Distributed Parameter Watershed Model Tri-Valley Area Watershed

Submitted to

Owens Valley Groundwater Authority

Prepared by

DBS&A
Daniel B. Stephens & Associates, Inc.

a Geo-Logic Company

3916 State Street, Garden Suite
Santa Barbara, CA 93105
www.dbstephens.com
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Certification

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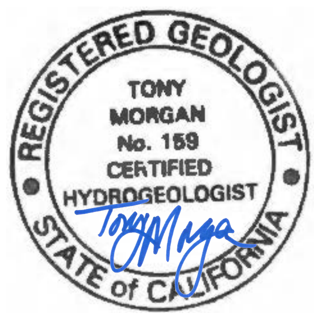

Farag Botros, PhD, PE
Senior Engineer
fbotros@dbstephens.com
2777 East Guasti Road, Suite 1
Ontario, CA 91761

Tony Morgan, PG, CHG
VP / Principal Hydrogeologist
tmorgan@geo-logic.com
3916 State Street, Garden Suite
Santa Barbara, CA 93105

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1. Introduction and Purpose

Daniel B. Stephens & Associates, Inc. (DBS&A) has completed an estimate of natural groundwater recharge within the Tri-Valley area and Fish Slough subbasin (CA DWR Subbasin Number 6-012.02). Both areas are within the Owen Valley Groundwater Basin (CA DWR Basin Number 6-012). This Report has been prepared for the Owens Valley Groundwater Authority (OVGA) in support of the development of the Owens Valley Groundwater Sustainability Plan (GSP).

The Tri-Valley area is the northern arm of the Owens Valley Groundwater Basin extending to the California and Nevada State Line (Figure 1) and includes the Benton, Chalfant, and Hammil valleys. Fish Slough subbasin is located west of the Tri-Valley area (Figure 1).

The objective of this work is to estimate the amount of natural groundwater recharge that occurs via precipitation or surface water percolation within the Tri-Valley area and Fish Slough subbasin using the Distributed Parameter Watershed Model (DPWM) developed by DBS&A. This model is a spatially discretized “tipping bucket” type soil-water balance model, which evaluates precipitation, evapotranspiration, and resultant percolation through the soil column. The modeling approach includes methods previously applied in similar basin and range locations by the U.S. Geological Survey (USGS) (e.g., Flint and Flint, 2007). A description of the model approach and equations used to estimate different water balance components is explained in Appendix A.

Application of the DPWM allows for mass-conservative quantitative estimates based on site-specific climatological, geologic, soils and vegetation factors. DPWM provides estimates of net infiltration in any basin area that result from mountain front recharge, streamflow infiltration, and infiltration from precipitation at the basin floor. However, DPWM is not a fully-coupled groundwater and surface water model. Water table elevation can rise in some locations (at some times to near land surface), which would then restrict recharge to groundwater. As DPWM does not simulate groundwater flow, it can overestimate recharge in these areas and at those times. Furthermore, it cannot estimate subsurface flows into or out of the basin. Although simulation of groundwater flow would require additional modeling efforts, results obtained from DPWM could be used to quantify some of the required inputs for any future groundwater model developed for the area.

With understanding these limitations of DPWM, it is still a useful tool to estimate the natural recharge from precipitation and streamflow percolation into a basin and is especially useful tool in areas like Tri-Valley where there are insufficient data to determine estimates of recharge within a reasonable level of precision.

2. Study Area and Model Simulation Area

The study area of this report includes the Tri-Valley area and Fish Slough subbasin. The Tri-Valley area consists of unconsolidated alluvial sediments underlying Paleozoic and Mesozoic-age metamorphic and igneous rocks of the Benton Range and White Mountains, respectively.

The area is bounded on the west by the Benton Range and Volcanic Tablelands (Bishop Tuff), on the north by the Huntoon Mountains, and on the east by White Mountains (Figure 2). The southern boundary of the project area was delineated based on the approximate discharge point of the project area into Owens River (Figure 2). The climate in Tri-Valley is arid with an average precipitation of approximately 5.5 to 8 inches per year (in/yr) as indicated by Parameter-elevation Regressions on Independent Slopes Model (PRISM) 30-Year average precipitation. In general, as land surface elevation increases above the valley floors, precipitation increases while temperature decreases. Average annual precipitation rates at high elevations along the margins of the watershed exceed 20 in/yr.

Natural recharge in the study area is sourced from precipitation that falls within the watershed defined by the crest of peaks and ridges of the White Mountains, Huntoon Mountains, and Glass Mountain (Figure 2).

The simulated area is approximately 852 square miles with elevations ranging from about 4,100 feet above mean sea level (ft amsl) at the southern end of the modeled area to greater than 14,200 ft amsl at White Mountain Peak (Figure 3).

3. Water Balance Modeling

DBS&A has developed a distributed parameter water balance model (DPWM) code based on the MASSIF model [Sandia National Laboratory, 2007] for Yucca Mountain and similar in concept to water balance models used by the USGS (e.g., Precipitation Runoff Modeling System (PRMS) [Leavesley et al., 1983], INFIL [Hevesi et al., 2003], Basin Characterization Model (BCM) [Flint and Flint, 2007]). The DPWM uses a daily time step over rectangular grid cells. Each cell is assumed to have uniform attributes (e.g., elevation, soil type, vegetation class) across its entire area

DBS&A applied the DPWM code to the simulated watershed (Figure 2). For the purpose of this report, DPWM will be used when referencing the code itself. The application of DPWM to the simulated watershed will be called the Tri-Valley model.

For the Tri-Valley model, the simulated 852 square mile watershed was divided into 78,465 square cells approximately 168 meters by 168 meters (550 feet) on a side. The model generally relies on the widely accepted FAO-56 procedure for computing actual evapotranspiration (AET) from the reference evapotranspiration (ET_0) estimated with the Penman-Monteith method (Allen et al., 1998; Allen et al 2005).

For each cell in the model, the water budget components accounted for include:

- Precipitation
- Runon from upstream cell
- Bare soil evaporation
- Transpiration
- Runoff to downstream cell
- Snow accumulation
- Snow melt
- Snow sublimation

- Soil water storage
- Net infiltration (e.g. recharge to groundwater)

A detailed description of the equations used to estimate each component of the above list is explained in Appendix A.

In DPWM, a bedrock boundary is placed at the bottom of the model cells with shallow soil depths; this boundary will restrict infiltration when the saturated hydraulic conductivity of the bedrock is less than that of the soil. Unlike the USGS BCM model, DPWM accounts for the routing of runoff through the watershed; unlike the MASSIF model, DPWM accounts for flow in washes using a mass balance approach for the area of a wash within a cell.

3.1 Input Data for Tri-Valley Model

One of the advantages of DPWM is that most of the required input data comes from publicly available sources. The inputs for DPWM can be categorized into topography, climate, vegetation, soil, and surface geology data. This section describes the input data for Tri-Valley model.

3.1.1 Topography and Surface Drainage

Topography in the Tri-Valley model was derived from USGS 30-meter Digital Elevation Models (DEM) and values were averaged over the model grid cells. Geographic Information System (GIS) tools were used to estimate slope and azimuth of each grid cell. These data were then used to route surface water flows from one cell to another.

In the Tri-Valley model, washes were classified based on their drainage areas and approximate width of each wash (Figure 3) which was obtained from a review of Google Earth aerial imagery. Internally in DPWM, model cells that contain washes are divided into two cells (a wash cell and an interwash cell), based on the active area of wash within the cell. The total active area of the wash cell is calculated as the length of the wash within the original cell times the width of the wash. The remaining cell area becomes an interwash cell. The soil properties of the wash cells are specified separately in the DPWM input files. The soil depth of the wash cell is assumed to be the same as that of the interwash cell.

3.1.2 Climate

Climate data required for DPWM includes the average spatial distribution of precipitation over the entire watershed and daily total precipitation, maximum daily air temperature, minimum daily air temperature, and average daily wind speed for one or more weather stations within the watershed.

In the Tri-Valley model, PRISM estimates of the mean precipitation for the calendar years 1981-2010 was used for the spatial distribution of precipitation (Figure 4). PRISM 30-year average precipitation interpolates precipitation data of available weather stations in the area and varies precipitation by elevation and accounts for orographic effects (e.g., rain shadows).

Daily climate data collected from the Bishop CIMIS Station (https://cimis.water.ca.gov/) and Benton RAWS station (https://wrcc.dri.edu/wraws/ccaF.html) were used in the Tri-Valley model. These stations have the longest available records and their geographic locations make them more representative of conditions in the Tri-Valley (Figure 4). Based on the coinciding periods of record from both stations, the Tri-Valley water budget was simulated for the 25-year period from October 1, 1994 through September 30, 2019. For days with missing or obviously out of range records (e.g., daily low temperature equal to daily high temperature), daily PRISM data at the location of the stations are used instead of these missed or out-of-range records at the stations.

Figure 5 shows total annual precipitation rates for water years 1995 through 2019 for the Bishop and Benton stations in the Tri-Valley model. In most years during the period of record, the Benton station records higher water year totals than the Bishop station, with 2005 being the most notable exception. Years 2000 through 2002 also provide the largest discrepancy between Bishop and Benton records with Benton's precipitation values at least 15 times greater than Bishop's records for those years. The Benton station is located at an elevation of 5,450 ft amsl in a relatively narrow valley compared to the Bishop station which is located at a lower elevation of 4,180 ft amsl.

In the Tri-Valley model, daily precipitation data are extrapolated from the two weather stations (i.e., Bishop and Benton) to each grid cell in the model using the PRISM 30-year average precipitation distribution and the cell elevation. Temperature data are extrapolated from the Bishop station only. Temperature in the model is assumed to decrease (or increase) by 0.0037 degree Fahrenheit (^{0}F) for every increase (or decrease) in elevation of 1 foot.

Duration of Precipitation Events

In DPWM, when precipitation occurs the daily time step is divided into two periods: (1) the duration of the precipitation event, and (2) the remainder of the day. The water balance is calculated separately for each of the two time steps. In the Tri-Valley model, the precipitation intensity during any precipitation event was assumed to be 0.1 inch per hour and the duration of the event was calculated based on the recorded daily precipitation for that event.

Snow

Precipitation in the model is assumed to occur as snow when the average daily temperature is below freezing. Snow is stored as an equivalent depth of water in the model. The sublimation rate applied is a fraction of the reference evapotranspiration (ET_0). In the Tri-Valley model, a value of 30 percent of ET_0 was used for the snow sublimation rate. This is within the suggested range of 10 to 40 percent of ET_0 [USGS, 2008].

When snow pack is present, the rate of snow melt is determined using the methodology described in the HELP model (Schroeder et al., 1994). In the Tri-Valley model, the rate of snowmelt varies from 2.0 millimeters per day per degree Celsius (mm/d/ºC) on December 21 to 5.2 mm/d/ºC on June 21.

3.1.3 Vegetation

Vegetation types vary considerably within the Tri-Valley model area from desert scrub at the lowest elevations to evergreen forests at higher elevations. The distribution of vegetation classes in the Tri-Valley model (Figure 6) was obtained from digital land cover datasets provided by the

Table 1. Simulated Plant Height and Root Depth for the Different Vegetation Classes in the Tri-Valley Model

Vegetation Class	Plant Height (m)	Root Depth (m)	Number of Cells in the Model
Rocky Mountain Subalpine-High Montane Conifer Forest	12.19	3.50	1,353
Southern Rocky Mountain Lower Montane Forest	12.19	3.50	2
Southern Vancouverian Montane-Foothill Forest	12.19	3.50	283
Vancouverian Subalpine Forest	12.19	3.50	452
Intermountain Singleleaf Pinyon - Utah Juniper - Western Juniper Woodland	7.62	4.57	23,469
Southern Rocky Mountain & Colorado Plateau Two-needle Pinyon - One-seed Juniper Woodland	7.62	4.57	3
Western North American Montane-Subalpine Marsh, Wet Meadow & Shrubland	7.62	4.57	238
Rocky Mountain-Great Basin Montane Riparian Forest	7.62	4.57	1
Rocky Mountain-Vancouverian Subalpine-High Montane Mesic Meadow	7.62	4.57	26
Cool Interior Chaparral	7.62	4.57	17
Arid West Interior Freswater Marsh	0.50	2.00	79
Warm & Cool Desert Alkali-Saline marsh, Playa & Shrubland	0.50	2.00	953
Great Basin-Intermountain Dry Shrubland & Grassland	0.50	2.00	3,047
Mojave-Sonoran Semi-Desert Scrub	0.50	2.00	1,858
Great Basin Saltbush Scrub	0.50	2.00	12,158
Great Basin-Intermountain Tall Sagebrush Steppe & Shrubland	10.67	4.00	28,668
Western North American Temperate Cliff, Scree & Rock Vegetation	0.10	0.15	1,062
Intermountain Basins Cliff, Scree & Badlands Sparse Vegetation	0.10	0.15	149
Vancouverian Alpine Tundra	0.10	0.15	3,060
Herbaceous Agricultural Vegetation	3.00	0.50	310
Pasture & Hay Field Crop	1.00	1.00	500
Introduced & Semi Natural Vegetation	0.30	1.00	14
Recently Disturbed or Modified	0.30	1.00	30
Open Water	0.00	0.15	210
Developed & Urban	0.30	1.00	523

GAP/LANDFIRE National Terrestrial Ecosystems 2011 (USGS, 2011). Table 1 summarizes the rooting depths and plant heights assigned to each vegetation class.

Leaf area index (LAI), the ratio of one-sided leaf area over the total land area (L^2/L^2), data are used to calculate actual evapotranspiration (ET) in the Tri-Valley model. DPWM requires monthly LAI values for each model cell. In Tri-Valley model, values of LAI were obtained from datasets published by USGS from the Moderate Resolution Imaging Spectroradiometer (MODIS) (https://lpdaac.usgs.gov/products/mcd15a2hv006/). The data were obtained monthly for the relatively wet water year of 2005 (October 2004 through September 2005) which would provide a conservative upper estimate of vegetation transpiration rates. The pattern of LAI measured by MODIS was also used to determine the phenology for the vegetation associations (initiation of leaves, peak growing season, decline in growth, and dormant season) on a monthly basis.

3.1.4 Soils

Soil texture (e.g., percent sand, silt, and clay) and saturated hydraulic conductivity data for the Tri-Valley model were obtained from the USDA SSURGO database (Soil Survey Staff, 2019). The Rosetta program (Schaap et al., 2001) was used to estimate other soil hydraulic parameters required by DPWM (i.e., residual and saturated water contents, and van Genucthen parameters α and β) based on texture data. Soil type and depth data are presented on Figures 7 and 8, respectively. The SSURGO database reports depth to bedrock (i.e., soil thickness) for depths shallower than 2 meters (approximately 6.6 ft). In the Tri-Valley model, soil thicknesses for cells with deep bedrock (i.e., greater than 6.6 ft) were assumed to be greater than the maximum rooting depth of the predominant vegetation association for these cells.

3.1.5 Geology

Bedrock underlying soils may restrict net infiltration when the saturated hydraulic conductivity of the bedrock is less than the infiltration rate and soils are shallow. In the Tri-Valley model, the distribution of bedrock types (Figure 9) was obtained from geologic maps of California (USGS, 2005) and Nevada (USGS, 2003). The saturated hydraulic conductivities used in the Tri-Valley model at each unit were estimated from literature sources and are listed in Table 2.

