

A Monthly Water-Balance Model Driven By a Graphical User Interface

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By Gregory J. McCabe and Steven L. Markstrom

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Conversion Factors

Inches (in) are converted to millimeters (mm) by multiplying by 25.4.

Millimeters (mm) are converted to inches (in) by dividing by 25.4.

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

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

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

A Monthly Water-Balance Model Driven By A Graphical User Interface

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Abstract

This report describes a monthly water-balance model driven by a graphical user interface, referred to as the Thornthwaite monthly water-balance program. Computations of monthly water-balance components of the hydrologic cycle are made for a specified location. The program can be used as a research tool, an assessment tool, and a tool for classroom instruction.

Introduction

Monthly water-balance models have been used as a means to examine the various components of the hydrologic cycle (for example, precipitation, evapotranspiration, and runoff). Such models have been used to estimate the global water balance (Mather, 1969; Legates and Mather, 1992; Legates and McCabe, 2005); to develop climate classifications (Thornthwaite, 1948); to estimate soil-moisture storage (Alley, 1984; Mintz and Serafini, 1992), runoff (Alley, 1984, 1985; Yates, 1996; Wolock and McCabe, 1999), and irrigation demand (McCabe and Wolock, 1992); and to evaluate the hydrologic effects of climate change (McCabe and Ayers, 1989; Yates, 1996; Strzepek and Yates, 1997; Wolock and McCabe, 1999).

This report provides a description of a monthly water-balance model that is driven by a graphical user interface (GUI) developed by the U.S. Geological Survey. The GUI permits the user to easily modify water-balance parameters and provide useful estimates of water-balance components for a specified location. The model, referred to as the Thornthwaite water-balance program, can be used as a research tool, an assessment tool, and as a tool for classroom instruction. The program can be downloaded from the internet at <http://water.usgs.gov/lookup/get?crresearch/mms/thorn> and can run on any platform.

The Water-Balance Model

The water-balance model (fig. 1) analyses the allocation of water among various components of the hydrologic system using a monthly accounting procedure based on the

methodology originally presented by Thornthwaite (Thornthwaite, 1948; Mather, 1978, 1979; McCabe and Wolock, 1999; Wolock and McCabe, 1999). Inputs to the model are mean monthly temperature (T , in degrees Celsius), monthly total precipitation (P , in millimeters), and the latitude (in decimal degrees) of the location of interest. The latitude of the location is used for the computation of day length, which is needed for the computation of potential evapotranspiration (PET). The model is referred to as the Thornthwaite model. A discussion of the individual components of the water balance follows.

Snow Accumulation

The first computation of the water-balance model is the estimation of the amount of monthly precipitation (P) that is rain (P_{rain}) or snow (P_{snow}), in millimeters. When mean monthly temperature (T) is below a specified threshold (T_{snow}), all precipitation is considered to be snow. If temperature is greater than an additional threshold (T_{rain}), then all precipitation is considered to be rain. Within the range defined by T_{snow} and T_{rain} , the amount of precipitation that is snow decreases linearly from 100 percent to 0 percent of total precipitation. This relation is expressed as:

$$P_{snow} = P \times \left[\frac{T_{rain} - T}{T_{rain} - T_{snow}} \right]. \quad (1)$$

P_{rain} then is computed as:

$$P_{rain} = P - P_{snow}. \quad (2)$$

Based on an analysis of water-balance results for a number of sites, a useful value for T_{rain} is 3.3°C (McCabe and Wolock, 1999). Useful values for T_{snow} appear to vary by elevation. For elevations below 1,000 m, $T_{snow} = -10^\circ\text{C}$ seems to work best, and for locations above 1,000 m $T_{snow} = -1^\circ\text{C}$ is more appropriate. (These values were determined from previous model calibrations during testing and evaluation for streamflow-gage sites in the conterminous United States. (David Wolock, U.S. Geological Survey, Lawrence, Kans., personal commun).)

P_{snow} accumulates as snow storage ($snstor$).

