User Guide For Gridded Water Balance Model Dataset – Version 2

December 2018

Michael Tercek[1], David Thoma[2], John Gross[3], Kirk Sherrill[2]

1. Walking Shadow Ecology, PO Box 1085, Gardiner, Montana, 59030 USA.
Tercek@YellowstoneEcology.com, www.ClimateAnalyzer.org

2. US National Park Service Inventory and Monitoring Program.
3. US National Park Service Climate Change Response Program.

Purpose

This document describes the characteristics of a gridded (GIS-based) water balance model data set covering most of North America for the period 1980 – 2017 at 1km resolution (approximately 63 million locations) in both daily and monthly timesteps. The data are available as about 3 TB of Network Common Data Format (NetCDF) files that can be downloaded from the following URL: https://s3-us-west-2.amazonaws.com/daymet/index.html

This work was funded by the National Park Service Inventory and Monitoring Program and the National Park Service Climate Change Response Program.

Description of the Water Balance Model

Water balance modeling is a tool for increasing our understanding of climate influence on natural resources. Like balancing a check book, it is a way of tracking the balance of nature's most important asset. Most natural resources we manage are either water itself (springs, rivers, wetlands), or life that depends on water. Water and temperature interactions are based in physics that we can mathematically model. We find (and many others before us have too) that these modeled values are more strongly correlated with the things we manage than simple measures of temperature or precipitation.

We use a simple model based on methods described by Thornthwaite and Mather (1955) and Lutz et al. (2010). The model tracks the fate of precipitation after it falls. After precipitation (snow or rain) hits the ground it has three options: (1) Stay put temporarily as stored snow pack or soil moisture, (2) Go up, via evaporation or through plants via transpiration. (3) Go down and become either ground water or runoff to wetlands, lakes, streams, rivers. Temperature determines the time water is stored as snow and when it melts, as well as the rate of evapotranspiration. The movement of water between compartments depends on the amount of energy (heat) in the system and the amount of water available.

Version 2 of the model differs from version 1 in the following ways: (1) Snow Water Equivalent (SWE) is estimated using temperature-indexed equations (Lutz et al. 2010) rather than taking Daymet-provided SWE without modification. The melt threshold temperature used in the snow estimation equations is different for each 1km grid cell, using values supplied by Jennings et al. 2018. (2) Actual Evapotranspiration (AET) is calculated based on 30-year daily NDVI values, using methods provided by the USGS (Gabriel Senay, personal communication), (3) daily precipitation is adjusted into "effective precipitation" using an Igrid vegetation structure layer provided by Senay et al. (personal communication), (4) during each day of model run, all soil water is available for AET, rather than being removed at a rate governed by equations found in Lutz et al. (2010).

Output Variables

The output parameters of the model (available for download from the URL above) are defined as follows:

Potential Evapotranspiration (PET, mm): The amount of evaporation and transpiration (movement of water into the atmosphere by plants) that would occur if soil moisture were unlimited. Temperature, wind, solar radiation, cloudiness and a variety of other factors affect PET. Sixty to ninety percent of annual precipitation is evapotranspired back to the atmosphere, mostly through plant leaves. There are many ways to calculate PET. In the current model, we used methods described by Oudin et al (2005) and Oudin et al. (2010). We also used a heat load correction that incorporated slope and aspect for each grid location, as described by Lutz et al. (2010).

Actual Evapotranspiration (AET, mm): AET is the water balance value that is most closely related to vegetation growth. When plants transpire vigorously they are alive and growing. If the water in the soil is insufficient to meet the evaporative demand of the atmosphere, then AET < PET. In version 2 of the model, AET will sometimes PET because of the NDVI correction, which incorporates field data on vegetation structure and green-ness. Methods for calculating AET are on lines 324 – 368, 508 – 511 and 593 in the source code (linked below).

Moisture Deficit (Deficit, mm): Use simple subtraction, i.e., Deficit = PET – AET. Deficit is the amount of water vegetation would use if it was available. Deficit can never be negative.