4. Results

DPWM uses input topography, climate, vegetation, soil, and geology data to partition input precipitation into evapotranspiration, sublimation, surface runoff, soil-water storage, and net infiltration. For the purpose of this study, net infiltration below the soil thickness of a model cell is considered groundwater recharge.

Annual water budgets for the entire DPWM model, Tri-Valley area, and Fish Slough subbasin (Figure 10) provide a lot of information about general system behavior. Up to nearly 800,000 ac-ft of water passes through the simulated area annually. Except for water year 2001, no net runoff was produced from the entire model domain; all precipitation was partitioned into ET, groundwater recharge, and changes in storage. The runoff observed in 2001 can be explained by a single high-i

Table 2. Simulated bedrock hydraulic conductivity

Geology Code	Rock Type 1	Rock Type 2	Hydraulic Conductivity (cm/sec)	Hydraulic Conductivity (ft/day)	Number of Cells in the Model
Ca	sandstone	dolostone (dolomite)	1.00E-06	2.83E-03	5,128
CZs	siltstone	limestone	3.53E-07	1.00E-03	300
gr-m	plutonic rock (phaneritic)	gneiss	1.00E-06	2.83E-03	1,084
grMz	granodiorite	quartz monzonite	1.00E-06	2.83E-03	14,347
Jgr	quartz monzonite	granodiorite	1.00E-06	2.83E-03	322
Kgr	granodiorite	quartz monzonite	1.00E-06	2.83E-03	564
KJd	diorite	quartz diorite	1.00E-06	2.83E-03	223
m	schist	gneiss	1.00E-06	2.83E-03	995
Mzv	felsic volcanic rock	intermediate volcanic rock	3.53E-06	1.00E-02	2,260
Os	chert	shale	3.53E-08	1.00E-04	59
pC	sandstone	mudstone	3.53E-07	1.00E-03	3
PZ	hornfels	quartzite	1.00E-06	2.83E-03	1,592
Q	alluvium	terrace	5.00E-04	1.42E+00	16,310
Qa	alluvium	mass wasting	5.00E-04	1.42E+00	1,393
Qg	glacial drift		5.00E-04	1.42E+00	2
Qls	landslide	colluvium	5.00E-04	1.42E+00	224
QPc	sandstone	conglomerate	3.53E-05	1.00E-01	1,145
Qrv	rhyolite		3.53E-05	1.00E-01	729
QTb	basalt	andesite	1.00E-06	2.83E-03	1,608
QToa	alluvium	lake or marine deposit (non-glacial)	5.00E-04	1.42E+00	239
Qv	rhyolite	andesite	3.53E-05	1.00E-01	2,978
Qvp	rhyolite	ash-flow tuff	3.53E-05	1.00E-01	16,876
sch	schist	hornfels	1.00E-06	2.83E-03	48
Ta3	andesite	latite	3.53E-06	1.00E-02	1,384
Tr3	rhyolite	dacite	3.53E-05	1.00E-01	191
Tt2	rhyolite	dacite	3.53E-05	1.00E-01	124
Tt3	rhyolite	No data	3.53E-05	1.00E-01	236
Tv	tephrite (basanite)	trachybasalt	1.00E-06	2.83E-03	7,594
Tvp	rhyolite	dacite	3.53E-05	1.00E-01	297
water	water		3.53E-10	1.00E-06	210

event. This event also explains the significant increase of water in storage (negative storage value) in 2001, followed the next year by a large reduction of water in storage (positive storage value) as the system re-equilibrated. Other years with relatively large storage changes such as 2017-2018 and 2011-2012 follow a similar pattern: a wet year results in filling up of the soil profile (negative storage value) for most of the watershed, followed the next year by a reduction in soil storage (positive storage value) as that additional water in storage is utilized for evapotranspiration by vegetation.

The Tri-Valley area and Fish Slough subbasins exhibited greater interannual variability compared with the entire model, and both showed precipitation volumes were disproportionate to the relative size of the area. For example, the Tri-Valley area accounts for 14% of the total simulated watershed yet only received about 8% of the total precipitation volume. The most apparent difference between the Tri-Valley area and Fish Slough subbasin water budgets, aside from the magnitude of the component values which can be explained by the size discrepancy between the two, was the difference in runon/runoff patterns. The Tri-Valley area budget showed more water entering than leaving as surface flow, resulting in net runon for all years. The opposite pattern was observed for the Fish Slough subbasin, where net runoff was produced but only during wet years (e.g., water years 2005, 2008, and 2011). Very little groundwater recharge is simulated for the Fish Slough subbasin, as most precipitation is utilized by vegetation and converted to evapotranspiration.

Figure 10a shows the average 25-year recharge in the Tri-Valley model while Figures 10b and 10c provide a close-up of simulated recharge within the Tri-Valley area and Fish Slough subbasin, respectively. Simulated average 25-year recharge within the boundaries of Tri-Valley area is 10,563 acre-feet per year (ac-ft/yr) and simulated average recharge within the boundaries of Fish Slough subbasin is 33 ac-ft/yr. Figure 10a shows that only a small portion of the average recharge is simulated at the basin floor of the Tri-Valley area. Most of the estimated 10,563 ac-ft/yr average recharge occurs as either mountain front recharge or streamflow infiltration that is spatially focused along washes. This is expected in most mountainous areas in the southwest (Wilson and Guan, 2004).

Annual simulated recharge volumes in both the Tri-Valley area and Fish Slough subbasin (Figure 11) show a high degree of interannual variability. Recharge in the Tri-Valley area ranges from 1,100 ac-ft/yr in 2007 to approximately 29,000 ac-ft/yr in 2017 (Figure 11). Annual recharge in the Tri-Valley area shows a stronger correlation with annual precipitation at the Benton station compared to the Bishop station (Figure 12). However, we see the opposite for the Fish Slough subbasin, where annual recharge volume is more strongly correlated with precipitation measured at the Bishop station (Figure 12). This is expected for Fish Slough as the subbasin is geographically closer to the Bishop Station. Although precipitation is the only input component of the water budget in the Tri-Valley model, the correlation between simulated annual precipitation and simulated annual recharge is only around 70 to 75 percent. This is because groundwater recharge only occurs when field capacity of the soil is exceeded and gravity drainage can occur. The daily time steps used in DPWM allow the model to take into consideration antecedent soil conditions in addition to precipitation timing and rate. The transient nature of these factors is not considered in the simple plots of the annual correlation of precipitation and recharge.

For the entire watershed, the model shows that, on average, approximately 77 percent of the precipitation water that falls in the watershed is lost to evapotranspiration and snow sublimation (Table 3). The model also indicates that direct precipitation onto the valley floor (36,637 ac-ft/yr) contributes a negligible amount of water to groundwater recharge, as nearly all is lost to ET and snow sublimation (36,485 ac-ft/yr). Simulated streamflow into the Tri Valley area (or surface water runon) is approximately 12,271 ac-ft/yr, while simulated streamflow out of the Tri Valley area (or surface water run-off) is approximately 1,529 ac-ft/yr.

Caution must be exercised when interpreting the surface water runon and runoff values in Table 3 as DPWM does not simulate baseflow portion of streamflows. There is likely negligible baseflow contribution to streams in the Tri-Valley area as evidenced by the lack of exiting surface water features and mapped wetlands. However, the Fish Slough subbasin does appear to have a significant component of groundwater discharge to surface water. Precipitation-runoff simulated by the Tri-Valley model significantly underpredicts observed total runoff from the Fish Slough subbasin (Figure 11). Timing of peaks in observed total runoff appear to be correlated with timing of precipitation-runoff events simulated by the Tri-Valley model. This indicates that a large portion of the observed total runoff from the Fish Slough subbasin is sourced from the groundwater system which is not simulated by DPWM.

Table 3. Average 25 Year Simulated Water Balance Components

Water Balance Component	Average Simulated Volume (ac-ft/yr) Entire Watershed	Average Simulated Volume (ac-ft/yr) Tri-Valley area	Average Simulated Volume (ac-ft/yr) Fish Slough subbasin
Precipitation	457,167	36,637	1,435
Surface water runon from upstream cells	0	12,271	2
Actual Evapotranspiration	319,744	35,465	1,330
Snow Sublimation	34,243	1,020	20
Surface water runoff leaving the area	3,353	1,529	48
Change in storage of the soil	7,174	332	4
Net Infiltration (Recharge)	92,653	10,563	33

5. Discussion and Conclusion

The Tri-Valley region's water budget is the least understood in the Owens Valley Groundwater Basin (OVGB). The water budget in the Owens Lake portion of OVGB and other portions of the Basin underlying Los Angeles Department of Water and Power (LADWP) lands benefit from long record sets and frequent monitoring conducted by LADWP and the Great Basin Air Pollution Control District (Harrington, 2016). Jackson (1993), using the Maxey-Eakon method, estimated an average annual natural recharge in the Tri-Valley area of 1,270 ac-ft/yr. However, he concluded that this method resulted in an unrealistically low estimate and the simple 10 percent of precipitation method (i.e., 13,160 ac-ft/yr) is a better estimate (Harrington, 2016).

Assuming that all streamflow that was not diverted for agricultural use was recharged to groundwater, Phillip Williams & Associates (PWA, 1980) estimated that recharge in the Tri-Valley area from the White Mountains is 14,100 ac-ft/yr. They estimated that total recharge into Tri-Valley from precipitation and streamflows (i.e., components considered in DPWM) is 16,600 ac-ft/yr. The estimated 25-year average of recharge into Tri-Valley area from DPWM results (10,563 ac-ft/yr) is less than the PWA (1980) estimate. However, it is not clear what period of time PWA used to estimate the recharge value. DPWM results (Figure 11) show that in some years, the simulated recharge is significantly higher than the PWA estimate.

MHA (2001) discussed the PWA (1980) recharge estimates and noted that in PWA's water budget, inflow and outflow are equal which connotes that the groundwater system was in balance. This is contrary to groundwater level data gathered during the same time period which showed declining water levels (MHA, 2001). This could also indicate that PWA may have overestimated recharge in the Tri-Valley Area.

While DPWM allows for mass-conservative quantitative estimates of recharge based on site-specific climatological, geologic, soils and vegetation factors, it is also important to understand the limitations of the model not simulating the groundwater system. As such, DPWM cannot directly estimate either groundwater underflow to a basin or baseflow into a stream. While this does not appear to be a significant limitation for the Tri-Valley area, groundwater appears to be a significant contributor to the water budget of the Fish Slough subbasin. This groundwater must be derived from somewhere upgradient, which includes the Tri-Valley area among possible sources. A groundwater model or groundwater budget analysis is needed to further quantify the water balance components for the entire hydrologic system.

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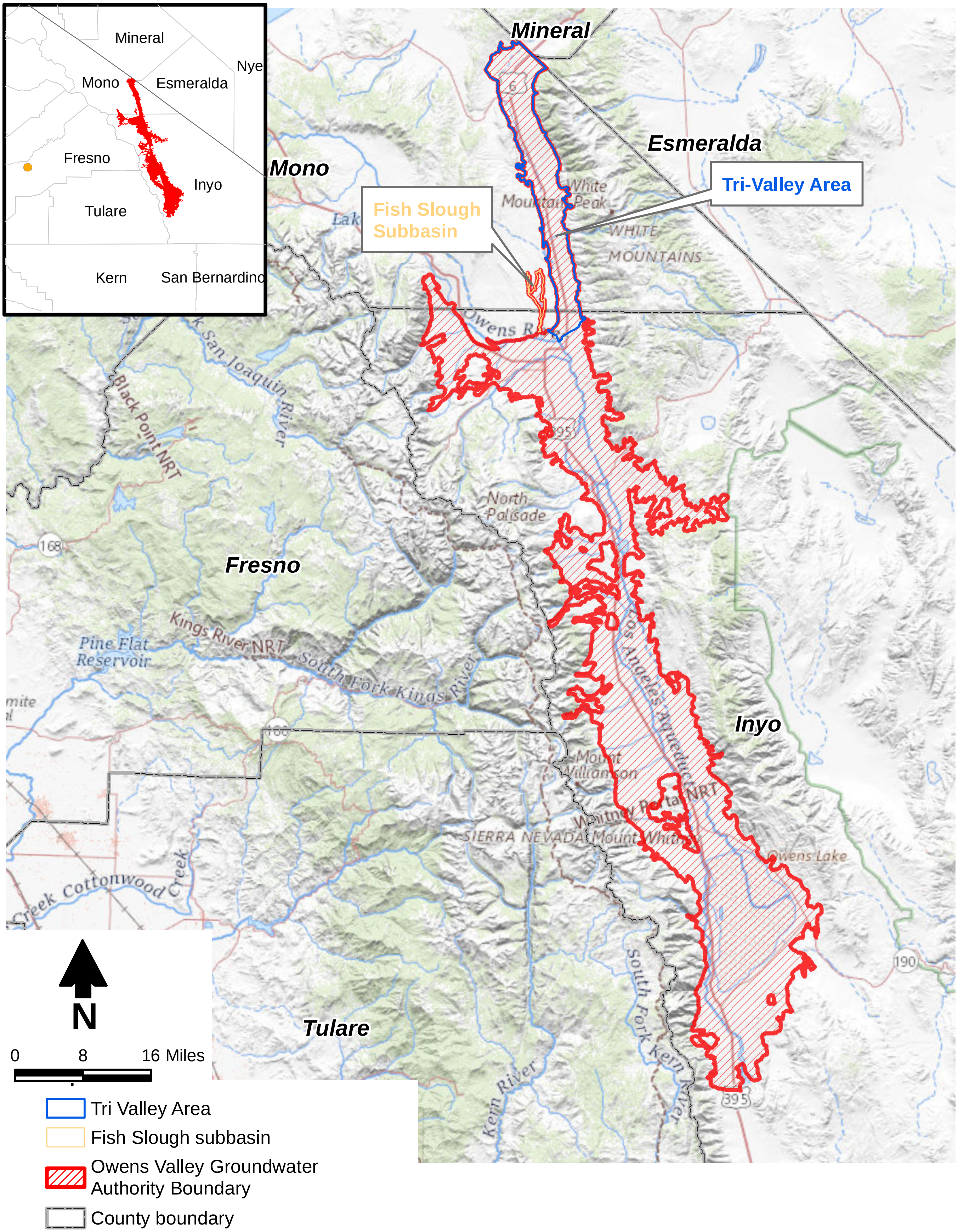

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OWENS VALLEY GSP
Owens Valley Groundwater Basin

