude and longitude of each grid cell for each day of the year; the form of the equations used to calculate extraterrestrial solar radiation are in Meeus (1991).

Jensen-Haise Method

Jensen and Haise (1963) developed an empirical method that related potential evapotranspiration to solar radiation and air temperature for several crops grown in the southwestern United States—crop types included alfalfa, oats, cotton, and winter wheat. The equation is as follows:

$$ET_p = \left(0.014 \cdot T_{mean} - 0.38\right) R_s \qquad (1\text{–}12)$$

where

- ET_p is the daily potential evapotranspiration, in inches;
- T_{mean} is the mean daily air temperature, in degrees Fahrenheit; and
- R_s is the solar radiation received at the crop surface, in inches per day.

Solar radiation at the crop surface is estimated as a function of the percentage of total possible sunshine that was received on a given day:

$$R_s = \left(a + b \cdot f_{sun}\right) R_a \qquad (1\text{–}13)$$

where

- R_s is the solar radiation received at the crop surface, in inches per day;
- a is the fraction of total solar radiation received on an overcast day (dimensionless), often 0.25;
- b is the fraction of total solar radiation received on a clear day (dimensionless), often 0.75;
- f_{sun} is the amount of daily sunshine as a fraction of total possible sunshine (dimensionless); and
- R_a is the extraterrestrial solar radiation, in inches per day.

The use of equation 1–13 requires data on the fraction of total sunshine, which is usually difficult to find on a consistent basis. SWB uses minimum and maximum air temperature to estimate the fraction of total possible sunshine (Allen and Pruitt, 1986):

$$f_{sun} = \left(0.35\sqrt{T_{max} - T_{min}}\right) - 0.5 \qquad (1\text{–}14)$$

where

- f_{sun} is the amount of daily sunshine as a fraction of total possible sunshine (dimensionless);
- T_{max} is the maximum daily air temperature, in Kelvin; and
- T_{min} is the minimum daily air temperature, in Kelvin.

Hargreaves-Samani Method

The Hargreaves and Samani equation was developed as a way to calculate reference evapotranspiration using only limited data. The coefficients were developed with data derived from a weighing lysimeter planted with Alta fescue grass (Hargreaves and Samani, 1985). The equation is as follows:

$$ET_0 = 0.0023\left(T_{mean} + 17.8\right)\sqrt{T_{max} - T_{min} R_a} \qquad (1\text{–}15)$$

where

- ET_0 is the grass-reference evapotranspiration, in millimeters per day;
- T_{mean} is the mean daily air temperature, in degrees Celsius;
- T_{max} is the maximum air temperature, in degrees Celsius;
- T_{min} is the mean daily air temperature, in degrees Celsius; and
- R_a is extraterrestrial solar radiation, in millimeters per day.

Monthly Grid

If available, users also may use gridded daily or monthly estimates of reference or potential evapotranspiration. These gridded estimates allow SWB to be run using more sophisticated evapotranspiration estimates, including satellite-derived estimates.

Actual Evapotranspiration/ Soil-Moisture Retention

Actual evapotranspiration is the soil moisture that can be extracted from a soil of a given soil-moisture condition; by definition, actual evapotranspiration will be equal to or less than the potential evapotranspiration. In the days following a rainstorm, soil moisture is close to field capacity, and moisture is evaporated from bare soil and transpired by plants at rates close to the maximum rate sustainable for given climatic conditions. Assuming no further precipitation or other moisture input (such as irrigation), in subsequent days the evaporation and transpiration rates decrease as remaining soil moisture is held more tightly within the soil matrix (Dunne and Leopold, 1978).

Common terms regarding these concepts are listed and defined in table 1–10. More detail about each of these concepts is in Allen and others (1998).

A way of simulating decreasing rates of soil-moisture evapotranspiration is to assume that the actual evapotranspiration is some function of the potential or reference evapotranspiration and the current soil-moisture amount (eq. 1–16).

$$AET = PET \cdot f\left(\frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}}\right) \qquad (1\text{–}16)$$

where

AET is the actual evapotranspiration, in inches;
PET is the potential evapotranspiration, in inches;
f is a function of arbitrary shape;
θ is the current soil-moisture amount, in inches;
θ_{WP} is the soil-moisture amount at the permanent wilting point, in inches; and
θ_{FC} is the soil-moisture amount at field capacity, in inches.

Many different functions have been developed to relate potential evapotranspiration to actual evapotranspiration. Veihmeyer (1938) suggested that soil evapotranspiration is equal to potential evapotranspiration regardless of how close the soil moisture is to the wilting point. Zahner (1967) proposed a set of relations that changed depending on whether the soils in question were predominantly sand, loam, or clay. The relation included in FAO–56 (Allen and others, 1998) assumes that actual evapotranspiration and potential evapotranspiration are equal up to some critical

Table 1–10. Definitions of common terms used in describing soil-moisture retention and actual evapotranspiration.

Term	Units	Definition
Field capacity	Inches	Soil-moisture value at which the soil matrix is nearly saturated and gravity drainage from the soil ceases.
Wilting point	Inches	Soil-moisture value below which plants are incapable of extracting further soil moisture for growth. Sometimes called the permanent wilting point because irreversible plant stress and subsequent death are common once the soil reaches this moisture value.
θ_{FC}	Inches	Soil-moisture amount at field capacity.
θ_{WP}	Inches	Soil-moisture amount at the permanent wilting point.
TAW	Inches	Total available water. This is the amount of water available in the soil for potential plant growth and can be calculated as $\theta_{FC} - \theta_{WP}$.
RAW	Inches	Readily available water. In the FAO–56 methodology, the readily available water is available to plants at a rate equal to potential evapotranspiration.
p	Unitless	Plant water stress depletion fraction. This is the fraction of total available water that may be used by plants before they begin to experience water stress (and subsequent reduction in actual evapotranspiration rates); $p = \frac{RAW}{TAW}$.
$\theta_{threshold}$	Inches	Threshold soil moisture. This is the soil moisture below which plants begin to experience water stress; $\theta_{threshold} = p \cdot (\theta_{FC} - \theta_{WP}) + \theta_{WP}$.

soil-moisture level. At the point of critical soil moisture (coinciding with the onset of plant water stress), the ratio of actual to potential ET decreases until the soil moisture equals the wilting point where the ratio of actual to potential ET reaches a value of zero. At soil moisture equal to the field capacity, Thornthwaite and Mather (1957) considered the ratio of actual to potential ET to be equal to one, decreasing linearly to zero at a soil moisture equal to the wilting point.

The two soil-moisture retention methods implemented in SWB are discussed in this section; one method developed by Thornthwaite and Mather (1957) and the other method included in the FAO–56 approach (Allen and others, 1998).

Thornthwaite-Mather Method

In the late 1940s and early 1950s, C.W. Thornthwaite and his associates studied plant growth and water utilization. As a result of this work, Thornthwaite observed that the relation between the actual ET to potential ET ratio and the soil moisture was linear (fig. 1–4).

The first versions of SWB included full-tabularized versions of the soil-moisture retention function, along with methods to interpolate among the various table values. The original published method (Thornthwaite and Mather, 1957) also introduced a variable, accumulated potential water loss (APWL), to track the cumulative unmet potential evapotranspiration; this term APWL was developed in an age before easy access to computers and calculators; when used with the table values, this set of tabulated, APWL values made calculation of the daily water balance simpler. SWB updates the soil-moisture value by means of the relation derived in equations 1–17 through 1–25. Daily soil moisture may be estimated from this relation by first defining the instantaneous soil evapotranspiration as equal to the change in soil-moisture storage:

$$et_a = -\frac{d\theta}{dt} \tag{1–17}$$

where

et_a is the instantaneous actual evapotranspiration, and

$\frac{d\theta}{dt}$ is the rate of change in soil moisture relative to time.

The relation shown in figure 1–4 can be used to define a function relating actual and potential evapotranspiration as:

$$et_a = et_0 \cdot \frac{\theta}{\theta_{FC}} \tag{1–18}$$

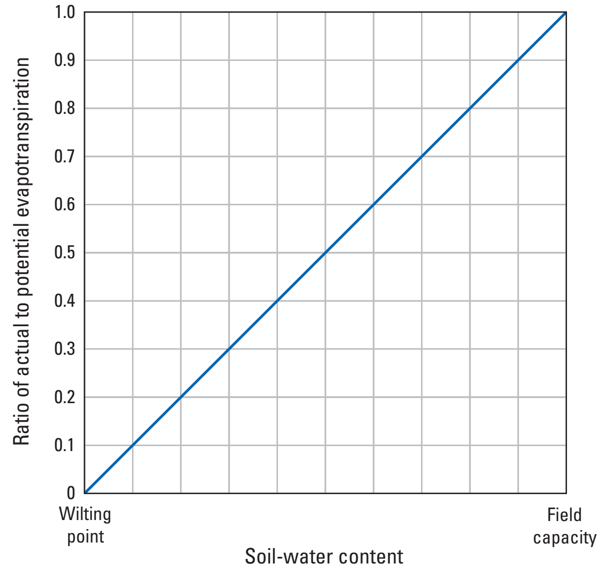


Figure 1–4. Thornthwaite-Mather relation between actual and potential evapotranspiration.

where

et_a is the instantaneous actual evapotranspiration,

et_0 is the instantaneous potential evapotranspiration,

θ is the soil moisture, and

θ_{FC} is the soil-moisture value at field capacity.

Equation 1–17 and equation 1–18 can be set equal to one another, and the terms can be rearranged and integrated to yield an estimate of the current daily soil moisture:

$$-\frac{d\theta}{dt} = et_0 \cdot \frac{\theta}{\theta_{FC}}, \tag{1–19}$$

$$\frac{d\theta}{\theta} = -\frac{et_0}{\theta_{FC}} dt, \tag{1–20}$$

and

$$\int \frac{d\theta}{\theta} = -\frac{1}{\theta_{FC}} \int et_0 dt \tag{1–21}$$

where

$\frac{d\theta}{dt}$ is the rate of change in soil moisture relative to time,

et_0 is the instantaneous potential evapotranspiration,

θ is the soil moisture,

θ_{FC} is the soil-moisture value at field capacity,

$d\theta$ is the change in soil-moisture, and

dt is the change in time.

The integral of the instantaneous potential ET during the course of a day is equal to the total daily reference ET_0 value. An interim soil-moisture value may be defined

$$\theta_{interim} = \theta_{t-1} + rainfall + irrigation + snowmelt + runon - interception - runoff \quad (1\text{–}22)$$

where

$\theta_{interim}$ is the interim soil moisture, and

θ_{t-1} is the soil moisture on the previous day.

The integral of soil moisture is evaluated from $\theta_{interim}$ to θ_t:

$$\ln\theta\Big|_{\theta_{interim}}^{\theta_t} = -\frac{ET_0}{\theta_{FC}} \quad (1\text{–}23)$$

where

θ_t is the soil moisture on the current day,

$\theta_{interim}$ is the interim soil moisture,

ET_0 is the reference evapotranspiration, and

θ_{FC} is the soil moisture at the field capacity for the soil.

Exponentiating both sides and solving for the current soil moisture θ_t yields:

$$\theta_t = \theta_{interim} \cdot e^{\left(-\frac{ET_0}{\theta_{FC}}\right)} \quad (1\text{–}24)$$

where terms are the same as those defined for equation 1–23.

The actual ET value ET_{actual} is the difference between the interim and final soil-moisture values:

$$ET_{actual} = \theta_{interim} - \theta_t \quad (1\text{–}25)$$

FAO–56 Method

The FAO–56 method for determining actual evapotranspiration considers the process in two phases (fig. 1–5). In the first phase, soil-moisture levels are between a threshold soil-moisture level and field capacity, and the actual ET is assumed to be equal to the reference ET_0. At soil-moisture levels below the threshold level, the ratio between actual and reference ET_0 is assumed to decrease linearly, with the ratio having a value of zero as the soil moisture reaches the permanent wilting point.

The first step toward estimating the daily actual evapotranspiration is to eliminate evapotranspiration from the water balance equation and calculate an interim soil-moisture:

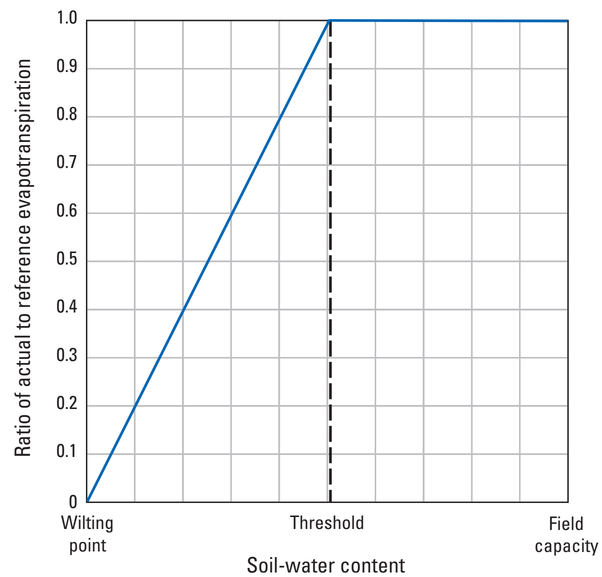


Figure 1–5. FAO–56 relation between actual and reference evapotranspiration.

$$\theta_{interim} = \theta_{t-1} + rainfall + irrigation + snowmelt + runon - interception - runoff \quad (1\text{–}26)$$

where

$\theta_{interim}$ is the interim soil moisture, and

θ_{t-1} is the soil moisture on the previous day.

The relation shown in figure 1–5 may be used to update the interim soil moisture by considering the following three cases:

1. $\theta_{threshold} = 0$, which eliminates the sloped part of figure 1–5;
2. $\theta_{interim} > \theta_{threshold}$, which implies that actual ET equals reference ET_0 for all or part of the day; and
3. $\theta_{interim} \le \theta_{threshold}$, which means that the actual ET is some fraction of reference ET_0 for the entire day.

In the first case, actual ET equals reference ET_0, so the new soil-moisture value is:

$$\theta_t = \theta_{interim} - ET_0 \quad (1\text{–}27)$$

where

$\theta_{interim}$ is the interim soil-moisture amount, in inches; and

ET_0 is the daily reference evapotranspiration amount, in inches.

The second case is a linear combination of the first and third cases, and f can be defined as the fraction of the day that the soil-moisture value would exceed the threshold value:

$$f = \frac{\left(\theta_{interim} - \theta_{threshold}\right)}{ET_0} \tag{1–28}$$

where

$\theta_{interim}$ is the interim soil-moisture amount, in inches;

$\theta_{threshold}$ is the soil-moisture amount below which plant stress occurs, in inches; and

ET_0 is the daily reference evapotranspiration amount, in inches.

The new soil-moisture value for the current day can then be determined as:

$$\theta_t = \theta_{threshold} \cdot e^{\left(-\frac{(1-f)\,ET_0}{\theta_{threshold}}\right)} \tag{1–29}$$

where

$\theta_{threshold}$ is the soil-moisture amount below which plant stress occurs, in inches;

f is the fraction of the day that soil moisture exceeds the threshold (eq. 1–28), in inches; and

ET_0 is the daily reference evapotranspiration amount, in inches.

The actual ET value is then the difference between the interim and final soil-moisture values:

$$ET_{actual} = \theta_{interim} - \theta_t \tag{1–30}$$

where

$\theta_{interim}$ is the interim soil-moisture amount, in inches; and

θ_t is the soil-moisture amount at the end of the current day, in inches.

In the third case, new soil-moisture value for the current day can be determined as:

$$\theta_t = \theta_{interim} \cdot e^{\left(-\frac{ET_0}{\theta_{interim}}\right)} \tag{1–31}$$

Growing Degree Day

SWB calculates the growing degree day (GDD) specific to each crop type, if desired. The GDD is calculated by summing the difference between the mean air temperature and some base temperature for a specified number of days:

$$GDD = \sum_n \left[\frac{(T_{max} + T_{min})}{2} - T_{base} \right] \tag{1–32}$$

where

GDD is growing degree days;

n is the number of days during which the calculation is performed;

T_{max} is the maximum daily air temperatures;

T_{min} is the minimum daily air temperatures; and

T_{base} is a reference temperature, often crop or plant specific.

Temperature values in the GDD calculation are often restrained to prevent the GDD values from growing unreasonably. When applying the method to corn, for example, T_{base} is often set to 50 degrees Fahrenheit (°F), T_{max} is set to 86 °F, and T_{min} is set to 50 °F. If no values are provided by the user, SWB uses the values for corn (T_{base} of 50 °F, a T_{max} of 86 °F, and a T_{min} of 50 °F).

Growing Season

SWB keeps track of a binary state variable (a variable having a value of either zero or one) that indicates growing season status. Growing season in SWB is either active or inactive. Growing season status affects plant interception calculations and antecedent runoff conditions (table 1–7).

The growing season is tracked independently of other plant-growth related parameters, such as the planting date defined for use with the crop-coefficient module. These parameters remain unlinked and unrelated because the crop-coefficient module will not necessarily be active for every SWB simulation.

Two methods are available for keeping track of the growing/nongrowing season status. The simplest method allows a day of year or month and day to be input for each land-use type in order to control when the growing season status is flipped. The second method allows a minimum growing degree-day value to be set to initiate plant growth and a minimum mean-air temperature (killing air temperature) to be set to halt plant growth.

The two methods may be mixed, in other words, a set of starting and ending dates may be defined for a particular land-use or crop type, whereas a growing degree-day threshold and killing air temperature may be specified for another land-use or crop type.

Crop Coefficients

The FAO–56 methodology links the estimation of actual evapotranspiration to growth patterns of vegetation and crops by means of a crop-coefficient curve that changes during a growing season. The amount of water required by the vegetation of a crop at any point during a growing season is given in equation 1–33:

$$ET_c = K_c ET_0 \tag{1–33}$$

where

ET_c is crop evapotranspiration,
K_c is the crop coefficient, and
ET_0 is the reference evapotranspiration.

The crop evapotranspiration equation (eq. 1–33) is valid for ideal or standard conditions—a condition in which soil moisture stays close to field capacity regardless of plant water use. An example of the simplified crop-coefficient curve used in the FAO–56 calculation is shown in figure 1–6. The curve is made up of a set of piecewise linear functions that define the overall shape of the crop-coefficient curve during a growing season. Specification of this curve for each crop and plant type (land-use type) in the model requires that a set of growth stage lengths L_{ini}, L_{dev}, L_{mid}, L_{late}, and L_{fallow}, and a set of corresponding crop coefficients that are included in the irrigation lookup table. The growth stage lengths represent the number of days each growth stage lasts. The growth stage lengths are added to the day of year at time of planting which yields the day of year associated with the inflection points defining the crop coefficient curve in figure 1–6. Note that because the crop-coefficient values may have values greater than one, the crop water requirement can easily exceed the potential or reference ET values during peak growth periods. The length values that form the crop-coefficient curve may be replaced with growing degree days. SWB calculates, if desired, the growing degree days specific to each crop type.

The calculation of actual evapotranspiration during nonstandard (moisture-limited) growing conditions is to multiply the crop evapotranspiration amount by a plant water stress factor whose value may range between 0.0 and 1.0. The water stress factor declines toward zero as the amount of available soil moisture decreases. The adjusted crop evapotranspiration is given in equation 1–34.

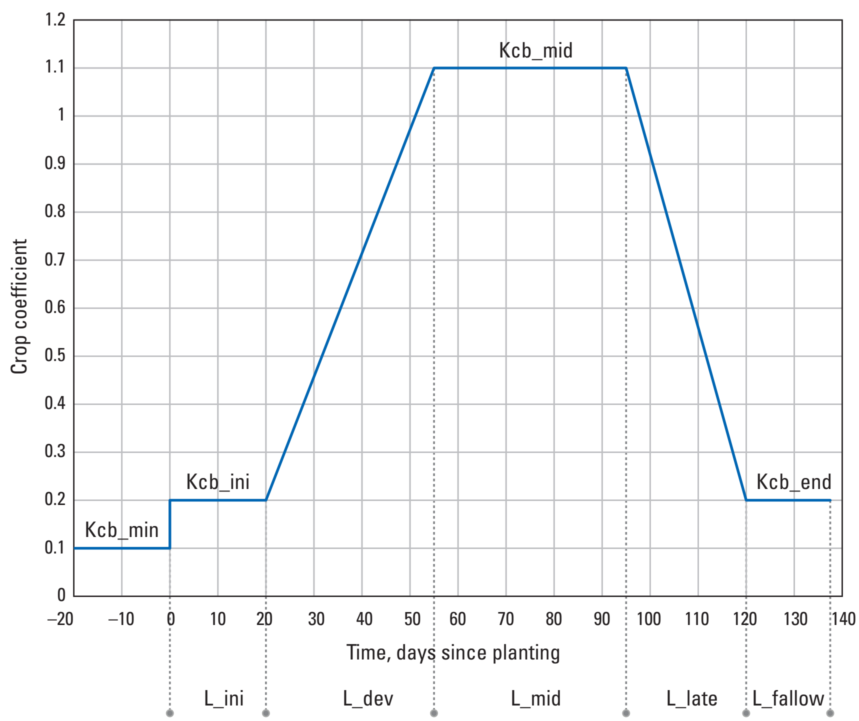


Figure 1–6. Example simplified crop-coefficient curve (Allen and others, 1998).

$$ET_{c,adj} = K_s K_c ET_0 \tag{1–34}$$

where

$ET_{c,adj}$ is adjusted crop evapotranspiration,
K_s is the plant water stress factor,
K_c is the crop coefficient, and
ET_0 is the reference or potential evapotranspiration.

The plant water stress factor is defined by the soil-moisture deficit relative to two soil-moisture amounts—the readily available water and total available water amounts. Total available water is defined as the maximum amount of water that can be present within the root zone and is calculated in SWB as:

$$TAW = AWC \cdot \left(rooting\ depth \right) = \theta_{FC} - \theta_{WP} \tag{1–35}$$

where

TAW is the total available water;
AWC is the available water capacity, in inches per foot;
rooting depth is the current rooting depth of vegetation, in feet;
θ_{FC} is the soil-moisture amount at the field capacity of the soil, in inches; and
θ_{WP} is the soil-moisture amount at the permanent wilting point, in inches.

Readily available water is defined as the amount of water that can be withdrawn by a plant from soil-moisture storage without the plant suffering water stress. Readily available water may be defined as some fraction of the total available water:

$$RAW = p \cdot TAW \tag{1–36}$$

where

RAW is readily available water, and
p is the fraction of total available water (TAW) that can be removed from soil-moisture storage before a plant begins suffering from water stress; p is called the plant_stress_depletion_fraction in the SWB irrigation lookup table.

The soil-moisture deficit is calculated as $deficit = TAW - \theta_t$ and represents the amount by which the current daily soil moisture departs from the total available moisture storage capacity of the soil. At soil-moisture deficits less than the readily available water amount, plants are assumed to have adequate available moisture for growth; plants are assumed to not have water stress, and the plant water stress factor has a value of one.

Once soil-moisture deficit increases beyond the readily available water amount, the plant water stress factor decreases linearly, reaching a value of zero as the soil-moisture deficit approaches the total available water value, or alternatively, as the daily soil-moisture value reaches a value close to the wilting point. How the plant water stress factor changes with changing soil-moisture amounts is shown in figure 1–7.

In the SWB irrigation lookup table, the plant_stress_depletion_fraction (p) defines the soil-moisture conditions below which the actual to potential ET ratio begins to decline toward zero. SWB uses this parameter to define the soil-water content threshold at which plant water depletion begins to stress vegetation and reduce evapotranspiration, as indicated in equation 1–37.

$$\theta_{threshold} = \theta_{WP} + p \cdot \left(\theta_{FC} - \theta_{WP} \right) = \theta_{WP} + p \cdot TAW \tag{1–37}$$

where

$\theta_{threshold}$ is the soil-moisture amount below which plant stress occurs, in inches;
θ_{WP} is the soil-moisture amount at the permanent wilting point, in inches;
p is the plant stress depletion fraction (dimensionless);
θ_{FC} is the soil-moisture amount at the field capacity, in inches; and
TAW is the total available soil-moisture storage amount, in inches.

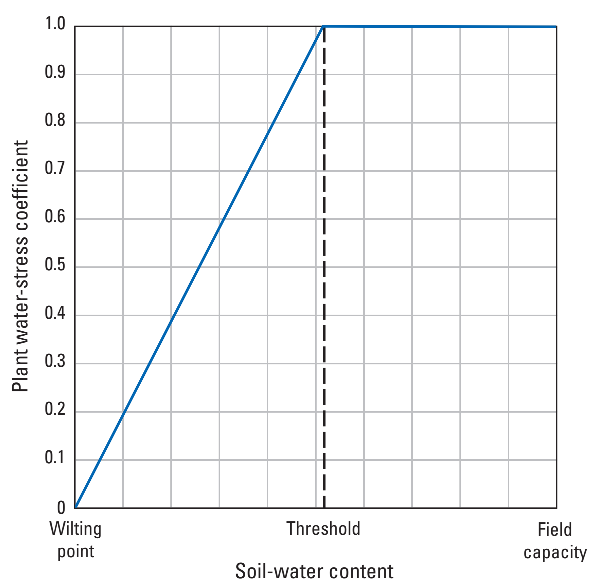


Figure 1–7. Plant water stress coefficient as a function of the soil-water content.

Rooting Depth

The dynamic rooting-depth method is a way to account for the fact that when plants are small, less of the moisture within the soil-moisture reservoir is actually available for uptake and growth. When this method is selected, the current rooting depth is allowed to range between a small value (0.15 foot) and the maximum root-zone depth specified in the lookup table. The minimum root-zone depth is assumed during initial plant growth (L_{ini} in fig. 1–6) and is assumed to increase linearly during plant development (L_{dev} in fig. 1–6), reaching the maximum root-zone depth at the start of the primary plant-growth stage (L_{mid} in fig. 1–6).

Dynamic rooting depth has no effect on calculations unless FAO–56 crop coefficients are being used in the simulation. With dynamic rooting depth enabled, the amount of total available water is allowed to grow larger as plant growth increases. Soil-moisture conditions in springtime often result in plant water stress when rooting depths are at a minimum. As the total available water and current rooting depths increase through the growing season, a larger soil-moisture reservoir is available to plants; therefore, the soil-moisture conditions are less likely to result in plant stress. Of course, those generalizations assume a constant amount of precipitation.

Irrigation Demand and Application

Once the FAO–56 procedure has been used to estimate the crop-water requirements, the next step in the process of simulating irrigation-water demand is to apply the water in a realistic manner. The applied irrigation water is not a source that is explicitly modeled by SWB; the irrigation water is supplied as an unspecified source external to SWB. Linkage to the groundwater system could be accomplished by postprocessing the SWB-calculated irrigation amounts and supplying those values to the MODFLOW WELL package (McDonald and Harbaugh, 1988) along with the SWB-calculated net-infiltration values.

The first step in simulating irrigation application is to compare the depletion fraction value to the user-specified maximum allowable soil-moisture deficit. The depletion fraction is calculated as follows:

$$depletion\ fraction = 1 - \frac{\left(\theta_{t-1} - \theta_{WP}\right)}{\left(\theta_{FC} - \theta_{WP}\right)} \qquad (1\text{–}38)$$

where

θ_{t-1} is the soil-moisture amount calculated on the previous day, in inches;

θ_{WP} is the soil-moisture amount at the permanent wilting point of the soil, in inches; and

θ_{FC} is the soil-moisture amount at the field capacity of the soil, in inches.

The depletion fraction in equation 1–38 takes on a value of zero when soil-moisture values are at the soil's field capacity and a value of one when soil-moisture values reach the wilting point. Like the depletion fraction, the maximum allowable deficit takes on values in the range from 0 to 1. A value of zero indicates that no soil-moisture deficit is tolerable for the crop and will result in almost continuous irrigation. A value of one effectively indicates that depletion of the soil reservoir is tolerable and will result in irrigation almost never being applied. The maximum allowable depletion fraction is often set equal to the plant water stress fraction (see table 1–10 for definition). Setting the maximum allowable depletion equal to the plant stress depletion fraction in simulated irrigation being applied whenever the soil moisture declines below the threshold soil-moisture value at which plant growth begins to become impaired.

Once a cell's soil-moisture status has triggered a need for simulated irrigation, SWB has a few rules that may be specified per land-use or crop type. These rules determine how much of the soil-moisture deficit is eliminated in the simulated irrigation event. The following is a list of these rules.

Restore soil moisture to field capacity.—Complete elimination of soil-moisture deficit on a cell by cell basis. This option calculates the amount of water to be applied as the difference between the maximum soil-moisture value and the soil-moisture value from the previous day. Thus, this amount ignores the current day's water-balance components; the same irrigation amount will be calculated regardless of rainfall conditions.

Restore soil moisture to some fraction of field capacity.—Restore soil moisture to some specified tolerable level of soil-moisture deficit (deficit irrigation). This option calculates the amount of water to be applied as the difference between the soil moisture at some preset deficit amount and the soil-moisture value from the previous day. The parameter value supplied to SWB to define this deficit amount is best described as the fraction of the maximum soil moisture that should be used as the baseline value in the calculation. In other words,

$$irrigation\ amount = f \cdot \theta_{FC} - \theta_{t-1} \qquad (1\text{–}39)$$

Apply fixed amount of irrigation.— Apply the same, constant amount of water once the soil-moisture deficit exceeds the maximum allowable deficit. Many irrigators have sized their equipment to handle application events of average size; for example, a center-pivot irrigation setup might only be capable of delivering water within a narrow range of values. Under this option, a set amount of water is applied to the cell. If the set amount brings the soil moisture to a value in excess of field capacity, a recharge event will be triggered.

Apply demand-based amount on a prescribed monthly schedule.— This option is similar to the “restore soil moisture to field capacity” option, except that the calculated irrigation amount accounts for the daily or monthly rainfall and runoff amount and only is applied on a set schedule. This option was extracted from the Hawaii water-budget code and is designed to simulate the unique irrigation conditions in the Pacific Islands; the calculation is dependent on the monthly, rather than daily, datasets that generally are available in the Pacific Islands.