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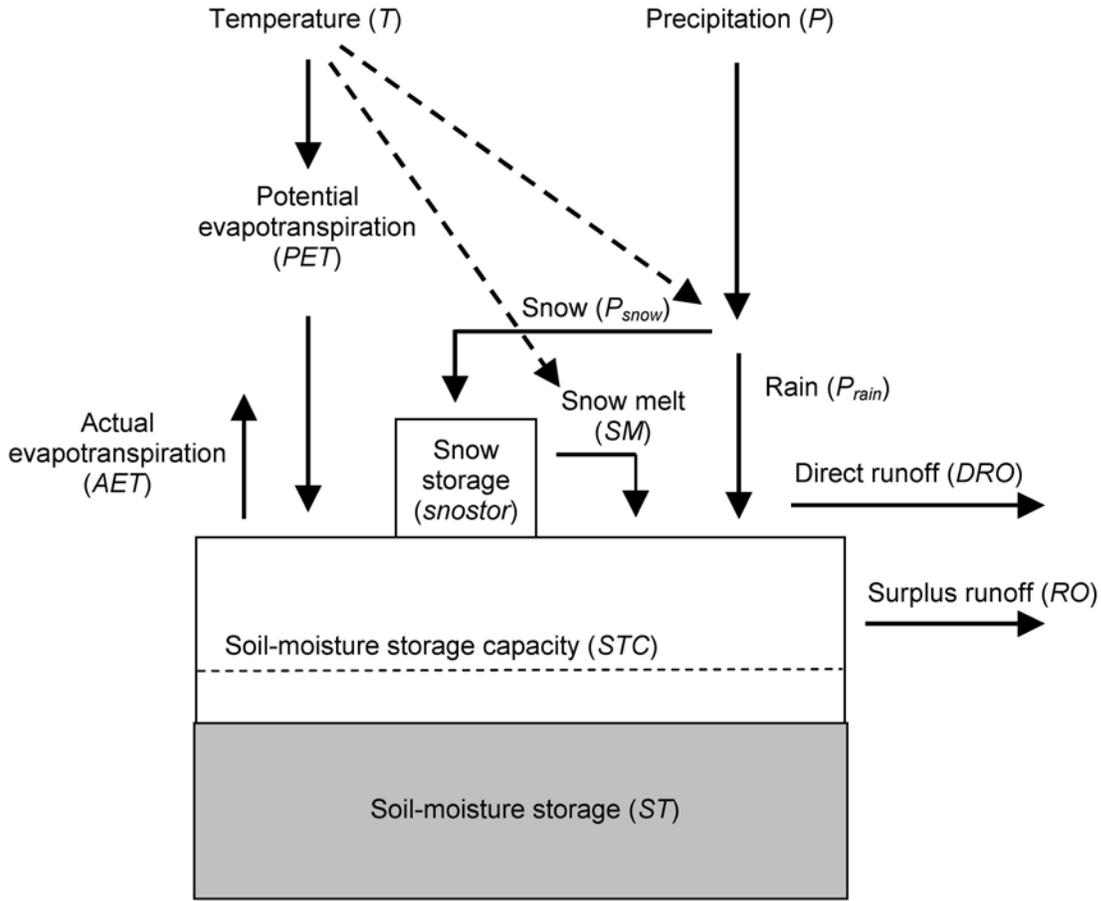


Figure 1. Diagram of the water-balance model.

Direct Runoff

Direct runoff (DRO) is runoff, in millimeters, from impervious surfaces or runoff resulting from infiltration-excess overflow.

The fraction ($drofrac$) of P_{rain} that becomes DRO is specified; based on previous water-balance analyses, 5 percent is a typical value to use (Wolock and McCabe, 1999). The expression for DRO is:

$$DRO = P_{rain} \times drofrac \quad (3)$$

Direct runoff (DRO) is subtracted from P_{rain} to compute the amount of remaining precipitation (P_{remain}):

$$P_{remain} = P_{rain} - DRO \quad (4)$$

Snow Melt

The fraction of $snostor$ that melts in a month (snow melt fraction, SMF) is computed from mean monthly temperature

(T) and a maximum melt rate ($meltmax$); $meltmax$ is often set to 0.5 (McCabe and Wolock, 1999; Wolock and McCabe, 1999). The fraction of snow storage that melts in a month is computed as:

$$SMF = \frac{T - T_{snow}}{T_{rain} - T_{snow}} \times meltmax \quad (5)$$

If the computed SMF is greater than $meltmax$, then SMF is set to $meltmax$. The amount of snow that is melted in a month (SM), in millimeters of snow water equivalent, is computed as:

$$SM = snostor \times SMF \quad (6)$$

SM is added to P_{remain} to compute the total liquid water input (P_{total}) to the soil.

Evapotranspiration and Soil-Moisture Storage

Actual evapotranspiration (AET) is derived from potential evapotranspiration (PET), P_{total} , soil-moisture storage (ST),

and soil-moisture storage withdrawal (STW). Monthly PET is estimated from mean monthly temperature (T) and is defined as the water loss from a large, homogeneous, vegetation-covered area that never lacks water (Thornthwaite, 1948; Mather, 1978). Thus, PET represents the climatic demand for water relative to the available energy. In this water balance, PET is calculated by using the Hamon equation (Hamon, 1961):

$$PET_{Hamon} = 13.97 \times d \times D^2 \times W_t, \quad (7)$$

where PET_{Hamon} is PET in millimeters per month, d is the number of days in a month, D is the mean monthly hours of daylight in units of 12 hrs, and W_t is a saturated water vapor density term, in grams per cubic meter, calculated by:

$$W_t = \frac{4.95 \times e^{0.062 \times T}}{100} \quad (8)$$

where T is the mean monthly temperature in degrees Celsius (Hamon, 1961).