Figure 1

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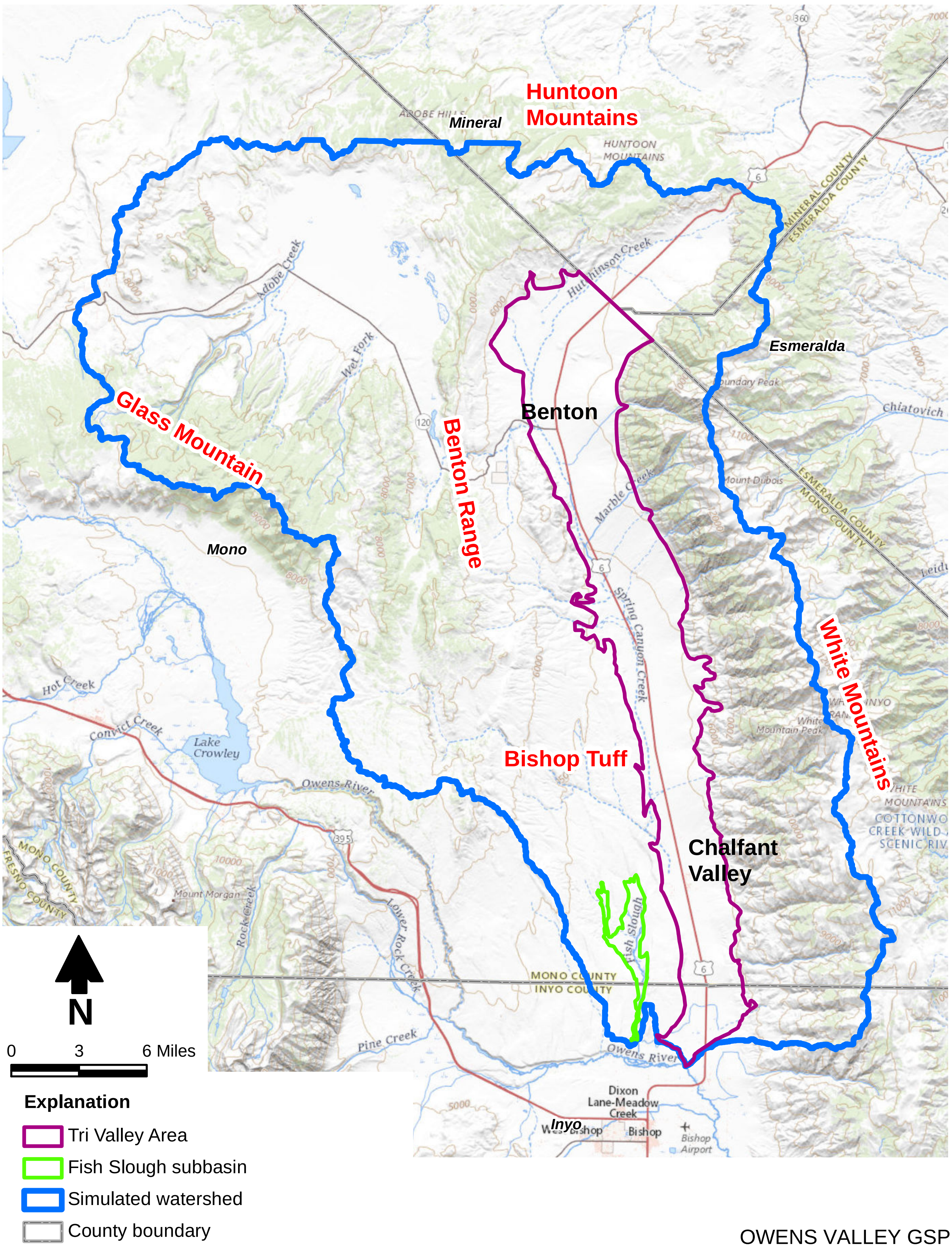

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OWENS VALLEY GSP

Tri Valley Area and Simulated Watershed

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Figure 2

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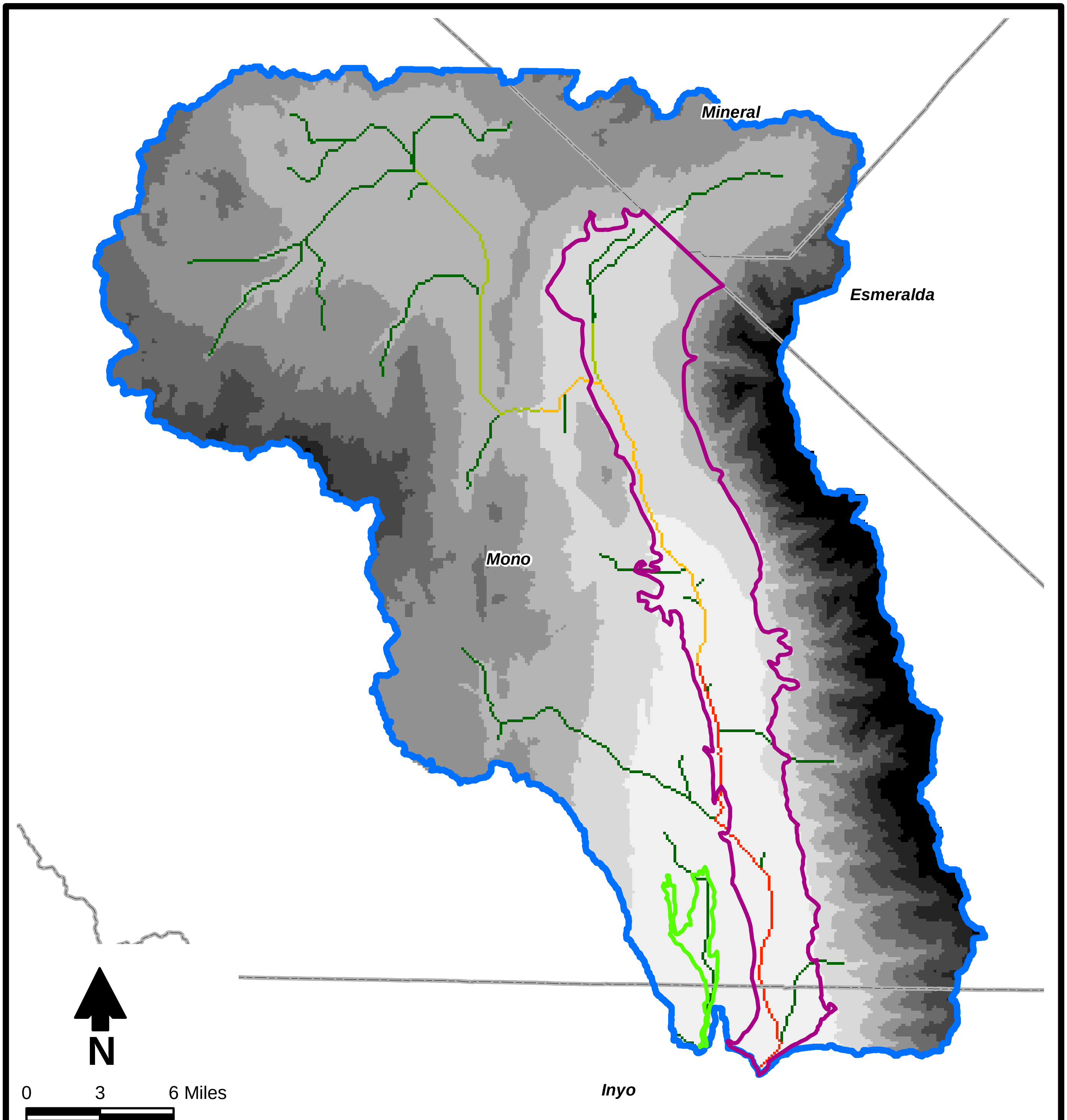

Explanation

- Tri Valley Area
- Fish Slough subbasin
- Simulated watershed
- County boundary

Wash width (feet)

- 10
- 20
- 30
- 50

Land surface elevation (ft)

- < 5,000
- 5,000 - 6,000
- 6,000 - 7,000
- 7,000 - 8,000
- 8,000 - 9,000
- 9,000 - 10,000
- 10,000 - 11,000
- > 11,000

OWENS VALLEY GSP

Elevations and Wash Widths within Tri-Valley Model

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Figure 3

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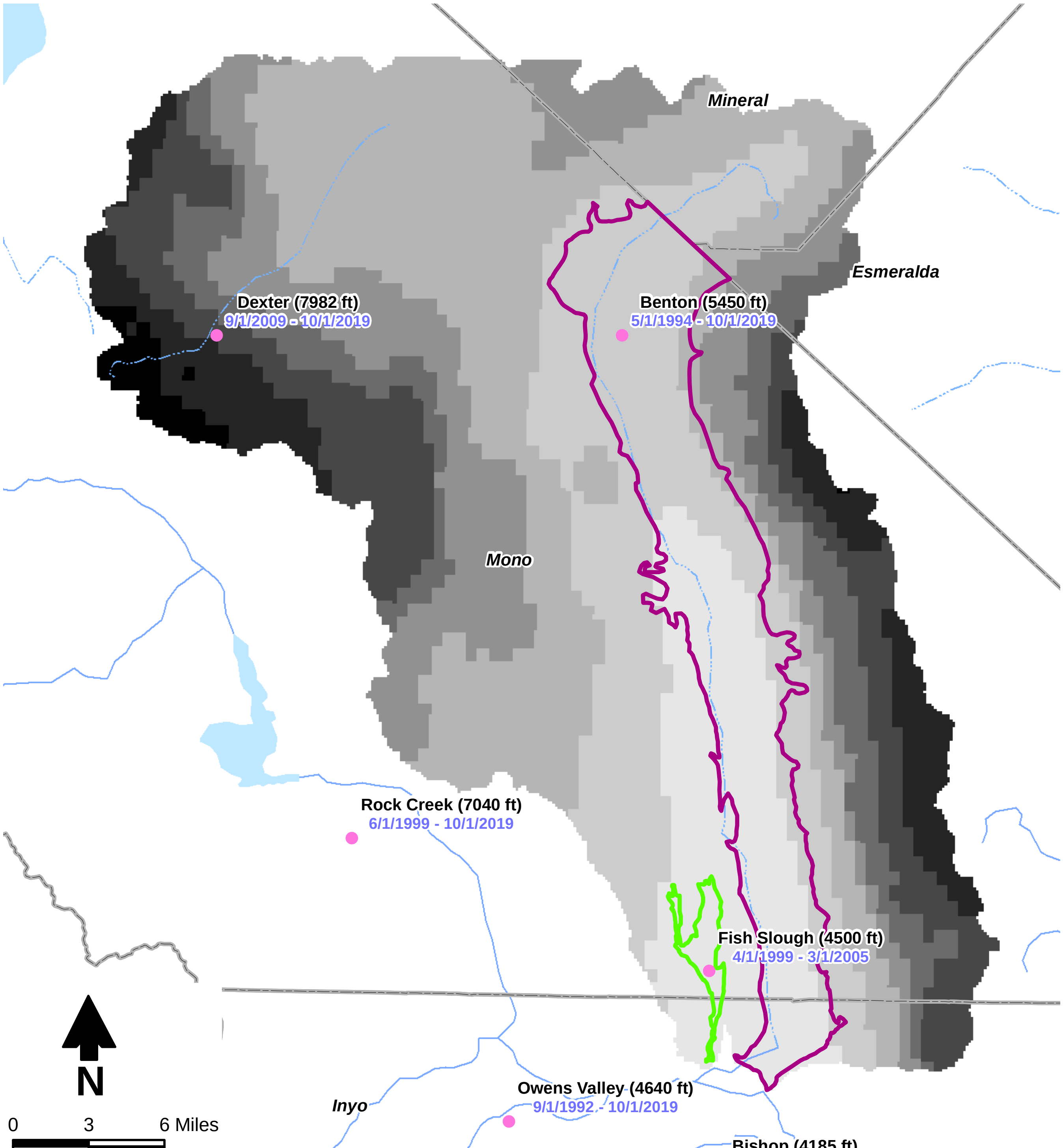

Explanation

Weather station (Elevation ft)
- CIMIS
- RAWS
- Tri Valley Area
- Fish Slough subbasin
- County boundary

Average Precipitation (in/yr)
- < 6.0
- 6.0 - 8.0
- 8.0 - 10.0
- 10.0 - 12.5
- 12.5 - 15.0
- 15.0 - 20.0
- 20.0 - 25.0
- 25.0 - 26.6

OWENS VALLEY GSP

PRISM 30-Year Average Precipitation and Location of Weather Stations

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure04_PRISM_WeatherStations.mxd