The irrigation amount for each day that irrigation is scheduled is calculated as:

$$irrigation\ amount = \frac{(ET_{crop} \cdot n_{irr} + runoff - rainfall)}{n_{month}} \quad (1\text{–}40)$$

where

ET_{crop} is the crop evapotranspiration value, the amount of water the plant would use if not water limited;

n_{irr} is the number of irrigation days in the month;

$runoff$ is the monthly total runoff amount;

$rainfall$ is the monthly total rainfall amount; and

n_{month} is the number of days in the month.

The number of irrigation days in the month is determined by the monthly irrigation schedule parameter, which is a pattern of zeros and ones. The monthly irrigation schedule parameter values are 31 characters long, which determine the timing of irrigation (table 1–11).

Irrigation can be defined for whole crop and vegetation types; however, at times, more control is needed regarding the simulation of irrigation at a particular location. A supplemental irrigation mask grid can be provided to SWB to fine tune which portions of various crop and vegetation types are given simulated irrigation. A value of one means the cell is allowed to receive irrigation, whereas a value of zero blocks the cell from receiving irrigation water. An example of an irrigated lands mask is shown in figure 1–8.

Rejected Net Infiltration

Specification of maximum daily net-infiltration values is a crude but effective way of preventing SWB from calculating unreasonably high net-infiltration values. With flow routing enabled, downslope cells can have large amounts of water diverted to them. The resulting calculated net-infiltration values sometimes exceed the values that might be reasonable given the soils and underlying geology. Setting a maximum daily net-infiltration value will prevent these cells from taking on unrealistic net-infiltration values.

In cases where the calculated daily net infiltration is greater than the cell’s maximum daily net-infiltration limit, the net infiltration for the cell is set to the maximum daily net-infiltration value, and the remaining water is converted to rejected net infiltration. This rejected net infiltration is then routed to the next downslope cell where the water becomes available for runoff, recharge, or evapotranspiration. Maximum net-infiltration values are user-defined and are often set to values approximating the vertical hydraulic-conductivity values for the underlying MODFLOW application. If left unspecified, SWB enforces no limits on calculated net-infiltration rates.

Table 1–11. Example of monthly irrigation schedule parameter values for several irrigation frequencies.

Irrigation frequency	Monthly irrigation schedule value
Weekly (approximate)	`1000000100000010000001000000100000`
Every other day	`0101010101010101010101010101010`
Every 3 days	`0010010010010010010010010010010`

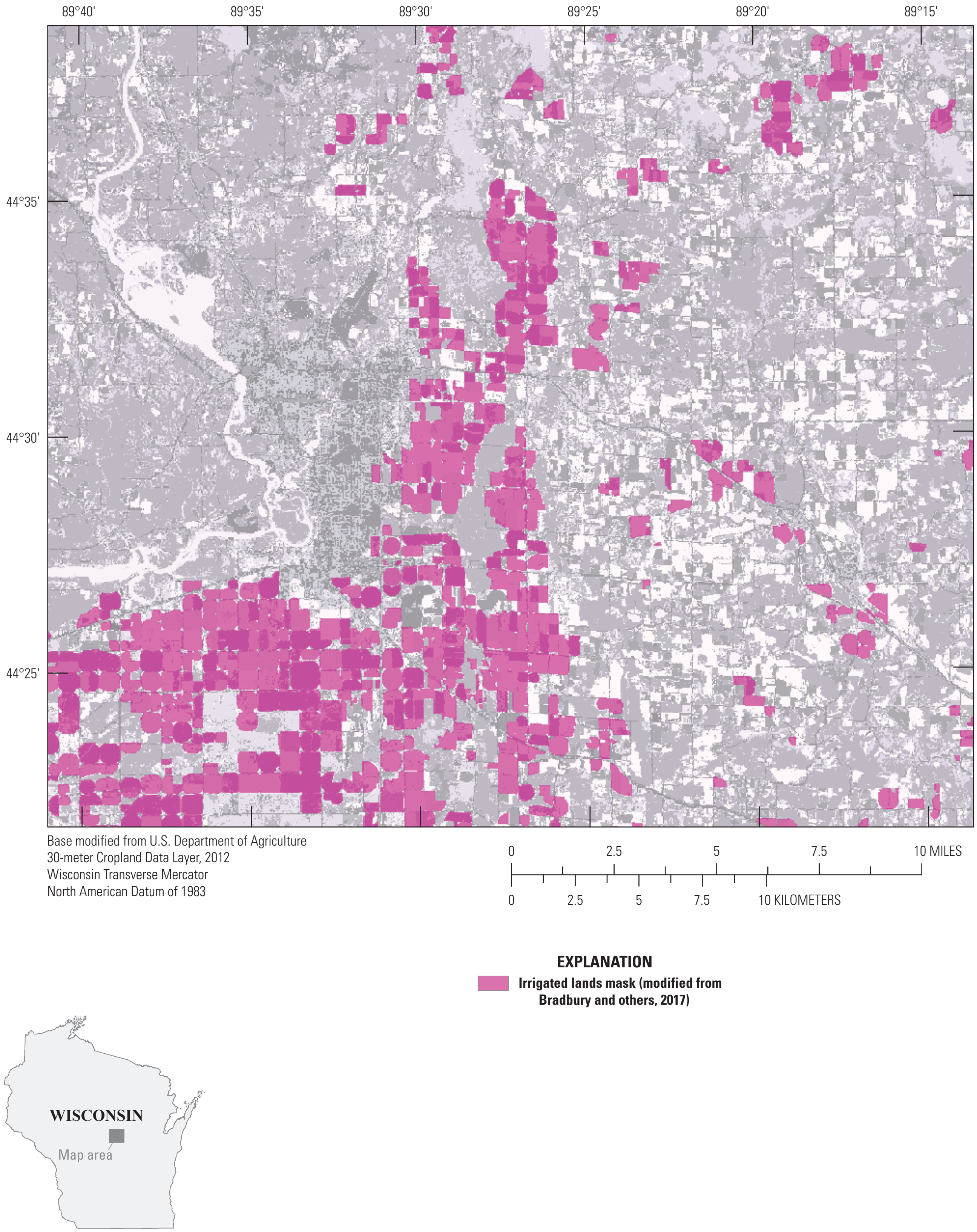


Figure 1–8. Example of irrigated lands mask.

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Appendix 2. User Guide

This document is a user guide that discusses the basic application and operation of the Soil-Water-Balance (SWB) version 2.0 code.

Installing and Running Soil-Water-Balance Version 2.0

SWB is compiled Fortran 2008 code; no installation is needed other than copying the executable program to the desired location on the system hard drive. When the name of the executable is typed at a terminal command prompt, SWB will start up, list the compilation date, list the Git commit hash and branch, and finally, list any options that may be invoked. Git is a software tool designed to keep track of changes made to a source code such as SWB (Torvalds and Hamano, 2010). A Git commit hash is a symbol that uniquely identifies the state of the code modules used to compile the version of SWB the user is running. If a SWB run has issues, the Git commit hash is crucial for recreating the code as it existed during compilation.

The procedure for running SWB is the same for an Apple Macintosh, Linux, or Windows-based computer. An example of SWB execution with no command-line arguments when run on a Macintosh is shown in figure 2–1.

System Requirements

SWB can be compiled and run on any modern hardware including Apple Macintosh, Linux, or Windows-based systems. Performance will improve if SWB is run on a system with greater processing speed and more random access memory (RAM). A small problem, consisting of a model domain of about 100 cells by 100 cells, will run on a small single-board computer such as a Raspberry Pi, albeit slowly.

An important point about system requirements is that the code is capable of accessing large gridded climate datasets and will run efficiently by pulling out only the data needed for the simulation. This point can be viewed as a positive and a negative attribute about SWB. From an ease of use standpoint, a user can save a lot of work by downloading a gridded dataset, such as Daymet (Thornton and others, 2016), for the conterminous United States. SWB will run efficiently while accessing national gridded datasets, pulling the local values as needed. However, a year of Daymet data takes up almost 3 gigabytes (GB) of disk space; a simulation spanning from 1980 to 2016 would require more than 100 GB of disk storage for just the daily weather dataset. Although a considerable amount of space may be saved by creating a subset of the gridded data, the task would require a considerable amount of time and effort. The purchase of a larger hard drive, therefore, would be more efficient.

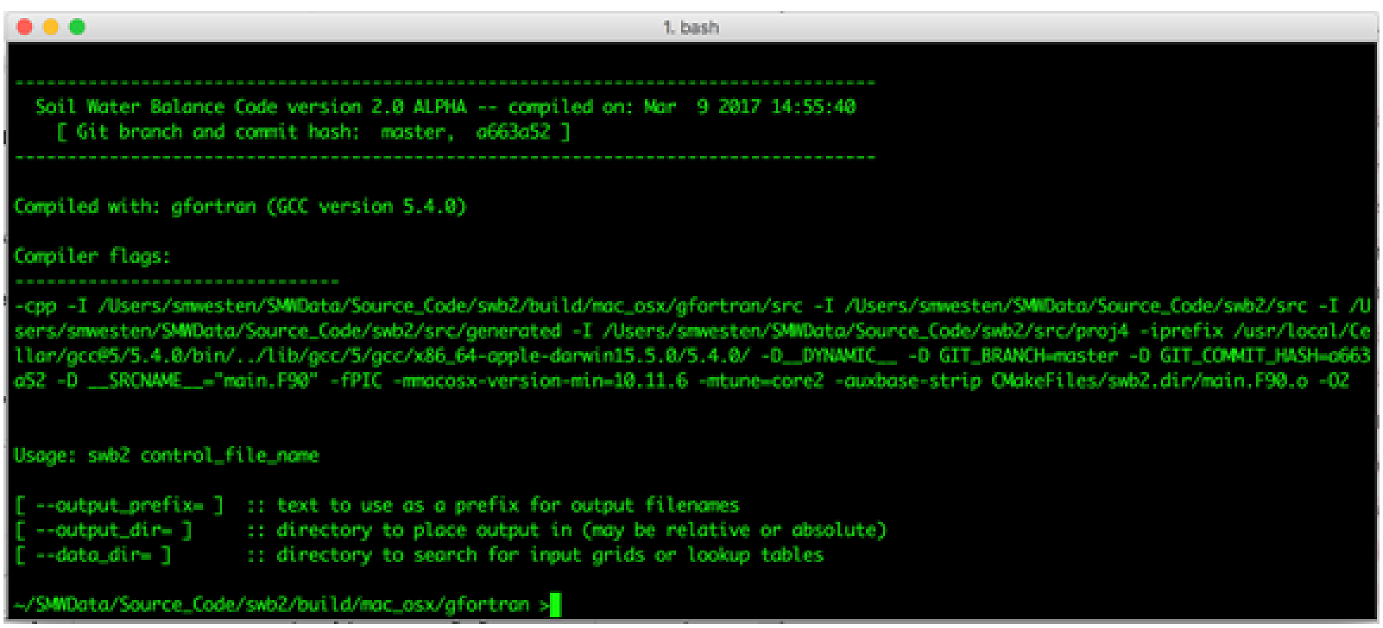


Figure 2–1. Command-line response when Soil-Water-Balance (SWB) version 2.0 is executed with no other arguments.

Output from SWB is now in the form of a compressed Network Common Data Form (netCDF) file (Unidata, 2014). A 346 by 400-cell example problem run with SWB for a 2-year period generated about 900 megabytes (MB) of file output. For a typical SWB simulation, a hard drive with empty space ranging from 100 GB or greater is recommended to accommodate the output files generated by SWB.

Running SWB

SWB must be run from an operating system command line, with a control filename specified. If the command 'swb2' is entered at the command prompt without providing a control filename, SWB will print out some diagnostic information. The information includes the date of compilation and a Git hash that uniquely identifies the source code used in the compilation SWB also prints out a message that mentions three command-line options: --output_prefix, --output_dir, and --data_dir.

Within the control file, paths may be specified so that the input datasets may stay in their own dedicated space on the hard drive. SWB will use relative or absolute paths to files. The --output_prefix option allows the user to specify a text string that will be affixed to the front of each output file name. The --output_dir option allows the user to specify the location in which program output should be stored. The --data_dir option may be used to specify the location on the disk that SWB will search for input data.

If

```
swb2 my_control_file.ctl --output_prefix=WI_ --output_dir=output --data_dir=input
```

is entered at the command line, an SWB run will begin with whatever options are contained within the control file. Output files will be prefixed with the characters WI_ and saved in the output subdirectory, and the required data will be accessed in the input subdirectory.

Overview of Input and Output Files

SWB requires a combination of gridded and tabular files as input and produces several gridded netCDF files and logfiles as output. This section discusses the input files required by and output files generated by SWB.

Input Files

Several different input files must be in place for an SWB simulation to work. The most important of these files is the SWB control file. The control file specifies the location of input data grids and climate datasets and is the place where the user may select specific program options. A lookup table, or possibly several lookup tables, are required to relate SWB model parameters to the land use or hydrologic soil group, or both. Input-data grids are used to provide SWB with a map of land-use and soil-related information. Finally, daily weather data must be provided in either tabular or gridded form. These input files are discussed in greater detail in the following sections.

Control File

The SWB control file contains all details about the grid specifications, gridded and tabular datasets to be used, and the location and name of lookup tables. SWB does not require the control file entries to be made in any particular order. The control file statements do not need to be in uppercase letters; `Lookup_table` works as well as `LOOKUP_TABLE`. Note that in SWB version 2.0, the cartographic projection of the SWB project grid is required to be supplied by means of the `BASE_PROJECTION_DEFINITION` directive in the form of a PROJ.4 string (fig. 2–2). Figures 2–2 through 2–4 together present an annotated SWB control file.

```
## SWB 2 will ignore lines that begin with one of the following:  #%!+=
## also, SWB doesn't care about blank lines

% the order of lines makes no difference to SWB; however, it is useful for
% users to see the definition of the underlying grid up front:

!        nx    ny          xll             yll      resolution
!----------+-----+------------+-------------+--------------
GRID 400  346   545300.     432200.          90.

! where:      nx, ny        are the number of columns and number of rows
!             xll, yll      are the coordinates for the lower left-hand corner of the *grid*
!             res           is the grid cell resolution

% SWB grid projection *must* be defined in SWB 2.0
% projection in this example is Wisconsin Transverse Mercator(!)
BASE_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000
+y_0=-4480000 +datum=NAD83 +units=m

% Select which methods SWB should use
%------------------------------------------------------------------------
INTERCEPTION_METHOD                     BUCKET
EVAPOTRANSPIRATION_METHOD               HARGREAVES
RUNOFF_METHOD                           CURVE_NUMBER
SOIL_MOISTURE_METHOD                    FAO-56_TWO_STAGE
FOG_METHOD                              NONE
FLOW_ROUTING_METHOD                     NONE
IRRIGATION_METHOD                       FAO-56
ROOTING_DEPTH_METHOD                    DYNAMIC
CROP_COEFFICIENT_METHOD                 FAO-56
DIRECT_RECHARGE_METHOD                  NONE
SOIL_STORAGE_MAX_METHOD                 CALCULATED
AVAILABLE_WATER_CONTENT_METHOD          GRIDDED
```

Figure 2–2. First segment of a Soil-Water-Balance (SWB) control file showing base-grid definition and method-specification syntax.

The section of the SWB control file in figure 2–3 shows how the SCALE_FACTOR and ADD_OFFSET suffixes can be used to ensure that gridded data in the International System of Units (millimeter, degrees Celsius) are converted to U.S. customary units (inch, degrees Fahrenheit) as the grids are read in by SWB.

Toward the end of the control file syntax shown in figure 2–4 are several directives that need additional explanation. The INITIAL_PERCENT_SOIL_MOISTURE directive allows the user to set the percent of soil saturation for each grid cell in the model. Likewise, the INITIAL_SNOW_COVER_STORAGE directive allows the user to set the amount of snow as water equivalent for each grid cell in the model. Both of these directives may be specified as CONSTANT values or may be specified using Arc ASCII or Surfer grids. If gridded values are supplied, the grids must be in the same cartographic projection and of the same dimensions as the SWB project grid.

```
% not much new here; SWB 1.0 supports all of the same syntax

! precipitation: converting mm to inches
PRECIPITATION NETCDF ../Daymet_V3_2016/daymet_v3_prcp_%y_na.nc4
PRECIPITATION_GRID_PROJECTION_DEFINITION +proj=lcc +lat_1=25.0 +lat_2=60.0
+lat_0=42.5 +lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80 +datum=NAD83 +units=m
+no_defs
PRECIPITATION_NETCDF_Z_VAR              prcp
PRECIPITATION_SCALE_FACTOR          0.03937008

! maximum air temperature: converting degrees Celsius to degrees Fahrenheit
TMAX NETCDF ../Daymet_V3_2016/daymet_v3_tmax_%y_na.nc4
TMAX_GRID_PROJECTION_DEFINITION +proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5
+lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80 +datum=NAD83 +units=m +no_defs
TMAX_SCALE_FACTOR                   1.8
TMAX_ADD_OFFSET                     32.0

! minimum air temperature: converting degrees Celsius to degrees Fahrenheit
TMIN NETCDF ../Daymet_V3_2016/daymet_v3_tmin_%y_na.nc4
TMIN_GRID_PROJECTION_DEFINITION +proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5 +lon_0=-
100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80 +datum=NAD83 +units=m +no_defs
TMIN_SCALE_FACTOR                   1.8
TMIN_ADD_OFFSET                     32.0
TMIN_MISSING_VALUES_CODE        -9999.0
TMIN_MISSING_VALUES_OPERATOR        <=
TMIN_MISSING_VALUES_ACTION        mean

INITIAL_CONTINUOUS_FROZEN_GROUND_INDEX CONSTANT        100.0
UPPER_LIMIT_CFGI                83.
LOWER_LIMIT_CFGI                55.
```

Figure 2–3. Second segment of a Soil-Water-Balance (SWB) control file demonstrating syntax for defining weather data and growing season specification.

```
FLOW_DIRECTION ARC_GRID ../swb/input/d8_flow_direction.asc
FLOW_DIRECTION_PROJECTION_DEFINITION  +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996
+x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

HYDROLOGIC_SOILS_GROUP ARC_GRID ../swb/input/hydrologic_soils_group.asc
HYDROLOGIC_SOILS_GROUP_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0
+k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

LANDUSE ARC_GRID ../swb/input/landuse.asc
LANDUSE_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996
+x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

% SWB 2.0 can accommodate multiple lookup tables; however, column names
% may not be repeated from one table to another. Thus, if the land-use code column
% heading in the land use lookup table has the name LU_CODE, the irrigation lookup
% table heading could be called LU_CODE2
LANDUSE_LOOKUP_TABLE std_input/landuse_table_SWB2.txt
IRRIGATION_LOOKUP_TABLE std_input/irrigation_table_SWB2.txt

AVAILABLE_WATER_CONTENT ARC_GRID ../swb/input/available_water_capacity.asc
AVAILABLE_WATER_CONTENT_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0
+k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

IRRIGATION_MASK ARC_GRID ../swb/input/irrigation_mask_from_cdl.asc
IRRIGATION_MASK_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996
+x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

INITIAL_PERCENT_SOIL_MOISTURE        CONSTANT 100.0
INITIAL_SNOW_COVER_STORAGE           CONSTANT     2.0

% this option is good for debugging, but might be useful when one wants a lot of
% detail about what SWB is doing
DUMP_VARIABLES COORDINATES 563406. 454630.
DUMP_VARIABLES COORDINATES 552982. 439512.

% for SWB 2.0, the start and end dates need not follow calendar year bounds; the run may
% start and end on any arbitrary day.
START_DATE 01/01/2013
END_DATE 12/31/2014
```

Figure 2–4. Final segment of a Soil-Water-Balance (SWB) control file showing syntax used to specify input grids, initial conditions, and starting and ending dates.

The choice regarding the use of a constant value instead of a gridded set of initial conditions for these values is project-specific. If the first year of a simulation is to be discarded as a spool-up period (a period in which soil-moisture and snow-depth values lose the memory of their initial condition values), then reasonable values suitable for average project area conditions may be specified as CONSTANT values. For a project in the northern Midwest of the United States, the INITIAL_PERCENT_SOIL_MOISTURE might be set to 70 percent, and the INITIAL_SNOW_COVER_STORAGE might be set to 2.0 inches. Alternatively, SWB could be run for several years with the last day of the simulation ending just before the start date of the period of interest. The soil-moisture and snow-storage values on the last day of such a simulation could be extracted and supplied as initial conditions to SWB for the run covering the time period of interest.

Lookup Tables

In addition to the gridded data, one or more lookup tables must be provided to supply parameter values to the SWB methods. Many parameters are specified for specific combinations of land-use categories and hydrologic soil groups. The required parameters for each SWB method are listed in appendix 3. At a minimum, a SWB application requires the user to supply parameter values for the Soil Conservation Service curve number, the maximum recharge rate, the growing and nongrowing season interception values, and the rooting depths; except for the interception values, these parameters are specified for each combination of land use category and hydrologic soil group.

In the original version of the SWB model (version 1.0), the location of the parameters was hardwired; in other words, SWB version 1.0 required the lookup table to be structured such that the parameters were supplied in a nonflexible column order. Parameter values for curve numbers were supplied in the first columns, followed by the maximum recharge rates, interception values, and rooting depths. In addition, SWB version 1.0 required that the number of soil types and land uses be specified and did not allow nor require a table header.

SWB version 2.0 uses keywords to identify parameter values within the table; the new lookup tables allow parameters to be supplied in any arbitrary column order. A separate column of parameter values must be supplied for each soil type. A snippet of the new table format is listed in table 2–1). Of the field values listed, the land-use code (LU_Code) is the key that relates the table values back to the land-use grid. The "Description" field is ignored by SWB, and the remaining fields specify the maximum surface storage for a given land use and the range of curve numbers for combinations of land-use categories and hydrologic soil groups. Tables could be easily prepared using spreadsheet software such as Microsoft Excel; however, tables should be saved as a tab-delimited text file for use with SWB.

In SWB 2.0, each column should be clearly identified so that the proper parameters may be linked to their respective process methods. Parameters that are tied to land use and to soil type are identified in the header in the form `parameter_name_#`, where # is the index value of the hydrologic soil group and must correspond to the values given in that grid. There must be a column for each index value found in the grid file. Soil types (hydrologic soil groups) are assumed to be numbered from 1 to *n*, where *n* is the number of different soil groupings. If a soil with five distinct hydrologic soil groups is supplied, the lookup table would need curve numbers for each land use and soil type combination; the column names for these curve numbers would be CN_1, CN_2, CN_3, CN_4, and CN_5. The required column names for each method are listed in appendix 3.

If multiple lookup tables are used, the row ordering must be consistent from one table to the next; SWB will perform some basic sanity checks on the table values, but will assume that values from all tables are defined relative to the order of land-use codes read from the first table that the SWB checks.

Input Data Grids

Several input data grids are required to perform a basic SWB run. As a SWB model, basic information about the soils is required. The typically required data grids are discussed in the following sections. Choosing other optional process methods may negate the need for the grids discussed in this section; however, additional gridded data types may be required.

Table 2–1. Extract from the Soil-Water-Balance (SWB) version 2.0 table format.

[LU, land use; CN, curve number]

LU_code	Description	Surface_storage_max	CN_1	CN_2	CN_3	CN_4
0	Background	0	100	100	100	100
2	Pineapple	0	42	64	76	81
3	Coffee	0	52	70	80	84
4	Diversified agriculture	0	55	72	82	85
5	Macadamia	0	44	65	77	82
6	Fallow_grassland	0	37	61	74	79
7	Developed open space	0	37	61	74	79
8	Developed low intensity	0	60	75	84	87
9	Developed medium intensity	0.25	70	82	88	91
10	Developed high intensity	0.25	81	88	92	94

Hydrologic Soil Group

The hydrologic soil group grid is an integer-valued grid that contains the soil group for each cell in the model. Any number of soils may be used in this grid, but frequently SWB models use the integers 1, 2, 3, and 4 to represent the 4 standard hydrologic soil groups defined as part of the curve number literature. The U.S. Department of Agriculture, Natural Resources Conservation Service, formerly the Soil Conservation Service, has categorized more than 14,000 soil series within the United States into 1 of 4 hydrologic soil groups (A–D) on the basis of infiltration capacity. Hydrologic soil group information may be input to the model as an Arc ASCII or Surfer integer grid with values ranging from 1 (soil group A) to 4 (soil group D). Soils in hydrologic soil group A have a high infiltration capacity and, consequently, a low overland flow potential. In contrast, soils in hydrologic soil group D, have a low infiltration capacity and, consequently, a high overland flow potential (table 2–2).

Table 2–2. Infiltration rates for hydrologic soil groups and associated Soil-Water-Balance (SWB) grid values.

Hydrologic soil group	Infiltration rate	Integer grid value
A	Greater than 0.3 inch per hour	1
B	0.15 to 0.3 inch per hour	2
C	0.05 to less than 0.15 inch per hour	3
D	Less than 0.05 inch per hour	4

Available Water Capacity

SWB needs one or more datasets for use in assigning the size of the soil-storage reservoirs. The user can specify gridded datasets of either (1) maximum soil-water capacity in inches, or (2) available-water capacity in inches per foot, along with tabular values of the rooting depth in feet. Traditionally SWB uses the gridded available water capacity and tabular rooting depth to calculate a maximum soil water-holding capacity for each grid cell. The maximum soil-water capacity is calculated as in equation 2–1.

$$\begin{aligned} &\mathit{maximum\,soil\text{-}water\,capacity} \\ &= \mathit{available\text{-}water\,capacity} \\ &\cdot \mathit{root\text{-}zone\,depth} \end{aligned} \tag{2–1}$$

If the maximum soil-water capacity is not specified directly, each grid cell within the model area must be assigned an available water capacity and each combination of land use and soil type assigned a rooting depth in the lookup table. Soil classifications, which include an estimate of the available water capacity or textural information, are typically available through the state offices of the Natural Resources Conservation Service or on the website at https:\\soils.usda.gov. If data for available water capacity are not available, the user can use soil texture to assign a value, listed in table 2–3 (original source table 10, Thornthwaite and Mather, 1957).

The available water capacity of a soil is typically given as inches of water-holding capacity per foot of soil thickness. For example, if a soil type has an available water capacity of 2 inches per foot and the root-zone depth of the cell under consideration is 2.5 feet, the maximum water capacity of that grid cell would be 5.0 inches. The 5.0 inches is the maximum amount of soil-water storage that can take place in the grid cell. Water added to the soil column in excess of this value will become recharge.

Table 2–3. Estimated available water capacities for various soil-texture groups.

Soil texture	Available water capacity (inches per foot of thickness)
Sand	1.20
Loamy sand	1.40
Sandy loam	1.60
Fine sandy loam	1.80
Very fine sandy loam	2.00
Loam	2.20
Silt loam	2.4
Silt	2.55
Sandy clay loam	2.70
Silty clay loam	2.85
Clay loam	3.00
Sandy clay	3.20
Silty clay	3.40
Clay	3.60

A grid containing the maximum soil-water capacity may be input directly into the SWB code, bypassing the internal calculation of the maximum soil-water capacity.

Land-Use Code

The model uses land-use information, together with the available-water-capacity information, to calculate surface runoff and assign a maximum soil-moisture holding capacity for each grid cell. The original model required that land-use classifications follow a modified Anderson Level II Land Cover Classification (Anderson and others, 1976). SWB can handle any arbitrary land-use classification method as long as the accompanying land-use lookup table contains curve-number, interception, maximum-recharge, and rooting depth data for each land-use type contained in the grid. Data from the Multi-Resolution Land Characteristics Consortium (https://www.mrlc.gov/) are a common source for land-use data, but any suitable gridded dataset may be used.

D8 Surface-Water-Flow Direction

The SWB code requires an integer flow-direction grid for the entire model domain when the flow-routing method is enabled. SWB uses the flow-direction grid to determine how to route overland flow between cells. The user must create the flow-direction grid consistent with the D8 flow-routing algorithm (O'Callaghan and Mark, 1984), with flow directions defined as shown in figure 2–5*B*. The original algorithm assigns a unique flow direction to each grid cell by determining the steepest slope between the central cell and its eight neighboring cells. For the cells shown in figure 2–5*A*, the steepest descent algorithm results in flow from the central cell to the southwest; the corresponding cell figure 2–5*B*, located to the southwest of the central cell, contains the number 8. By convention, therefore, the D8 flow direction for the cell shown in figure 2–5*A* is 8.

Many GIS software implementations of the D8 algorithm generate intermediate grids whereby neighboring cells are assigned a combination of flow-direction encodings. A cell for which all neighboring cells are of equal or greater elevation is a cell that Jenson and Domingue (1988) called a condition 4 cell. For example, if the cells to the east, southeast, south, and southwest of the central cell in figure 2–5*A* all share the same elevation as the central cell (109), water might be expected to flow to any one of the neighboring cells. The flow direction for such a cell might be encoded as *flow direction* = 1 + 2 + 4 + 8 = 15; a flow direction that is not a power of 2 is most likely to be generated from an unfilled digital elevation model. SWB is not equipped to handle these values.

In the SWB code, a cell for which the flow-direction value is not a power of 2 (as shown in fig. 2–5*B*) is considered to indicate a closed depression. The SWB code does not attempt to split flows between two or more cells; if a cell has more than one possible flow direction, the cell is identified as a closed depression. The SWB code allows no further surface runoff to be generated or ponding to occur. The SWB code, instead, requires water in excess of the soil-moisture capacity to contribute to net infiltration, with net infiltration in excess of any maximum net-infiltration rate extracted from the model domain and tracked as `runoff_outside` .

For best results, the user must carefully consider whether the D8 flow-direction grid should be generated from an unfilled or a filled digital elevation model and if SWB's treatment of flow-direction grid values that are not a power of 2 (as a depression) is acceptable. In addition, some researchers suggest that the traditional filling procedure used to prepare grids for use in determining D8 flow direction may be inappropriate for glaciated areas of the country where large areas of internal drainage reduce the size of the contributing area to streams. The presence of large areas of internal drainage may result in overestimation of surface-water runoff (Macholl and others, 2011; Richards and Brenner, 2004).