When P_{total} for a month is less than PET , then AET is equal to P_{total} plus the amount of soil moisture that can be withdrawn from storage in the soil. Soil-moisture storage withdrawal linearly decreases with decreasing ST such that as the soil becomes drier, water becomes more difficult to remove from the soil and less is available for AET .

STW is computed as follows:

$$STW = ST_{i-1} - \left[abs(P_{total} - PET) \times \left(\frac{ST_{i-1}}{STC} \right) \right], \quad (9)$$

where ST_{i-1} is the soil-moisture storage for the previous month and STC is the soil-moisture storage capacity. An STC of 150 mm works for most locations (McCabe and Wolock, 1999; Wolock and McCabe, 1999).

If the sum of P_{total} and STW is less than PET , then a water deficit is calculated as $PET - AET$. If P_{total} exceeds PET , then AET is equal to PET and the water in excess of PET replenishes ST . When ST is greater than STC , the excess water becomes surplus (S) and is eventually available for runoff.

Runoff Generation

Runoff (RO) is generated from the surplus, S , at a specified rate ($rfactor$). An $rfactor$ value of 0.5 is commonly used (Wolock and McCabe, 1999). The $rfactor$ parameter determines the fraction of surplus that becomes runoff in a month. The remaining surplus is carried over to the following month to compute total S for that month. Direct runoff (DRO), in millimeters, is added directly to the runoff generated from surplus (RO) to compute total monthly runoff (RO_{total}), in millimeters.

Running the Water-Balance Program

The window for the Thornthwaite monthly water-balance program will behave like any other window on the desktop. Resize, iconify, or close it like any other application by dragging the borders and clicking on the window controllers in the upper corners of the frame. Figure 2 is a screen image of the program's graphical user interface.

Input Parameters

The water-balance model has seven input parameters (runoff factor, direct runoff factor, soil-moisture storage capacity, latitude of location, rain temperature threshold, snow temperature threshold, and maximum snow-melt rate of the snow storage) that are modified through the graphical user interface (fig. 2). The range and default values for these parameters are set by the model. These values are changed by clicking on the corresponding slider bar and dragging the value. The system will not allow invalid values to be entered.

Data Files

The model requires a simple input data file. To select the input file, click on the button corresponding to the file ("Input file") and a file browser will appear. The input file must be a file on the user's local file system that contains monthly water-balance input data. A sample data file (input.file) is provided with the model and is located in the USGS_Thornthwaite installation folder. The data file must be organized into four columns with one or more space characters between the columns. The first column is the year, the second is the numeric month of the year, the third is mean monthly temperature in degrees Celsius, and the last is monthly total precipitation in millimeters.

When the model runs, tabular output is written to a popup window (fig. 3). The columns of the output are date, PET , P , $P - PET$, soil-moisture storage, AET , $PET - AET$ (also known as moisture deficit), snow storage, surplus, and RO_{total} . The contents of this window can be saved to a file by clicking on the Save button at the bottom of the window and specifying the name (and directory) of an output file in the file browser.

At the bottom of the main program window (fig. 2), the user can select the specific variables to be plotted by clicking on the corresponding circle. After the model runs, a window will open with the plotted time series (fig. 4). The model can be run any number of times, each time selecting a different set of variables to plot.