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Figure 4

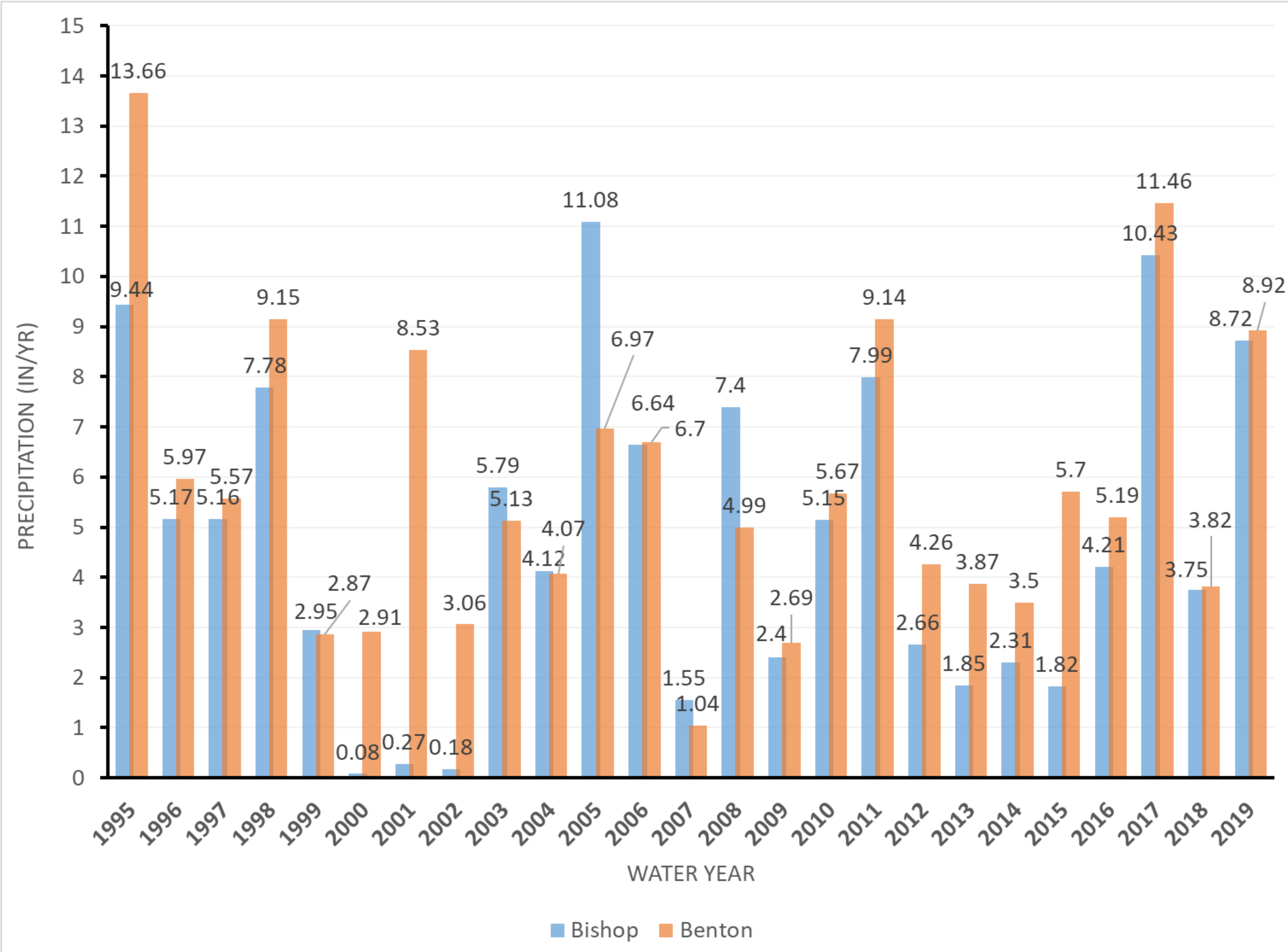

Figure 5. Annual Precipitation at Bishop and Benton Stations

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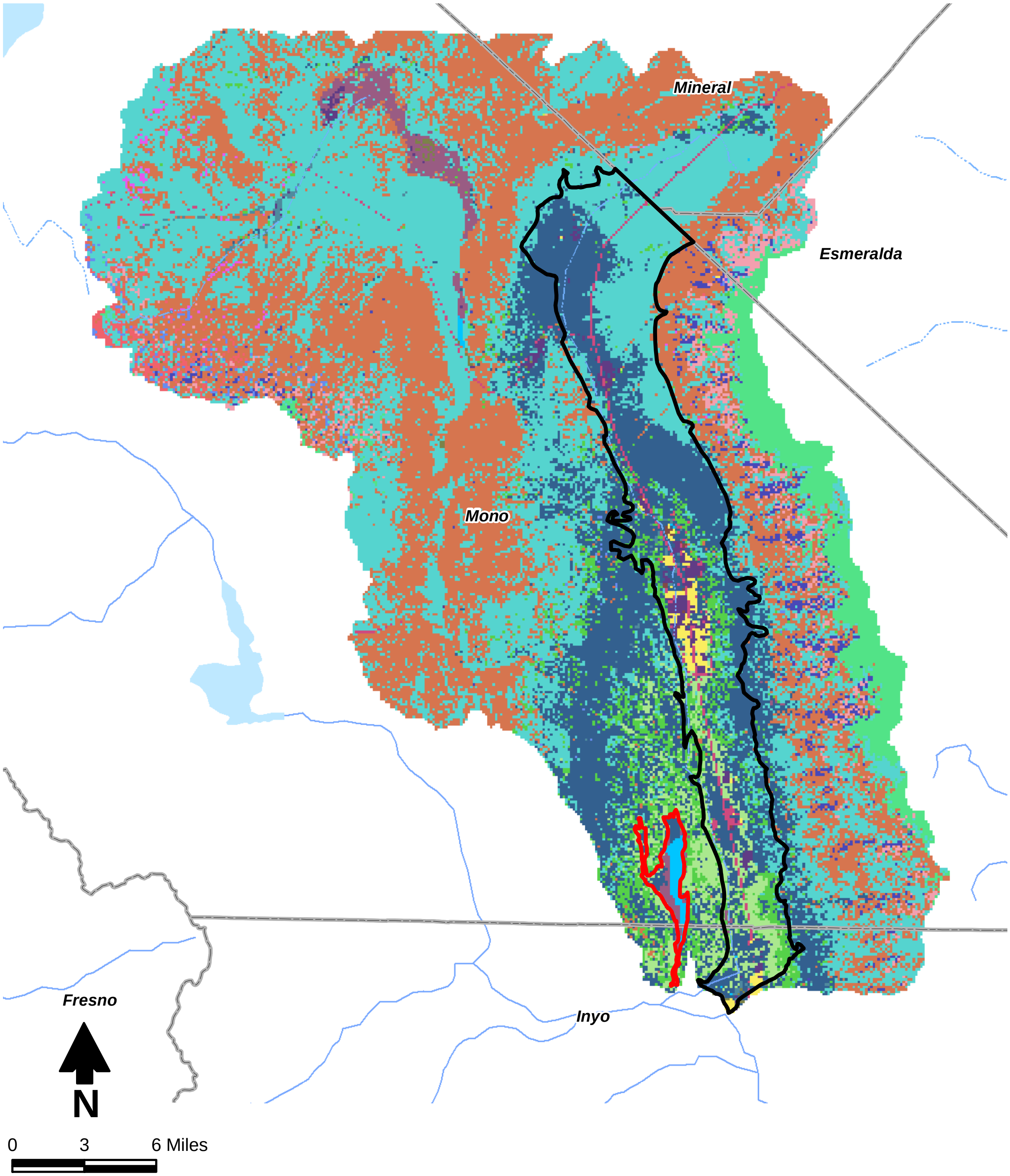

Explanation

Tri Valley Area

Fish Slough subbasin

County boundary

Expalanation of Each Color Symbol is in Figure 6b

OWENS VALLEY GSP

Vegetation Covergae within Tri-Valley Model

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JN DB18.1418

Figure 6a

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure06a_Vegetation.mxd

Vegetation code

- Arid West Interior Freswater Marsh
- Cool Interior Chaparral
- Developed & Urban
- Great Basin Saltbush Scrub
- Great Basin-Intermountain Dry Shrubland & Grassland
- Great Basin-Intermountain Tall Sagebrush Steppe & Shrubland
- Herbaceous Agricultural Vegetation
- Intermountain Basins Cliff, Scree & Badlands Sparse Vegetation
- Intermountain Singleleaf Pinyon - Utah Juniper - Western Juniper Woodland
- Introduced & Semi Natural Vegetation
- Mojave-Sonoran Semi-Desert Scrub
- Pasture & Hay Field Crop
- Recently Disturbed or Modified
- Rocky Mountain Subalpine-High Montane Conifer Forest
- Rocky Mountain-Great Basin Montane Riparian Forest
- Rocky Mountain-Vancouverian Subalpine-High Montane Mesic Meadow
- Southern Rocky Mountain & Colorado Plateau Two-needle Pinyon - One-seed Juniper Woodland
- Southern Rocky Mountain Lower Montane Forest
- Southern Vancouverian Montane-Foothill Forest
- Vancouverian Alpine Tundra
- Vancouverian Subalpine Forest
- Warm & Cool Desert Alkali-Saline marsh, Playa & Shrubland
- Western North American Montane-Subalpine Marsh, Wet Meadow & Shrubland
- Western North American Temperate Cliff, Scree & Rock Vegetation
- Open Water

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OWENS VALLEY GSP
Vegetation Codes

Figure 6b

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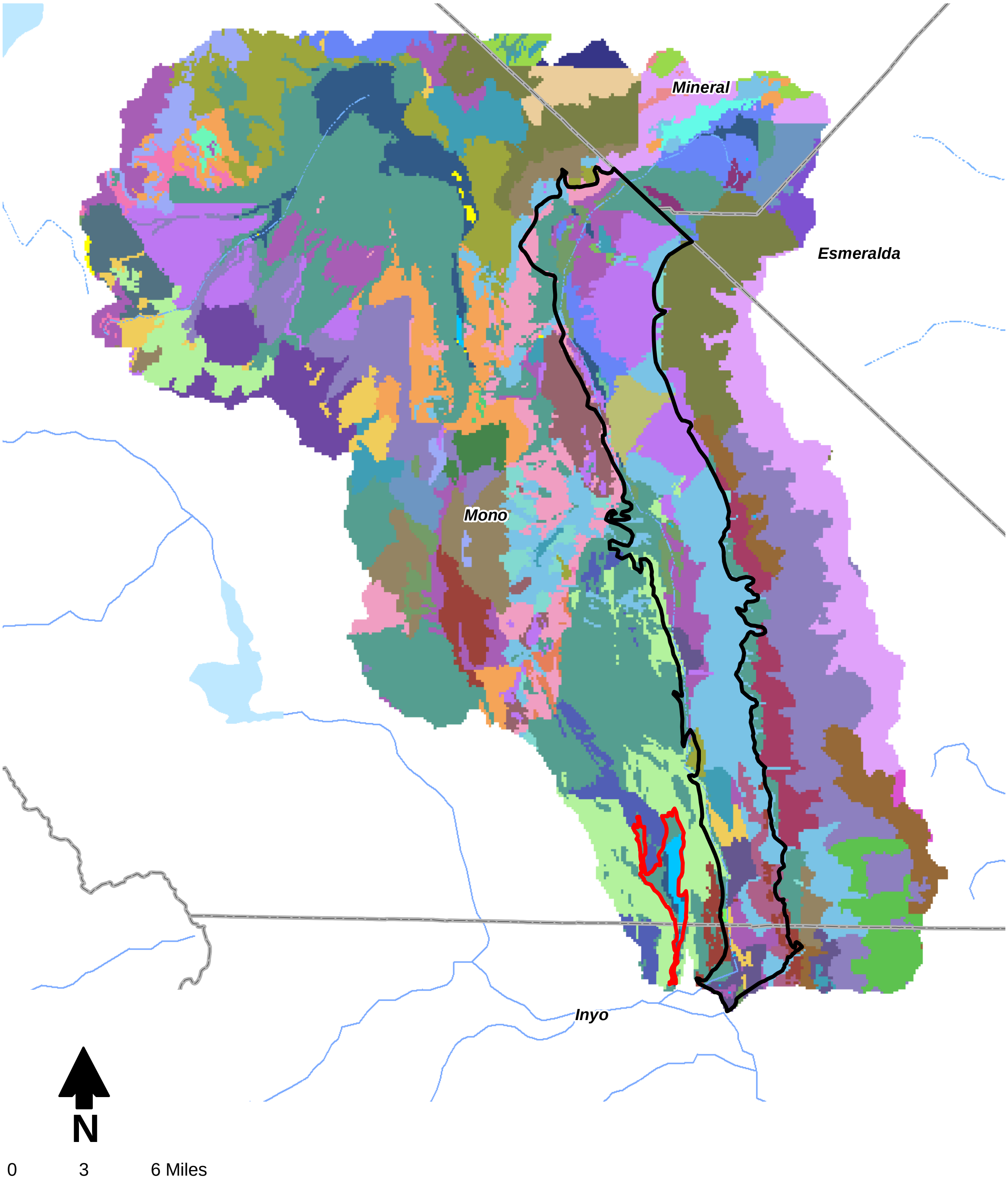

Expalanation of Each Color Symbol is in Figure 7b

Explanation

Tri Valley Area

Fish Slough subbasin

County boundary

OWENS VALLEY GSP

Soil Coverage within Tri-Valley Model

Figure 7a

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure07a_Soil_Type.mxd

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Soil Type

- Bedrock
- Bouldery loamy coarse sand
- Bouldery loamy sand
- Coarse sand
- Cobbly loam
- Cobbly loamy sand
- Extremely cobbly loamy sand
- Extremely gravelly loam
- Extremely gravelly loamy sand
- Extremely gravelly sandy loam
- Extremely stony sandy loam
- Fine sandy loam
- Gravelly coarse sand
- Gravelly coarse sandy loam
- Gravelly fine sandy loam
- Gravelly loam
- Gravelly loamy coarse sand
- Gravelly loamy fine sand
- Gravelly loamy sand
- Gravelly sand
- Gravelly sandy loam
- Loam
- Loamy coarse sand
- Loamy fine sand
- Loamy sand
- Mucky loam
- Sand
- Sandy loam
- Stony fine sandy loam
- Stony loamy sand
- Stony sandy loam
- Unknown
- Unweathered bedrock
- Variable
- Very bouldery
- Very bouldery coarse sandy loam
- Very cobbly loam
- Very cobbly loamy fine sand
- Very cobbly loamy sand
- Very cobbly sandy loam
- Very gravelly clay loam
- Very gravelly fine sandy loam
- Very gravelly loamy sand
- Very gravelly sandy loam
- Very stony ashy sandy loam
- Very stony loam
- Very stony loamy fine sand
- Very stony sandy loam
- Water

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure07b_Soil_Type_Codes.mxd

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OWENS VALLEY GSP
Soil Type

Figure 7b

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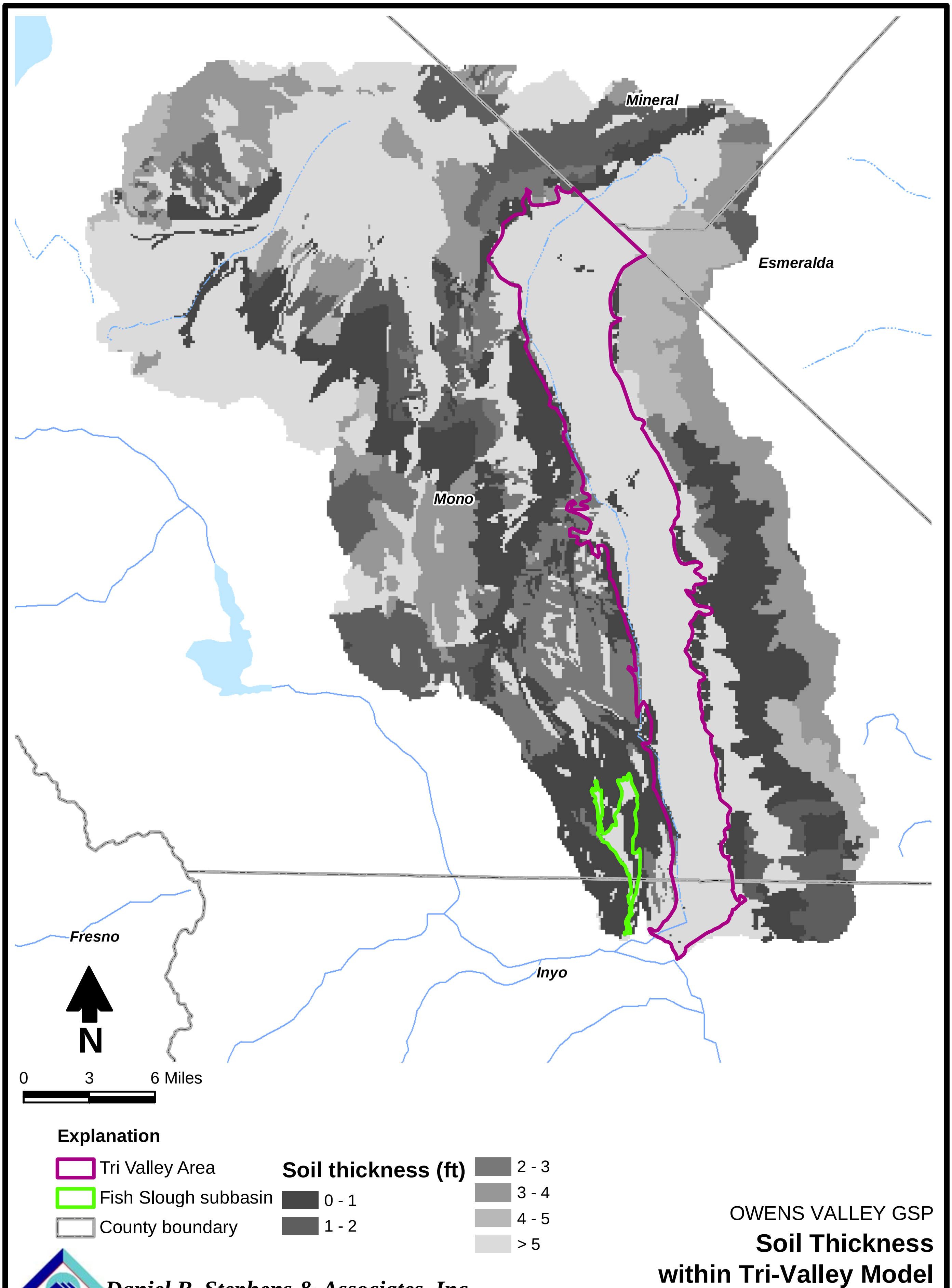

OWENS VALLEY GSP

Soil Thickness within Tri-Valley Model

Figure 8

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure08_Soil_Thickness_Model.mxd