Climate Data Tables or Grids

The most important component of the water budget when estimating net infiltration is precipitation. The next most important component is generally evaporation, which can be estimated from air temperature data. SWB accepts precipitation, and minimum and maximum air temperature data in the form of tabular or gridded files.

For a project that covers an area small enough to be described by a single climate station, these data may be entered directly by use of a table that has header and date formats the same as those shown in figure 2–6.

For many projects, the use of some type of gridded data may be desirable. The source of the gridded data might be a project-specific custom interpolation routine. Alternatively, a gridded data product such as Daymet (Thornton and others, 2016) can be used. Daymet uses consistent methodology to generate a continuous gridded dataset for the contiguous United States. The dataset contains precipitation, air temperature, and several other estimated data series (relative humidity, snow-water equivalent). The precomputed gridded datasets are generally much easier to use and save significant amounts of time relative to computing project-specific interpolated fields for precipitation and air temperature. Use of gridded datasets with SWB is discussed further in the "Gridded Datasets" section of this appendix.

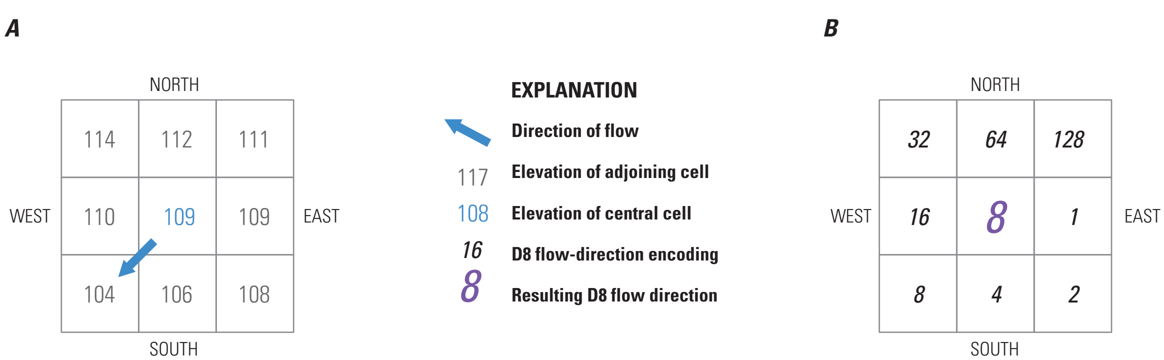


Figure 2–5. Example (*A*) elevation grid values, in meters, and (*B*) resulting D8 flow-direction encoding.

```
% Data obtained from ***** station in Roswell, NM
%
Date        PRCP       TMIN       TMAX
01-01-2015  0.0        20.0       26.0
01-02-2015  1.1        25.0       30.0
01-02-2015  0.3        24.0       29.0
01-04-2015  0.0        23.0       28.5
```

Figure 2–6. Sample climate data in tabular form.

Output Files

This section describes the gridded netCDF files and ASCII log files generated by SWB during a simulation run.

netCDF Files

Primary water-budget variables and other important variables are written to individual netCDF files. These variables are listed in table 2–4. The filenames include the variable name, the time range in years, and the dimensions of the grid. For example, the output filename for the rainfall variable for a model run that spans from 2013 to 2014 and covers a model domain of 346 rows by 400 columns would be named "rainfall_2013_2014__346_by_400.nc." Because of the efficiency of the underlying netCDF library, writing out netCDF files with SWB is still several times faster than writing to the custom binary files of SWB version 1.0.

A useful feature of netCDF files is that the files are able to hold information about multiple variables as well as metadata about the conditions under which these variable values were generated. The metadata for the snowmelt variable generated by SWB are shown in figure 2–7. The file holds daily SWB output for snowmelt, along with projected and geographic spatial coordinates and detailed information about the cartographic projection associated with the projected coordinates. In addition, details about the version of the SWB code used to generate those values are recorded to assist in future data archiving.

More details about making use of netCDF files are given in the "Gridded Datasets" section of this appendix.

Log Files

In addition to the gridded netCDF output files, SWB writes ASCII log files each time the code is run. If the user experiences an issue while running the code, the first response should be to examine the end of the log file. Often an important error or warning message will be printed to the log file just before the SWB run fails. A small subset of a SWB run log is shown in figure 2–8.

The log files are formatted as Markdown text files; Markdown is a set of text file conventions that can be used to produce HyperText Markup Language (HTML), Portable Document Format (PDF), or other formatted output (Gruber, 2012). The log files are not required to be viewed in a Markdown editor; the files are accessible as plain text and may be viewed in any standard text editor. However, Markdown tags have been selected so that error messages are more easily recognized within the voluminous text of the logfile output.

A warning message regarding missing solar-radiation data is shown in figure 2–8. SWB will print several similar warnings for each data type that does not have an existing file. These warnings are safely ignored, but might be useful if SWB reports missing datasets when the user believes the datasets have been properly specified.

Table 2–4. List of variables written to separate netCDF files.

Variable name	Units	Variable description
gross_precipitation	Inches	Precipitation amount as read into SWB before any further processing; this is a useful output to examine to ensure that any conversion factors have been specified and interpreted correctly.
rainfall	Inches	Precipitation amount that is considered to have fallen as rainfall; this amount is the gross rainfall—the amount of rainfall before any canopy or vegetation interception is calculated. Net rainfall must be calculated by subtracting interception from rainfall.

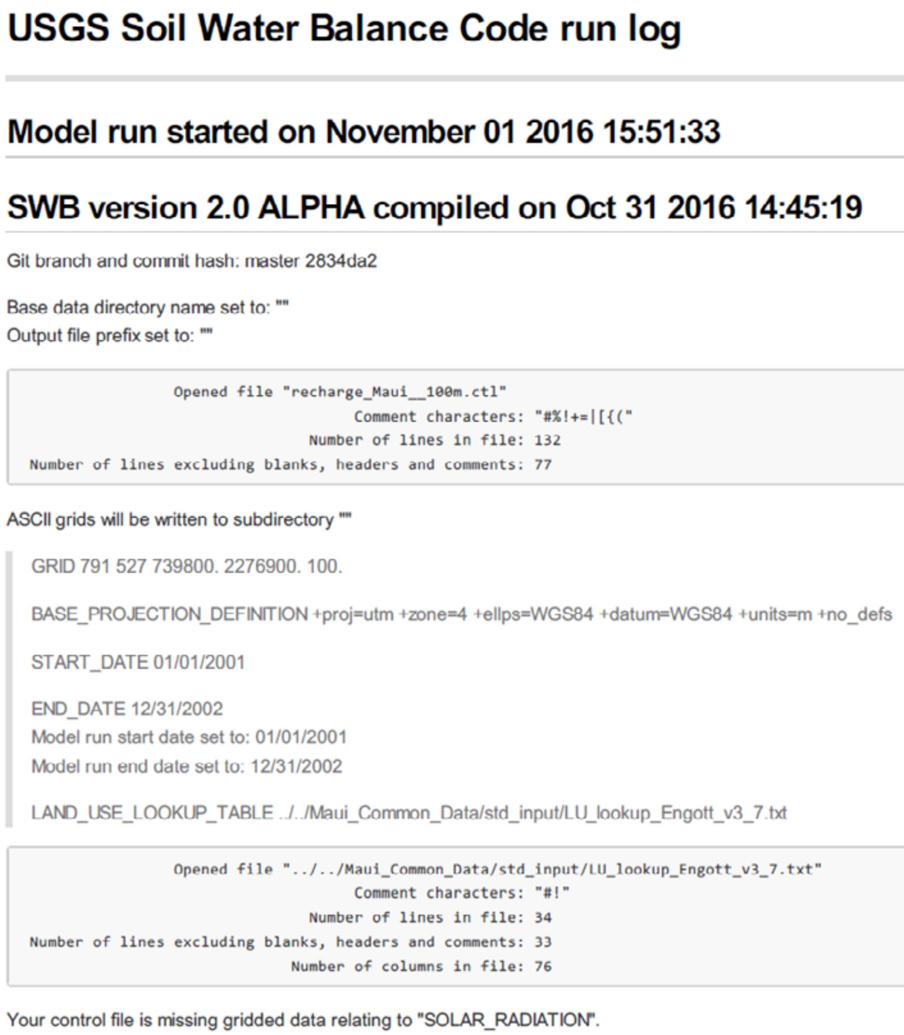
Table 2–4. List of variables written to separate netCDF files.—Continued

Variable name	Units	Variable description
snowfall	Inches	Precipitation amount that is considered to fall as snow; this amount is the gross snowfall—the amount of precipitation that falls as snow before any canopy or vegetative interception is calculated.
snowmelt	Inches	Water released to runoff and infiltration as snow melts.
interception	Inches	Canopy or vegetation interception amount.
runon	Inches	Water input to a cell derived from runoff from upslope cells.
runoff	Inches	Water generated as runoff from a cell.
reference_ET0	Inches	Reference or potential evapotranspiration amount as provided in gridded form or as calculated by means of one of the evapotranspiration calculation methods.
actual_et	Inches	Actual evapotranspiration from the soil root zone.
tmin	Degrees Fahrenheit	Minimum daily air temperature value as read into SWB; this is a useful output to examine to ensure that any scale factor or offset amounts, or both have been specified and interpreted correctly.
tmax	Degrees Fahrenheit	Maximum daily air-temperature value as read into SWB; this is a useful output to examine to ensure that any scale factor or offset amounts, or both have been specified and interpreted correctly.
net_infiltration	Inches	Water that escapes the evapotranspiration demands of the root zone and enters the top of the unsaturated zone.
rejected_net_infiltration	Inches	Net infiltration in excess of a user-specified maximum net-infiltration amount. With routing active, this is added to the runon for the cell immediately downslope of the current cell.
crop_et	Inches	Amount of water extracted from the root zone by plant transpiration; this is only a valid output if crop coefficients are being applied in the simulation.
soil_evaporation	Inches	Amount of water extracted from the root zone by evaporation from exposed and wetted soil surfaces; this is only a valid output if crop coefficients are being applied in the simulation and if the dual-stage FAO–56 method is specified as the SOIL_MOISTURE_METHOD.
gdd	Degree-days Fahrenheit	Accumulated growing degree-day value for each cell.
runoff_outside	Inches	Water that can be routed no further downslope because it enters a waterbody or a closed depression or is routed to an inactive model cell and is tracked as runoff outside.
irrigation	Inches	Total amount of water required to sustain crop growth based on the many user-defined FAO–56 irrigation parameters (maximum allowable depletion, irrigation method).
snow_storage	Inches	Water stored in the snow reservoir.
soil_storage	Inches	Water stored in the soil reservoir.
delta soil storage	Inches	Change in amount of water stored in soil-storage reservoir relative to the previous day.
impervious_surface_storage	Inches	Water stored in impervious surface storage.
interception_storage	Inches	Water stored in interception storage.

```
netcdf snowmelt_2013_2014__346_by_400 {
dimensions:
        time = UNLIMITED ; // (730 currently)
        y = 346 ;
        x = 400 ;
variables:
        double time(time) ;
                time:units = "days since 2012-01-01 00:00:00" ;
                time:calendar = "standard" ;
                time:long_name = "time" ;
        double y(y) ;
                y:units = "meter" ;
                y:long_name = "y coordinate of projection" ;
                y:standard_name = "projection_y_coordinate" ;
        double x(x) ;
                x:units = "meter" ;
                x:long_name = "x coordinate of projection" ;
                x:standard_name = "projection_x_coordinate" ;
        float snowmelt(time, y, x) ;
                snowmelt:units = "inches_per_day" ;
                snowmelt:valid_min = 0.f ;
                snowmelt:valid_max = 2000.f ;
                snowmelt:valid_range = 0.f, 2000 f ;
                snowmelt:_FillValue = -9.9e 20f ;
                snowmelt:coordinates = "lat lon" ;
                snowmelt:grid_mapping = "crs" ;
        int crs ;
                crs:grid_mapping_name = "transverse_mercator" ;
                crs:latitude_of_projection_origin = 0.f ;
                crs:longitude_of_central_meridian = -90.f ;
                crs:scale_factor_at_central_meridian = 0.9996f ;
                crs:false_easting = 520000.f ;
                crs:false_northing = -4480000 f ;
                crs:datum = "NAD83" ;
                crs:units = "meter" ;
                crs:PROJ.4_string = "+proj=tmerc +lat_0=0.0 +lon_0= 90.0 +k=0.9996 +x_0=520000
                                +y_0=-4480000·+datum=NAD83 +units=m" ;
        double lat(y, x) ;
                lat:units = "degrees_north" ;
                lat:long_name·=·"latitude"·;
                lat:standard_name·=·"latitude"·;
        double lon(y, x)·;
                lon:units = "degrees_east" ;
                lon:long_name = "longitude" ;
                lon:standard_name = "longitude" ;

// global attributes:
                :source = "snowmelt output from SWB run started on Mar 15 2017 16:51:01." ;
                :executable_version = "version 2.0 ALPHA, Git branch:  master,·Git commit hash
                                  string:  6aa729c, compiled on: Mar 15 2017 16:29:00 " ;
                :conventions = "CF-1.6" ;
                :history·= "Mar 15 2017 16:51:01: Soil Water Balance run started." ;
}
```

Figure 2–7. Example header data from a Soil-Water-Balance (SWB) version 2.0 output netCDF file.



USGS Soil Water Balance Code run log

Model run started on November 01 2016 15:51:33

SWB version 2.0 ALPHA compiled on Oct 31 2016 14:45:19

Git branch and commit hash: master 2834da2

Base data directory name set to: ""
Output file prefix set to: ""

```
                Opened file "recharge_Maui__100m.ctl"
                             Comment characters: "#%!+=|[{("
                         Number of lines in file: 132
 Number of lines excluding blanks, headers and comments: 77
```

ASCII grids will be written to subdirectory ""

> GRID 791 527 739800. 2276900. 100.
>
> BASE_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs
>
> START_DATE 01/01/2001
>
> END_DATE 12/31/2002
> Model run start date set to: 01/01/2001
> Model run end date set to: 12/31/2002
>
> LAND_USE_LOOKUP_TABLE ../../Maui_Common_Data/std_input/LU_lookup_Engott_v3_7.txt

```
                Opened file "../../Maui_Common_Data/std_input/LU_lookup_Engott_v3_7.txt"
                             Comment characters: "#!"
                         Number of lines in file: 34
 Number of lines excluding blanks, headers and comments: 33
                        Number of columns in file: 76
```

Your control file is missing gridded data relating to "SOLAR_RADIATION".

Figure 2–8. Subset of a Soil-Water-Balance (SWB) log file as displayed in a Markdown editor.

Cartographic Projections and Resampling

A significant feature added to SWB since the initial release is the ability to use datasets that differ from the base grid in grid cell size, cartographic projection, and geographic extent. To accomplish this ability, SWB incorporates a software library called PROJ.4 to perform transformations among various map projections. PROJ.4 was originally written by Gerald Evenden of the U.S. Geological Survey (Evenden, 1990).

The specific attributes of a projection are defined by supplying SWB with a PROJ.4 string. A PROJ.4 string may be assembled by specifying a combination of the appropriate PROJ.4 parameters (table 2–5) to describe the cartographic projection.

Assembling a string from several PROJ.4 parameters results in a definition of a cartographic projection. This string is used by SWB and PROJ.4 to transform coordinates to the base project coordinate system. Some common cartographic projections are listed in table 2–6. Note that the Michigan Oblique Mercator projection offers an example of a PROJ.4-supported projection that allows for grid rotation by means of the alpha parameter. Groundwater models are often rotated to align with underground geologic features; creating a custom oblique Mercator projection might be a clean way to allow for grid rotation while maintaining a way to reproject the results into a more common cartographic projection scheme.

Table 2–5. List of commonly used PROJ.4 parameter names.

Parameter	Definition
+a	Semimajor radius of the ellipsoid axis.
+alpha	Used with Oblique Mercator and possibly a few others.
+axis	Axis orientation.
+b	Semiminor radius of the ellipsoid axis.
+datum	Datum name.
+ellps	Ellipsoid name.
+k	Scaling factor (old name).
+k_0	Scaling factor (new name).
+lat_0	Latitude of origin.
+lat_1	Latitude of first standard parallel.
+lat_2	Latitude of second standard parallel.
+lat_ts	Latitude of true scale.
+lon_0	Central meridian.
+lonc	Longitude used with Oblique Mercator and possibly a few others.
+lon_wrap	Center longitude to use for wrapping.
+nadgrids	Filename of NTv2 grid file to use for datum transforms.
+no_defs	Do not use the /usr/share/proj/proj_def.dat defaults file.
+over	Allow longitude output outside -180 to 180 range, disables wrapping.
+pm	Alternate prime meridian.
+proj	Projection name.
+south	Denotes southern hemisphere Universal Transverse Mercator zone.
+to_meter	Multiplier to convert map units to 1.0 meter.
+towgs84	3 or 7 term datum transform parameters.
+units	Meter (for example, U.S. survey foot))
+vto_meter	Vertical conversion to meter.
+vunits	Vertical units.
+x_0	False easting.
+y_0	False northing.
+zone	Universal Transverse Mercator zone.

SWB takes the following additional steps to compute the correct coordinates for the project grid:

1. creates an array of coordinates for the data grid in native projected coordinates,
2. transforms the native projected coordinates to SWB base coordinates,
3. determines the indices (row, column) for the data grid cell closest to each of the SWB base coordinates,
4. obtains the data-grid values for the set of indices in step 3, and
5. returns an array of all the values obtained in step 4.

The process outlined in these steps is essentially a nearest-neighbor resampling scheme. A more complex process would result in much slower execution times. The SWB user, therefore, must determine whether or not a nearest-neighbor type process is acceptable.

If, for example, the data grid contains precipitation data at a 4-kilometer grid resolution and the underlying SWB base resolution is 200 meters, SWB will apply the precipitation value from the coarse grid that corresponds to the coordinates of the center of the SWB grid cell. Interpolating this type of data could be done, but would provide only the illusion of greater accuracy—a smoother precipitation surface.

Table 2–6. PROJ.4 strings for some commonly used cartographic projections.

[WGS84, World Geodetic System 1984]

Projection name	PROJ.4 string
Unprojected, WGS84 (geographic coordinates)	+proj=lonlat +datum=WGS84 +no_defs
Universal Transverse Mercator (UTM), zone 18	+proj=utm +zone=18 +north +ellps=GRS80 +datum=NAD83 +units=m +no_defs
Wisconsin Transverse Mercator (WTM)	+proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m
Lambert Conformal Conic	+proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5 +lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80 +datum=NAD83 +units=m +no_defs
Michigan Oblique Mercator	+proj=omerc +lat_0=45.30916666666666 +lonc=-86 +alpha=337.25556 +k=0.9996 +x_0=2546731.496 +y_0=-4354009.816 +ellps=GRS80 +datum=NAD83 +units=m +no_defs
North America Albers Equal Area Conic	+proj=aea +lat_1=20 +lat_2=60 +lat_0=40 +lon_0=-96 +x_0=0 +y_0=0 +datum=NAD83 +units=m +no_defs
United States Contiguous Albers Equal Area Conic (U.S. Geological Survey version)	+proj=aea +lat_1=29.5 +lat_2=45.5 +lat_0=23 +lon_0=-96 +x_0=0 +y_0=0 +ellps=GRS80 +datum=NAD83 +units=m +no_defs
United States Contiguous Albers Equal Area Conic	proj=aea +lat_1=29.5 +lat_2=45.5 +lat_0=37.5 +lon_0=-96 +x_0=0 +y_0=0 +ellps=GRS80 +datum=NAD83 +units=m +no_defs

However, if the SWB base grid is 1 kilometer and the underlying data grid contains land-use data at a 90-meter resolution, the algorithm implemented by SWB may or may not be acceptable. A majority filter may be invoked for integer grids, but will still characterize the land uses present in a subset of the data-grid cells corresponding to the SWB base-grid cell. In the case where the underlying data grid is of much higher resolution than the SWB computational grid, an external GIS procedure may be preferred to resample the land use to the SWB base-grid resolution; resampling with some type of mean (for real data) or modal function (for integer data) would be ideal.

Specification of a cartographic projection for an SWB model is accomplished with the `BASE_PROJECTION_DEFINITION` control file statement. For example, to specify that the coordinates of a model grid be interpreted by means of the Wisconsin Transverse Mercator projection, the following control file statement would be added:

```
BASE_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-
4480000 +datum=NAD83 +units=m.
```

Gridded Datasets

SWB currently can make use of gridded data in the following three formats: Surfer, Esri Arc ASCII, or netCDF. Of these formats, only Surfer and Arc ASCII grids may be used as a source for the input data grids discussed in the previous section. All three file formats may be used to supply daily weather data to SWB. Often, one or more files constituting a time series of gridded data are required to perform a simulation. In addition, missing values are often a feature of these gridded datasets, which can cause numerical errors in the simulation results. These topics are discussed further in the following sections. The functionality and control file syntax discussed in this section applies regardless of what type of grid file is being used.

Specifying Grid Filenames

To specify a series of grid files for use with SWB, a filename template can be used in place of a normal filename. For example, more than 43,000 individual Arc ASCII grids were supplied to make a 100-year model run for the Lake Michigan Pilot Water Availability Study. The files were given names with the pattern precip-month-day-year.asc; for example, precip-02-12-1967.asc. The control file syntax required to specify this file naming convention was as follows:

```
PRECIPITATION ARC_GRID precip-%0m-%0d-%Y.asc.
```

In the filename template, the meanings for the characters that immediately follow the percent symbol (%) are as follows: %0m, the month number (1-12), padded by a leading zero; %0d, the day of the month, padded by a leading zero; and %Y, the four-digit year value. More of these filename template values are listed in table 2–7.

In addition, three modifiers may be specified in the control file if SWB is being run on a computing platform where capitalization is significant, as is the case for the Linux or MacOS operating systems (fig. 2–9).

The modifiers are to be used in the control file prefixed by the data name. For example, to ensure uppercase month names are used in conjunction with precipitation data files, `PRECIPITATION_MONTHNAMES_UPPERCASE` can be added to the control file. When the various control- file modifiers are used together, SWB can locate and use a variety of files without requiring that the files be renamed. Some common file naming patterns and corresponding SWB template statements are listed in table 2–8.

Table 2–7. Soil-Water-Balance (SWB) control file template values for specifying a series of filenames.

Template value	Meaning
%Y or %y	Four-digit year value.
%m	Month number, not zero padded (1–12).
%0m	Month number, zero padded (01–12).
%b	Abbreviated (three-letter) month name (jan-dec).
%B	Full month name (january-december).
%d	Day of month, not zero padded (1–31).
%0d	Day of month, zero padded (01–31).
#	File counter, reset each year beginning with 1.
#000	File counter with three positions of zero padding, reset each year (1-n).

```
_MONTHNAMES_CAPITALIZED
_MONTHNAMES_UPPERCASE
_MONTHNAMES_LOWERCASE
```

Figure 2–9. Control file modifiers for use in specifying month name capitalization.

Table 2–8. Examples showing the use of filename templates.

[–, none]

Example filename	Template	Control file modifier entry
prcp09Jan2010.asc	prcp%0d%b%Y.asc	PRECIPITATION_MONTHNAMES_CAPITALIZED
tmin_2011.nc4	tmin_%Y.nc4	–
tasmax-02-22-1977.asc	tasmax-%0m-%0d-%Y.asc	–
precip_january_1981.nc	precip_%B_%Y.nc	PRECIPITATION_MONTHNAMES_LOWERCASE

Options for Gridded Datasets

SWB has a set of common control file directives that may be used with any input gridded dataset. For each of the applicable gridded datasets, a standard set of suffixes may be added to the dataset name to control how SWB treats the dataset. The dataset prefixes understood by SWB 2.0 are given in the previous section. The control file suffixes understood by SWB are listed in table 2–9.

More information regarding the use of some of the control file suffixes to handle missing data is in the “Treatment of Missing Values” and “Conversion Factors” sections.

Supported File Types

The following three file formats are supported as input to SWB: Surfer ASCII grids, Arc ASCII grids, and netCDF files. Both the Surfer and Arc ASCII grids amount to a rectangular matrix of data with several lines of header information prepended; any software could be used to create the data matrices as long as the header information can be provided. Each format is discussed further in the following sections.

Table 2–9. Control file suffixes for modifying gridded data input to Soil-Water-Balance (SWB) code.

[<, less than; <=, less than or equal to; >, greater than; >= greater than or equal to]

Suffix	Argument	Description
_SCALE_FACTOR	real value	Amount to multiply raw grid value by prior to use.
_ADD_OFFSET	real value	Amount to add to the raw grid value following application of the scale factor, if any.
_NETCDF_X_VAR	string	Name of the variable to be used as the x axis.
_NETCDF_Y_VAR	string	Name of the variable to be used as the y axis.
_NETCDF_Z_VAR	string	Name of the variable to be used as the z (value) axis.
_NETCDF_TIME_VAR	string	Name of the variable to be used as the time axis.
_NETCDF_VARIABLE_ORDER	“xyt or txy”	Description of the order in which the gridded data were written.
_NETCDF_FLIP_VERTICAL	none	If present, gridded data will be flipped around the vertical axis.
_NETCDF_FLIP_HORIZONTAL	none	If present, gridded data will be flipped around the horizontal axis.
_PROJECTION_DEFINITION		PROJ.4 string describing the geographic projection of the dataset.
_MINIMUM_ALLOWED_VALUE	real value	Ceiling to be applied to the data; data above this value will be reset to this amount.
_MAXIMUM_ALLOWED_VALUE	real value	Floor to be applied to the data; data beneath this value will be reset to this amount.
_MISSING_VALUES_CODE	real or integer value	Value.
_MISSING_VALUES_OPERATOR	<, <=, >, >=	Operator to use for comparison to the _MISSING_VALUES_CODE.
_MISSING_VALUES_ACTION	mean or zero	Supplying the keyword “mean” will substitute the mean value calculated over the remaining valid cells; supplying the keyword “zero” will substitute a value of 0.0 in place of missing values.

Surfer Ascii Grid

Golden Software's ASCII grid format consists of a five-line header followed by the data values arranged in a matrix. An example Surfer ASCII grid file is shown in figure 2–10.

The header values contain the following information.

- Line 1, DSAA, a label identifying the file format as a Golden Software ASCII grid
- Line 2, number of columns (number of X values) number of rows (number of Y values)
- Line 3, minimum X value, maximum X value
- Line 4, minimum Y value, maximum Y value
- Line 5, minimum Z value, maximum Z value
- Lines 6 through 10, Z-values

For the file shown in figure 2–10, the coordinate system has its origin in the lower left-hand corner, with x and y coordinates increasing toward the upper right-hand corner. Surfer files are not explicitly georeferenced to real-world coordinate systems.

Arc Ascii Grid

The publishers of ArcMap and ArcView software, Esri, developed one of the most commonly used raster-data formats in use. Esri's Arc ASCII grid format is a matrix representation of the gridded dataset with a short header tacked to the top of the file (U.S. Library of Congress, 2015). In an Arc ASCII grid, the data are arranged as though a user is viewing the data from above. The coordinates for the lower left-hand corner of the lower left-hand grid cell are specified as xllcorner and yllcorner in figure 2–11. The value stored in the lower left-hand grid cell is a 7, which is shown in the bottom row and left-most column of figure 2–11.

Note that SWB does not process the NODATA_ value codes as given in the Arc ASCII grid files; missing values should be handled through the use of user-supplied, control-file directives, discussed later in this section.

```
DSAA
14   5
0.5  7.0
-0.4 0.0
0.0  7.0
0.50 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
0.45 0.9 1.4 1.9 2.4 2.9 3.4 3.9 4.4 4.9 5.4 5.9 6.4 6.9
0.40 0.8 1.3 1.8 2.3 2.8 3.3 3.8 4.3 4.8 5.3 5.8 6.3 6.8
0.36 0.7 1.2 1.7 2.2 2.7 3.2 3.7 4.2 4.7 5.2 5.7 6.2 6.7
0.32 0.6 1.1 1.6 2.1 2.6 3.1 3.6 4.1 4.6 5.1 5.6 6.1 6.6
```

Figure 2–10. Example showing a Golden Software Surfer ASCII grid file.

```
ncols                34
nrows                 4
xllcorner      739475.0
yllcorner     2314000.0
cellsize           10.0
NODATA_value -9999
9 9 9 9 9 9 9 9 9 9 9 8 8 8 8 8 8 8 9 9 9 9 9 9 8 8 8 8 8 8 8 8 9 9
7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 6 6 6 7 7 7 6 6 6 6 6 6 6 6 6 6 6 6 6
7 7 7 7 6 6 6 7 7 7 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
7 7 7 7 7 7 7 7 7 7 6 6 6 7 7 7 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
```

Figure 2–11. Example showing an Arc ASCII grid file.

netCDF

NetCDF is a file format commonly used by researchers in atmospheric and oceanic sciences. A key benefit of netCDF files is that they are designed to be platform independent; in other words, a netCDF file generated on a Macintosh computer by an application compiled with the GNU compiler collection gfortran compiler should be able to be read by an application that is compiled with the Intel compiler and running on Windows. In addition, netCDF files are able to store arbitrary combinations of data. This ability allows for substantial metadata to be stored in the netCDF file along with the variable of interest.

A set of conventions, known as the Climate and Forecast Metadata Conventions, gives recommendations regarding the type and nature of metadata to be included along with the primary variable within a netCDF file (Eaton and others, 2011). SWB outputs written to netCDF files attempt to adhere to the Climate and Forecast Metadata Conventions version 1.6 (CF 1.6) to maximize the number of third-party netCDF tools that will work with SWB output.

In addition to these benefits of netCDF file use, the fact that dozens of open-source tools are available to read, write, and visualize netCDF files makes them a good format for use with SWB. A basic tool called ncdump—a program to dump the contents of a netCDF file—is distributed by Unidata, the maintainer of netCDF file format. Issuing the command `ncdump -h` along with the filename will cause the header information and other various metadata to be printed to the screen.