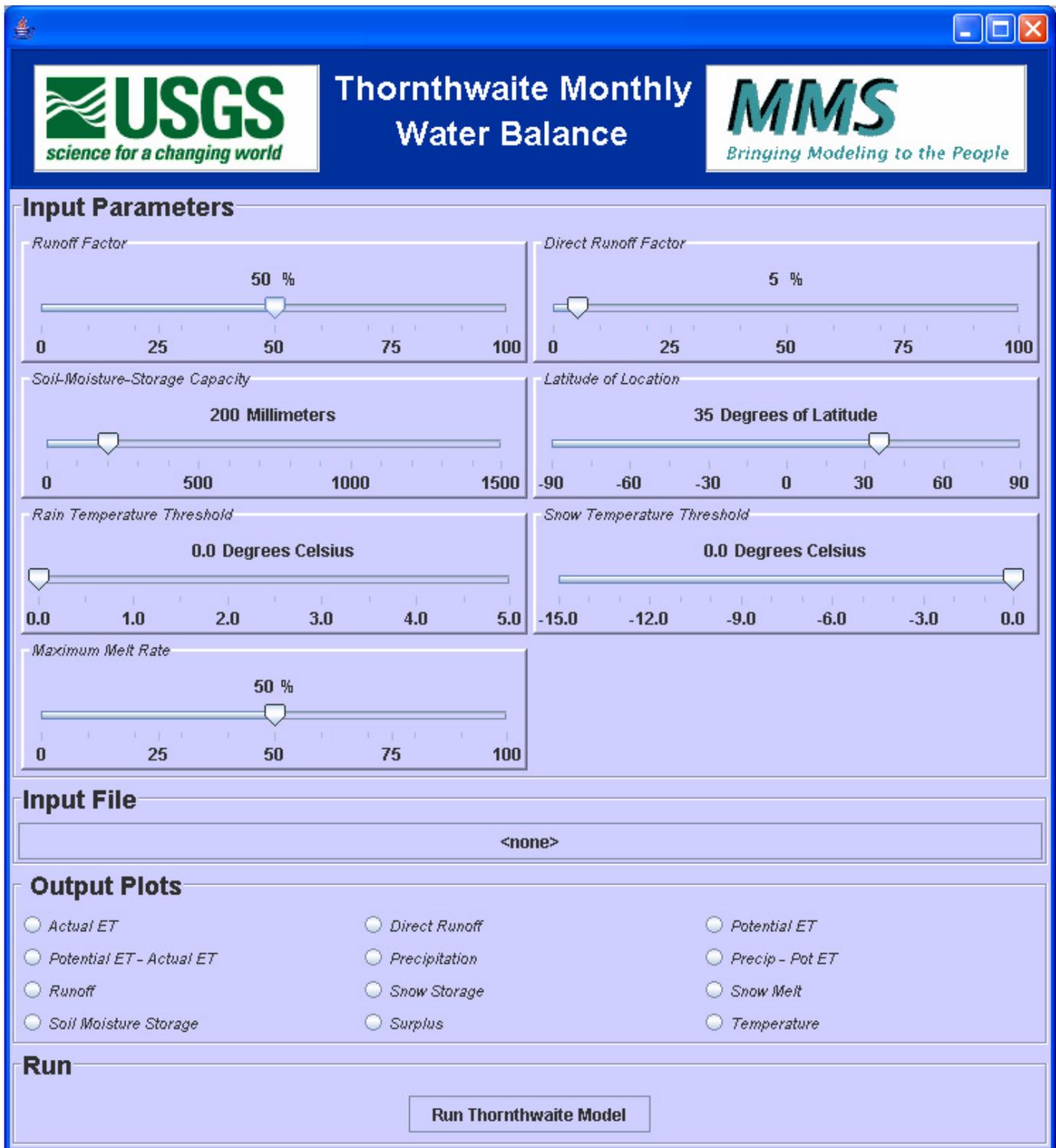


Figure 2. Screen image of the water-balance model graphical user interface.

Date	PET	P	P-PET	Soil Moisture	AET	PET-AET	Snow Storage	Surplus	R0total
Jan-1960	18.0	44.1	23.9	173.9	18.0	0.0	0.0	0.0	14.9
Feb-1960	18.2	62.9	41.6	200.0	18.2	0.0	0.0	15.5	17.2
Mar-1960	28.5	32.8	2.7	200.0	28.5	0.0	0.0	2.7	10.0
Apr-1960	70.1	48.5	-24.1	175.9	70.1	-0.0	0.0	0.0	6.6
May-1960	98.0	150.6	45.1	200.0	98.0	0.0	0.0	21.0	20.1
Jun-1960	147.5	74.7	-76.6	123.4	147.5	0.0	0.0	0.0	10.0
Jul-1960	156.7	151.8	-12.5	115.7	151.9	4.8	0.0	0.0	10.7
Aug-1960	142.1	88.1	-58.4	81.9	117.5	24.6	0.0	0.0	6.0
Sep-1960	96.2	60.6	-38.6	66.1	73.4	22.8	0.0	0.0	3.8
Oct-1960	56.8	115.6	53.0	119.1	56.8	0.0	0.0	0.0	6.2
Nov-1960	29.6	13.4	-16.8	109.1	22.8	6.8	0.0	0.0	0.9
Dec-1960	17.6	84.5	62.6	171.7	17.6	0.0	0.0	0.0	4.3
Jan-1961	17.5	10.0	-8.0	164.9	16.4	1.1	0.0	0.0	0.6
Feb-1961	24.0	43.5	17.4	182.3	24.0	0.0	0.0	0.0	2.2
Mar-1961	41.9	90.0	43.6	200.0	41.9	0.0	0.0	25.9	17.4
Apr-1961	60.7	27.0	-35.1	164.9	60.7	0.0	0.0	0.0	7.8
May-1961	100.5	123.5	16.9	181.8	100.5	0.0	0.0	0.0	9.4
Jun-1961	131.7	111.6	-25.6	158.5	129.3	2.3	0.0	0.0	7.2
Jul-1961	155.5	133.5	-28.7	135.8	149.6	5.9	0.0	0.0	7.5
Aug-1961	132.1	84.4	-51.9	100.6	115.4	16.7	0.0	0.0	4.6
Sep-1961	83.5	140.8	50.3	150.8	83.5	0.0	0.0	0.0	7.2
Oct-1961	53.6	66.5	9.5	160.3	53.6	0.0	0.0	0.0	3.4