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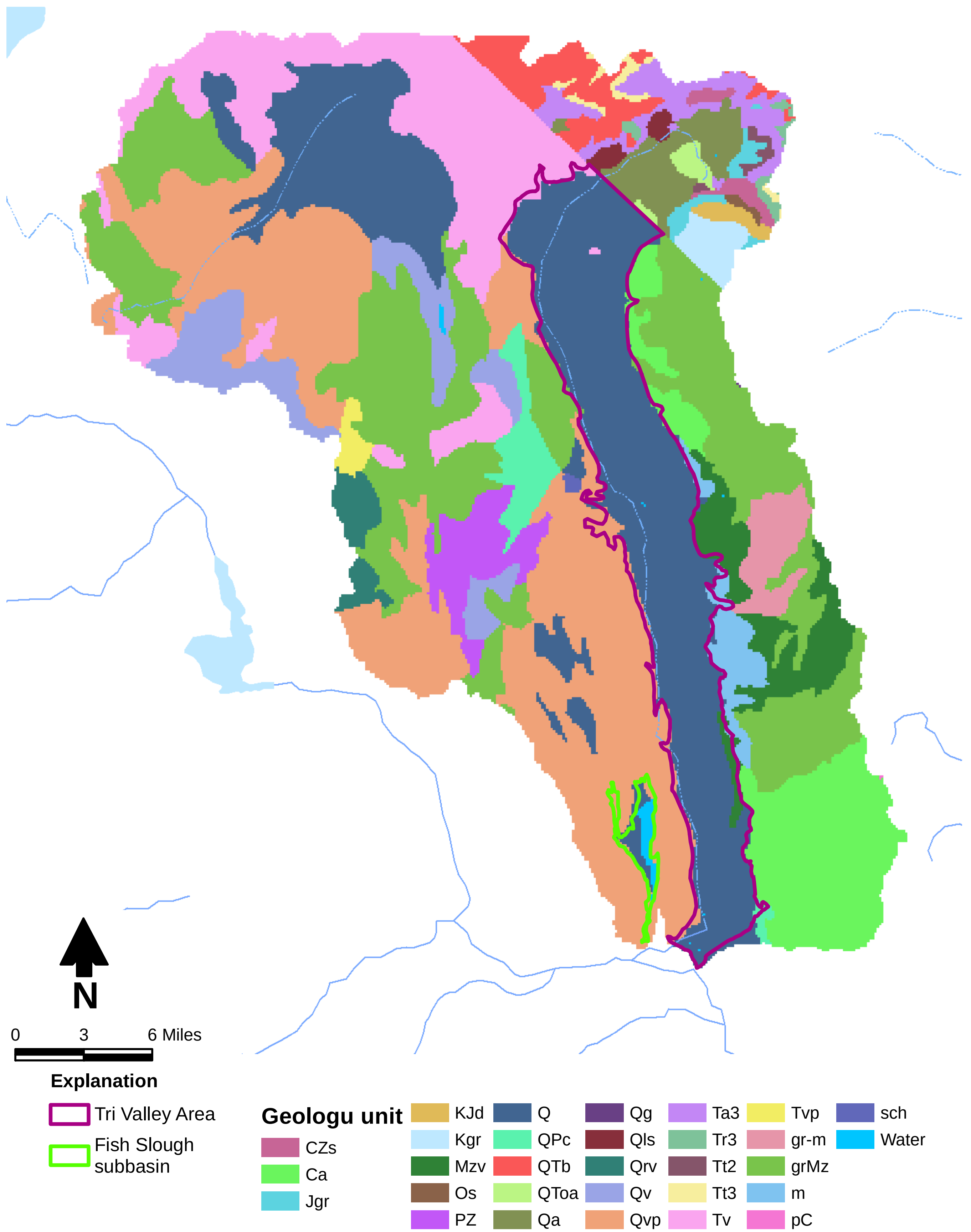

OWENS VALLEY GSP

Surface Geology within Tri-Valley Model

Figure 9

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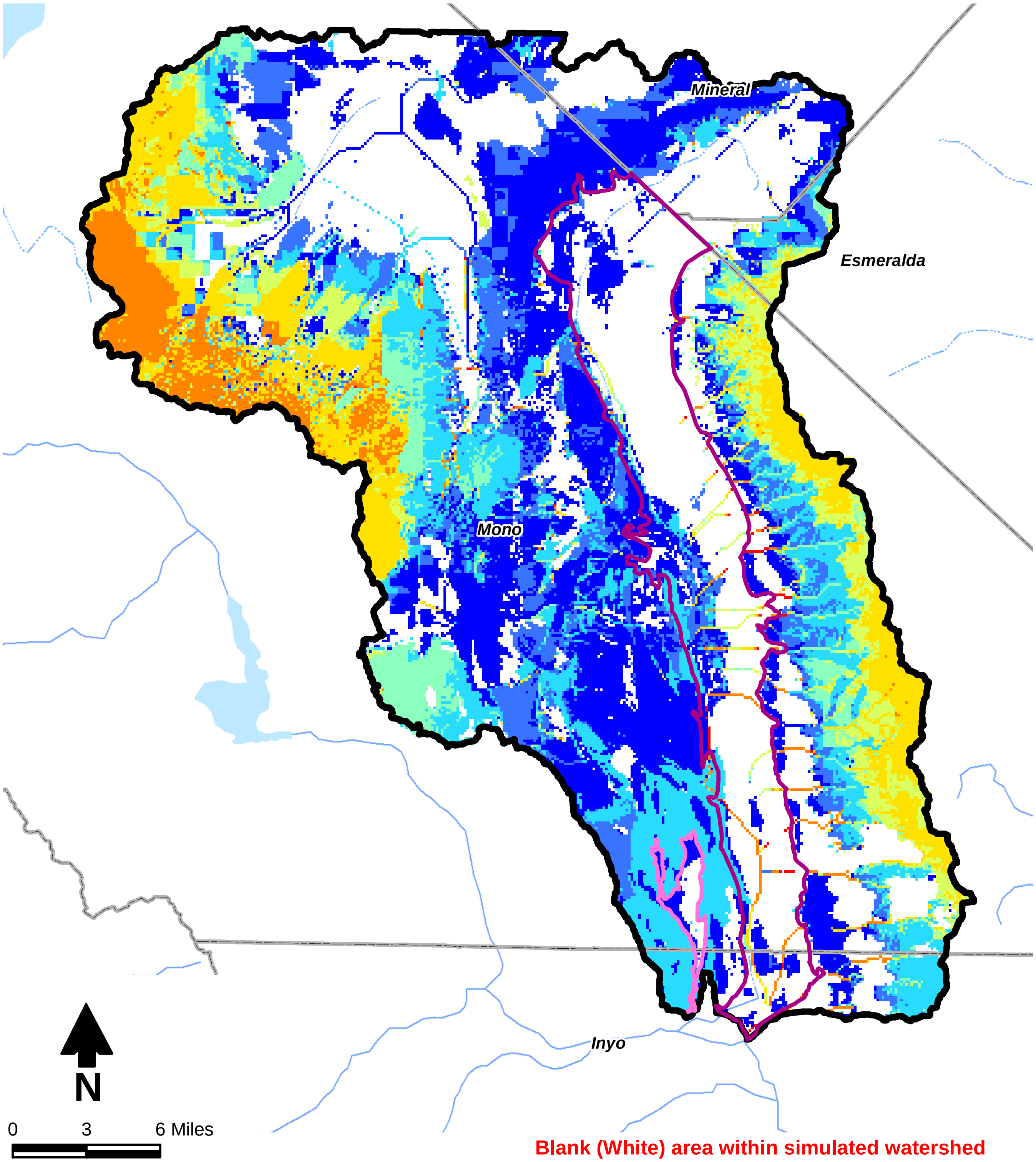

Blank (White) area within simulated watershed has average net infiltration of less than 0.01 in/yr

Explanation

- Simulated watershed
- Tri Valley Area
- Fish Slough subbasin
- County boundary

Net Infiltration (in/yr)

- 0.01 - 0.5
- 0.50 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 5.0
- 5.0 - 10.0
- 10.0 - 25.0
- > 25.0

OWENS VALLEY GSP

Simulated Average Net Infiltration within Tri-Valley Model

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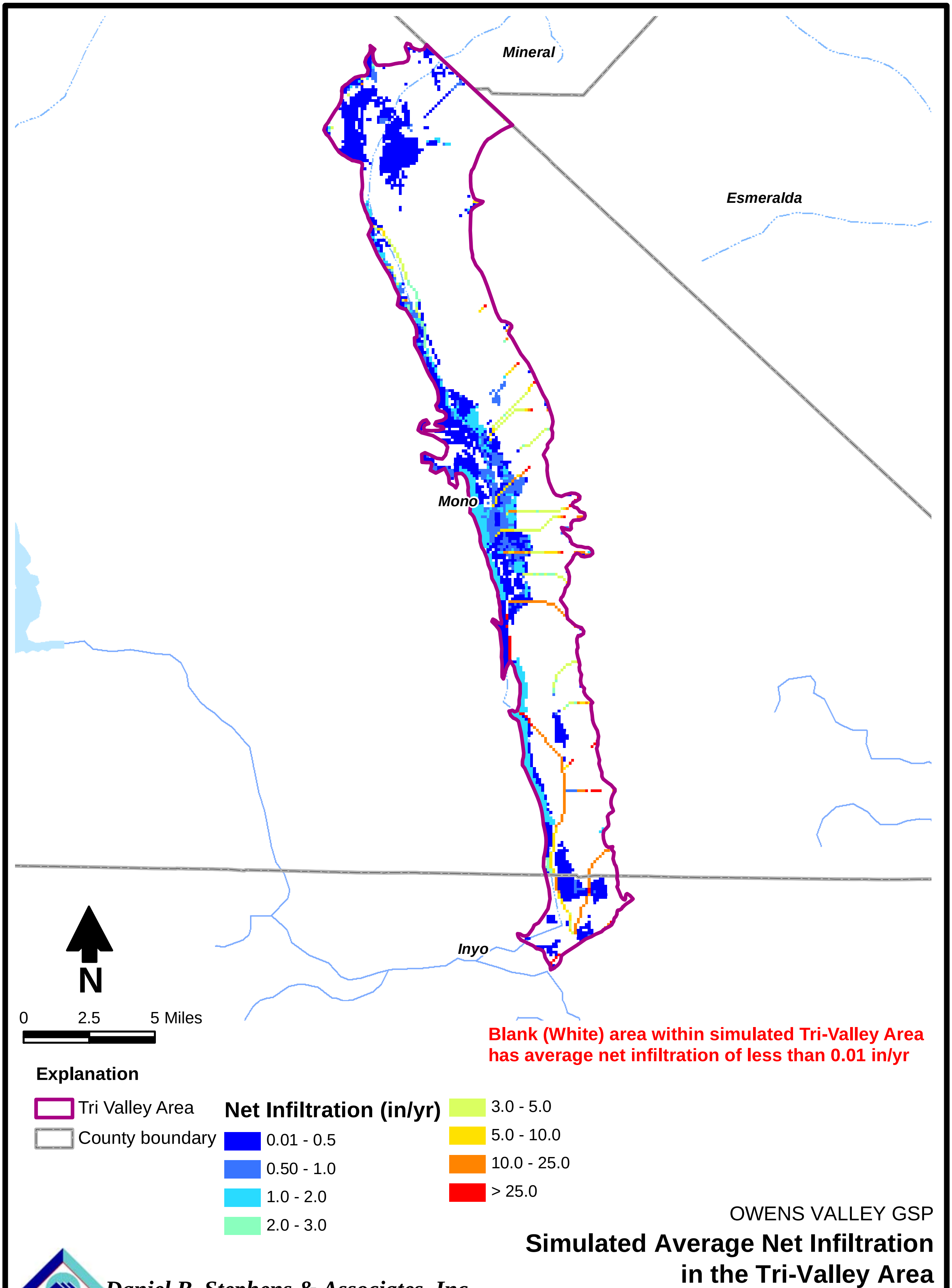
Figure 10a

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure10a_Average_Infiltration_Watershed.mxd



S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure10b_Average_Infiltration_Tri_Valley.mxd

OWENS VALLEY GSP

Simulated Average Net Infiltration in the Tri-Valley Area

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Figure 10b

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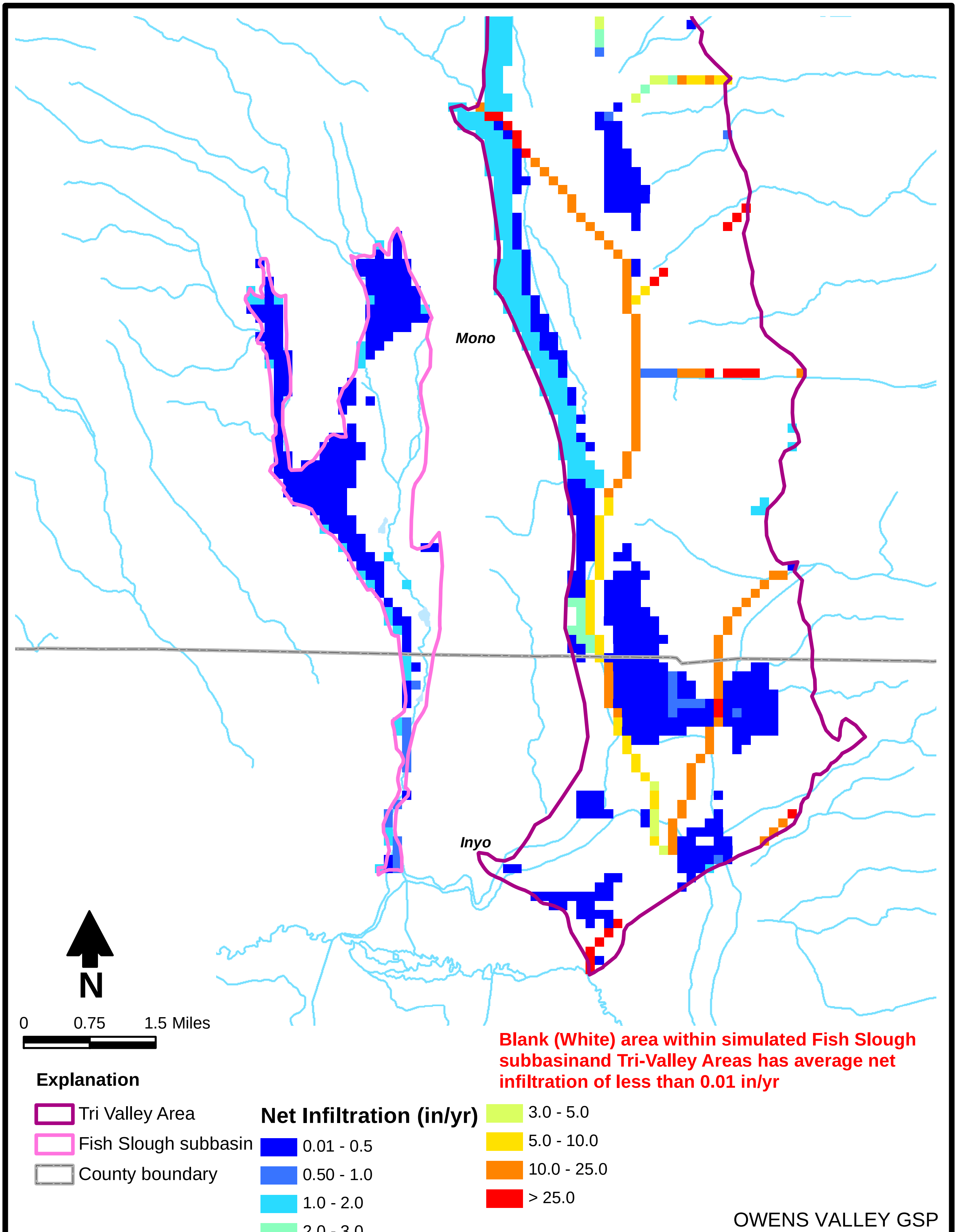