As an example, one useful source for gridded daily weather data is the Daymet product containing gridded daily precipitation and air temperature for the conterminous United States on a 1 kilometer grid-cell spacing (Thornton and others, 2016). The metadata stored in the file reveals a variety of useful information about the file contents (fig. 2–12).

This particular file contains three classes of metadata pertaining to dimensions, variables, and global attributes. The file contains data pertaining to four dimensions—x, y, time, and nv. For this file, the x and y dimensions may be thought of in terms of Cartesian coordinates—x refers to the number of cells in the east-west orientation, whereas y refers to the number of cells in the north-south orientation. The dimension time is declared unlimited; this file could contain many days of daily weather data. In this case, the time dimension is of size 365, which means the file contains 1 year of data. Dimension nv is of size 2 and exists so that the variable time_bnds can contain a starting and ending date and a time stamp.

Each of the nine variables defined is referenced in terms of the dimensions. The key variable in the file is named "prcp"—the daily precipitation value. The daily precipitation value is defined at each time (day) in the file for all values of x and y. Note the way that dates and times are specified in the netCDF file—as a real-valued number of days since 1980-01-01 00:00:00 UTC.

The grid-cell location is specified in the following two ways: in terms of projected (x, y) coordinates, as well as in geographic (longitude, latitude) coordinates. Often netCDF files will be written so that both projected and geographic coordinates are provided, ensuring that third-party software applications will be able to correctly interpret the location of each data value.

SWB does not have the ability to process and make use of much of the metadata included in the netCDF file header. The user is responsible for being aware of the physical units that each of the datasets is stored in, and must supply control file directive to SWB to ensure that the data are used correctly. For example, control file directives must often be included in the SWB control file to cause SWB to convert precipitation in metric units (millimeters per day) to inches per day. The authors recommend examining the SWB output values of air temperature and precipitation to verify that any such unit conversions have been done correctly. Some of the temperature conversion suffixes are particularly easy to forget, which leads to disastrous SWB results. SWB will still run with the incorrect daily weather values. For example, if air temperatures are given in degrees Celsius but no offset or scale factor values are provided, the air temperatures processed by SWB will never exceed a numerical value of 30 or 40 degrees Celsius; SWB will process these values as though the values are given in degrees Fahrenheit, which results in considerable snowfall and snowmelt and unrealistically elevated net infiltration values.

In addition, SWB cannot parse the netCDF variables and attributes associated with any map projection that may have been used when the netCDF file was created. The user needs to be aware of the geographic projection (if any) that was used. If the gridded data do not match the SWB project bounds exactly, a PROJ.4 string must be provided to enable SWB to translate between project coordinates and the netCDF file coordinates.

As an example, look again at the metadata included in figure 2–12. The creators of this dataset have provided a variable (lambert_conformal_conic) and have attached several attributes to the variable to help ensure correct georeferencing of the coordinate values. The PROJ.4 string can be constructed from the metadata attached to the lambert_conformal_conic variable (fig. 2–13).

```
netCDF daymet_v3_prcp_2014_na {
dimensions:
        x = 7814 ;
        y = 8075 ;
        time = UNLIMITED ; // (365 currently)
        nv = 2 ;
variables:
        float x(x) ;
                x:units = "m" ;
                x:long_name = "x coordinate of projection" ;
                x:standard_name = "projection_x_coordinate" ;
        float y(y) ;
                y:units = "m" ;
                y:long_name = "y coordinate of projection" ;
                y:standard_name = "projection_y_coordinate" ;
        float lat(y, x) ;
                lat:units = "degrees_north" ;
                lat:long_name = "latitude coordinate" ;
                lat:standard_name = "latitude" ;
        float lon(y, x) ;
                lon:units = "degrees_east" ;
                lon:long_name = "longitude coordinate" ;
                lon:standard_name = "longitude" ;
        float time(time) ;
                time:long_name = "time" ;
                time:calendar = "standard" ;
                time:units = "days since 1980-01-01 00:00:00 UTC" ;
                time:bounds = "time_bnds" ;
        short yearday(time) ;
                yearday:long_name = "yearday" ;
        float time_bnds(time, nv) ;
        short lambert_conformal_conic ;
                lambert_conformal_conic:grid_mapping_name = "lambert_conformal_conic" ;
                lambert_conformal_conic:longitude_of_central_meridian = -100. ;
                lambert_conformal_conic:latitude_of_projection_origin = 42.5 ;
                lambert_conformal_conic:false_easting = 0. ;
                lambert_conformal_conic:false_northing = 0. ;
                lambert_conformal_conic:standard_parallel = 25., 60. ;
                lambert_conformal_conic:semi_major_axis = 6378137. ;
                lambert_conformal_conic:inverse_flattening = 298.257223563 ;
        float prcp(time, y, x) ;
                prcp:_FillValue = -9999.f ;
                prcp:long_name = "daily total precipitation" ;
                prcp:units = "mm/day" ;
                prcp:missing_value = -9999.f ;
                prcp:coordinates = "lat lon" ;
                prcp:grid_mapping = "lambert_conformal_conic" ;
                prcp:cell_methods = "area: mean time: sum" ;

// global attributes:
                :start_year = 2014s ;
                :source = "Daymet Software Version 3.0" ;
                :Version_software = "Daymet Software Version 3.0" ;
                :Version_data = "Daymet Data Version 3.0" ;
                :Conventions = "CF-1.6" ;
                :citation = "Please see http://daymet.ornl.gov/ for current Daymet data citation information" ;

                :references = "Please see http://daymet.ornl.gov/ for current information on Daymet references" ;

}
```

Figure 2–12. Metadata embedded in a Daymet, version 3 precipitation netCDF file (Thornton and others, 2016).

The netCDF file metadata does not include any details about the ellipse (PROJ.4 keyword ellps) or datum associated with this projection. However, the semi_major_axis and inverse_flattening” attribute values are consistent with the GRS80 definition (Moritz, 2000). In this example, the standard parallels as defined by lat_1 and lat_2 in figure 2–13 differ from the standard parallels of 33 degrees and 45 degrees as described in Snyder (1987). Supplying the standard values in the SWB control file, at best, would cause SWB to issue a warning about a mismatch between the data coverage and the model domain and, at worst, would run anyway, supplying incorrect daily weather data to the model. In other words, SWB checks to see that numerically valid coordinates are present and that the weather data cover the region defined by the base grid. However, SWB cannot detect an incorrect user-supplied PROJ.4 string. Users are encouraged to examine the SWB output files containing air temperature and precipitation data to verify that daily weather data are being correctly interpreted by SWB.

An explicit definition of the grid spacing is not included as an attribute in the header of the netCDF file (fig. 2–12). However, grid spacing can be gleaned from the coordinate variable values themselves. Running the command-line utility ncdump with the option -v x (`ncdump -v x daymet_v3_prcp_2014_na.nc4`) produces the output shown in figure 2–14.

By subtracting two adjacent x coordinate values, the grid spacing in the x direction is 1,000 meters. Subtracting two adjacent y coordinate values (not shown) also produces 1,000 meters; therefore, the grid cells are square and measure 1 kilometer on a side.

Treatment of Missing Values

Missing values in datasets can be an issue during a SWB simulation. Generally, SWB will detect most obvious issues, such as numerical values outside of a reasonable range of values. However, missing values that are within the expected normal range of values for the dataset could lead to unexpected results. For example, an air temperature value that is interpreted as zero rather than being treated as a missing value would result in a cell being simulated with permanent winter conditions.

SWB has a few actions that may be taken to deal with the issue of missing values. These actions are triggered through a set of control file directives that are supplied as suffixes to the dataset they pertain to (table 2–10).

For example, gridded weather datasets typically end abruptly at the edge of a large waterbody, which from the perspective of interpolations is done for valid reasons. However, a dataset that ends abruptly at the edge of a large water body often leads to extreme edge effects on the SWB results.

A crude but effective way to overcome this limitation in the climate dataset is to enforce some type of value substitution for the affected cells. For example, to eliminate zones of zero precipitation around a large waterbody, control file statements might be added to inform SWB that the mean value is to be used in place of missing data values (fig. 2–15).

Including this syntax in the control file would result in the mean value of the valid cells being substituted for the missing values across the model grid for a day.

```
+proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5 +lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80
+datum=NAD83 +units=m +no_defs
```

Figure 2–13. PROJ.4 string for a Daymet, version3 netCDF file (Thornton and others, 2016).

```
   3232750, 3233750, 3234750, 3235750, 3236750, 3237750, 3238750, 3239750,
   3240750, 3241750, 3242750, 3243750, 3244750, 3245750, 3246750, 3247750,
   3248750, 3249750, 3250750, 3251750, 3252750 ;
```

Figure 2–14. Partial listing of the x variables embedded in a Daymet, version 3 netCDF file (Thornton and others, 2016).

Table 2–10. Control file suffixes for treatment of missing data.

[<, less than; <=, less than or equal to; >, greater than; >= greater than or equal to]

Suffix	Argument	Default value	Description
_MINIMUM_ALLOWED_VALUE	real value	_MINIMUM_ALLOWED_VALUE	Ceiling to be applied to the data; data above this value will be reset to this amount.
_MAXIMUM_ALLOWED_VALUE	real value	_MAXIMUM_ALLOWED_VALUE	Floor to be applied to the data; data beneath this value will be reset to this amount.
_MISSING_VALUES_CODE	real or integer value	_MISSING_VALUES_CODE	Value.
_MISSING_VALUES_OPERATOR	<, <=, >, >=	_MISSING_VALUES_OPERATOR	Operator to use for comparison to the _MISSING_VALUES_CODE.
_MISSING_VALUES_ACTION	mean or zero	_MISSING_VALUES_ACTION	Supplying the keyword "mean" will substitute the mean value calculated over the remaining valid cells; supplying the keyword "zero" will substitute a value of 0.0 in place of missing values.

```
PRECIPITATION_MISSING_VALUES_CODE          0.0
PRECIPITATION_MISSING_VALUES_OPERATOR      <
PRECIPITATION_MISSING_VALUES_ACTION        MEAN
```

Figure 2–15. Control file statements used to request that Soil Water Balance (SWB) code substitute mean daily air temperatures in areas of missing data.

Conversion Factors

SWB still uses U.S. customary units for many dimensions (inches, degrees Fahrenheit), primarily for historical reasons. Most available gridded climate data are encoded in metric units. In order for SWB to make use of these data sources, conversion factors or offsets, or both must be provided. In theory, to craft a code that would read the standard climate forecast elements from the metadata of a netCDF file should be possible; however, in practice, too many gridded datasets are still in existence that do not adhere to the standards. For now (2017), the user must handle unit conversion explicitly in the control file. The control-file syntax is listed in table 2–11.

For example, most air-temperature data are stored with units of degrees Celsius. To make use of this data grid with SWB, control-file syntax would be added to specify the scale factor and offset to apply to the data. The scale factor and offset values as applied to minimum air-temperature data (TMIN) are shown in figure 2–16.

Table 2–11. Control file suffixes for use in performing unit conversions of values read from grids.

Suffix	Argument	Description
_SCALE_FACTOR	real value	Amount to multiply raw grid value by prior to use.
_ADD_OFFSET	real value	Amount to add to the raw grid value following application of the scale factor.

```
TMIN_SCALE_FACTOR        1.8
TMIN_ADD_OFFSET          32.0
```

Figure 2–16. Control file syntax for conversion of minimum air temperature data from degrees Celsius to degrees Fahrenheit.

This syntax will cause SWB to convert all values in the minimum air temperature grid from Celsius to Fahrenheit before performing any water balance calculations.

Inactive Grid Cells

Grid cells outside the area of interest to the user may be inactivated. SWB will use information from certain standard grids to determine which grid cells should remain active during the course of a simulation; namely, the land-use, soil-type, and available water-capacity grids. *A negative value in the land-use, soil-type, or available water-capacity grids causes SWB to mark the cell as inactive; the cell will be removed from further calculations.* The missing value treatments discussed in the previous section could interfere with this interpretation; the user is discouraged from using the missing value treatments to these grids. Because integer grids with missing values are often encoded with -9999, these negative values were used to help define active and inactive grid cells.

If the user does not wish to have cells with missing values inactivated, some GIS preprocessing will be needed to ensure that SWB can separate inactive cells from those with missing values. A strategy might be to convert active-cell missing values to an extremely large positive number, then use SWB's control file directives to find these values and convert them to appropriate values.

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Appendix 3. Input Data, Lookup-Table Entries, and Control-File Directives by Method

Soil-Water-Balance (SWB) code was designed so that parameters may be supplied to the model on an as-needed basis. As more calculation methods were added to the original SWB version 1.0 code, the input requirements increased and become more complicated. For this reason, the authors created a flexible table-based format that allows parameters to be supplied in any order convenient to the user. As with SWB version 1.0, the key value in the lookup table (or tables) is the land-use code; all parameter values supplied in the tables must contain values for each of the land-use values present in the land-use grid file. Land-use values must be in the same order in all of the tables. For example, if one supplied two tables, one ordered by increasing land-use code values, and the other with land-use codes in random order, it is certain that the output SWB results would be corrupted. The mismatch in land-use codes between the tables would result in parameter values being paired with incorrect land-use codes.

For table-based parameter entry, the proper parameter name must be entered in the header of the file. Case does not matter for these heading entries: DEPLETION_FRACTION will work as well as depletion_fraction or Depletion_Fraction. For some methods, multiple heading values are recognized as equivalent to one another. For example, to identify a particular table column as holding land-use/land-cover codes, SWB recognizes any of the following: LU_Code, Land_use_Code, or Land use lookup Code. Note also, that SWB will fill any blank spaces in the header with underscores before evaluating the values therein. Thus, Land use lookup Code will be treated as Land_use_Lookup_Code by SWB. The idea is that if an identification makes sense to the modeler, the identification should be recognized by SWB.

Note that many processes require entries in both the control file and the lookup tables. In addition, some parameters have been designed so that they may be provided by lookup-table entries and by a control-file entry that specifies a gridded parameter set. The provision for accepting values from tables or grid files was done to provide the user with maximum flexibility regarding parameter-value specification.

This section describes in detail the data, lookup-table entries, and control-file requirements for each method currently implemented in SWB.

Precipitation

Three methods exist to supply SWB with daily precipitation data. The required control-file syntax and lookup-table entries for each method are listed in tables 3–1 and 3–2.

The method of fragments requires the following specific datasets to function: (1) grid of rainfall zones, (2) month-year or monthly grids of precipitation, and (3) a fragments file containing a record of the fraction of monthly rainfall falling on each day of the month, associated with a set of rain gages. Rain gages considered for fragment generation should be selected based on proximity to the area of interest and the length and completeness of daily records. Thiessen polygons are drawn around each of the selected rain gages and the daily rainfall pattern within each Thiessen polygon is assumed to be the same as the pattern at the rain gage. Daily rainfall fragments are generated by dividing each daily rainfall measurement for a particular month by the total rainfall measured at the gage for that month. This calculation results in a set of fragments for that particular month in which the total number of fragments is equal to the number of days in the month. Daily rainfall for a given month is synthesized by multiplying total rainfall for that month by each fragment in the set.

Fragment sets are compiled for every selected gage for every month in which complete daily rainfall measurements are available. Fragment sets are grouped by month of the year and by rain gage. In the water-balance calculation, the fragment set used for a given gage for a given month is selected randomly from among available sets for that gage for that month. An extract from a fragments file is shown in figure 3–1.

Table 3–1. Precipitation-method control-file entries.

[–, no entry]

Control-file syntax		Notes
	Method—Tabular	
PRECIPITATION_METHOD	**TABULAR**	TABLE is also an acceptable method name.
	Method—Gridded data	
PRECIPITATION_METHOD	**GRIDDED**	Control-file entries pertaining to the specification of the input-precipitation grids are not listed in this table. Information about specification of gridded datasets is in appendix 2.
	Method—Method of fragments	
PRECIPITATION_METHOD	**METHOD_OF_FRAGMENTS**	–
PRECIPITATION	**{grid type} {gridfile name}**	This statement identifies a time series of monthly total-precipitation grids. These precipitation grids could include a set of 12 monthly total precipitation grids representing average total precipitation over a range of years, or a time series of monthly total precipitation grids for which a separate grid exists for each month and year in the simulation.
RAINFALL_ZONE **RAINFALL_ADJUST_FACTOR_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	This grid associates a Thiessen Polygon rainfall zone with a particular precipitation gage.
RAINFALL_ADJUST_FACTOR **RAINFALL_ADJUST_FACTOR_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid allowing for spatial correction of monthly precipitation values. If this grid is not desired, the user can specify RAINFALL_ ADJUST_FACTOR CONSTANT 1.0.
FRAGMENTS_DAILY_FILE	**{path and filename of rainfall fragments file}**	See figure 3–1 for an example showing the contents of a daily fragments file.

Table 3–2. Precipitation-method lookup-table entries.

[mm/dd/yyyy, month/day/year; –, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
Method—Tabular input				
`weather_date`	mm/dd/yyyy	Character	Number of date values	–
`precipitation_amount`	Inch	Float	Number of date values	–
Method—Gridded input				
–	–	–	–	–
Method—Method of fragments				
–	–	–	–	–

```
10  1  1  0.073 0.000 0.139 0.000 0.230 0.048 0.007 0.005 0.000 … 0.180
10  2  1  0.013 0.032 0.040 0.021 0.005 0.023 0.038 0.001 0.000 … 0.042
10  3  1  0.014 0.101 0.127 0.000 0.000 0.043 0.000 0.000 0.000 … 0.000
10  4  1  0.000 0.000 0.049 0.175 0.000 0.000 0.014 0.497 0.000 … 0.000
10  5  1  0.006 0.000 0.000 0.000 0.011 0.357 0.055 0.006 0.011 … 0.000
10  6  1  0.018 0.000 0.000 0.000 0.002 0.002 0.029 0.210 0.000 … 0.000
10  7  1  0.023 0.109 0.117 0.141 0.070 0.023 0.020 0.098 0.039 … 0.000
10  8  1  0.021 0.000 0.019 0.000 0.008 0.036 0.061 0.000 0.000 … 0.000
```

Figure 3–1. Extract from a fragments file.

The fragments file (fig. 3–1) contains columns of data that consist of the following information.

- Column 1 contains of month number (ranges from 1 to 12).
- Column 2 contains of rainfall zone (gage) identification number (ranges from 1 to the number of rainfall gages).
- Column 3 contains fragment index number (ranges from 1 to number of fragments for the given rainfall gage).
- Columns 4 through 34 consist of daily fragment values for each day of the month.

The sum of any given row for columns 4 through 34 will, by definition, equal 1. Values must be provided for columns 32 through 34 regardless of the actual number of days in the month. Providing values of zero in these columns for months with less than 31 days is suggested. SWB ignores the value provided for nonexistent days of the month.

The SWB control file needs to have a RAINFALL_ZONE directive specifying the distribution of rainfall zones (rainfall zone grid) for the model domain. A sequence of monthly rainfall grids also must be specified in the control file (for example, PRECIPITATION ARC_GRID precip_%0m_%Y.asc).

Interception

The bucket, Horton, and Gash methods are available for estimating the amount of precipitation intercepted by vegetation before reaching the soil reservoir. The bucket method is the simplest of the three methods, requiring that daily precipitation exceed some interception threshold before allowing the precipitation to reach the soil surface. The Horton method extends the bucket method by allowing for some additional fraction of daily precipitation to be captured as intercepted water. Finally, the Gash method allows interception to be estimated based on parameters describing the storage capacity and density of the vegetation. The control-file syntax and lookup-table entries required to use any of these interception methods are listed in tables 3–3 and 3–4.

Table 3–3. Interception-method control-file entries.

[–, no entry]

Control-file syntax		Notes
Method— Bucket		
INTERCEPTION_METHOD BUCKET		–
Method—Horton		
INTERCEPTION_METHOD HORTON		–
Method—Gash		
INTERCEPTION_METHOD GASH		–
FRACTION_CANOPY_COVER FRACTION_CANOPY_COVER_PROJECTION_DEFINITION	{grid type} {gridfile name} {PROJ4 string defining projection}	–
EVAPORATION_TO_RAINFALL_RATIO EVAPORATION_TO_RAINFALL_RATIO_PROJECTION_DEFINITION	{grid type} {gridfile name} {PROJ4 string defining projection}	–

Table 3–4. Interception-method lookup-table entries.

[–, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
		Method—Bucket		
`growing_season_interception`	Inch	Float	Number of land-use codes	Amount of plant interception during the growing season, per day.
`nongrowing_season_interception`	Inch	Float	Number of land-use codes	Amount of plant interception during the nongrowing season, per day.
		Method—Horton		
`growing_season_interception_a`	Inch	Float	Number of land-use codes	a in $interception = a + bP^n$
`growing_season_interception_b`	Inch	Float	Number of land-use codes	b in $interception = a + bP^n$
`growing_season_interception_n`	Unitless	Float	Number of land-use codes	Exponent n in $interception = a + bP^n$; Horton (1919) generally used an exponent value of 1.0.
`nongrowing_season_interception_a`	Inch	Float	Number of land-use codes	a in $interception = a + bP^n$
`nongrowing_season_interception_b`	Inch	Float	Number of land-use codes	b in $interception = a + bP^n$
`nongrowing_season_interception_n`	Unitless	Float	Number of land-use codes	Exponent n in $interception = a + bP^n$; Horton (1919) generally used an exponent value of 1.0.
		Method—Gash		
`canopy_storage_capacity`	Inch	Float	Number of land-use codes	$P_{sat} = -\frac{S}{c \cdot V} \ln\left(1 - \mathrm{V}\right)$, see equation 1–1 in appendix 1 for details.
`trunk_storage_capacity`	Inch	Float	Number of land-use codes	–
`stemflow_fraction`	Unitless	Float	Number of land-use codes	–

Snowfall

SWB version 2.0 contains a single method for partitioning precipitation into rainfall and snowfall, the `SINGLE_TEMPERATURE` method. This method is the default method; therefore, a control-file entry is not required.

Snowmelt

SWB version 2.0 contains a single snowmelt method, the `TEMPERATURE_INDEX` method. This method is the default method; therefore, a control-file entry is not required.

Fog Interception

The fog-interception method is set to NONE by default. Fog interception may be enabled by supplying a set of grids that specify the ratio of captured fog relative to the monthly rainfall rate. The control-file syntax and lookup-table entries needed to include fog interception in a simulation are listed in tables 3–5 and 3–6.

Table 3–5. Fog-interception control-file entries.

[–, no entry]

Control-file syntax		Notes
Method— None		
FOG_METHOD	**NONE**	TABLE is also an acceptable name.
Method—Gridded Data		
FOG_METHOD	**GRIDDED**	Control-file entries pertaining to the input precipitation grids are not shown in this table.
Method—Gash		
FOG_RATIO **FOG_RATIO_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	The fog-ratio grid is meant to quantify the amount of fog interception as a ratio of fog to monthly rainfall amount.

Table 3–6. Fog-interception lookup-table entries.

[–, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
Method—None				
–	–	–	–	–
Method—Monthly grid				
fog_catch_efficiency	Unitless	Float	Number of land-use codes	Fog-catch efficiency is meant to quantify the fraction of the fog that is captured and actually ends up reaching the soil surface; the remainder of the captured fog is assumed to evaporate.

Runoff

Runoff may be simulated in one of two ways. The first, and original, method is the Natural Resources Conservation Service CURVE_NUMBER method, which uses hydrologic soil groups and land-use codes to differentiate rainfall-runoff responses for each grid cell. The second method, derived from the Hawaii water-budget code, is the MONTHLY_GRID method, which uses externally calculated monthly runoff ratios relative to rainfall to derive runoff values. The control-file syntax and lookup-table entries required for these methods are listed in tables 3–7 and 3–8.

Table 3–7. Runoff method control-file entries.

[–, no entry]

Control-file syntax		Notes
	Method— Curve number	
RUNOFF_METHOD	**CURVE_NUMBER**	–
	Method—Monthly grid	
RUNOFF_METHOD **-or-** **RUNOFF_METHOD**	**MONTHLY GRID** **RUNOFF_RATIO**	–
RUNOFF_ZONE **RUNOFF_ZONE_PROJECTION_DEFINITION projection}**	**{grid type} {gridfile name}** **{PROJ4 string defining**	A set of runoff zones for which externally calculated runoff ratios should be applied.
RUNOFF_RATIO_MONTHLY_FILE	**{path and filename of monthly runoff ratio file}**	See figure 3–1 for an example showing the contents of a daily-fragments file.

Table 3–8. Runoff method lookup-table entries.

[–, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
			Method—Curve number	
CN_#	Unitless	Float	Number of land-use codes x number of soil groups	For each land use, a curve number must be provided for each hydrologic soil group. If four hydrologic soil groups exist such that A=1, B=2, C=3, and D=4, the columns would be named as follows: CN_1, CN_2, CN_3, and CN_4.
			Method—Monthly grid	
–	–	–	–	No curve numbers are needed when using the monthly grid.

Impervious Surface Runoff

Runoff from impervious surfaces may be simulated in a more detailed manner by including a gridded dataset defining the proportion of each grid cell that is comprised of impervious materials. Data on pervious surface coverage may be supplied either as a fraction (0.0–1.0) using the FRACTION_PERVIOUS_COVER control-file entry or as a percentage (0–100 percent) using the PERCENT_PERVIOUS_COVER control-file entry. Data on impervious surface coverage may be supplied either as a fraction (0.0–1.0) using the FRACTION_IMPERVIOUS_COVER control-file entry or as a percentage (0–100 percent) using the PERCENT_IMPERVIOUS_COVER control-file entry. A METHOD directive is not required because the impervious surface calculations are always made during an SWB run. However, because the default PERCENT_PERVIOUS_COVER is 100 percent, the results of these subgrid calculations will not be seen unless some amount of impervious surface is specified for one or more grid cells. The control file entries for the activation and use of the impervious surface runoff method are listed in table 3–9.

Table 3–9. Impervious-surface control-file entries.

[SWB, Soil-Water-Balance Code]

Control-file syntax		Notes
Method— Tabular		
`PERCENT_PERVIOUS_COVER` `PERCENT_PERVIOUS_COVER_PROJECTION_DEFINITION`	`{grid type} {gridfile name}` `{PROJ4 string defining projection}`	PERCENT_IMPERVIOUS_COVER, FRACTION_IMPERVIOUS_COVER, FRACTION_PERVIOUS_COVER are also acceptable grid specifications. Note that the range of values for percent-cover grids (0–100) is different from the range for the fraction grids (0–1). SWB will screen the input-grid values for nonsensical values.

Runoff Routing

Runoff from pervious and impervious surfaces may be routed to downslope cells if desired. A runoff routing fraction grid may be supplied to allow an externally calculated fraction of surface runoff to either be routed downslope or be extracted from the model domain. The required control-file syntax for the routing methods is listed in table 3–10.

Table 3–10. Flow-routing method control-file syntax.

[–, no entry]

Control-file syntax		Notes
Method— No flow routing		
RUNOFF_ROUTING	**NONE**	–
Method—Downhill routing		
RUNOFF_ROUTING	**D8**	–
Method—Downhill routing with routing fraction		
RUNOFF_ROUTING **RUNOFF_ROUTING_FRACTION** **RUNOFF_ROUTING_FRACTION_PROJECTION_DEFINITION**	**D8** **{grid type} {gridfile name}** **{PROJ4 string defining projection}**	–

Potential Evapotranspiration

SWB can calculate potential evapotranspiration by means of the Jensen-Haise or Hargreaves-Samani methods or can accept externally calculated grids of monthly potential evapotranspiration. The required control-file syntax for the three methods are listed in table 3–11.

Table 3–11. Potential evapotranspiration-method control-file entries.

[SWB, Soil-Water-Balance Code; ET_0, reference evapotranspiration]

Control-file syntax		Notes
	Method— Jensen-Haise	
POTENTIAL_EVAPOTRANSPIRATION_METHOD	**JENSEN-HAISE**	JENSEN_HAISE and JH are also recognized as valid method names.
	Method—Hargreaves-Samani	
POTENTIAL_EVAPOTRANSPIRATION_METHOD	**HARGREAVES-SAMANI**	HARGREAVES_SAMANI and HARGREAVES are also recognized as valid method names.
	Method—Monthly grid	
POTENTIAL_EVAPOTRANSPIRATION_METHOD **REFERENCE_ET0** **REFERENCE_ET0_PROJECTION_DEFINITION**	**GRIDDED** **{grid type} {gridfile name}** **{PROJ4 string defining projection}**	This filename template should be a template that specifies a series of monthly reference ET0 grids. SWB expects this data to be in the form of a monthly ET0 sum, in inches. SWB will divide this number by the number of days in the month to arrive at an appropriate daily ET0 value.

Available Water Capacity/Available Water Content

SWB contains a single method (GRIDDED) for populating the available water-capacity parameter. Units of the gridded data are inches per foot; in other words, the number of inches of water storage per foot of plant-rooting depth. The required control-file syntax is listed in table 3–12.

The capacity of the soil-moisture reservoir is determined by multiplying the available water capacity in inches per foot by the root-zone depth in feet, which yields the capacity of the soil-moisture reservoir in inches. Specifying gridded-available water capacity implies that a set of root-zone depths also will be supplied in one of the lookup tables in order that SWB can calculate the soil-moisture reservoir capacity.

Table 3–12. Available water-capacity control-file entries.

[–, no entry]

Control-file syntax		Notes
Method— Gridded		
AVAILABLE_WATER_CAPACITY_METHOD	**GRIDDED**	AVAILABLE_WATER_CONTENT is also valid. If the soil-storage maximum is to be read in as a gridded dataset, this method may be listed as NONE.
AVAILABLE_WATER_CAPACITY	**{grid type} {gridfile name}**	–
AVAILABLE_WATER_CAPACITY_PROJECTION_DEFINITION	**{PROJ4 string defining projection}**	

Rooting Depth

Rooting depth may be treated as static or dynamic. Dynamic rooting depths only have relevance when the crop-coefficients module is invoked. The required control-file syntax and lookup-table entries are listed in tables 3–13 and 3–14.

Table 3–13 Rooting-depth method control-file entries.