Soil water: The amount of water that is held in the soil. The model treats the soil like a bucket that can be filled by inputs (e.g. rain, snowmelt) and emptied by outputs (e.g. evaporation, transpiration). If the soil gets full, then runoff to streams results. Water holding capacity is the amount of water soil retains after it is saturated then drains. Think of a saturated sponge left on a counter without squeezing. Soil typically fills with water in winter and spring. As plants use water from soil it can be replenished by rain. If rain doesn't fall, deficit or summer drought occurs. Plants "drink" water from soil and soil stores water, but not all soils are equal. Some are shallow, some rocky, sandy, or loamy, thus different soils store different amounts of water. In the current model, we used SSURGO soil data from the Natural Resources Conservation Service to determine the water holding capacity for each area (Soil Survey Staff, NRCS, 2018). SSURGO data was only available for the Conterminous United States. In areas where no soil data were available, soil water holding capacity was assumed to be 100 mm. Units = mm.

Runoff (mm): When the soil water bucket overflows, the water is lost as runoff.

Accumulated Growing Degree Days (AGDD, mm): This is a traditional measure of heat for growing plants, calculated here with a base temperature of 10 ^{0}C. Plants develop through annual phenological stages (germination, first leaf or bud, flowering) based on availability of plant nutrients, water and heat. A single day's growing degree days is GDD = ((Daily Maximum Temperature + Daily Minimum Temperature) / 2) – 10. AGDD is the sum of all GDD for the water year. Water years run from October 1 – September 30 of the following year. *Units = Degrees C.*

Rain (mm): Rain = total daily precipitation – daily snow accumulation, where snow is taken directly as Snow Water Equivalent (SWE) increase from the Daymet input dataset.

Accumulated Snow Water Equivalent (SWE, mm): total SWE at each location. Estimated using equations described by Tercek and Rodman (2016) with melt threshold temperatures at each lkm grid cell provided by Jennings et al. (2018).

Technical Details of the Data Files

Input Data

The model uses Daymet Daily Data Version 3 (Thornton et al. 1997, Thornton et al. 2000) as input data. Detailed specifications for Daymet data are here: https://daac.ornl.gov/DAYMET/guides/Daymet_V3_Annual_Climatology.html

To calculate daily SWE, Daymet uses methods described by Running and Coughlan (1988). We do not calculate SWE in our model, instead taking the SWE values directly from Daymet.

Output Data Characteristics

We have exactly copied the NetCDF data structure used by Daymet. Details of the structure appear in Appendix 1. See also the Daymet documentation link above. Importantly, both Daymet and our output data maintain 365 days in every year, regardless of leap years. During leap years, December 31 is omitted. The projection is Lambert Conformal Conic.

Functions Used to Make Monthly Summaries

The model was run on a daily time step and monthly summaries were generated by applying the following summary functions to the daily values for each month separately.

Soil Water = Mean
AET = Sum
PET = Sum
Deficit = Sum
Melt = Sum
Rain = Sum
Water input to soil = Sum
Runoff = Sum
Accumulated Precip = Last value of month
Accumulated SWE = Last value of month

Source Code Availability

The analytical code was written in Python version 3.6 (Millman and Aivazis 2011) using the Numpy and Scipy libraries (van der Walt et al. 2011) and run as parallel processes on the Amazon cloud. The source code can be downloaded here.

Literature Cited

Jennings, K., T. Winchell, B. Livneh, and N. Molotch. 2018. Spatial variation in the rain-snow temperature threshold across the northern hemisphere. Nature Communications 9:1148.

Lutz J, J. van Wagtendonk and J. Franklin. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. Journal of Biogeography 37: 936 – 950.

Millman, K. and M. Aivazis. 2011. Python for Scientists and Engineers, Computing in Science & Engineering 13: 9–12.

Oudin, L., F. Hervieu, C. Michel, C. Perrin, V. Andreassian, F. Anctil, C. Loumange. 2005. Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 = Towards a simple and efficent potential evapotranspiration model for rainfall-runoff modelling. Journal of Hydrology 303: 290 – 306.