OWENS VALLEY GSP

Simulated Average Net Infiltration in the Fish Slough Subbasin

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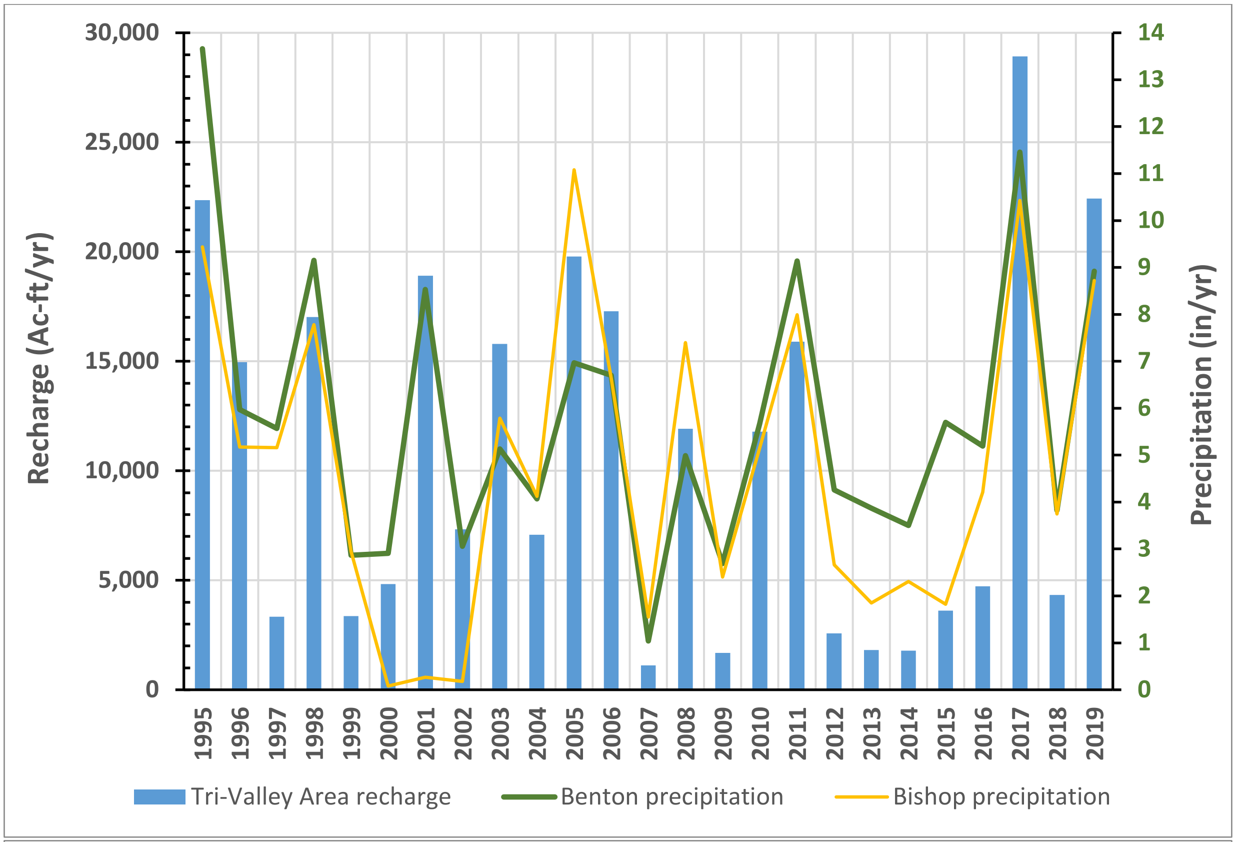
Figure 10c

S:\Projects\DB18.1418_Owens_Valley\GIS\MXDs\Figures\Figure10c_Average_Infiltration_FishSlough.mxd



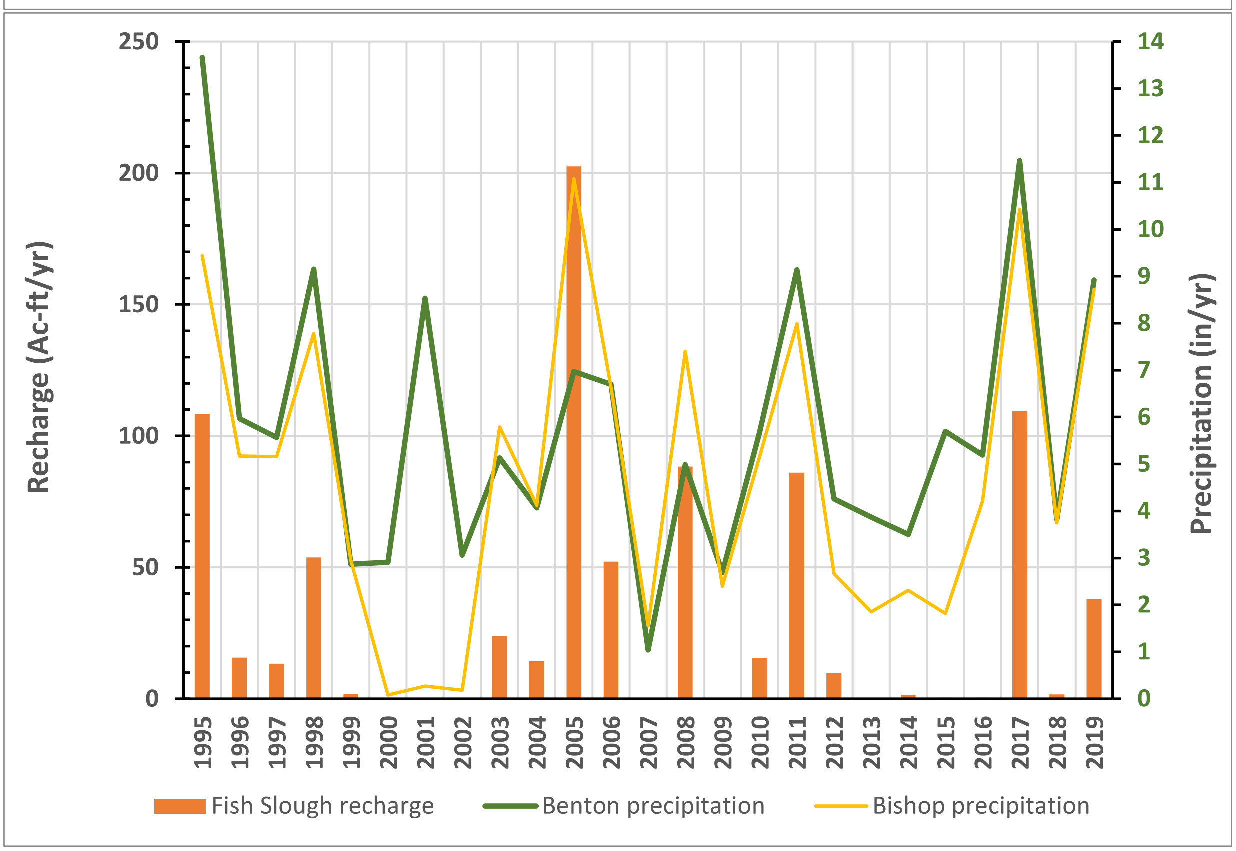


Figure 11. Simulated Infiltration (Recharge) in the Tri-Valley Area (top) and Fish Slough Subbasin (bottom)

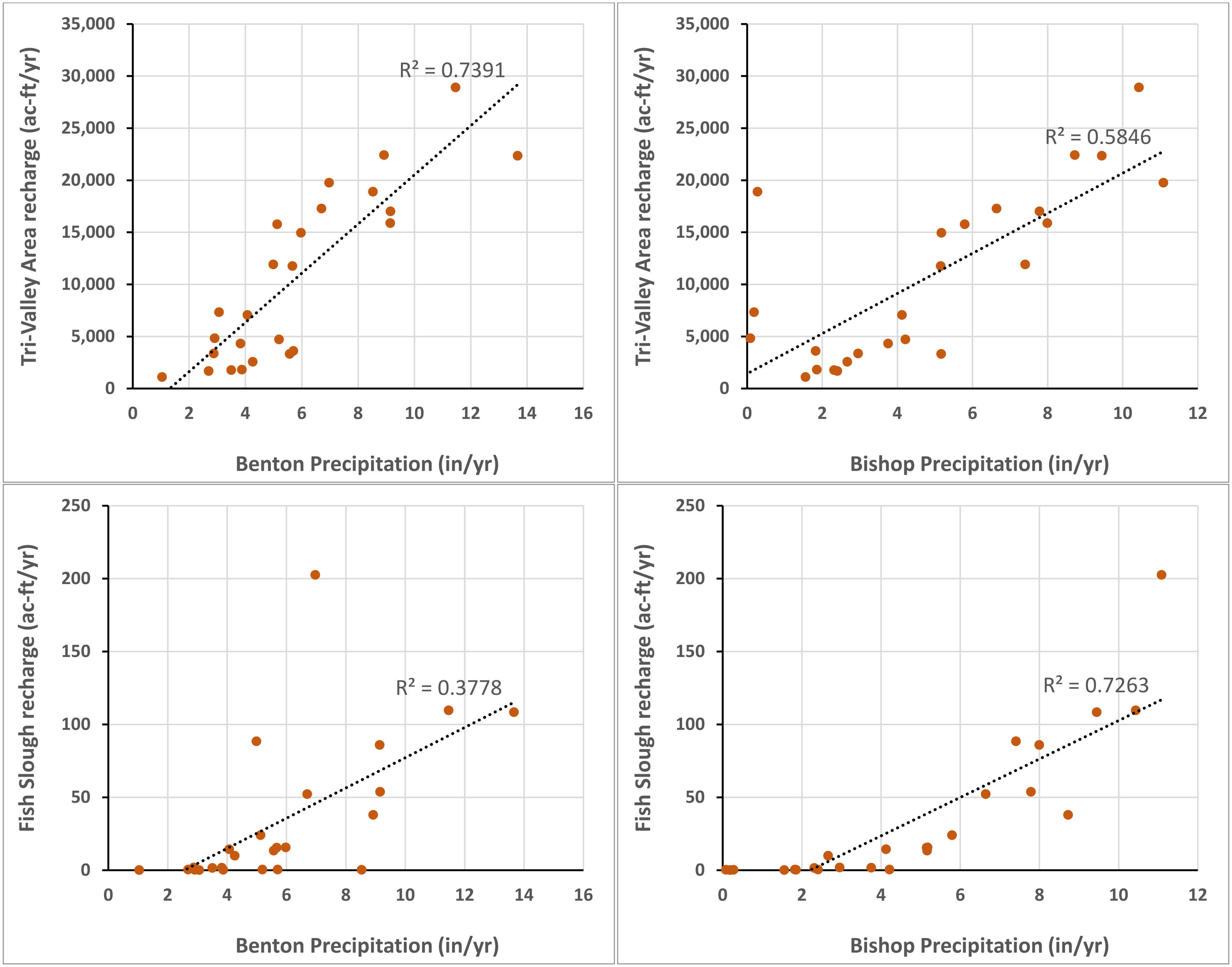


Figure 12. Correlation between Annual Precipitation at Different Stations and Annual Recharge in the Study Area

Appendix A DPWM Manual

User’s Guide for the Distributed Parameter Watershed Model (DPWM)

May 20, 2020

Daniel B. Stephens & Associates, Inc.

6020 Academy NE, Suite 100 • Albuquerque, New Mexico 87109

Table of Contents

DRAFT

List of Figures

1. Introduction

This manual documents the Distributed Parameter Watershed Model (DPWM). The DPWM is a soil-water balance model that estimates the daily water balance components of precipitation, transpiration, evaporation, net infiltration (e.g., recharge), snow accumulation, snow melt, sublimation, run-on and runoff.

A soil-water balance model is a tool that allows one to evaluate the magnitude of various components of the hydrologic cycle as it is applied to the soil. Such models have been available for many years (e.g., Leavesley et al., 1983) and applied in arid areas (Flint et al., 2004; Flint and Flint, 2007). These models generally simulate water within a certain depth of soil and recognize topography, the hydraulic properties of soil and bedrock, and meteorological data in order to distribute precipitation among snow sublimation, evapotranspiration, runoff, soil moisture storage, and deep percolation. In the model, basin surface is discretized so that the water balance is computed over relatively small areas. It is assumed that the deep percolation below the root zone, sometimes referred to as net infiltration, will eventually become groundwater recharge. These models can be useful predictors of the amount and spatial distribution of recharge at the basin scale.

DPWM is based on the model developed by Sandia National Laboratory (2007) for Yucca Mountain (MASSIF) and similar in concept to water balance models used by the USGS (e.g., BCM [Flint and Flint, 2007], INFIL [Hevesi et al., 2003]). The DPWM uses a daily time step over variable grid cell sizes that typically range up to 72,900 square meters (m^2) (270 meters by 270 meters) but can be any size that the user specifies. The model generally relies on the widely accepted FAO-56 procedure for computing actual evapotranspiration (AET) from the reference evapotranspiration (ET_0) estimated with the Penman-Monteith method (Allen et al., 1998; Allen et al 2005). Water budget components accounted for in the model include precipitation, bare soil evaporation, transpiration, runoff, runon, snow accumulation, snow melt, snow sublimation, soil water storage, and net infiltration. A bedrock boundary is placed at the bottom of cells with shallow soil depths that will restrict infiltration when the saturated hydraulic conductivity of the bedrock is less than that of the soil. Unlike the USGS BCM model, DPWM accounts for the routing of runoff through the watershed. Cells that intersect washes are divided into two cells: one small cell containing the wash soils and one large cell with the interwash properties.

The FAO-56 method (Allen et al., 1998) computes a reference evapotranspiration value using the Penman-Monteith equation that represents evapotranspiration from an extensive surface of green grass of uniform height, actively growing and adequately watered. The reference evapotranspiration is modified for any agricultural or natural vegetation type using crop coefficients (K_{cb}). A coefficient of 1.0 represents the reference grass vegetation. Coefficients less than 1 represent less dense vegetation, while coefficients greater than 1 represent dense vegetation. The FAO-56 method supplies equations for computing crop coefficients for natural vegetation using site-specific climate data and a measure of the vegetation density (e.g., leaf area index [LAI]). Further adjustments to the crop coefficient provided by FAO-56 include stomatal resistance adjustments that account for the ability of desert vegetation to conserve water.

1.1 Description of Water Balance Methodology

To conduct the water balance, the watershed is divided into grid cells. In each cell, the soil profile is divided into three layers with four nodes (Figure 1). The upper layer (Layer 1) has bare soil evaporation and transpiration, and its thickness is based on the maximum depth of bare soil evaporation ("evaporation layer depth" [Z_e] in FAO-56 [Allen et al., 1998]). Layer 1 is divided into two nodes (Nodes 1 and 2). Node 1 is the bare soil fraction of the cell where evaporation is dominant, and Node 2 is the fraction of the cell surface covered by vegetation canopy where transpiration is dominant. Bare soil evaporation does not occur in Node 2, but transpiration occurs to some degree in both Nodes 1 and 2. The areas of Nodes 1 and 2 are adjusted over the year as the vegetation grows, peaks, and then declines based on the basal transpiration coefficient (K_{cb}).