[–, no entry]

Control-file syntax		Notes
	Method—Gridded	
`ROOTING_DEPTH_METHOD`	`STATIC`	–
	Method—Dynamic	
`ROOTING_DEPTH_METHOD`	`DYNAMIC`	–

Table 3–14. Effective rooting-depth lookup-table entries.

[–, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
			Method—None	
`RZ_#`	Foot	Float	Number of land-use codes x number of soil groups	For each land use, a root-zone depth must be provided for each hydrologic soil group. If four hydrologic soil groups exist such that A=1, B=2, C=3, and D=4, the columns would be named: RZ_1, RZ_2, RZ_3, and RZ_4.

Soil-Storage Maximum

The original way to parameterize the total volume of soil-moisture storage (or plant-available water) was to specify an available water-capacity grid and a set of effective plant-rooting depths in the lookup table. SWB would multiply these two values to come up with the size of the soil-storage reservoir.

In some cases, calculating the size of the soil-moisture reservoir outside of the SWB framework may be useful. This calculation may be accomplished by specifying that the soil-storage maximum will be read into SWB from an external grid file. Specifying the soil-storage maximum this way will cause the rooting depths and available water-capacity values to be ignored; any soil-moisture reservoir-capacity value that has been calculated previously will be overwritten with the soil-moisture maximum-grid values.

The required control-file syntax and lookup-table entries are listed in tables 3–15 and 3–16.

Table 3–15. Soil-storage maximum control-file entries.

[–, no entry]

Control-file syntax		Notes
Method—Thornthwaite-Mather		
`SOIL_STORAGE_MAX_METHOD`	`CALCULATED`	Calculation requires that an available water-capacity grid and a set of rooting depths (discussed in tables 3–12 and 3–14) be provided.
Method—Gridded		
`SOIL_STORAGE_MAX_METHOD`	`GRIDDED`	–
`SOIL_STORAGE_MAX` `SOIL_STORAGE_MAX_PROJECTION_DEFINITION`	`{grid type} {gridfile name}` `{PROJ4 string defining projection}`	Grid specifying the size of the soil-moisture reservoir for each grid cell in inches.

Table 3–16. Actual evapotranspiration/soil-moisture method control-file syntax.

[–, no entry; FAO–56, Food and Agriculture Organization of the United Nations, Paper No. 56 (Allen and others, 1998)]

Control-file syntax		Notes
Method—Thornthwaite-Mather		
`SOIL_MOISTURE_METHOD`	`THORNTHWAITE-MATHER`	–
Method—Thornthwaite-Mather equations		
`SOIL_MOISTURE_METHOD`	`THORNTHWAITE-MATHER_EQUATIONS`	These regression equations were developed from a set of digitized Thornthwaite-Mather soil-moisture-retention tables. This method is present to serve as a check on other methods.
Method—FAO–56 single stage		
`SOIL_MOISTURE_METHOD`	`FAO-56`	This is a faithful reimplementation of the single-stage FAO–56 soil-moisture retention algorithm as described in Allen and others (1998).
Method—FAO–56 two stage		
`SOIL_MOISTURE_METHOD`	`FAO-56_TWO_STAGE`	The two-stage FAO–56 method allows for evaporation of soil moisture from bare and exposed ground, and transpiration from plants. This method is thought to be better suited to applications involving long-term (length of a growing-season) simulation of irrigated crops.

Actual Evapotranspiration/Soil Moisture Retention

SWB has four methods for simulating the soil-moisture retention and actual evapotranspiration. Of the four methods, two methods implement the Thornthwaite-Mather soil-moisture-retention relations, whereas the other two methods implement the FAO–56 soil-moisture-retention relations, in varying degrees of complexity. The control-file syntax and lookup-table entries for the various methods are listed in tables 3–16 and 3–17.

Table 3–17. Actual evapotranspiration/soil-moisture method lookup-table entries.

[–, no entry; FAO–56, Food and Agriculture Organization of the United Nations, Paper No. 56 (Allen and others, 1998); RAW, readily available water; TAW, total available water]

Field name (column name)	Units	Data type	Dimension	Notes
		Method—Thornthwaite-Mather		
–	–	–	–	–
		Method—Thornthwaite-Mather equations		
–	–	–	–	–
		Method—FAO–56 single stage, FAO–56 two stage		
depletion fraction	Unitless	Float	Number of land-use codes	The depletion fraction defines the soil moisture below which actual evapotranspiration stops being equal to potential evapotranspiration. $depletion\ fraction\ p = \frac{RAW}{TAW}$
		Method—FAO–56 two stage		
total evaporable water	Inch	Float	Number of land-use codes x number of soil groups	Evaporation is assumed to take place only within the band of readily evaporable water.
readily evaporable water	Inch	Float	Number of land-use codes x number of soil groups	Evaporation is assumed to take place at the maximum possible rate within the readily evaporable water band; as soil moisture decreases toward the limits of the total-evaporable water band, evaporation trends toward zero.
mean plant height	Foot	Float	Number of land-use codes	Mean plant height at maturity. Plant height is used in equation 76, (Allen and others, 1998), to estimate the fraction of area currently covered by vegetation.

Crop Coefficients

Crop-coefficient calculations are made using FAO–56 methodology (Allen and others, 1998). The method involves construction of a simplified crop-coefficient curve by defining a few key growth milestones. SWB allows these crop-coefficient curves to be defined in three different ways as follows: (1) by number of days since planting, (2) by number of growing degree days since planting, and (3) by month. Each land use (or crop type) may have its crop-coefficient curve specified in one of these three ways. SWB will determine which crop-coefficient definition method to use for each crop type based on the presence or absence of valid data in the associated lookup-table entries.

The required control-file syntax and lookup-table entries are listed in tables 3–18 and 3–19.

Table 3–18. Crop-coefficient control-file entries.

[FAO–56, Food and Agriculture Organization of the United Nations, Paper No. 56 (Allen and others, 1998)]

Control-file syntax		Notes
	Method—None	
CROP_COEFFICIENT_METHOD	**NONE**	This is the default method. If crop coefficients are not in use, this method statement may be eliminated.
	Method—Curve number	
CROP_COEFFICIENT_METHOD	**FAO–56**	FAO_56 and FAO56 are also recognized.

Table 3–19. Crop-coefficient lookup-table entries.

[–, no entry; FAO–56, Food and Agriculture Organization of the United Nations, Paper No. 56 (Allen and others, 1998); DOY, day of year; mm/dd, month/day; GDD, growing degree day]

Field name (column name)	Units	Data type	Dimension	Notes
		Method—None		
–	–	–	–	–
		Method—FAO–56		
Planting_date	DOY or date as mm/dd	Integer or character	–	This value represents the DOY or mm/dd on which the crops are planted. Planting_date is only used if the crop-coefficient curve is defined in terms of days or dates; Plant_date is not used when this curve is defined by month or by GDD. A planting date of May 15 could be specified as either 135 or 05/15.
L_ini **L_dev** **L_mid** **L_late** **L_fallow**	Days or date as mm/dd	Integer or character	Number of land-use codes	Time values for use in defining the inflection points of the crop-coefficient curve. Day values may be specified as the integer number of days elapsed since planting or may be specified as a date in mm/dd format.
Kcb_ini **Kcb_mid** **Kcb_end** **Kcb_min**	Unitless	Float	Number of land-use codes	Crop coefficients defining the height of the crop-coefficient curve. See appendix 1, figure 1–6 for an example of how these coefficients are used, along with the planting day or GDD thresholds to produce a simplified crop-coefficient curve.
GDD_plant **GDD_ini** **GDD_dev** **GDD_mid** **GDD_late**	Degree day (Fahrenheit)	Float	Number of land-use codes x number of soil groups	GDD thresholds for defining the inflection points on the crop-coefficient curve. Planting_date lookup-table entry is ignored when the crop-coefficient curve is defined in terms of GDD. Plant growth is considered to begin once the accumulated GDD for the cell exceeds GDD_plant.
Kcb_Jan **Kcb_Feb** **Kcb_Mar** **Kcb_Apr** **Kcb_May** **Kcb_Jun** **Kcb_Jul** **Kcb_Aug** **Kcb_Sep** **Kcb_Oct** **Kcb_Nov** **Kcb_Dec**	Unitless	Float	Number of land-use codes	Crop coefficients for each month of the calendar year. Definition of the crop coefficients by month may be useful for a crop that has multiple plantings and harvests in the course of a year.

Direct Additions

External estimates for important components of the water budget may be supplied as supplemental grids or as table values. These additional water sources may be applied to the soil-storage reservoir or added directly as net infiltration. For both direct addition types, either gridded or table data, may be supplied. SWB will always look for gridded data first. If no gridded data are detected, SWB will look for table values. Table values are expected to correspond to the land-use codes contained in the main land-use grid.

Direct additions to net infiltration are processed after all other water-balance components; therefore, little interaction is between these terms and the rest of the model. Direct additions to soil moisture are processed before net infiltration is calculated; therefore, direct additions to soil moisture do affect the daily soil moisture amount and the calculated net infiltration. The names of the terms themselves are descriptive for the user; SWB processes them as additional water sources to net infiltration or the soil-moisture storage reservoir.

The required control-file syntax and lookup-table entries for the possible direct net-infiltration methods are listed in tables 3–20 and 3–21. The required control-file syntax and lookup-table entries for the possible direct soil-moisture methods are listed in tables 3–22 and 3–23.

Table 3–20. Direct net-infiltration additions control-file syntax.

[–, no entry]

Control-file syntax		Notes
Method—None		
DIRECT_NET_INFILTRATION_METHOD	**NONE**	–
Method—Direct net infiltration		
DIRECT_NET_INFILTRATION_METHOD	**GRIDDED.**	–
CESSPOOL_LEAKAGE **CESSPOOL_LEAKAGE_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid-file definition for adding cesspool leakage directly to the net-infiltration estimate. The units are inches per day. This entry can be a single grid or a time series of grids.
STORM_DRAIN_LEAKAGE **STORM_DRAIN_LEAKAGE_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid-file definition for adding storm-drain leakage directly to the net-infiltration estimate. The units are inches per day. This entry can be a single grid or a time series of grids.
DISPOSAL_WELL_DISCHARGE **DISPOSAL_WELL_DISCHARGE_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid-file definition for adding disposal-well discharges directly to the net-infiltration estimate. The units are inches per day. This entry can be a single grid or a time series of grids.
WATER_BODY_LEAKAGE **WATER_BODY_LEAKAGE_PROJECTION_DEFINITION**	**{grid type} {gridflie name}** **{PROJ4 string defining projection}**	Grid-file definition for adding water-body leakage directly to the net-infiltration estimate. The units are inches per day. This entry can be a single grid or a time series of grids.
ANNUAL_DIRECT_NET_INFILTRATION_RATE **ANNUAL_DIRECT_NET_INFILTRATION_PROJECTION _DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid-file definition for adding a generic water source directly to the net-infiltration estimate. The units are inches per year. This entry can be a single grid or a time series of grids.

Table 3–21. Direct net-infiltration additions lookup-table syntax.

Field name (column name)	Units	Data type	Dimension	Notes
		Method—Gridded		
cesspool_leakage	Inches per day	Float	Number of land-use codes	A daily cesspool leakage rate may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.
storm_drain_leakage	Inches per day	Float	Number of land-use codes	A daily storm-drain leakage rate may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.
disposal_well_leakage	Inches per day	Float	Number of land-use codes	A daily disposal-well leakage rate may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.
water_body_leakage	Inches per day	Float	Number of land-use codes	An annual generic addition to net infiltration may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.
annual_direct_net_infiltration	Inches per day	Float	Number of land-use codes	An annual generic addition to net infiltration may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.

Table 3–22. Direct soil-moisture additions control-file syntax.

[–, no entry]

Control-file syntax		Notes
	Method—None	
DIRECT_SOIL_MOISTURE_METHOD	**NONE**	–
	Method—Direct soil moisture	
DIRECT_SOIL_MOISTURE_METHOD	**GRIDDED**	–
DAILY_SEPTIC_DISCHARGE **DAILY_SEPTIC_DISCHARGE_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid-file definition for adding daily septic discharge directly to the soil-moisture reservoir. The units are inches per day. This entry can be a single grid or a time series of grids.
ANNUAL_SEPTIC_DISCHARGE **ANNUAL_SEPTIC_DISCHARGE_PROJECTION_DEFINITION**	**{grid type} {gridfile name}** **{PROJ4 string defining projection}**	Grid-file definition for adding daily septic discharge directly to the soil-moisture reservoir. The units are inches per year. This entry can be a single grid or a time series of grids.

Table 3–23. Direct soil-moisture additions lookup-table entries.

Field name (column name)	Units	Data type	Dimension	Notes
		Method—Gridded		
`daily_septic_discharge`	Inches per day	Float	Number of land-use codes	A daily septic discharge rate may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.
`annual_septic_discharge`	Inches per year	Float	Number of land-use codes	An annual septic discharge rate may be supplied for each land use in the lookup table. This value will be ignored if gridded data are also provided.

Growing Degree Day

The calculation of the growing degree day depends on a number of parameter values that define the way in which the calculation will proceed. Specifically, the base and maximum temperatures may be redefined, as well as the date on which to reset the growing degree-day calculation. These lookup-table entries are optional. If these values are not supplied, GDD_base_temperature is assumed to be 50 degrees Fahrenheit, GDD_maximum_temperature GDD_maximum_temperature is assumed to be 86 degrees Fahrenheit, and the GDD_reset_date is assumed to be the first day in January of each year. The required control-file syntax is listed in table 3–24.

Table 3–24. Growing degree-day lookup-table entries.

Lookup table entries					
Field name (column name)	**Units**	**Data type**	**Dimension**	**Description**	**Notes**
		Method—Gridded			
`GDD_base_temperature`	Degrees Fahrenheit	Float	Number of land-use codes	Base temperature from which to calculate GDD.	Default value is 50 degrees Fahrenheit.
`GDD_maximum_temperature`	Degrees Fahrenheit	Float	Number of land-use codes	Maximum temperature for consideration in the GDD calculations.	Default value is 86 degrees Fahrenheit.
`GDD_reset_date`	Day of year or date as month and day	Integer or character	Number of land-use codes	Day of year or month and day on which the accumulated GDD value is reset to zero.	Default reset date is the first day in January of each simulation year.

Growing Season

A control-file entry is not required for setting the growing-season determination method. A method may be applied on a land-use by land-use basis. If the day of year or date-based growing-season method is used for a particular land use or crop type, the growing degree-day and end of season air-temperature fields should be left blank. Conversely, if the growing degree-day and end of season air-temperature fields contain valid data, the start and end of growing-season date fields should be left blank. The required lookup-table entries pertaining to the growing season are listed in table 3–25.

Table 3–25. Growing-season method lookup-table entries.

[DOY, day of year; mm/dd, month/day; –, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
`growing_season_start`	DOY or date as mm/dd	Integer or character	Number of land-use codes	–
`growing_season_end`	DOY or date as mm/dd	Integer or character	Number of land-use codes	–
`GDD_growing_season_start`	Degrees-Fahrenheit day	Float	Number of land-use codes	–
`air_temperature_growing_season_end`	Degrees Fahrenheit	Float	Number of land-use codes	–

Irrigation Demand and Application

Irrigation demand and application calculations require several additional parameters; the control-file syntax and lookup-table entries are listed in tables 3–26 and 3–27.

Table 3–26. Irrigation-method control-file entries.

[FAO–56, Food and Agriculture Organization of the United Nations, Paper No. 56 (Allen and others, 1998); –, no entry]

Control-file syntax		Notes
`IRRIGATION_METHOD`	`FAO–56`	–

Table 3–27. Irrigation-method lookup-table entries.

[DOY, day of year; mm/dd, month/day; MAD, maximum allowable depletion; FAO–56, Food and Agriculture Organization of the United Nations, Paper No. 56 (Allen and others, 1998); –, no entry]

Field name (column name)	Units	Data type	Dimension	Notes
`irrigation_start`	DOY or date as mm/dd	Integer or character string	Number of land-use codes	First DOY or mm/dd on which to consider application of irrigation water.
`irrigation_end`	DOY or date as mm/dd	Integer or character string	Number of land-use codes	Last DOY or mm/dd on which to consider application of irrigation water.
`irrigation_application_efficency`	Unitless	Float	Number of land-use codes	Efficiency with which irrigation water is delivered and applied. The irrigation-application method determines the effect that this number has on the calculated irrigation amounts.
`maximum_allowable_depletion`	Unitless	Float	Number of land-use codes	MAD is the amount of depletion of plant available water tolerable before irrigation water is applied. This value is often the same as the depletion_ fraction defined in the FAO–56 available water-capacity modules, but does not need to be the same.
`monthly_irrigation_schedule`	–	Integer or character string	Number of land-use codes	This field is used to define a predetermined monthly irrigation application schedule. A 0 indicates no irrigation on that day of the month; a 1 indicates that irrigation will take place. An irrigation schedule specifying that irrigation take place approximately every fourth day would look something like: `1000100010001000100010001000100010000`
`irrigation_application_scheme`	–	Integer or character string	Number of land-use codes	This field is used to specify the irrigation application scheme for a given land use or crop type. Irrigation water is applied when the soil-moisture deficit within the current root zone exceeds the `maximum_allowable_depletion` .When the MAD is exceeded, irrigation water is applied using one of the following five schemes: • `field_capacity_original` –the soil-moisture deficit is completely eliminated; soil within the root zone is restored to field capacity; water that is delivered inefficiently is added directly to the soil-moisture reservoir • `field_capacity`–the soil-moisture deficit is completely eliminated; soil within the root zone is restored to field capacity; water that is delivered inefficiently is considered lost to the mass balance • `defined_deficit`–the soil-moisture deficit is reduced until the deficit is equal to or less than the deficit_irrigation_fraction • `constant_amount` –a constant, defined amount of irrigation water is applied regardless of whether or not this results in net infiltration • `monthly_demand_based`–irrigation water is applied on a scheduled monthly basis in proportion to the difference between the monthly rainfall and potential evapotranspiration amounts.

Rejected Net Infiltration

Rejected net-infiltration amounts, if specified, must be given for each combination of land use and soil type (table 3–28).

Table 3–28. Rejected net-infiltration lookup-table entries.

Field name (column name)	Units	Data type	Dimension	Notes
max_net_infil_#	Inch	Float	Number of land-use codes x number of soil groups	A maximum net-infiltration rate may be specified for each combination of land uses and soil groups. If the user chooses to use this feature, the same number of maximum net-infiltration columns must be specified as numbers of soil groups. Thus, if a given set of inputs encompasses four soil groups, the following four columns of max_net_infil should be given: max_net_infil_1, max_net_infil_2, max_net_infil_3, and max_net_infil_4.

References Cited

Allen, R.G., Pereira, L.S., Raes, Dirk, and Smith, Martin, 1998, Crop evapotranspiration—Guidelines for computing crop water requirements: Rome, Food and Agriculture Organization of the United Nations, FAO Irrigation and Drainage Paper No. 56, 174 p.

Horton, R.E., 1919, Rainfall interception: Albany, N.Y., Monthly Weather Review, v. 47, no. 9, p. 608, p. 603–623, accessed September 6, 2017, at ftp://ftp.library.noaa.gov/docs.lib/htdocs/rescue/mwr/047/mwr-047-09-0603.pdf.

Appendix 4. Example Applications

This appendix includes two example Soil-Water-Balance (SWB) applications. The first example application is the base test case for the Hawaii water-budget code, which simulates net infiltration for the Hawaiian Island of Maui (not shown). The original Hawaii water-budget code contains numerous features and capabilities that are adapted to calculation of net infiltration in a tropical island environment (Engott and others, 2015; Izuka and others, 2010; Oki, 2002). The Maui example demonstrates the use of several new methods, including the simulation of fog, direct additions to net infiltration, rainfall syntheses by the method of fragments, and runoff and evapotranspiration by means of gridded monthly inputs. The second example, the Central Sands example application, demonstrates the application of SWB's crop-water demand/irrigation estimation capabilities to an irrigated region of Wisconsin.

All model daily weather grids and tables, control files, lookup tables, and data files are available for download at https://github.com/smwesten-usgs/swb2_examples.

Maui, Hawaii

SWB was used to estimate net infiltration for the Island of Maui, Hawaii. These estimates were compared to the net-infiltration estimates generated for a previous U.S. Geological Survey (USGS) study (Johnson and others, 2014) that made use of the Hawaii water-budget code.

Study Area

The Island of Maui has an area of 728 square miles and is the second largest island in the Hawaiian archipelago. Maui is composed of two shield volcanoes. The older volcano, the West Maui Mountain, is at an altitude of 5,788 feet at Puʻu Kukui, and the younger volcano, the East Maui Volcano (commonly referred to as Haleakalā), is at an altitude of 10,023 feet at Puʻu ʻUlaʻula (Red Hill). The two volcanoes are connected by an isthmus that is covered with terrestrial and marine sedimentary deposits that are more than 5 miles wide (Stearns and Macdonald, 1942). Erosion of the West Maui Mountain has carved deep valleys and sharp crested ridges that radiate from near the summit. On Haleakalā, the rainy eastern slope has valleys that are separated by broad areas and ridges. The drier western slope of Haleakalā is less incised and retains the broad, smooth topography of the shield volcano (fig. 4–1).

Steep gradients in mean annual rainfall patterns on Maui reflect the influence of persistent trade winds and orographic rainfall (Giambelluca and others, 2013). On an island-wide basis, mean rainfall on Maui is about 81 inches per year (in/yr). Mean rainfall is more than 360 in/yr at Puʻu Kukui. About 5 miles southwest of Puʻu Kukui, mean rainfall is less than 15 in/yr. Mean rainfall exceeds 100 in/yr for much of the interior uplands of the West Maui Mountain. On Haleakalā, mean rainfall exceeds 200 in/yr on mid-altitude windward slopes. At a rain gage (not shown) about an altitude of 5,400 feet on windward Haleakalā, mean rainfall is about 404 in/yr, which is among the highest rainfall values in the Hawaiian Islands and the world during 1978–2007 (Giambelluca and others, 2013). Leeward slopes in the rain shadow of Haleakalā are much drier. Mean rainfall is less than 25 in/yr for most leeward areas along the coastline and the isthmus. The summit area of Haleakalā is also relatively dry, with mean rainfall between about 35 and 50 in/yr.

Input Grids and Tables

This section discusses the important features of each of the gridded and tabular datasets needed to run a simplified version of the Maui example. An SWB version 1.0 application would typically have four gridded datasets that provide data regarding the D8 flow direction, available water capacity, hydrologic soil group, and land use. SWB version 2.0 incorporates many of the features of the Hawaii water-budget code (Engott and others, 2015; Izuka and others, 2010) because many of the SWB version 1.0 methods (curve-number method, bucket interception) have been determined to be poorly suited for application to islands in the Pacific Ocean. A comparison between process methods used in a more typical or traditional SWB application (in other words, a humid environment on the conterminous United States) to methods used in the Maui example is listed in table 4–1.

The use of some different methods in the Maui example requires a different set of inputs relative to a more typical SWB application. A data requirement that does not change, however, is the requirement to provide a gridded land-use code as a means to structure the relevant model parameters. The land-use grid supplied with the SWB Maui example is shown in figure 4–2. Irrigated land uses include the major crop types (pineapple, coffee, diversified agriculture, macadamia nuts, sugarcane), golf courses, and tree plantations. An interesting aspect of the Maui example is that unlike applications in more temperate climates, crops such as sugarcane have growing seasons that persist for multiple years; SWB accommodates multiple-year crop-coefficient curves for this reason.

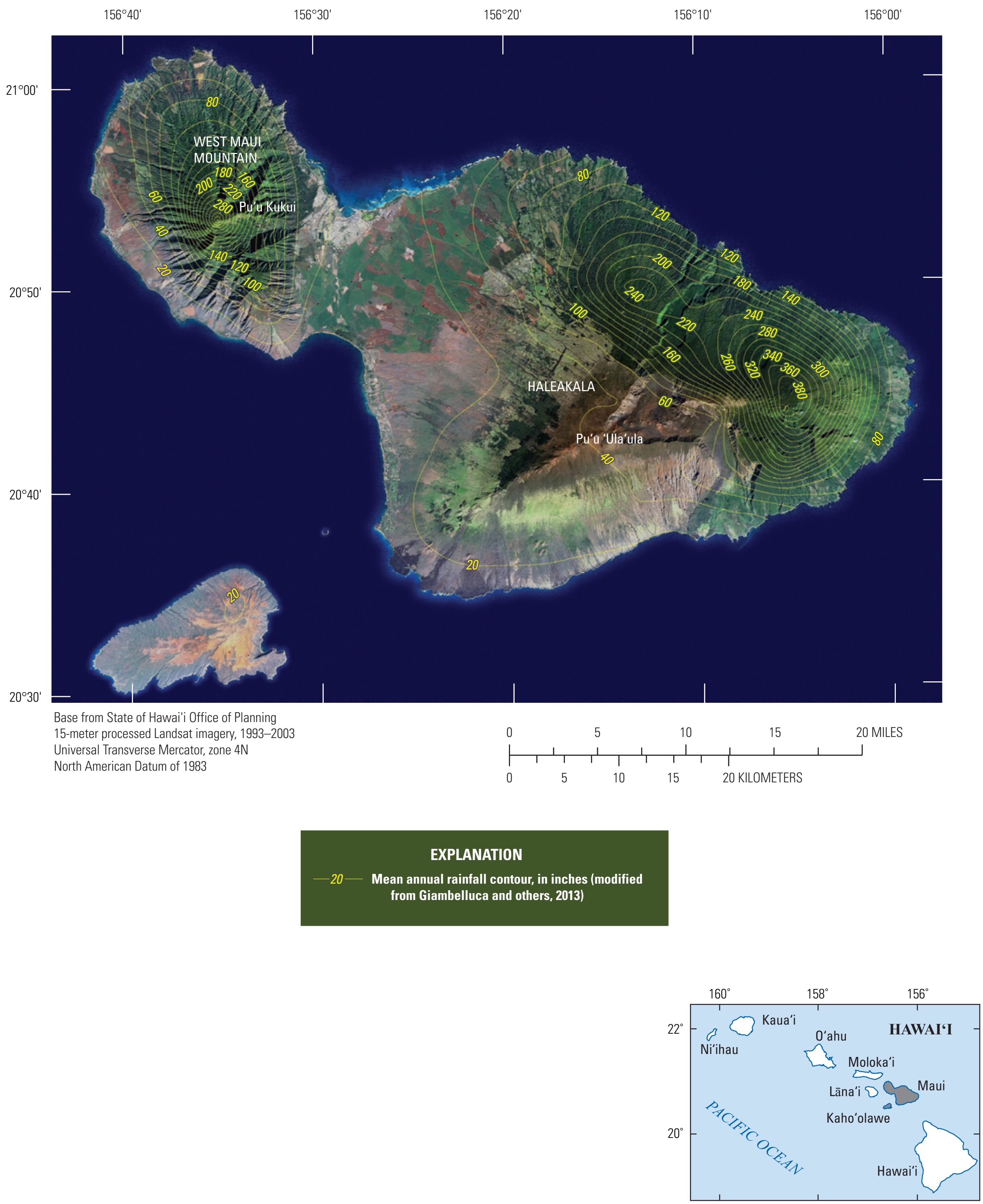


Figure 4–1. Mean annual rainfall during 1978–2007 for the islands of Maui and Kaho'olawe, Hawaii.

Table 4–1. Comparison of differences between typical Soil-Water-Balance (SWB) process methods and those used in the Maui example application.

[SWB, soil water balance; –, no data]

Process	Typical SWB application	Maui SWB application
Runoff generation	Curve-number hydrology	Monthly runoff coefficients.
Flow routing	D8	None.
Precipitation	Gridded daily values	Method of fragments.
Interception by vegetation	Bucket	Gash.
Fog interception by vegetation	–	Gridded.
Potential or reference evapotranspiration	Hargreaves-Samani	Gridded Priestly-Taylor, externally calculated.
Irrigation demand	Replenish to field capacity	Scheduled application, amount determined by monthly rainfall, evapotranspiration, and runoff.
Direct contributions to net infiltration (leakage from reservoirs, taro ponds, storm drains, and other diffuse sources)	–	Gridded or tabular.
Soil-moisture reservoir capacity	Calculated from available water capacity and rooting depth	Gridded.

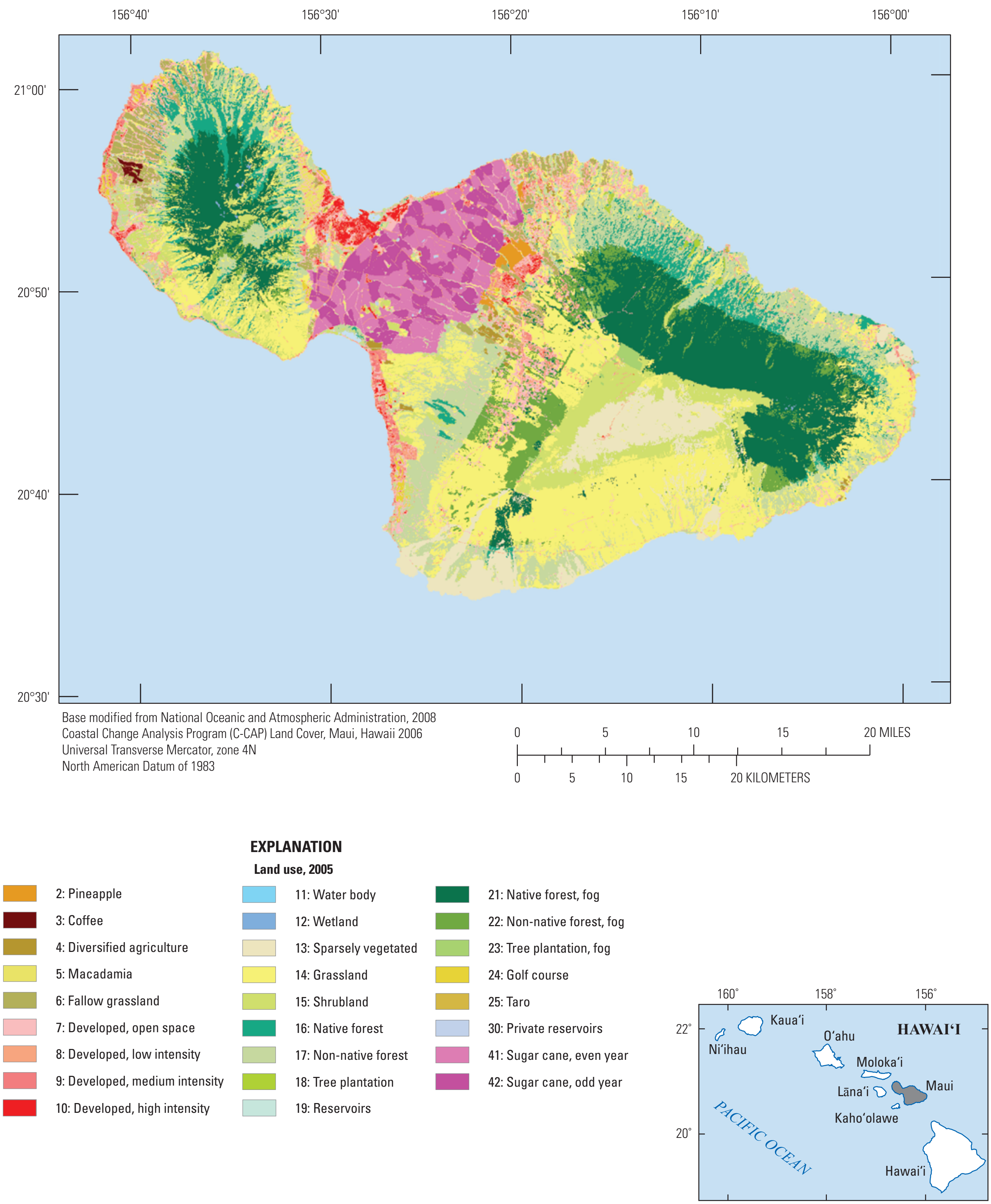


Figure 4–2. Soil-Water-Balance (SWB) land-use grid for the Maui, Hawaii, study area, 2005.