Oudin, L., L. Moulin, H. Bendjoudi, and P. Ribstein. 2010. Estimating potential evapotranspiration without continuous daily data: possible errors and impact on water balance simulations. Hydrological Sciences Journal 55(2): 209 – 222.

Running, S. and J. Coughlan. 1988. A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modelling 42: 125 – 154.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at https://websoilsurvey.nrcs.usda.gov/. Accessed 04/10/2018.

Tercek, M. and A. Rodman. 2016. Forecasts of 21st Century snowpack and implications for snowmobile and snowcoach use in Yellowstone National Park. PloS One 11(7): e0159218. doi:10.1371/journal.pone.0159218

Thornthwaite, C.W. and Mather, J.R. 1955. The water balance. Publications in Climatology, Centerton.

Thornton, P.E., Running, S.W., White, M.A. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology 190: 204-251. http://dx.doi.org/10.1016/S00022-1694(96)03128-9

Thornton, P.E., H. Hasenauer, and M.A. White. 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. Agricultural and Forest Meteorology 104:255-271. http://dx.doi.org/10.1016/S0168-1923(00)00170-2

van der Walt S., S. Colbert S and G. Varoquaux. 2011. The NumPy Array: A Structure for Efficient Numerical Computation, Computing in Science & Engineering 13: 22–30.

Appendix 1 – Metadata for the 1980 Deficit file. All files have the same structure, which follows exactly the structure used by Daymet. See https://daac.ornl.gov/DAYMET/guides/Daymet_V3_Annual_Climatology.html for more detail.

Dataset type: Hierarchical Data Format, version 5

```
netcdf file: 1980_Deficit.nc4 {
 dimensions:
   x = 7814;
   y = 8075;
   time = 365;
   nv = 2;
 variables:
   float x(x=7814);
     :units = "m";
     :long_name = "x";
     :standard_name = "projection_x_coordinate";
     :_ChunkSize = 7814; // int

   float y(y=8075);
     :units = "m";
     :long_name = "y";
     :standard_name = "projection_y_coordinate";
     :_ChunkSize = 8075; // int

   float lat(y=8075, x=7814);
     :units = "degrees_north";
     :long_name = "lat";
     :standard_name = "latitude";
     :_ChunkSize = 1010, 977; // int

   float lon(y=8075, x=7814);
     :units = "degrees_east";
     :long_name = "lon";
     :standard_name = "longitude";
     :_ChunkSize = 1010, 977; // int

   float time(time=365);
     :long_name = "time";
     :calendar = "standard";
     :units = "days since 1980-01-01 00:00:00 UTC";
     :bounds = "time_bnds";
     :_ChunkSize = 365; // int

   short yearday(time=365);
     :long_name = "yearday";
     :_ChunkSize = 365; // int

   float time_bnds(time=365, nv=2);
     :long_name = "time_bnds";
     :_ChunkSize = 365, 2; // int
```

```
    short lambert_conformal_conic;
      :grid_mapping_name = "lambert_conformal_conic";
      :longitude_of_central_meridian = -100.0; // double
      :latitude_of_projection_origin = 42.5; // double
      :false_easting = 0.0; // double
      :false_northing = 0.0; // double
      :standard_parallel = 25.0, 60.0; // double
      :semi_major_axis = 6378137.0; // double
      :inverse_flattening = 298.257223563; // double
      :long_name = "lambert_conformal_conic";

    float Deficit(time=365, y=8075, x=7814);
      :cell_methods = "area: mean time: minimum";
      :_FillValue = -9999.0f; // float
      :long_name = "Deficit";
      :units = "mm";
      :missing_value = -9999.0f; // float
      :coordinates = "lat lon";
      :grid_mapping = "lambert_conformal_conic";
      :_ChunkSize = 12, 279, 270; // int

  // global attributes:
  :_NCProperties = "version=1|netcdflibversion=4.4.1|hdf5libversion=1.8.17";
}
```