The second layer (Layer 2 and Node 3) is the remainder of the root zone for the vegetation type; its thickness is the maximum rooting depth minus the thickness of Layer 1. Transpiration is dominant in Layer 2, but some diffuse evaporation also occurs.

The final layer (Layer 3) is below the root zone and does not have any transpiration or evaporation. Its thickness is the depth to bedrock minus the thicknesses of Layers 1 and 2. In cells with deep alluvium, the thickness is limited to 5 meters minus the root layer thicknesses. Drainage from Layer 3 is limited by the bedrock saturated hydraulic conductivity when less than the soil saturated hydraulic conductivity.

2. Model Description

The following model description describes the operation of DPWM, the input and output text file formats, and then provides detailed descriptions of the functions used in DPWM.

2.1 Compiling and Executing DPWM

The DPWM was written in the C/C++ computer language. The code is relatively easy to understand for anyone experienced with computer languages, in that it is simply composed of function calls, if-then statements, arithmetic expressions, and for-loops. Executables have been compiled in release mode with Microsoft Visual C++ version 7.1.6030. Microsoft compilers (available for free at http://www.microsoft.com/express/vc/) have also been used to successfully compile DPWM. The DPWM is executed at the command line. All input and output files have the same root name with different extensions. The DPWM will query the user to enter the root name for a simulation or the user can use the DOS redirection command to enter the root name automatically from a text file (e.g., DPWM < root.txt).

2.2 Input Files

There are ten input files for the DPWM, four of which are optional. All files are standard ASCII text files that can be edited with any text editing software. The nomenclature for the input file extension names is "i" for input followed by a two-letter abbreviation for the input file type (e.g., ipm for the input parameter file).

The row order of cells must match between the IWS, IDN, IPZ, IMT, ILC, ISM, and IPV files.

2.2.1 Input Parameter File (IPM)

The parameter input file has several input blocks that represent the soil, vegetation, bedrock, and general model parameter values. The file can be either space or tab delimited. Extra spaces and/or tabs at the ends of lines should be removed to prevent input errors. The input should be confirmed by checking an echo of the input in the CHK file. This file is required. The text below describes the setup of ipm for the field capacity version of DPWM.

2.2.1.1 Block A – Basic Information

- CellPrint – Logical for printing output files. 0 = false and only final results (OWA file) are printed. 1 = true and text output files are generated. 2 = generate text output files and additional binary file output.

- CalWY – The initial water year (e.g., 1980).

- Sindex – Sindex is not currently implemented in DPWM. In previous versions of DPWM, the Sindex is the index number for the soil type found in ephemeral streams (e.g., washes or arroyos) and corresponding with Block B. The Sindex has an origin of 1. Cells with areas smaller than specified in the MaxWashArea will be assigned hydraulic properties based on Sindex.

- Vindex – The index number for the vegetation type representing bare rock. The VIndex has an origin of 1. If bare rock is not found in the vegetation data, VIndex should be set to a value greater than the number of vegetation types. The VIndex is used to assign a minimal soil depth equal to the evaporation layer thickness to the cell. If Vindex is set to -1, there is no vegetation type assigned to represent bare rock.

- WVindex -- The vegetation index number for the vegetation type in washes. If WVindex is set to -1, the interwash vegetation type for the cell will be used for the wash vegetation type.

- MaxWashArea – The maximum wash area for a model cell in square meters. Cells with this area or less are assigned the wash soil hydraulic properties but retain the surrounding soil depth. This variable is obsolete in the current DPWM version. Wash area is set in the IWS using the wash width.

- BalanceModel – DPWM can use a field capacity (fc), van Genuchten-Mualem (vgm), or Richard's equation (re) modeling approach. At present, only the field capacity model is fully implemented and so BalanceModel should be set to fc.

- FC_head_cm – The absolute value of the field capacity capillary pressure head in centimeters of water. The typical field capacity values of 1/10 bar and 1/3 bar are equivalent to 102 cm and 341 cm, respectively.

- WP_head_cm – The absolute value of the wilting point capillary pressure head in centimeters of water. Agricultural vegetation typically has a wilting point of 15 bars (15,323 cm) but desert vegetation in the southwest can extract water down to 60 bars (61,293 cm).

- KsImPv - Saturated hydraulic conductivity of the impervious surface (m/s). If value is not given in the IPM file, the default of 0 is used.

- Ncells – The number of cells in the model and should correspond with the watershed file (iws)

- Nveg – the number of vegetation types found in Block D of the ipm file.

- Nsoils – the number of soil types found in Block B of the ipm file including the wash soil.

- Nrock – the number of rock types found in Block C of the ipm file.

- Ndays – the number of days in the simulation and should correspond with the climate file (icl)

- Nyear – the number of water years in the simulation.

- Nstations – the number of climate stations used for precipitation. Typically only one station is used.

- Nlayer – the number of layers in the model. Typically NLayer should be set to 3.

- Nexits – The total number of surface flow exits to track in the model. If multiple surface water exits do not exist or do not need to be tracked separately, Nexits should be set to 1. Multiple surface flow exits can be designated with sequential negative numbers in the watershed (iws) and downstream receptor (idn) files starting with -1 (e.g., -1, -2, -3, etc.). Nexits is then set to the total number of exits.

- Kdew_amp, Kdew_wave, Kdew_Xoff and Kdew_Yoff – Harmonic function parameters for varying the dew point offset with the day of year as described in the KdewOffset_fcn. If Kdew_Yoff is negative (or if Kdew_amp, Kdew_wave, and Kdew_Xoff are all equal to 1.0), the dew point offset is constant (ºC) and equal to the absolute value of Kdew_Yoff and the remaining harmonic function parameters are ignored.

- Elev_avg_m – The average elevation in the basin in meters.

- Elev_ref_m – The elevation of the reference climate station in meters. If multiple stations exist as specified in Nstations, then multiple values are present on this line.

- Lat_avg – the average latitude in decimal degrees for the basin.

- CTcor – The absolute value of the dry temperature lapse rate with elevation (ºC/m). Lapse rates of about -7.5 ºC/km (-7.5E-03 ºC/m) are commonly observed in the PRISM mean annual maximum air temperature data. Maidment 1993 reports a dry temperature lapse rate of -10ºC/km, which was used as the nominal value for present day conditions at Yucca Mountain (SNL 2007). A saturated adiabatic lapse rate ranging from 6.9ºC/km at 0ºC to 3.6ºC/km at 30ºC at sea level can be used under conditions of condensation (SNL 2007 after Rosenberg et al 1983). A value is given for CTcor but is not used if PRISM temperature data are implemented.

- Cprecipcor – The precipitation lapse rate with elevation (1/m). A value is given but is not used if PRISM is implemented. Cprecipcor is estimated by regression of the observed mean annual precipitation (MAP) and elevation at climate stations in the area. The regression parameters are used to estimate MAP at the reference location. The slope (mm/km) from the regression is then divided by the estimate at the reference location (mm). The nominal present day value of Cprecipcor used at Yucca Mountain was 6.3%/100m, which would be inputted as 6.28E-04 in the ipm file (SNL 2007). A value is given for Cprecipcor but is not used if PRISM precipitation data are implemented.

- CWindcor – The mean daily wind speed lapse rate with elevation (m/s/m). Zero can be given if it is assumed that wind speed does not vary with elevation.

- Ks_exp – exponent coefficient for relating the transpiration stress factor (Ks) to the water level in the root zone. If less than zero, the linear transpiration stress equation (equation 84 in Allen et al 1998) is implemented.

- LAI_exp – exponent coefficient for estimating the Kcb transpiration coefficient from leaf area index (LAI) (equation 97 in Allen et al 1998). The nominal value for this coefficient is 0.7.

- K_rs – The Hargreaves' coefficient for estimating incoming solar radiation (°$C^{-0.5}$). Typically ranges from 0.16 to 0.19 (Allen et al 1998) and a nominal value of 0.19 °$C^{-0.5}$ was used for Yucca Mountain (SNL 2007). K_rs can be estimated from observed solar radiation data.

- Ze – Evaporation layer thickness in meters. Typically the evaporation layer is 10 to 15 cm (Allen et al 1998; p. 144).

- REW – Readily evaporable water in millimeters. This is the quantity of water that can be readily evaporated from upper evaporation layer in the model (Allen et al 1998; p. 144). REW ranges from 2 – 7 mm in sands to 8 – 12 mm in clay. A uniform value is given here for the model.

- p – Average fraction of the total available soil water that can be depleted before moisture stress occurs (Allen et al 1998; p. 162). The value of p ranges from 0.3 for shallow rooted plants at high rates of ET (> 8 mm/d) to 0.7 for deep rooted plants at low rates of ET (< 3 mm/d) with a typical value of 0.5 for many crops (Allen et al 1998). p is set to vary with the rate of evapotranspiration if bPadj is set to true.

- Kc_min – The minimum basal transpiration coefficient. Typically set to zero in arid climates.

- Kcln – Turbidity coefficient for solar radiation in Allen et al 2005, eq. D.2 (unitless). 1.0 recommended for clean air and <=0.5 for extremely turbid, dusty or polluted air.

- Fc_switch – The area fraction covered by vegetation in a cell. Determines distribution between nodes 1 and 2 in layer 1. If negative, the vegetation area varies with the transpiration coefficient (Kcb) as given in Allen et al 1998 (eq. 76; p. 149).

- Ze_Rock –This is the storage component for cell identified as bare rock by VIndex in units of meters. Typically, this is set equal to Ze_m

- MFMIN – minimum snow melt factor as given in the HELP model for December 21 or a constant melt factor if the MASSIF snow model is implemented. Typically set to 2mm/ºC.

- MFMAX – maximum snow melt factor as given in the HELP model for June 21. Typically set to 5.2mm/ºC. If zero, the MASSIF snow model for snowmelt is implemented.

- SUBPAR1 – sublimation fraction. In the MASSIF snow model, this is a constant value for the season that occurs on the day snow fall (0.15 reported for Colorado and used in the Yucca Mountain model). In the INFIL snow model, this is the fraction of daily reference evapotranspiration that occurs as sublimation for below freezing conditions.

- SUBPAR2 – daily sublimation fraction of reference evapotranspiration for above freezing temperatures. If zero, the MASSIF snow model for sublimation is implemented.

- IC_1_cm, IC_2_cm, IC_3_cm, IC_4_cm – Initial capillary pressure heads in centimeters. Although IC_4_cm is given here, it is set equal to the field capacity value by DPWM.

- Duration_slope – Relation between precipitation daily quantity and duration of precipitation. If negative, the duration of precipitation is obtained from the climate input file (icl).

- Precip_adj – Uniform adjustment to precipitation. Typically set to 1 unless sensitivity to precipitation is being tested.

- Temp_adj – Uniform adjustment to minimum and maximum air temperature. Typically set to 1 unless sensitivity to temperature is being tested.

- TETMIN - minimum air temperature (ºC) for transpiration. When the average daily air temperature is below TETMIN, the crop coefficient (K_cb) is set to the minimum (Kc_min).

- TETMAX - maximum air temperature (ºC) for transpiration. When the average daily air temperature is above TETMAX, the crop coefficient (K_cb) is set to the minimum (Kc_min).

- Ndur - Number of zones with varied precipitation rate. The duration of precipitation can vary spatially over the model domain. Zones are set in the IWS file up to a maximum number of Ndur. Durations of precipitation are set in Ndur columns in the ICL file.

- bLAI – Boolean on whether to use leaf area index (LAI) data. If TRUE, LAI data are provided for each grid cell in the imt file.

- bMETRIC – If TRUE, read ETrF data from the imt file. bLAI and bMETRIC cannot both be true.

- bBCM – if TRUE, runoff is not routed downstream as is implemented in the USGS BCM model.

- bPRISM_PPT – If TRUE, read PRISM mean annual precipitation data for each grid in the ipz file. Cprecipcor is not used.

- bPRISM_TEMP – If TRUE, read PRISM monthly temperature data. CTcor is not used.

- bPRISM_MON – If TRUE, read PRISM data for each month of simulation. Cprecipcor is not used.
- bAlbedo – If TRUE, read cell specific albedo data from the watershed file.
- bRH – If TRUE, read relative humidity data from the input climate file (icl)
- bDPO – If TRUE, dew point offset is provided in climate file (icl) rather than estimating with a harmonic function or using a constant offset.
- bMETRIC_Sat – if TRUE, directly insert moisture data from METRIC into the model.
- bSat_Reset – If TRUE, water contents are reset to the initial condition at the beginning of each year. Typically used if running non-sequential water years in one simulation.
- bDataAssim – If TRUE, data assimilation routines are implemented.
- bGDD – if TRUE, growing degree day (GDD) method for estimating crop coefficients is implemented. Additional polynomial coefficients are provided in the vegetation block of the IPM file. If both bGDD and bLAI are TRUE, bGDD is used rather than bLAI.
- bPadj - If TRUE, the fraction (p) of TAW that can be depleted from the root zone before moisture stress (reduction in ET) occurs is set to vary with the ET rate (Allen et al 1998; p. 162). If FALSE or not given, the p is constant for the simulation.

2.2.1.2 *Block B – Soil Data*

Soil data are provided in the order as specified in the soil index of the watershed file. For example, a cell in the watershed file with soil index 5 will refer to the data on the 5th line of Block B in the ipm file.

- Soil Name (no spaces)

- Soil saturated hydraulic conductivity (m/s). Typical values range from 5.6E-08 m/s for silty clay to 8.2E-05 m/s for sand (Carsel and Parrish, 1988).

- Van Genuchten curve parameter alpha (1/cm). Typical values range from 0.005 1/cm for silty clay to 0.145 1/cm for sand (Carsel and Parrish, 1988).

- Van Genuchten curve parameter n (unitless). Should be greater or equal to 1.0. Typical values range from 1.09 for silty clay to to 2.68 for sand (Carsel and Parrish, 1988).

- Saturated volumetric water content (unitless). Similar in value to total porosity. Typical values range from 0.36 for silty clay to 0.46 for silt (Carsel and Parrish, 1988).

- Residual water content (unitless). Typical values range from 0.034 for silt to 0.1 for sandy clay (Carsel and Parrish, 1988).

- Soil depth (m). The depth to a restrictive layer (e.g., bedrock). Deep soils can be represented with a soil depth greater than the maximum rooting depth of vegetation.

2.2.1.3 Block C – Bedrock Data

Bedrock data are ordered to relate to the bedrock index number given in the watershed file (Rock index 5 in the watershed file refers to data on line 5 in block C of the ipm).

- Name (no spaces)

- Bulk saturated hydraulic conductivity of the bedrock considering fractures (m/s)

2.2.1.4 *Block D – Vegetation Data*

Vegetation data are ordered to relate to the bedrock index number given in the watershed file (e.g., vegetation index 5 in the watershed file refers to line 5 of Block D in the ipm file).

The first Nveg number of lines in Block D provide the following parameters

- Name (no spaces)
- H_plant – mean maximum plant height in meters. Values greater than 2 meters do not influence evapotranspiration calculations (e.g, Allen et al 1998, Chapter 9).
- Zr_m – mean maximum rooting depth in meters.
- LAI_ini – leaf area index at the initiation of growth in the spring. Not used if bLAI, bMETRIC, or bGDD are implemented.
- LAI_mid – peak leaf area index during the middle of the growing season. Not used if bLAI, bMETRIC, or bGDD are implemented.
- LAI_late – late season leaf area index. Not used if bLAI, bMETRIC, or bGDD are implemented.
- rl_ini – mean leaf resistance for the vegetation at the initiation of growth (s/m). Nominal values of 100 s/m indicate no adjustment to transpiration coefficients (Allen et al 1998, p. 191).
- rl_mid – mid-season mean leaf resistance for the vegetation (s/m). Nominal values of 100 s/m indicate no adjustment to transpiration coefficients (Allen et al 1998, p. 191).