In a more typical SWB application, a gridded, hydrologic soil-group dataset would be provided, and rooting depths corresponding to each soils group would be included in the lookup table. The maximum size of the soil-moisture reservoir would then be calculated during model initialization by multiplying the available water capacity by the rooting depth. For the Maui example, the size of the soil-moisture reservoir for each cell was provided by means of an externally calculated grid (fig. 4–3).

Many Pacific Islands, if not most, do not have a convenient source of gridded daily air temperature and precipitation data. For Maui, the method of fragments (discussed in appendix 1) was applied; the data requirements for this method include a table of rainfall fragments calculated from observed daily rainfall records at discrete locations, as well as a grid of rainfall zones corresponding to the observation locations associated with the fragment sets. These rainfall zones are derived by drawing Thiessen polygons around the set of daily rain gages from which the fragments are generated.

The rainfall zones shown in figure 4–4 allow for the rainfall fragment sets to be linked to the appropriate grid cells; daily rainfall for each cell is produced by multiplying the monthly rainfall sum by the rainfall fragment corresponding to the rainfall-zone number and day of month. A small piece of the Maui rainfall fragment file is listed in table 4–2; the reduced-case table included with this example contains only a single fragment set for each month of the year for each of the 56 rainfall zones, for a total of 672 lines of fragment data. A single fragment set corresponds to a calendar year of rainfall observations. Because each rainfall gage might have 20 or 30 years of observations, a file used in a real application might be tens of thousands of lines long.

The method of fragments as implemented in SWB allows for a rainfall correction grid to be applied as a way to alter the spatial distribution of the rainfall as calculated by the method of fragments. This method was done in the Maui example because the grid files used as the source of the month-year precipitation grids (Frazier and others, 2016), when summed and averaged, result in a slightly different spatial rainfall distribution than the Hawaii Rainfall Atlas (Giambelluca and others, 2013). A rainfall correction grid was developed and supplied to SWB to ensure similar rainfall distributions between this application and earlier projects (Johnson and others, 2014).

Fog interception on the windward slopes of Maui can alter the water budget (Juvik and others, 2011; Juvik and Ekern, 1978). Simulating the mechanics of fog formation and interception is beyond the capabilities of SWB; however, externally calculated gridded datasets quantifying fog interception as a function of the total rainfall received during a month is possible. A discussion regarding the development of the relations between fog interception and rainfall is documented in Johnson and others (2014). An example of the grid defining fog as a fraction of rainfall for March is shown in figure 4–5. Fog interception, thus, is calculated for each day by multiplying the disaggregated monthly rainfall amounts by the monthly fog-fraction grid.

Table 4–2. Subset of a rainfall fragment file for use with the method of fragments.

[* * *, one or more data entries omitted]

Month	Rainfall zone number	Fragment set	Day 1	Day 2	Day 3	Day 4	* * *	Day 31
1	1	1	0.1895	0.0000	0.0000	0.0000	* * *	0.0000
1	2	1	0.0463	0.0000	0.0366	0.0171	* * *	0.0341
1	3	1	0.0000	0.0000	0.0000	0.0000	* * *	0.0000
1	4	1	0.1571	0.0000	0.0000	0.0000	* * *	0.0616

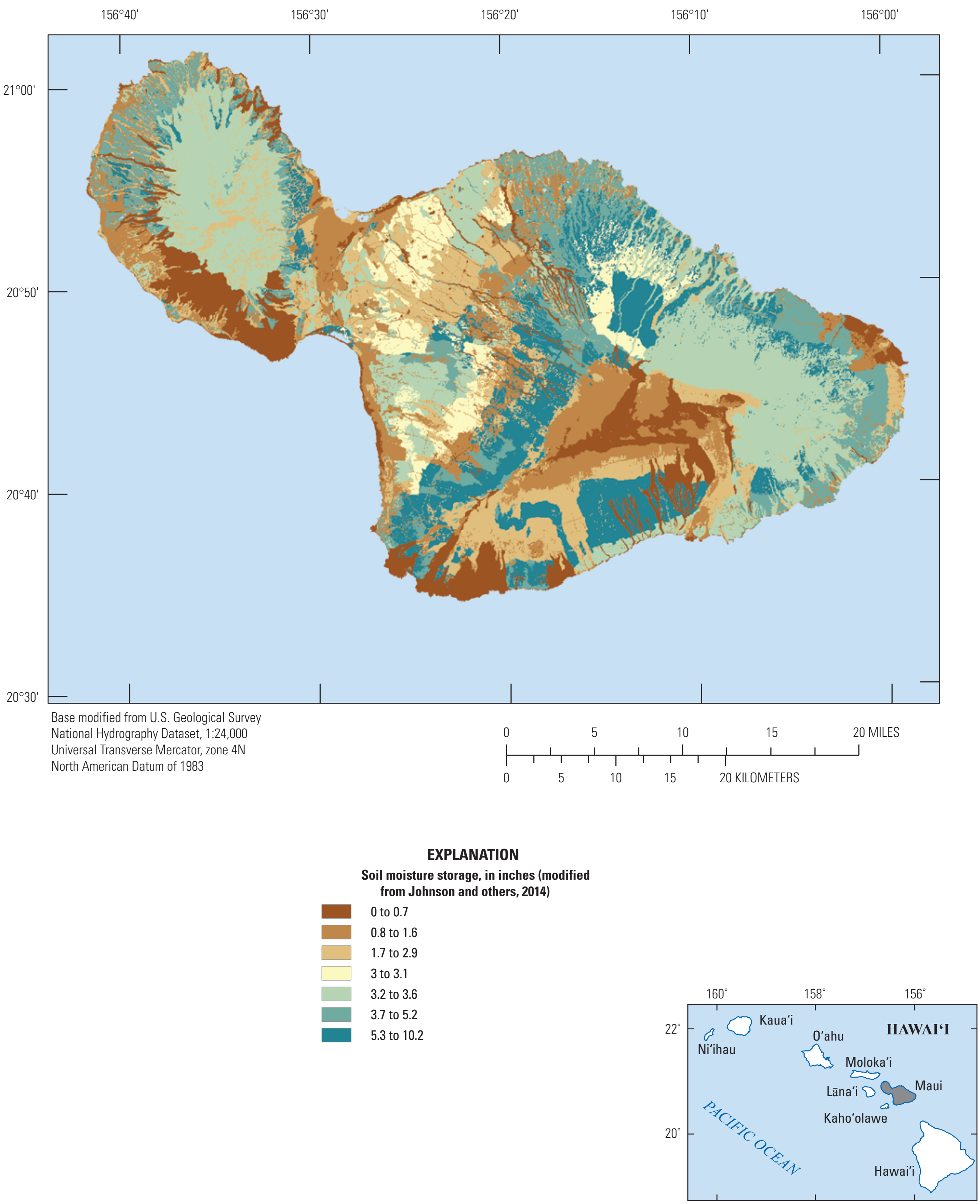


Figure 4–3. Soil-Water-Balance (SWB) soil-moisture storage grid for the Maui, Hawaii, study area.

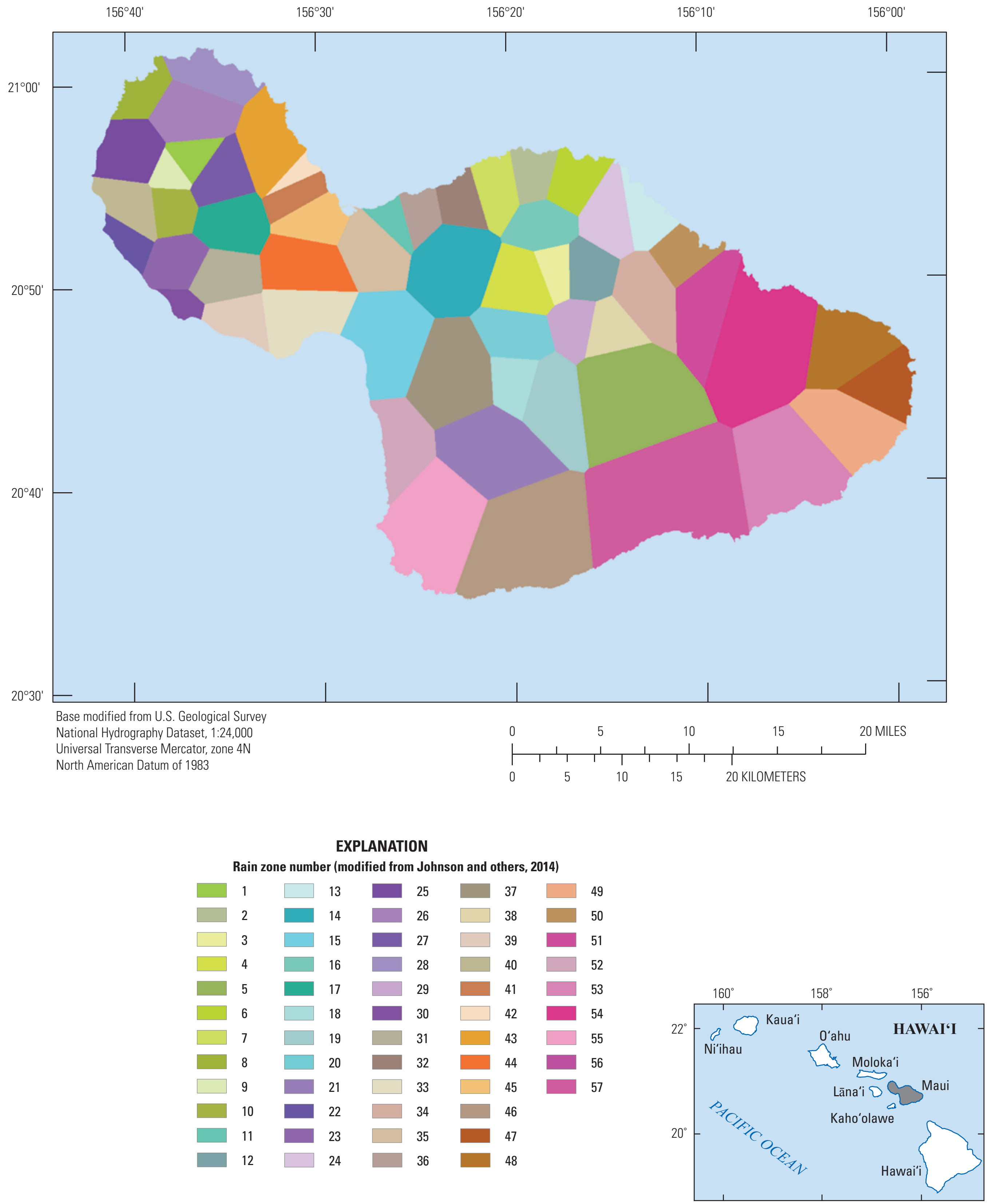


Figure 4–4. Soil-Water-Balance (SWB) rainfall zone number grid for the Maui, Hawaii, study area.

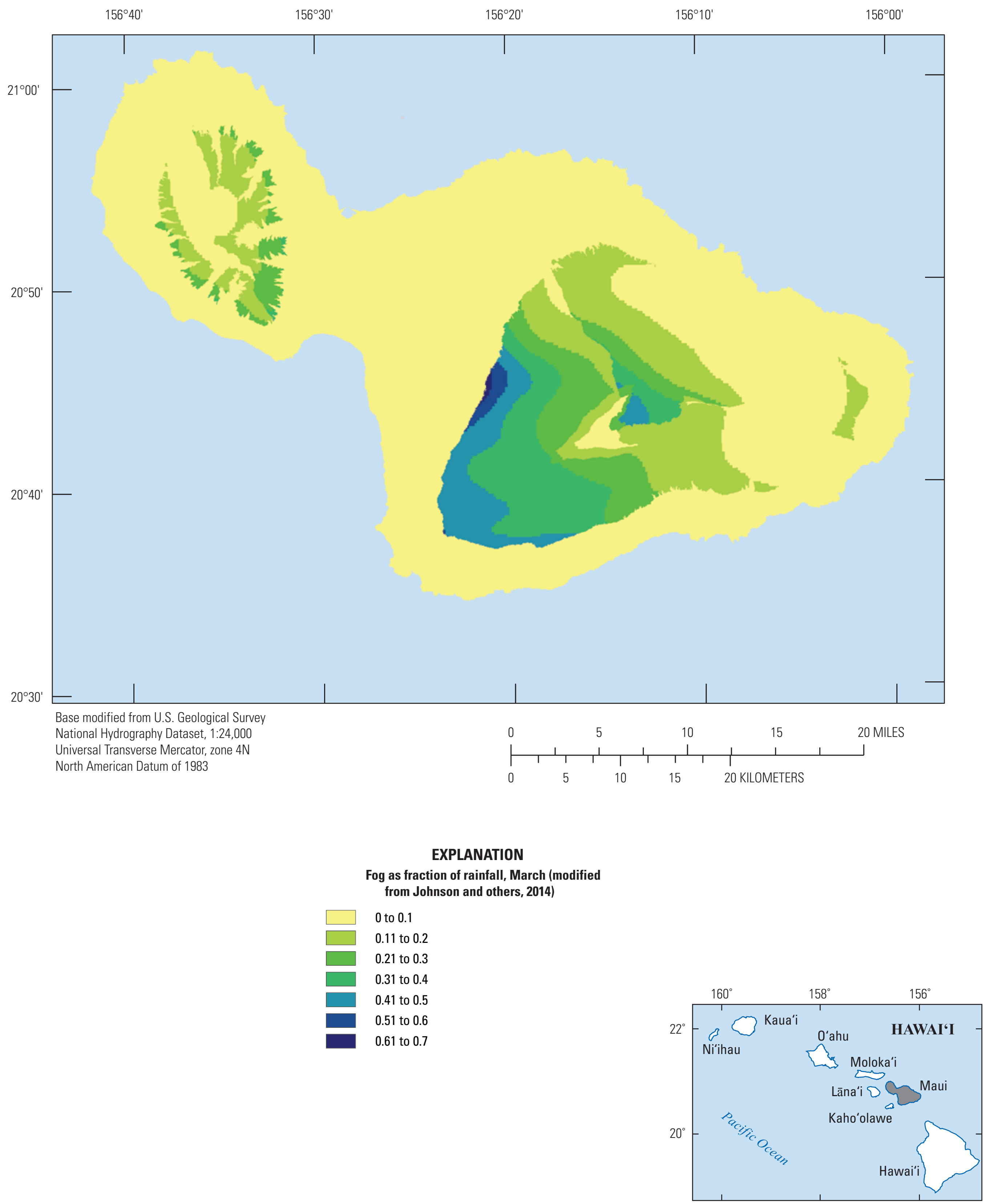


Figure 4–5. Soil-Water-Balance (SWB) fog-fraction grid for the Maui, Hawaii, study area for March.

A feature of the Hawaii Water Budget model involves subgrid simulation of impervious-surface runoff (Engott and others, 2015; Johnson and others, 2014). SWB simulates the subgrid impervious-surface runoff processes for any cell for which impervious-surface percentages are specified greater than zero. Subgrid impervious-surface simulation, thus, was activated for the cells in figure 4–6, which contain nonzero percentages of impervious-surface cover; these cells are represented in figure 4–6 by the red-shaded cells.

The curve-number approach has not been determined to be successful as applied to the steep mountainous slopes of Maui. For this reason, SWB applies a set of monthly runoff ratios (as a set of tabular data) to calculate runoff as a function of monthly rainfall. The runoff ratio table values are calculated from streamflow and rainfall records and are applied to individual runoff zones. The runoff zones were developed through spatial analysis of digital-elevation models and land-use and soil-type data; runoff ratios were developed through an analysis of streamflow records relative to daily rainfall amounts. The runoff zones are shown in figure 4–7.

A table of monthly runoff ratios must be supplied along with the runoff zone number grid so that runoff may be calculated for each grid cell. A small subsection of a runoff ratio file is listed in table 4–3. A column is required for each runoff zone in the model; file may contain as many dates as needed to cover the time period of interest.

The runoff ratio file contains a single date column, which indicates the first day of each month that the ratios pertain to, and as many additional columns as there are runoff zones. The Maui example has 765 runoff zones; therefore, table 4–3 contains 765 columns of runoff ratio values for each month of the file. Derivation of these runoff ratios is documented in Johnson and others (2014).

Interception of rainfall by vegetation is simulated for Maui with the Gash method (Gash, 1979; Gash and others, 1995). The Gash method requires several additional parameter values to be supplied to SWB. An example of an additional parameter is the canopy cover fraction, which is used to scale the amount of interception by the estimated amount of canopy cover present in each grid cell (fig. 4–8).

Another parameter necessary for application of the Gash canopy interception method is the evaporation to rainfall ratio. This parameter is shown in figure 4–9; the derivation of this grid is described in Johnson and others (2014).

Table 4–3. Subsection of a runoff ratio file.

[* * *, date or data value omitted]

Date	1	2	3	4	5	6	* * *	765
01-01-00	0.2705	0.2182	0.3372	0.0626	0.0963	0.3850	* * *	0.3905
02-01-00	0.2705	0.2182	0.3372	0.0626	0.0963	0.3850	* * *	0.3905
03-01-00	0.2705	0.2182	0.3372	0.0626	0.0963	0.3850	* * *	0.3905
04-01-00	0.2705	0.2182	0.3372	0.0626	0.0963	0.3850	* * *	0.3905
05-01-00	0.2167	0.1398	0.2788	0.0645	0.0956	0.3000	* * *	0.3229
* * *	* * *	* * *	* * *	* * *	* * *	* * *	* * *	* * *
12-31-08	0.1722	0.1811	0.2214	0.0523	0.0804	0.2901	* * *	0.3065

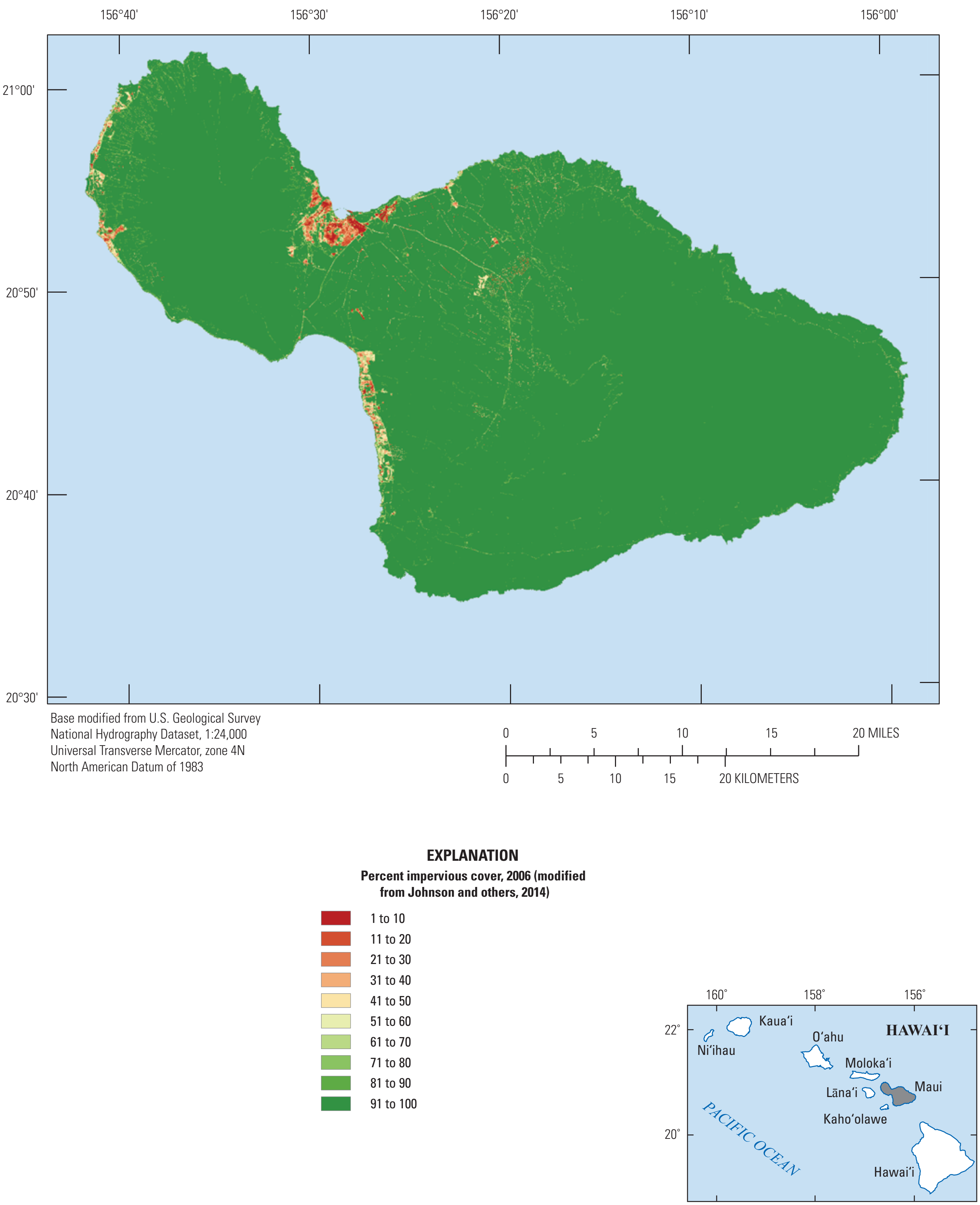


Figure 4–6. Soil-Water-Balance (SWB) percent pervious cover grid for the Maui, Hawaii, study area.

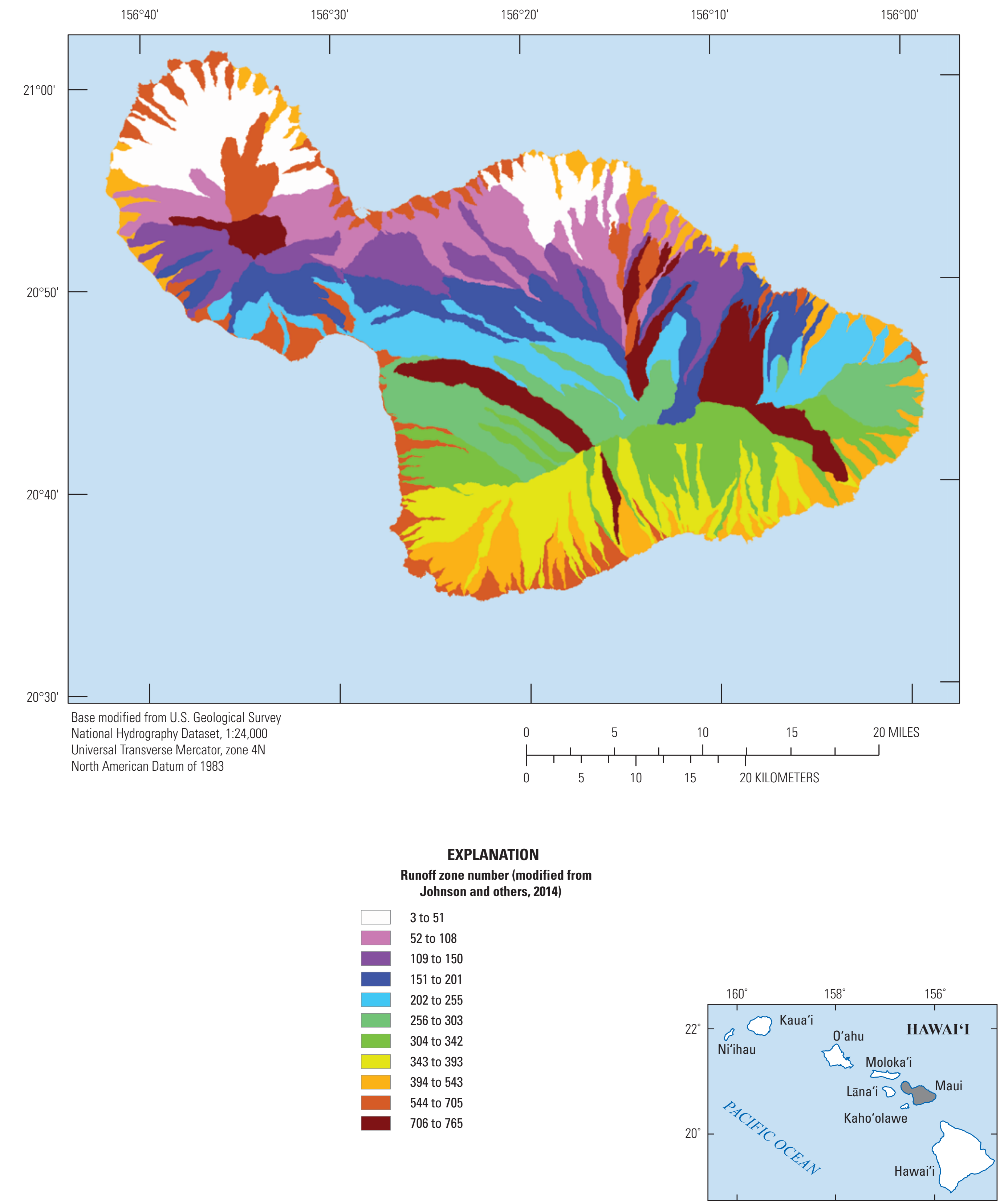


Figure 4–7. Soil-Water-Balance (SWB) runoff zone number grid for the Maui, Hawaii, study area.

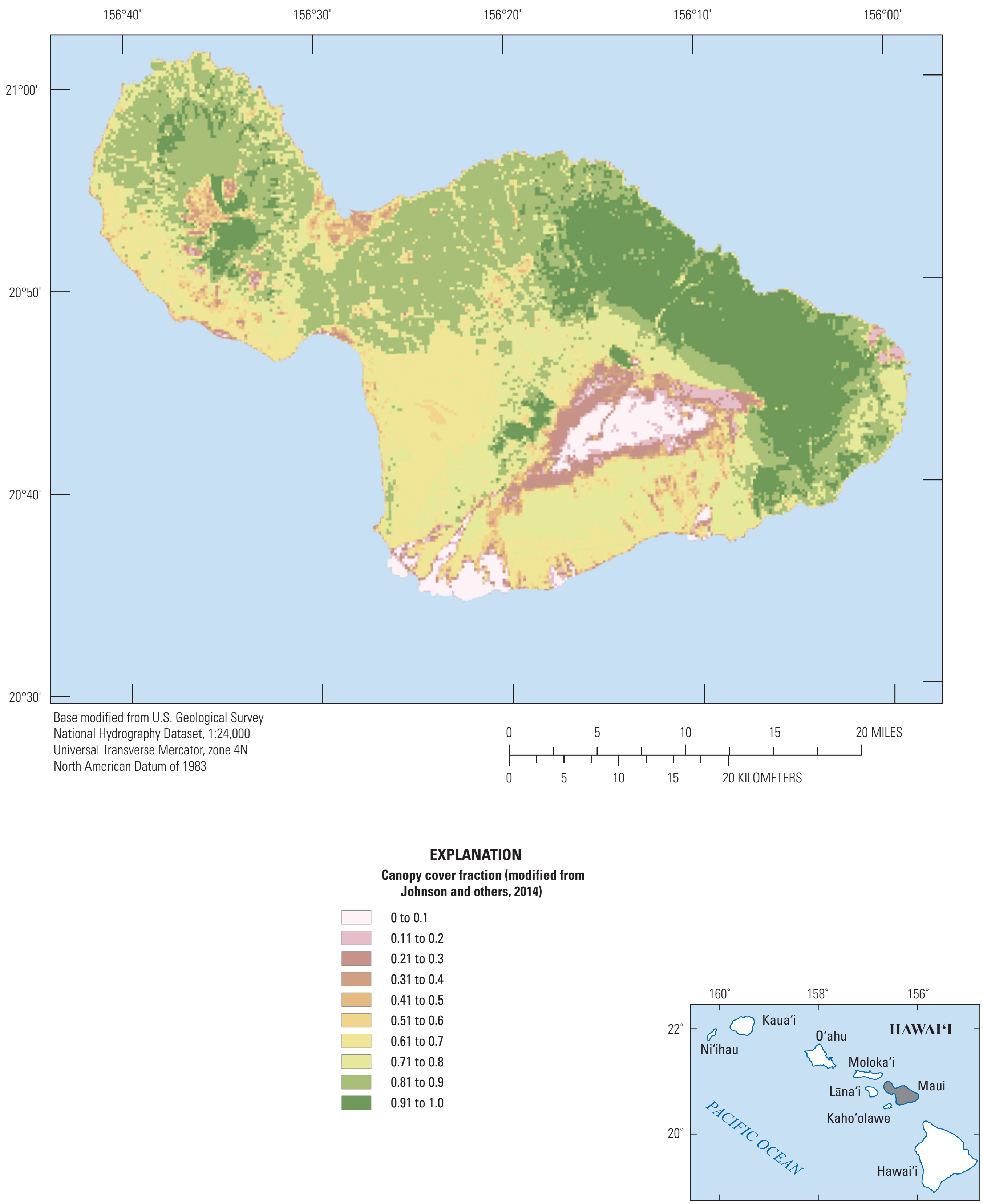


Figure 4–8. Soil-Water-Balance (SWB) canopy cover fraction grid for the Maui, Hawaii, study area.