Save

Figure 3. Screen image of example output from the water-balance model.

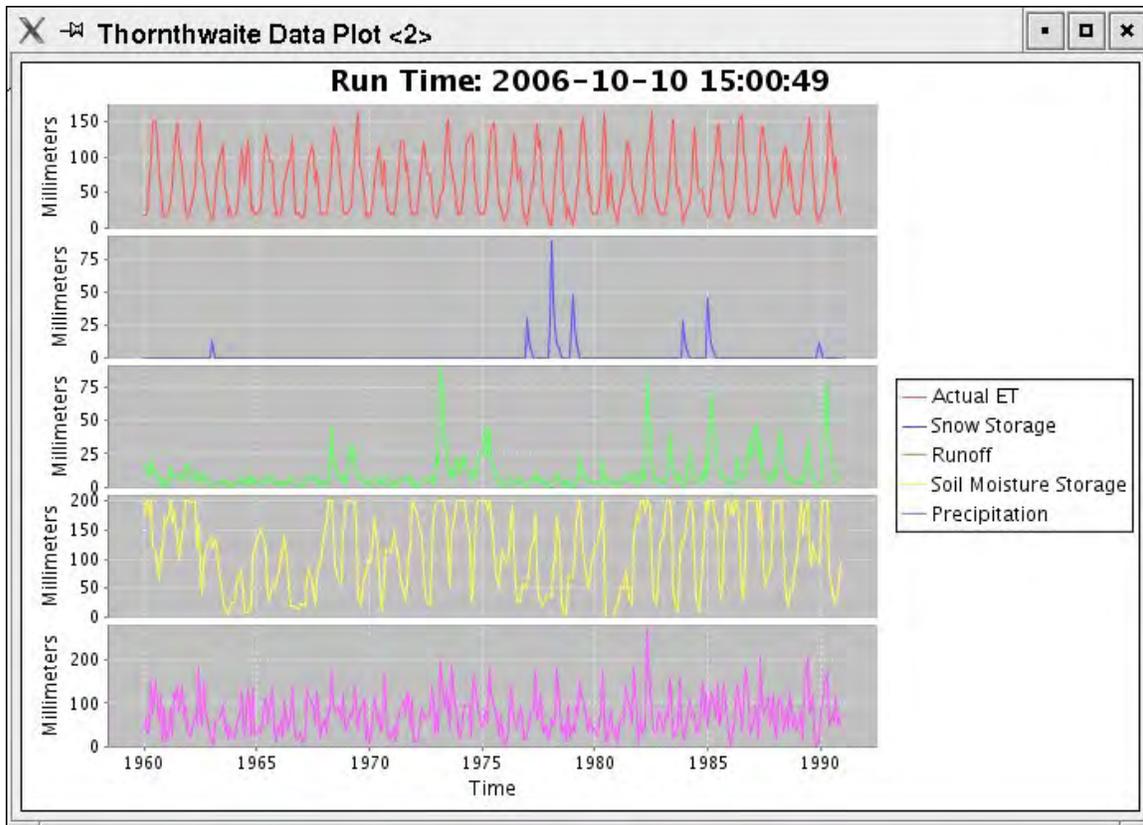


Figure 4. Screen image of example time series plotted by the water-balance model.

Summary

Monthly water-balance models have been used to examine the various components of the hydrologic cycle (for example, precipitation, evapotranspiration, and runoff). This report presents a description of a monthly water-balance model, the Thornthwaite monthly water-balance program, which includes computations of monthly water-balance components for a specified location driven by a graphical user interface. The program can be downloaded from the internet and run on any computer platform. The program can be used for research, assessment purposes, and classroom instruction.

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