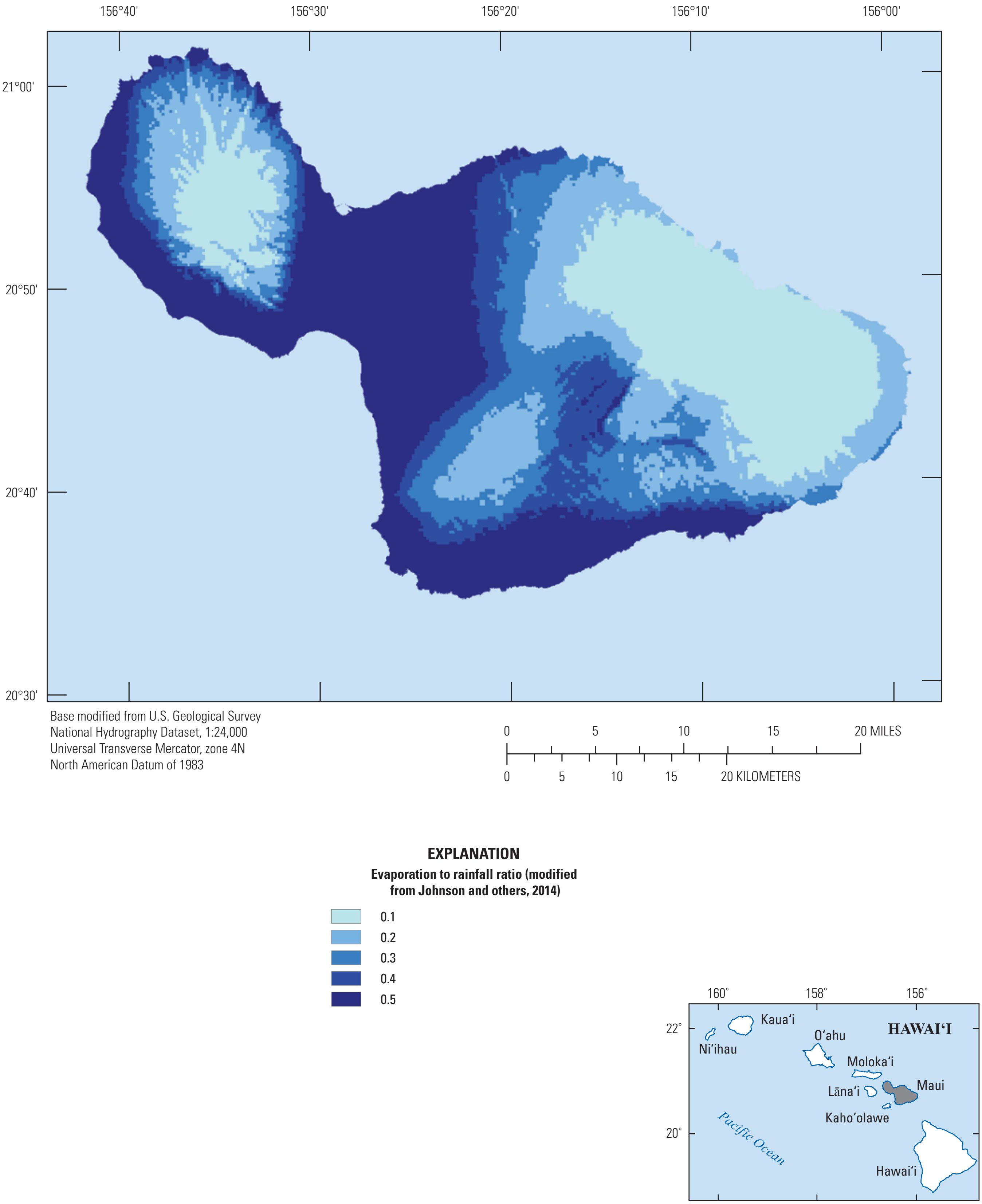


Figure 4–9. Soil-Water-Balance (SWB) evaporation to rainfall ratio grid for the Maui, Hawaii, study area.

Control File

This section presents an SWB control file that may be used to run a simplified version of the Maui Hawaii model. The control file has been separated into three figures (figs. 4–10, 4–11, and 4–12) for ease of viewing and explanation.

The first part of the SWB control file specifies the spatial resolution and base projection for the study area. A variety of characters (including the characters !#$%*()-[]) may be used to indicate comment lines (fig. 4–10), which allows, for more flexibility in writing internal documentation into the control file. Section (0) of the control file (a comment line) specifies the project-grid definition; section (1) of the control file contains the module specifications.

```
# Input file for swb2, Maui low-res Test Case
# Base projection: Hawaii Albers Equal Area Conic
# (comment characters: !#$%*()-[])
-----------------------------------------------------------

(O) PROJECT GRID DEFINITION
-----------------------------------
!                         Lower LH Corner        Grid
!                     |______________________| Cell
!          nx      ny        xo         yo         Size
!  "hi-res" version
#GRID   1582     1054     739800.   2276900.      50.

!  "lo-res" version
GRID   316     210         739800.   2276900.      250.
BASE_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

(1) MODULE SPECIFICATION
-------------------------------

INTERCEPTION_METHOD                      GASH
EVAPOTRANSPIRATION_METHOD                MONTHLY_GRID
RUNOFF_METHOD                            RUNOFF_RATIO
SOIL_MOISTURE_METHOD                     FAO-56
PRECIPITATION_METHOD                     METHOD_OF_FRAGMENTS
FOG_METHOD                               MONTHLY_GRID
FLOW_ROUTING_METHOD                      NONE

IRRIGATION_METHOD                        FAO-56
CROP_COEFFICIENT_METHOD                  FAO-56
DIRECT_RECHARGE_METHOD                   GRIDDED
SOIL_STORAGE_MAX_METHOD                  GRIDDED
```

Figure 4–10. Part 1 of an example Soil-Water-Balance (SWB) control file showing specification of standard SWB gridded inputs for the Maui, Hawaii, study area.

Section (2) of figure 4–11 defines initial conditions for the snow and soil-moisture reservoirs. The INITIAL_SNOW_COVER_STORAGE directive is not necessary because SWB will set the snow storage to zero if this directive is omitted. However, best practice is to include such directives if only to better document the initial conditions.

```
(2) Initial conditions for soil moisture, snow
----------------------------------------------------

INITIAL_PERCENT_SOIL_MOISTURE    CONSTANT  50.0
INTIAL_SNOW_COVER_STORAGE        CONSTANT  0.0

(3) Daily rainfall-related grids and data
----------------------------------------------
PRECIPITATION ARC_GRID input/month_year_rainfall/maui_prcp_%0m_%Y.asc
PRECIPITATION_GRID_PROJECTION_DEFINITION +proj=lonlat +datum=WGS84 +no_defs

FRAGMENTS_DAILY_FILE input/rain_fragments_maui_reduced_case.prn
FRAGMENTS_SEQUENCE_FILE input/frag_sequence_2yrs_5sims.out
FRAGMENTS_SEQUENCE_SIMULATION_NUMBER 1

RAINFALL_ZONE ARC_GRID input/maui_RAIN_ZONE__50m.asc
RAINFALL_ZONE_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

RAINFALL_ADJUST_FACTOR ARC_GRID input/Maui_RF_adj_factors/maui_RF_adj_%b__50m.asc
RAINFALL_ADJUST_FACTOR_PROJECTION_DEFINITION  +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs
RAINFALL_ADJUST_FACTOR_MONTHNAMES_LOWERCASE

(4) Monthly air temperature grids
---------------------------------------

TMAX ARC_GRID input/Air_Temperature_Monthly/Tmax%b_250m_maui.asc
TMAX_GRID_PROJECTION_DEFINITION +proj=lonlat +datum=WGS84 +no_defs
TMAX_SCALE_FACTOR                 1.8
TMAX_ADD_OFFSET                  32.0
TMAX_MISSING_VALUES_CODE      -9999.0
TMAX_MISSING_VALUES_OPERATOR     <=
TMAX_MISSING_VALUES_ACTION       mean

TMIN ARC_GRID input/Air_Temperature_Monthly/Tmin%b_250m_maui.asc
TMIN_GRID_PROJECTION_DEFINITION +proj=lonlat +datum=WGS84 +no_defs
TMIN_SCALE_FACTOR                 1.8
TMIN_ADD_OFFSET                  32.0
TMIN_MISSING_VALUES_CODE      -9999.0
TMIN_MISSING_VALUES_OPERATOR     <=
TMIN_MISSING_VALUES_ACTION       mean
```

Figure 4–11. Part 2 of an example Soil-Water-Balance (SWB) control file showing specification of standard SWB gridded inputs for the Maui, Hawaii, study area.

Section (3) of figure 4–11 specifies the name, location, and projection of several datasets required for use with the method of fragments—the month-year, rain zone, and rainfall adjustment factor grids.

Section (4) of figure 4–11 specifies the template names for the minimum and maximum air temperatures. These data are not necessary for the Maui application. Air temperature data, however, are included in section (4) to allow for more accurate partitioning of precipitation into rain and snow, despite the fact that precipitation only falls in the form of snow on rare occasions at the points of highest elevation on Maui. Air temperature data are typically needed to drive the calculation of growing degree day and reference ET_0; however, in the Maui example, ET_0 is input directly as a series of grids, and growing degree day is not used.

Section (5) of figure 4–12 defines only one of the standard grids—the land-use grid. An available water-capacity grid is not needed because the capacity of the soil-storage reservoir is read in directly, a D8 flow-direction grid is not needed because flow routing is disabled, and a hydrologic-soil grid is not needed because runoff is not calculated with the curve-number methodology.

Section (6) of figure 4–13 specifies several grids not normally used but required when using the gridded ET, fog, and direct net-infiltration methods.

Section (7) of figure 4–13 specifies two grids needed for use with the Gash canopy interception method—an evaporation to ratio grid and a fraction of canopy cover grid.

Section (8) of figure 4–13 specifies two grids and a text file for handling surface runoff—a runoff zone grid file associates runoff zones with other information contained in the runoff ratio monthly file. A percent pervious, cover-grid file triggers subgrid-scale, impervious- surface runoff calculations.

Section (9) of figure 4–13 specifies the location and name of the land-use lookup table.

Section (10) of figure 4–13 gives the start and end date for the simulation.

```
(5) “standard” GIS input grids:  hydrologic soils group, available water capacity, soils, and flow direction
-------------------------------------------------------------------------------------------------------------------

#  HYDROLOGIC_SOILS_GROUP ARC_GRID input/maui_HYDROLOGIC_SOILS_GROUP__50m.asc
#  HYDROLOGIC_SOILS_GROUP_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

LAND_USE ARC_GRID input/LU2010_w_2_season_sugarcane_simulation_1_50m.asc
LAND_USE_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

%% in this case, the maximum soil storage is read in directly, so there is no need
%% for an available water capacity grid (soil_storage_max = awc * rooting_depth).

SOIL_STORAGE_MAX ARC_GRID input/maui_SOIL_MOISTURE_STORAGE__50m.asc
SOIL_STORAGE_MAX_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs
SOIL_STORAGE_MAX_MISSING_VALUES_CODE          0.0
SOIL_STORAGE_MAX_MISSING_ VALUES_OPERATOR     <
SOIL_STORAGE_MAX_MISSING_VALUES_ACTION      mean
```

Figure 4–12. Part 3 of an example Soil-Water-Balance (SWB) control file showing specification of standard SWB gridded inputs for the Maui, Hawaii, study area.

```
(6) other gridded datasets required for the Maui example
--------------------------------------------------------------------

REFERENCE_ET0 ARC_GRID input/gr0_in_month_ascii/gr0_in_%b__maui.asc
REFERENCE_ET0_PROJECTION_DEFINITION +proj=lonlat +datum=WGS84 +no_defs

FOG_RATIO ARC_GRID input/fog_fraction_grids/maui_fog_ratio_monthly_%0m__50m.asc
FOG_RATIO_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs
FOG-RATIO_MISSING_VALUES_CODE          0.0
FOG_RATIO_MISSING_VALUES_OPERATOR      <
FOG_RATIO_MISSING_VALUES_ACTION        zero

CESSPOOL_LEAKAGE ARC_GRID input/maui_CESSPOOL_EFFLUENT_INCHES_DAY__50m.asc
CESSPOOL_LEAKAGE_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

(7) Grids required for Gash Interception
-----------------------------------------------

FRACTION_CANOPY_COVER ARC_GRID input/maui_CANOPY_COVER_FRACTION__50m.asc
FRACTION_CANOPY_COVER_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

EVAPORATION_TO_RAINFALL_RATIO ARC_GRID input/maui_EVAPORATION_TO_RAINFALL_RATIO__50m.asc
EVAPORATION_TO_RAINFALL_RATIO_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

(8) Runoff-related data and grid
--------------------------------------

RUNOFF_ZONE ARC_GRID input/maui_RUNOFF_ZONE__50m.asc
RUNOFF_ZONE_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

RUNOFF_RATIO_MONTHLY_FILE input/monthly_runoff_ratios_maui_2000_2010_TRANSPOSED.txt

PERCENT_PERVIOUS_COVER ARC_GRID input/maui__PERCENT_PERVIOUS_COVER__50m.asc
PERCENT_PERVIOUS_COVER_PROJECTION_DEFINITION +proj=utm +zone=4 +ellps=WGS84 +datum=WGS84 +units=m +no_defs

(9) Lookup table(s)
----------------------

LAND_USE_LOOKUP_TABLE std_input/Landuse_lookup_maui.txt

(10) Start and end date for simulation
---------------------------------------------

START_DATE 01/01/2001
END_DATE    12/31/2002
```

Figure 4–13. Part 4 of a SWB control file showing definition of additional required grids and model start and end dates for the Maui, Hawaii study area.

Model Application

For the Maui example application, SWB model input was generated by resampling the polygon-based model input originally used for the Hawaii water-budget code in Johnson and others (2014) onto a 75-meter grid. For both models, the monthly rainfall time series used is 1978–2007 and the land cover is representative of 2010. The 75-meter grid size was determined after running SWB using multiple other resolutions, both finer and coarser than 75 meters and evaluating both (1) the differences in output between Johnson and others (2014) and SWB and (2) the computational effort. As expected, finer SWB grid sizes produced smaller differences in output between the two models, but at the cost of longer model-execution times and larger input/output file sizes. Using a 75-meter grid, SWB produced a net-infiltration estimate of 1,301 million gallons per day for the Island of Maui, which is 2.8 percent less than the estimate published in Johnson and others (2014); this result was achieved with a reasonable model-run time (several hours). A comparison of the output from SWB and Hawaii water budget is shown in figure 4–14.

The use of the method of fragments involves the random selection and use of one fragment from the many assembled for a given rain zone. Because this results in run-to-run variations owing to different sequences of storm events being applied to the soil, the Hawaii water-budget code was set up to run 15 or 20 simulations at a time, averaging all results together so as to average out the influence of storm sequencing. SWB is not set up with this facility in mind. SWB can replicate the Hawaii water-budget results by running SWB repeatedly for a number of randomly selected fragment sets, then calculating a mean of all output SWB grids.

The Maui example application demonstrates how SWB can be effectively used with alternative process methods to simulate net infiltration in climates different from the humid, temperate climate SWB was originally designed for (Wisconsin). In addition, SWB 2.0 is designed so that alternate process methods may be easily coded up and incorporated should the methods be needed for a particular study area.

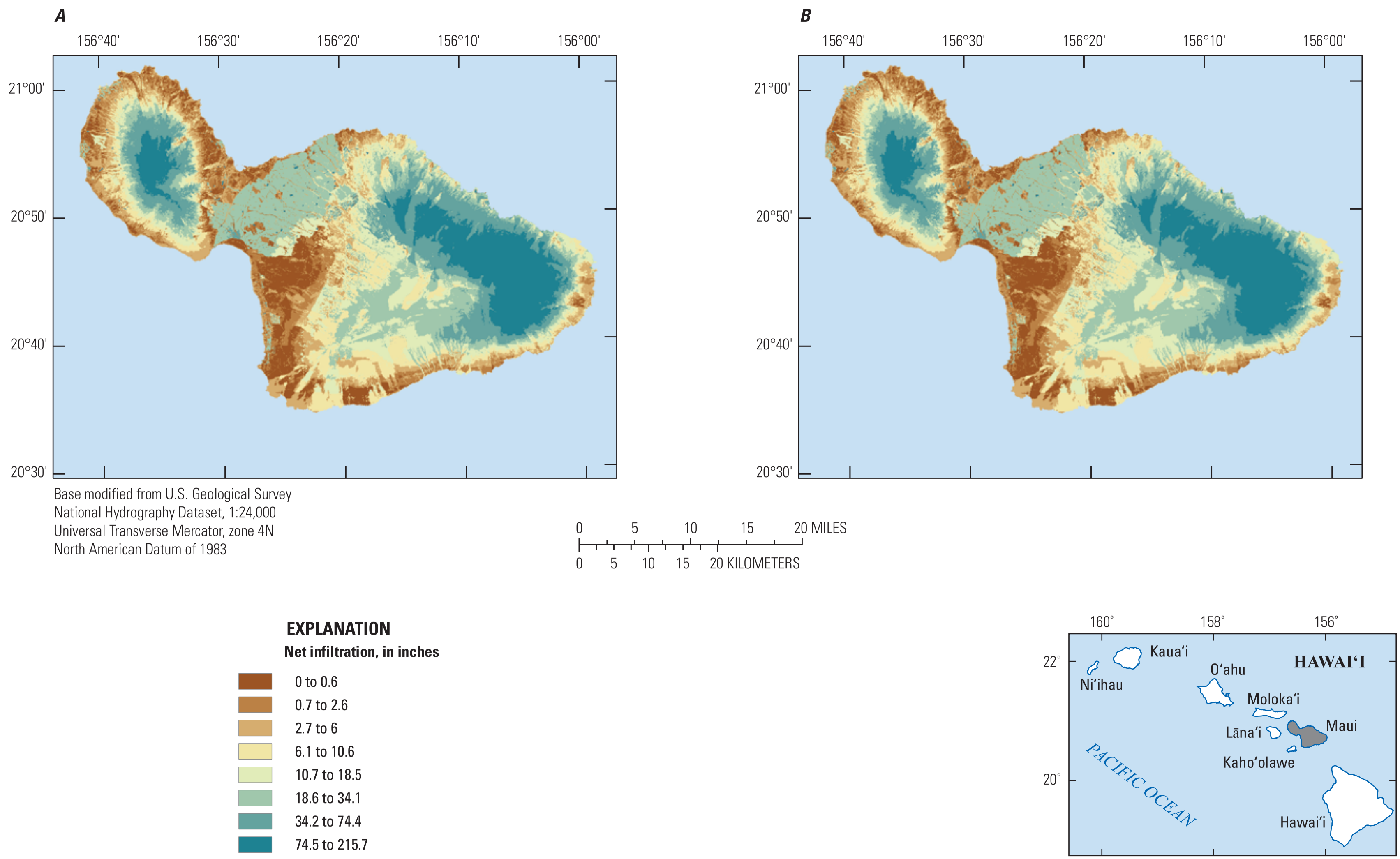


Figure 4–14. Modeled net-infiltration amounts from *A*, Soil-Water-Balance (SWB) version 2.0 and *B*, Hawaii water-budget code (modified from Johnson and others, 2014).

Central Sands, Wisconsin

SWB version 1.0 was applied to the Little Plover River in support of a groundwater study led jointly by the USGS and by the Wisconsin State Geological and Natural History Survey (Bradbury and others, 2017). SWB was used to estimate irrigation demand based on the crops present, as well as to calculate net infiltration for use in an underlying MODFLOW model. This example application uses the files from the Little Lover River project to demonstrate the use of the SWB (version 2.0) irrigation module.

Study Area

The Little Plover River runs for 21 miles and is in the Central Sands region of Wisconsin (Henrich and Daniel, 1983). The river is listed as a Class 1 trout stream for much of its length. Sandy soils in the region provide good conditions for crop growth, but require irrigation to sustain economically feasible crop yields (Weeks and others, 1965). Increases in irrigation pumping during the past 30 years to irrigate vegetable crops in the region have led to reduced summertime low flows in the Little Plover River; in some years, the discharge in July or August has decreased to zero.

Input Grids and Tables

Unlike the Maui example application, the Central Sands application uses a set of more typical input grids and tables. The curve-number approach is used to estimate runoff, which requires a hydrologic soil-group grid. The maximum soil-moisture storage is calculated from the rooting depths contained in a lookup table and an available water-capacity grid. Flow routing is enabled, which requires a D8 flow-direction grid. Land use is a required grid as well.

The land-use grid supplied to SWB for the Central Sands example is shown in figure 4–15. Because crops and irrigation play a significant role in this study area, the Cropland Data Layer (CDL) (Boryan and others, 2011) was used as the source of land-use data rather than the more typical National Land Cover Database (Homer and others, 2015). The CDL is a remote-sensing product; a certain fraction of the crops depicted in a given CDL image is incorrectly identified. To ensure that the most accurate land-use grid was being used, growers in the area of interest were invited to verify and correct the CDL crops indicated on their lands.

Hydrologic soil group and available water-capacity data were extracted from Soil Survey Geographic Database (SSURGO) soils datasets (U.S. Department of Agriculture, 2009). The hydrologic soils group grid as supplied to SWB is shown in figure 4–16. The available water-capacity grid used in the example application is shown in figure 4–17.

A D8 flow-direction grid was prepared from 30-meter USGS digital elevation model data (Gesch and others, 2002). Sinks in the digital elevation dataset were filled prior to assigning D8 flow directions. The D8 flow-direction grid supplied to SWB is shown in figure 4–18.

Because of the nature of the project, finer control regarding which cells received simulated irrigation water was needed than could be accomplished by establishing irrigated and nonirrigated land-use codes. An irrigation mask (fig. 4–19) was developed from the crop-data layer, which was modified after discussions with growers and after examination of well pumping records. Fields associated with wells not pumped during the period of interest were assumed to have nonirrigated fields.

The grid depicted in figure 4–19 is a simple Arc ASCII integer grid with values of 0 and 1; nonirrigated land is indicated by 0, and irrigated land is indicated by 1.

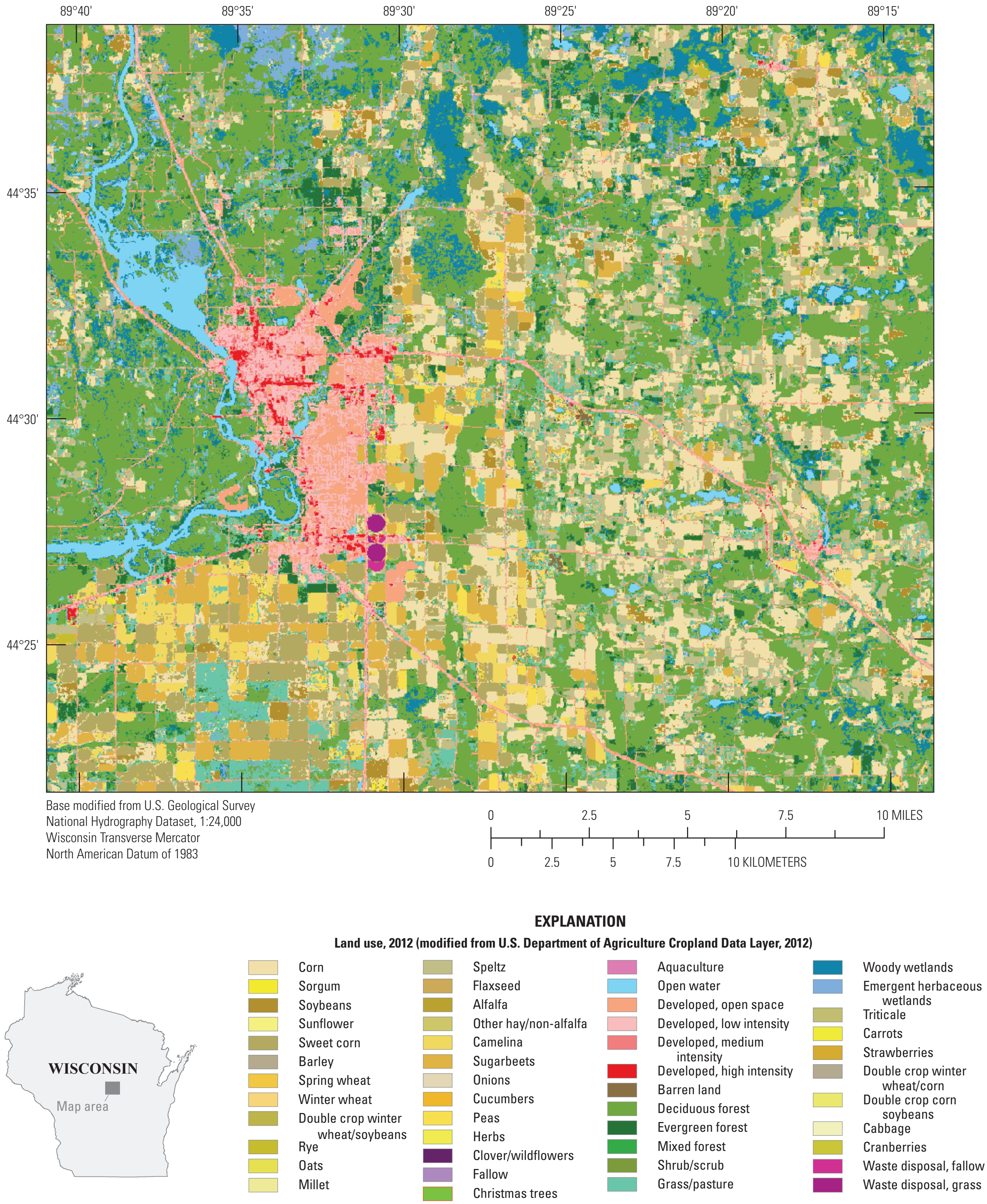


Figure 4–15. Soil-Water-Balance (SWB) land-use grid for the Central Sands study area, 2012.

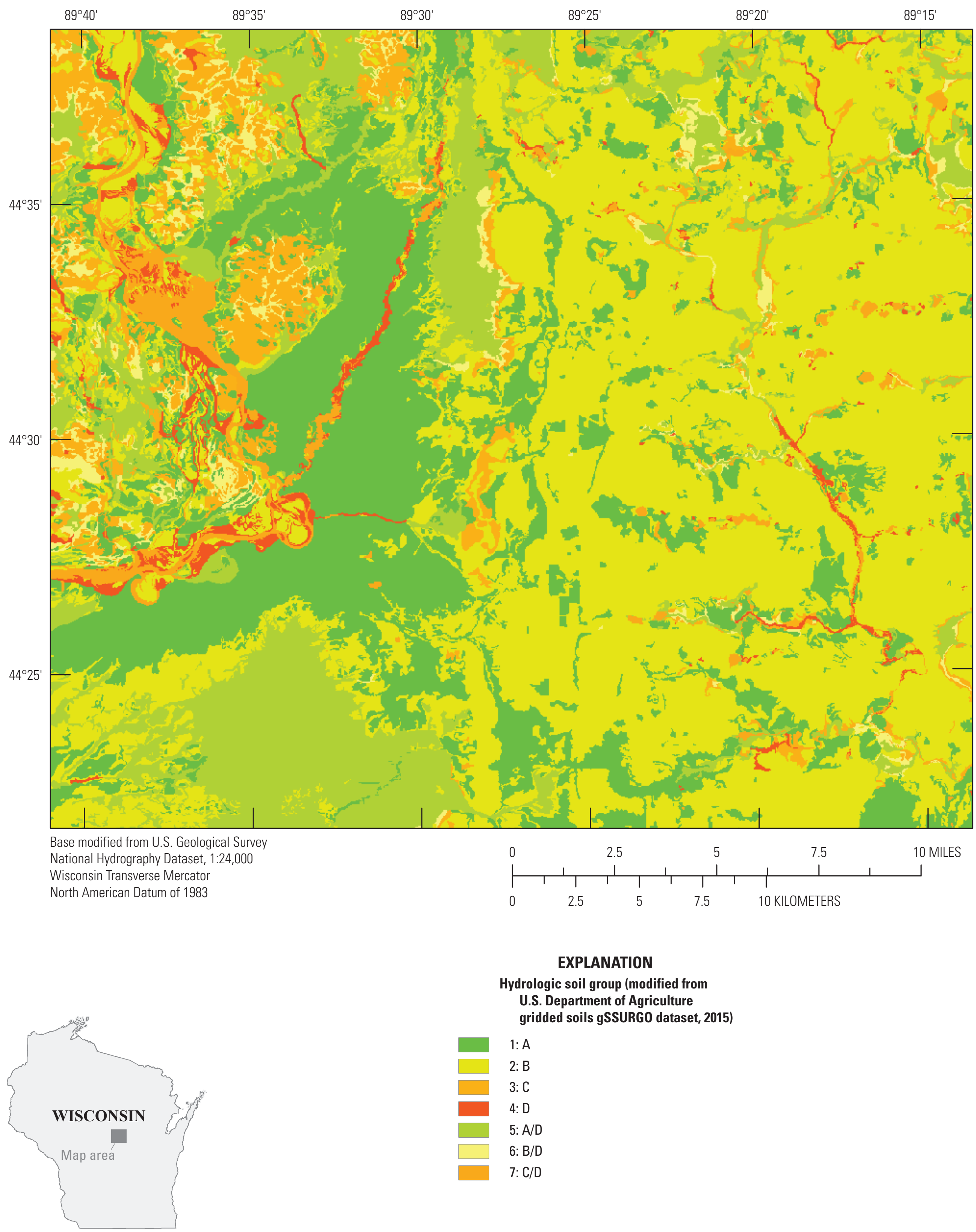


Figure 4–16. Soil-Water-Balance (SWB) hydrologic soil group grid for the Central Sands study area.

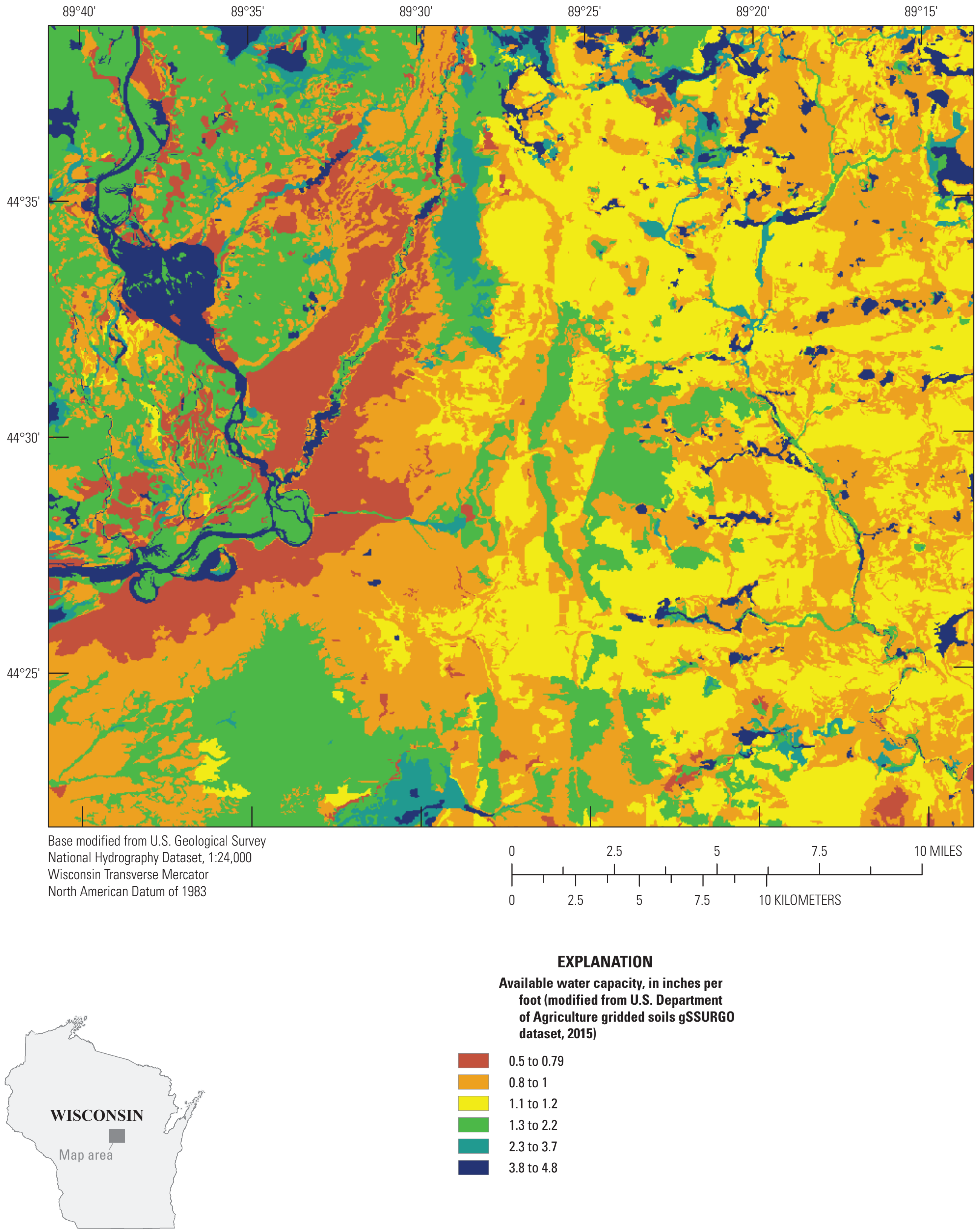
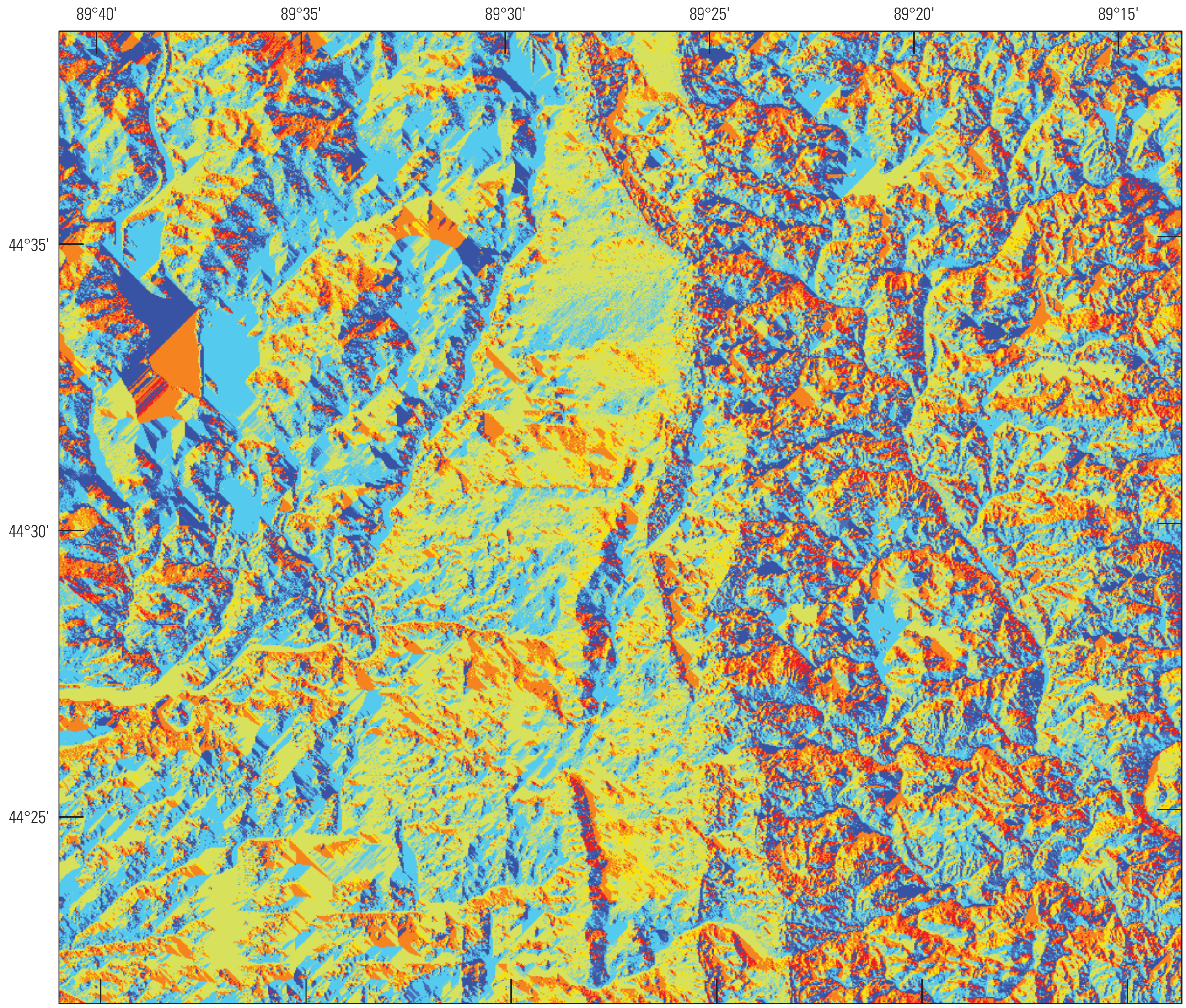


Figure 4–17. Soil-Water-Balance (SWB) available water-capacity grid for the Central Sands study area.



Base modified from U.S. Geological Survey
National Hydrography Dataset, 1:24,000
Wisconsin Transverse Mercator
North American Datum of 1983

0 2.5 5 7.5 10 MILES
0 2.5 5 7.5 10 KILOMETERS

EXPLANATION

D8 flow direction (modified from U.S. Geological Survey National Elevation Dataset, 2002)

- 1: East
- 2: Southeast
- 4: South
- 8: Southwest
- 16: West
- 32: Northwest
- 64: North
- 128: Northeast

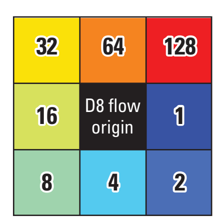


Figure 4–18. Soil-Water-Balance (SWB) D8 flow-direction grid for the Central Sands study area.

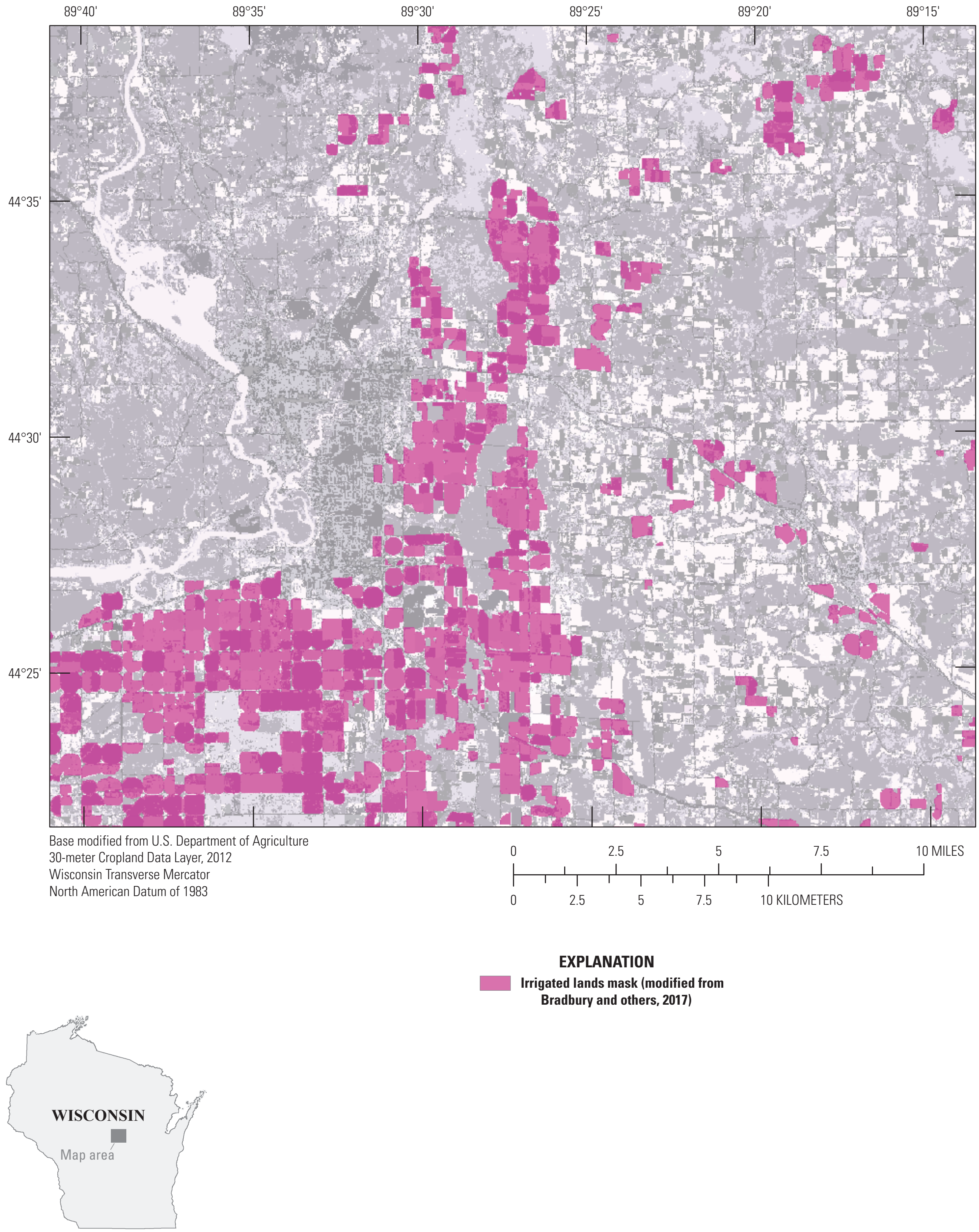


Figure 4–19. Soil-Water-Balance (SWB) irrigation mask grid for the Central Sands study area.

Control File

This section presents an SWB control file that may be used to run a simplified version of the Central Sands model.

Section (0) of figure 4–20 shows the control file syntax that defines the grid and base projection for the Central Sands example application; section (1) shows the module specification.

Section (2) of figure 4–21 shows the syntax specifying gridded datasets for precipitation and air temperature as well as the syntax for missing data handling and specification of the initial continuous frozen ground index. The weather grids specified are tiled versions of the Daymet gridded daily weather data (Thornton and others, 2016).

Section (3) of figure 4–22 shows the specification of the land use, hydrologic soil group, available water capacity, and flow-direction grids. Note that section (3) also includes the specification of an irrigation mask to limit simulated irrigation applications to areas known to actually make use of center-pivot irrigation systems. Sections (4) and (5) specify the names of the lookup tables and provide initial condition values. Section (6) demonstrates syntax that may be used to extract all pertinent variable values, including some temporary variable values; values may be extracted for a cell identified either with project coordinates or with a cell/row pair. Section (7) specifies the start and end date for the simulation.

```
%% Central Sands, Wisconsin
%% Example of net infiltration calculation with crop water demand
%% and irrigation included in water budget
%% (comment characters: !#$%*()-[] )
--------------------------------------------------------------------------------

(0) PROJECT GRID DEFINITION
------------------------------------
! Grid definition; projected coordinates are Wisconsin Transverse Mercator (83/91), meters
!      nx     ny     xll            yll       resolution
GRID 300    150  545300         432200        45.0
BASE_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

(1) MODULE SPECIFICATION
--------------------------------

INTERCEPTION_METHOD                BUCKET
EVAPOTRANSPIRATION_METHOD          HARGREAVES
RUNOFF_METHOD                      CURVE_NUMBER
SOIL_MOISTURE_METHOD               FAO-56_TWO_STAGE
PRECIPITATION_METHOD               GRIDDED
FOG_METHOD                         NONE
FLOW_ROUTING_METHOD                D8
IRRIGATION_METHOD                  FAO-56
ROOTING_DEPTH_METHOD               DYNAMIC
CROP_COEFFICIENT_METHOD            FAO-56
DIRECT_RECHARGE_METHOD             NONE
SOIL_STORAGE_MAX_METHOD            CALCULATED
AVAILABLE_WATER_CONTENT_METHOD     GRIDDED
```

Figure 4–20. Part 1 of an example Soil-Water-Balance (SWB) control file showing grid definition and method specification for the Central Sands, Wisconsin, study area.

```
(2) Define location, projection, and conversions for daily weather data
--------------------------------------------------------------------------------
PRECIPITATION NETCDF ../COMMON/prcp_Daymet_v3_%y.nc
PRECIPITATION_GRID_PROJECTION_DEFINITION +proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5 +lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80
+datum=NAD83 +units=m +no_defs
PRECIPITATION_NETCDF_Z_VAR                    prcp
PRECIPITATION_SCALE_FACTOR              0.03937008
PRECIPITATION_MISSING_VALUES CODE          -9999.0
PRECIPITATION_MISSING_VALUES_OPERATOR           <=
PRECIPITATION_MISSING_VALUES_ACTION           zero

TMAX NETCDF ../COMMON/tmax_Daymet_v3_%y.nc
TMAX_GRID_PROJECTION_DEFINITION +proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5 +lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80 +datum=NAD83
+units=m +no_defs
TMAX_SCALE_FACTOR                    1.8
TMAX_ADD_OFFSET                     32.0
TMAX_MISSING_VALUES_CODE        -9999.00
TMAX_MISSING_VALUES_OPERATOR          <=
TMAX_MISSING_VALUES_ACTION          mean

TMIN NETCDF ../COMMON/tmin_Daymet_v3_%y.nc
TMIN_GRID_PROJECTION_DEFINITION +proj=lcc +lat_1=25.0 +lat_2=60.0 +lat_0=42.5 +lon_0=-100.0 +x_0=0.0 +y_0=0.0 +ellps=GRS80 +datum=NAD83
+units=m +no_defs
TMIN_SCALE_FACTOR                    1.8
TMIN_ADD_OFFSET                     32.0
TMIN_MISSING_VALUES_CODE        -9999.00
TMIN_MISSING_VALUES_OPERATOR          <=
TMIN_MISSING_VALUES_ACTION          mean

INITIAL_CONTINUOUS_FROZEN_GROUND_INDEX CONSTANT 100.0
UPPER_LIMIT_CFGI            83.
LOWER_LIMIT_CFGI            55.
```

Figure 4–21. Part 2 of an example Soil-Water-Balance (SWB) control file showing precipitation and air temperature specification for the Central Sands, Wisconsin, study area.

```
(3) specify location and projection for "standard" input GIS grids
-----------------------------------------------------------------------------
FLOW_DIRECTION                 ARC_GRID   input/d8_flow_direction.asc
FLOW_DIRECTION_PROJECTION_DEFINITION  +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

HYDROLOGIC_SOILS_GROUP     ARC_GRID   input/hydrologic_soils_group.asc
HYDROLOGIC_SOILS_GROUP_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

LAND_USE                         ARC_GRID   input/landuse.asc
LANDUSE_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

AVAILABLE_WATER_CONTENT   ARC_GRID   input/available_water_capacity.asc
AVAILABLE_WATER_CONTENT_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

IRRIGATION_MASK                ARC_GRID   input/irrigation_mask_from_cdl.asc
IRRIGATION_MASK_PROJECTION_DEFINITION +proj=tmerc +lat_0=0.0 +lon_0=-90.0 +k=0.9996 +x_0=520000 +y_0=-4480000 +datum=NAD83 +units=m

(4) Specify location and names for all lookup tables
-------------------------------------------------------------

LAND_USE_LOOKUP_TABLE std_input/Landuse_lookup_CDL.txt
IRRIGATION_LOOKUP_TABLE std_input/Irrigation_lookup_CDL.txt

%% initial conditions for soil moisture and snow storage amounts
%% may be specified as grids, but using a constant amount and
%% allowing the model to "spin up" for a year is also acceptable.

(5) Specify initial conditions
----------------------------------
INITIAL_PERCENT_SOIL_MOISTURE   CONSTANT  100.0
INITIAL_SNOW_COVER_STORAGE      CONSTANT     2.0

(6) Specify locations or grid cell column and row for which detailed variable dump is desired
-----------------------------------------------------------------------------------------------------------
DUMP_VARIABLES COORDINATES 558059. 432426.
DUMP_VARIABLES 286 56
DUMP_VARIABLES 31 138
DUMP_VARIABLES 74 106

%% start and end date may be any valid dates in SWB version 2.0
%% remember to allow for adequate model spin up; running the
%% model for just a month or two will give questionable results

(7) Specify start and end dates for model run
------------------------------------------------------
START_DATE 01/01/2012
END_DATE    12/31/2013
```

Figure 4–22. Part 3 of an example Soil-Water-Balance (SWB) control file showing standard data grid specification, lookup-table names, and start and end dates for the Central Sands, Wisconsin, study area.

Model Application

The SWB model was applied to the Central Sands region for 2012, 2013, and 2014 to estimate irrigation amounts and their influence on net-infiltration amounts. The published SWB output (Bradbury and others, 2017) was generated with SWB version 1.0 (Westenbroek and others, 2010) and made use of precipitation data from a single station. The SWB 2.0 application was created by making some small changes to the SWB 1.0 control file so that it functions correctly with SWB version 2.0; the example files also make use of Daymet version 3 gridded daily weather data (Thornton and others, 2016). Results for the model made with the SWB version 2.0 code are nearly identical to results for the model made with the SWB version 1.0 code.

Estimated irrigation amounts for 2013 are shown in figure 4–23. The underlying soils in the extreme southwest of the grid (irrigation amounts that range from about 2 to 5 inches) correspond to the area of higher available water capacity (from 1.3 to 2.2 inches per foot) shown in figure 4–17. Crops slightly to the north indicate estimated irrigation amounts that range from about 8 to 11 inches and correspond to soils of lower available water capacity (from 0.5 to 1.0 inch per foot) shown in figure 4–17.

The SWB model produced estimates of irrigation water requirements (table 4–4) that were at most within about 10 percent difference than the reported irrigation application amounts (Bradbury and others, 2017). These results indicate that SWB may be useful in estimating irrigation amounts in study areas for which no pumping records exist.

Table 4–4. Comparison of irrigation amounts for specific crops estimated from pumping records and from Soil-Water-Balance (SWB) estimates.

[Irrigation amounts are in inches]

Irrigated crop type	Estimates based on pumping records	SWB estimates
Potatoes	9.0	10.3
Corn	8.6	7.5
Sweet corn	7.6	7.2
Snap beans	7.4	8.5

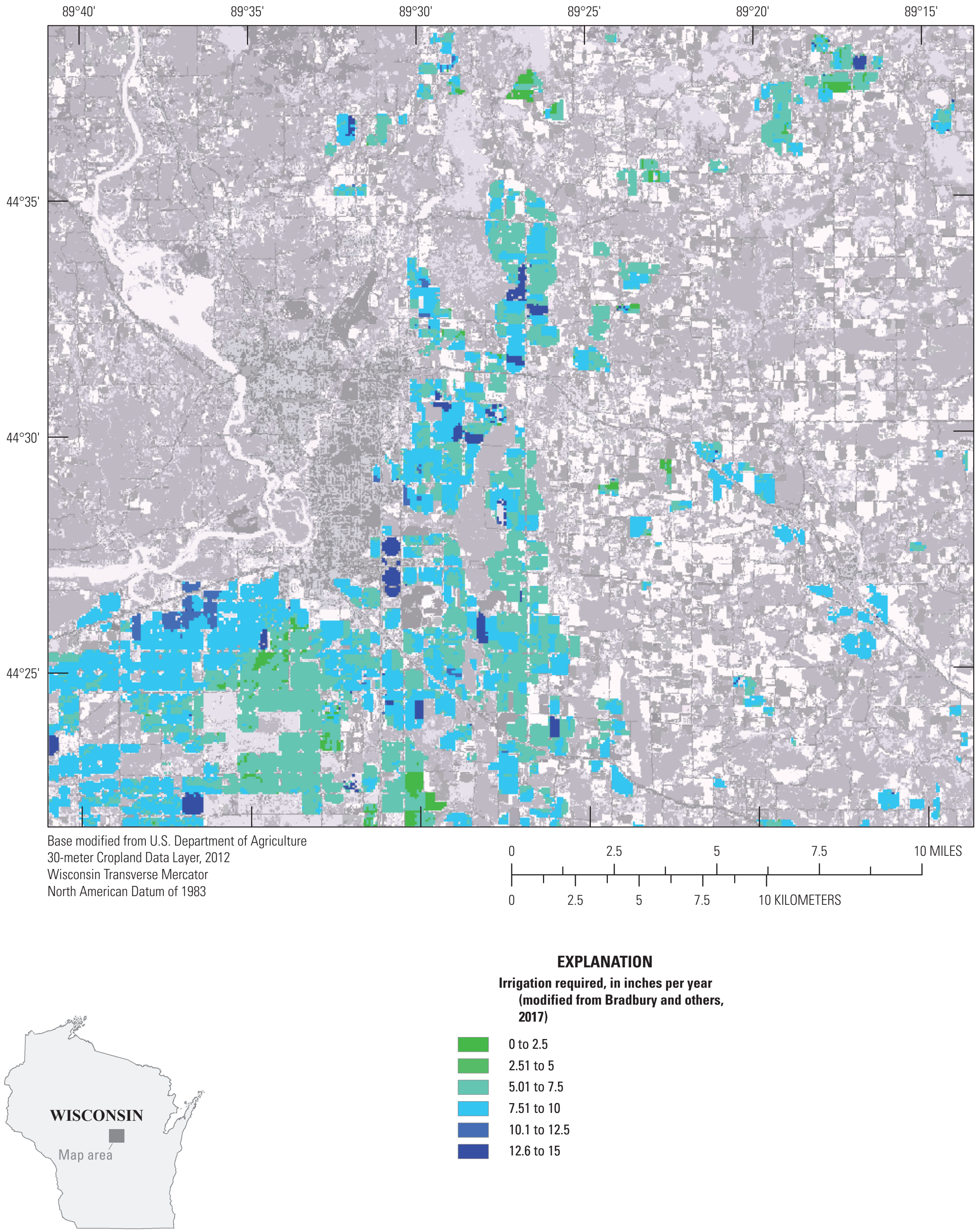


Figure 4–23. Soil-Water-Balance (SWB) estimated crop-irrigation water demand for 2013.

Monthly SWB version 1.0 results for net infiltration (fig. 4–24) were supplied to an underlying transient MODFLOW model (Harbaugh, 2005; McDonald and Harbaugh, 1988) to assist in completing a water balance of the area. This process indicated that a monthly time step may be too coarse in terms of SWB output utility in a transient model setting. The precipitation, snowmelt, runoff, and net-infiltration daily outputs from SWB were highly variable. The highly variable outputs resulted in an unrealistically smooth net-infiltration time series driving MODFLOW, with much of the temporal variability averaged away and the underlying MODFLOW model receiving a highly smeared net-infiltration pulse. In many settings, monthly aggregation of SWB results may be too coarse for realistic simulation of net infiltration.

Thoughtful application of the SWB model in areas where irrigation is active can yield reasonable estimates of irrigation application and net-infiltration amounts. Comparison of the SWB outputs to baseflow-estimated recharge amounts and to recorded pumping records is recommended if possible.

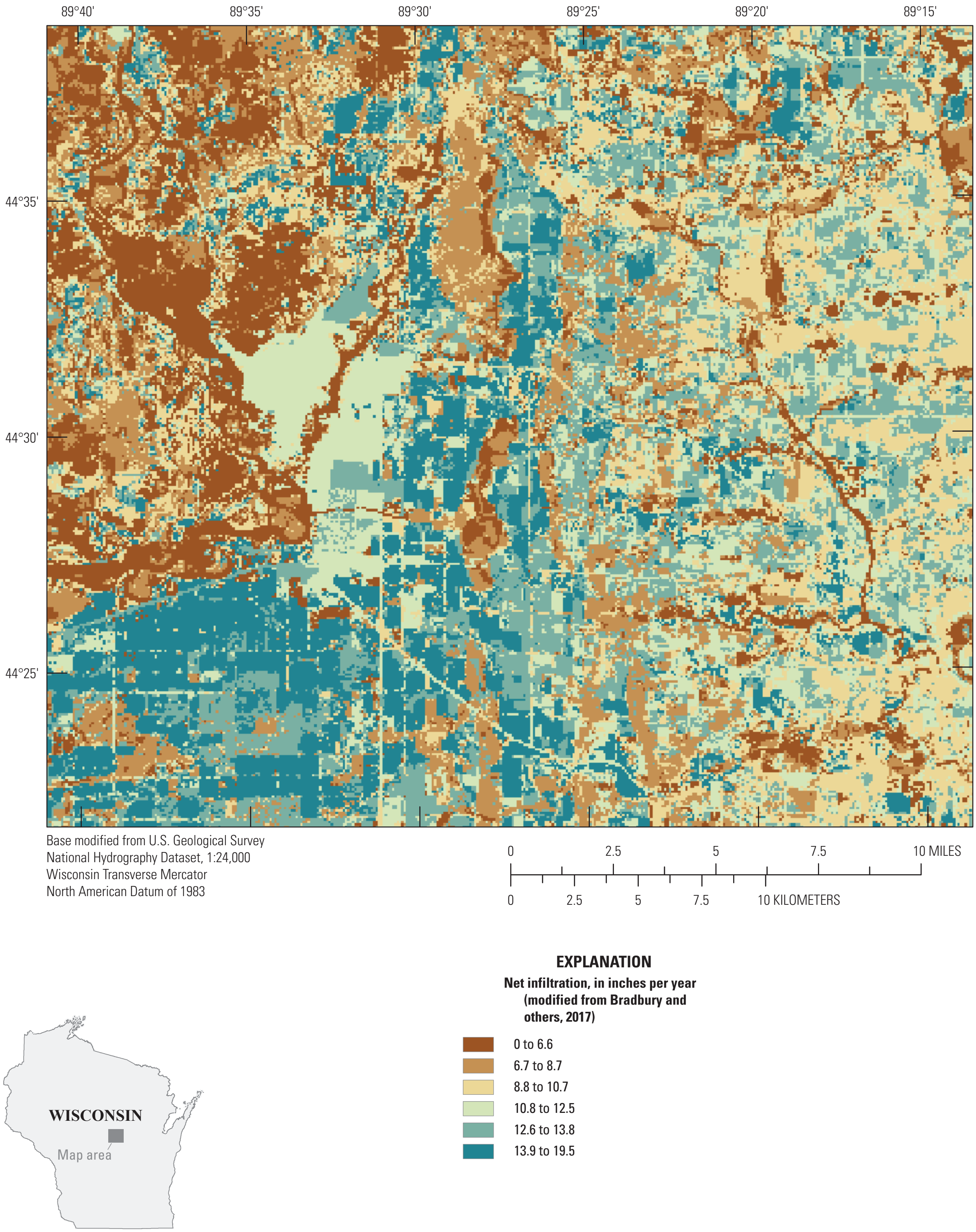


Figure 4–24. Soil-Water-Balance (SWB) estimated net infiltration for 2013.

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