- rl_late – late season mean leaf resistance for the vegetation (s/m). Nominal values of 100 s/m indicate no adjustment to transpiration coefficients (Allen et al 1998, p. 191).

- Develop_start – day of calendar year for start of vegetation growth development. Days of the year prior to Develop_start use LAI_ini for leaf area index. Between Develop_start and Mid_start, values are linearly interpolated from LAI_ini to LAI_mid. Not used if bLAI, bMETRIC, or bGDD are implemented.

- Mid_start – start of middle season. Between Mid_Start and Late_start, leaf area index values are set to LAI_mid. Not used if bLAI, bMETRIC, or bGDD are implemented.

- Late_start – End of midseason and start of vegetation decline. Leaf area index values are linearly interpolated between LAI_mid and LAI_late for days of the calendar year between Late_start and Late_end. Not used if bLAI, bMETRIC, or bGDD are implemented.

- Late_end – Day of calendar year for the end of the season. Leaf area index values are set to LAI_late for remainder of calendar year. Not used if bLAI, bMETRIC, or bGDD are implemented.

If the Growing Degree Days method is implemented (bGDD = TRUE), Nveg additional lines are provided with the six coefficients for the 5^{th} order polynomial relating growing degree days and the transpiration coefficient (Kcb; Brower 2008).

2.2.2 Input Climate File (ICL)

The climate input file has climate data for the reference location in the watershed. This file is required. Columns are as follows:

- Month
- Day of month [DOM]
- Water year

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- Day of water year [DOWY]
- Precipitation in millimeters (mm) [PRECIP]. Multiple columns if more than one reference weather station as specified by Nstations in the IPM file.
- Maximum daily temperature in °C [TMAX]
- Minimum daily temperature in °C [TMIN]
- Wind speed in meters per second (m/s) [WIND]
- Duration of precipitation in hours [DURATION]. Multiple columns if more than one zone for precipitation intensity.
- Daily maximum relative humidity (%) [RHMAX_Daily] if bRH is TRUE
- Daily minimum relative humidity (%) [RHMIN_Daily] if bRH is TRUE
- Daily dew point offset (°C) [DPO_Station] if bDPO is TRUE

The file is in a space delimited format.

2.2.3 Input Watershed File (IWS)

The watershed input file has the cell location and elevation along with the types of soil, vegetation and bedrock. This file is required. Columns are as follows:

- Cell ID [Cell_ID]
- UTM easting in NAD83 meters [POINT_X]
- UTM northing in NAD83 meters [POINT_Y]
- Elevation of cell in meters [ELEV_METER]
- Cell ID of downstream cell that receives runoff [DWNSTRM_ID]
- Slope of cell in degrees [SLOPE_DEG]
- Aspect of cell [ASPECT]
- Soil type index with array origin at 1 [Soil_Index]
- Bedrock type index with array origin at 1 [Rock_Index]
- Vegetation type with array origin at 1 [Veg_Index]

- Area of cell in meters squared [Area]
- Albedo of soil at cell [Albedo] if bAlbedo is true
- Width of wash in meters [WashWidth]
- Wash soil type [WASHSOIL]
- Precipitation intensity zone [DURTYPE]
- Albedo of soil at cell [Albedo] if bAlbedo is true.

This file must be ordered with upstream cell above downstream cell.

2.2.4 Input Downstream Receptor File (IDN)

The downstream contributor file instructs the DPWM how to route runoff. The rows of the IDN file must correspond with iws file. This file is required if bBCM is false. Columns are as follows:

- C/C++ array index with 0 origin [RankJ]
- Cell ID [Cell_ID]
- Cell ID of downstream cell that will receive runon [DWNSTREAM_ID]
- C/C++ array index of downstream cell with 0 origin [Dwnstrm_J]

Index values must correspond with positions in the watershed file (*.iws). The second line in this file (first line after header) corresponds with array index 0.

2.2.5 Input Daily Observation File for Specified Cells (IOB)

The input file identifies individual cells to monitor daily water balance. The first line is the number of cells to monitor. Subsequent lines have cell IDs. Daily output of monitored cells is in the output file *.ocd. The IOB file is required.

2.2.6 Input Observation File for Specified Times (IOT)

The input file identifies times to output water balance for entire watershed. The first line is the number of output times. Subsequent lines have water year, month, and day of month to generate output. Output for each cell on the specified output days can be found in the *.oct file. The IOT file is required.

2.2.7 Input METRIC/LAI data at specified Times (IMT)

This input file contains estimates of the METRIC estimate of the evaporative fraction (bMETRIC = TRUE) or the leaf area index (bLAI = true) for days of the water year. The first line of the file has the number of days with METRIC or LAI observations (nday). The second line contains the day of the water year where METRIC or LAI observations are available. The remainder of the file contains a vector of the cell id numbers concatenated with a matrix of the METRIC or LAI data of size ncell number of rows and nday number of columns (the resulting combined matrix is ncell rows by nday + 1 columns). The rows must be in the same order as found in the input watershed file (IWS). The columns are in water year order starting with October. This file is optional and is only needed if bMETRIC or bLAI are true. Often, satellite values of zero are reported for where LAI data are not available. DPWM assumes that these areas actually have vegetation and converts LAI values of zero to a value of 1.0.

2.2.8 Input annual PRISM data (IPZ)

This file contains mean annual estimates of precipitation for each grid cell from PRISM (bPRISM_PPT = TRUE) and monthly estimates of minimum and maximum air temperature for each grid cell from PRISM (bPRISM_TEMP = TRUE). The first line of the file contains the cell identification numbers for cells that represent the reference climate station and the mean elevation of the basin. The second line is a header file. The remaining columns have precipitation, monthly entries for mean minimum air temperature, and monthly entries for mean maximum air temperature. The number and order of lines should correspond with the input watershed file (IWS). If bPRISM_PPT is true and bPRISM_TEMP is false, then there is only one column of data. This file is optional and is only needed if bPRISM_PPT or bPRISM_TEMP are true.

2.2.9 Input monthly PRISM data (IZM)

This file contains the monthly estimate of precipitation from PRISM for each grid cell in the model for the simulation period. The first column contains the cell identification numbers and all subsequent columns correspond to each month of simulation. There should be a column of precipitation data for each month of simulation (e.g., 120 columns for a 10 year simulation) so this file can quickly become quite large. This file is optional and is only needed if bPRISM_MON is true.

2.2.10 Input Data Assimilation data (IDA)

This file is optional and is only read if bDataAssim is TRUE. This file contains a matrix of data for implementing data assimilation routines in DPWM. The first line contains the number of factors (Nfactor) to be applied for each grid cell. The remainder of the file is a matrix (Ncell rows by Nfactor + 2 columns) with the following columns:

- Cell ID
- Weight
- k_factor [Nfactor columns]

Currently, the data in the Weight column are not used and only one k_factor is implemented in DPWM. The k_factor modifies the dimensionless transpiration reduction factor (Ks_exp) for each grid cell. Where Ks_exp is negative, equation 84 in FAO-56 (Allen et al 1998) is used and the value of Ks_exp is ignored. Where Ks_exp is zero or greater, the Ks_expfcn function is implemented where Ks_exp is modified as Ks_exp* k_factor.

If bDataAssim is FALSE, the k_factor is set to one for all grid cells.

If bDataAssim is TRUE and the IDA file is not present, DPWM will prompt to create an IDA file.

2.2.11 Input Irrigation data (IRR)

If the IRR file is present, DPWM will read irrigation rates for specified cells or for specified vegetation types. If the IRR file is not present, DPWM does not implement any irrigation. Irrigation rates are in units of mm per day. Irrigation is not applied on days with precipitation and is not applied to the wash area of a cell. There are three types of irrigation data:

1. Monthly rate specified for irrigation cells (bType = 0)
2. Daily rate specified for irrigation cells (bType = 1)
3. Monthly rate specified by vegetation type (bType = -1)

The first line of the IRR file specified the type of irrigation data (bType) and the number of cells that have irrigation (NIrrCells) or the number of vegetation types. For rates by cell (bType = 0 or bType = 1), a list of the cell id's for the irrigation cells (NIrrCells rows) is given below the first line.

If the rates are monthly by cell (bType = 0), a matrix of the monthly irrigation rates is given below the list of irrigation cells for the months January through December (NIrrCells rows by 12 columns). Monthly rates are repeated for each month over each year of the simulation. The monthly rates are mapped to daily values for each day of the month. For example, if a rate of 5 mm/day is given for August in the IRR file at a cell, each day in the month of August will have 5 mm of irrigation at the cell for a total of 155 mm of irrigation applied for the month of August.

If the rates are daily by cell (bType = 1), a matrix of the daily irrigation rates for each day of the simulation and for each irrigation cells is given (NIrrCells rows by Nday columns).

If the rates are monthly by vegetation (bType = -1), a matrix of the monthly irrigation rates is given below the first line of the IRR file. Unlike the monthly by cell rates, the monthly by vegetation rates are specified for each month of the simulation so that matrix is Nyear*12 rows by NVeg columns. The monthly rates are mapped to daily values for each day of the month. For example, if a rate of 5 mm/day is given for August 2005 in the IRR file for a vegetation type, each day in the month of August 2005 will have 5 mm of irrigation at a cell with the corresponding vegetation type for a total of 155 mm of irrigation applied for August 2005.

2.2.12 Input Soil Moisture (ISM)

If bMETRIC_Sat is true, DPWM will read soil moisture data. The first line of the ISM file has the number of days with soil moisture data (n_SMday). The second line of the file has n_SMday days of the run for the soil moisture data (SM_DOR). The third and remaining lines of the file contain a matrix (METRIC_Sat) of soil moisture data for every grid cell and every day with soil moisture data [NCELL rows x n_SMday columns].

METRIC_Sat data are used in the SoilMoistureCorrection and Calc_dDr functions. However, these functions are not implemented in the current version of DPWM.

2.2.13 Land Use Change (ILC)

If the land use change input file (ILC) is present, the ILC file is read. The ILC file is structured so that the first line has the number of days with land use changes (NLUC), the second line has the elapsed simulation day(s) for the land use change(s), and the remainder of the file has a matrix with the vegetation type for each grid cell for each day of land use change (size is NCELL rows by NLUC columns). If the ILC file is not present, NLUC is set to zero and land use changes are not implemented.

2.2.14 Impervious Surface Data (IPV)

If the impervious surface input file (IPV) is present, the IPV file is read. The IPV file is structured so that the first line contains the number of days (NIpvDays) with impervious surface data, the second line contains NIpvDays elapsed simulation day(s) for when to apply the change in the impervious surface, and the remainder of the file has a matrix (size is NCELL rows by NIpvDays columns) of the area fraction of interwash area with impervious surface. Impervious surfaces are not present in the washes.

2.2.15 NDVI Data (NDVI)

The NDVI file is used to maintain backward compatibility with the MASSIF model and is typically not used. If the NDVI file is present, the Boolean variable bNDVI is set to true and LAI data, if present, are not used by DPWM. The NDVI file is structured so that first line has the variables PrecipRefNDVI, CKcb[1], and CKcb[2] followed by a matrix of NDVI data [365 x 25]. The NDVI matrix contains NDVI values for each day of the year and 25 columns that represent unique combinations of slope and aspect.

2.2.16 Input Runoff Observation (IRO)

This optional input file is no longer used in the current version of DPWM.

This input file contains observed runoff data over the period of an entire storm. The file instructs the DPWM to output the observed and simulated values for calibration of the model to runoff. The file has the following columns:

- Cell ID [locid]
- Storm number [storm]
- Day of run that storm starts [Start]
- Day of run that storm ends [End]
- Total observed runoff at cell in cubic meters over storm duration [Runoff]

2.3 Output Files

Output files provide the mass balance components (precipitation, evaporation, transpiration, net infiltration, runoff, storage, snowpack level, and error) for the water balance calculations at the watershed or cell level and at either daily, annual, or other specified time intervals. Generally the nomenclature for output file extensions is "o" for output, "c" for cell or "w" for watershed, and "d" for daily, "a" for annual or "s" for simulation period (e.g., owd is mass balance components for the watershed on a daily basis).

2.3.1 Output Watershed Daily Mass Balance (OWD)

This output file contains the daily water balance for the entire watershed on a lumped basis. Columns are as follows:

- Day of run [Day]
- Total precipitation in cubic meters [Precip]
- Change in water stored for watershed in cubic meters [dStorage]
- Change in water stored in the snowpack in cubic meters [dSnow]
- Evapotranspiration for watershed in cubic meters [ET]
- Net infiltration for watershed in cubic meters [Infil]
- Runoff at Toquop Gap in cubic meters [RunoffExit]
- Mass balance for model in cubic meters [Masscheck]
- Percent mass balance error [%MBE]
- Total runoff generated in the watershed in cubic meters (not part of the watershed mass balance) [RunoffinWS]
- Total runon generated in the watershed in cubic meters (not part of the watershed mass balance) [RunoninWS].
- Percent of watershed covered in snow [%SnowCover].
- Runoff from each watershed exit in cubic meters [ROexit]. There are Nexits number of columns for each watershed exit.

2.3.2 Output Cell Annual Mass Balance (OCA)

This output file has the annual water balance for each cell in the watershed. Columns are as follows:

- Cell ID [CellID]
- Water year [Year]
- UTM Zone 11 easting in NAD83 meters [UTM83_X]

- UTM Zone 11 northing in NAD83 meters [UTM83_Y]
- Precipitation volume for year on cell in cubic meters [Precip]
- Irrigation volume for year on cell in cubic meters [Irr]
- Actual evapotranspiration in cubic meters [AET]
- Net infiltration in cubic meters [Infil]
- Runoff in cubic meters [Runoff]
- Runon in cubic meters [Runon]
- Total change in water stored in soil in cubic meters [dWlevel]
- Total change of water in snowpack in cubic meters [dSnow]
- Sublimation in cubic meters [Sublimate]
- Snowmelt in cubic meters [SnowMelt]
- Snowfall in cubic meters [SnowFall]
- Area of cell in square meters [Area]
- Reference evapotranspiration in millimeters [RefETmm]
- Riparian evapotranspiration in millimeters (not used in DPWM calculations) [RiparianET]

The file is in a tab delimited format.

2.3.3 Output for Specified Cells Daily Mass Balance (OCD)

This file has the daily water balance for individual observation cells specified in the input file *.iob. The rows in the OCD file are ordered based on the position of the observation cell in the IWS file and do not necessarily follow the order given in the IOB file. There are 94 columns of data as follows:

1. Day of run [Day]
2. Cell ID [CellID]
3. Change in water stored in soil in cubic meters [dWlvl_m3]
4. Daily precipitation in cubic meters [Precp_m3]
5. Daily irrigation in cubic meters [Irr_m3]
6. Daily transpiration in cubic meters [Trans_m3]
7. Daily evaporation in cubic meters [Evap_m3]
8. Daily runon in cubic meters [Ron_m3]

9. Daily runoff in cubic meters [Roff_m3]
10. Daily net infiltration in cubic meters [Infil_m3]
11. Daily sublimation in cubic meters [Sub_m3]
12. Daily water balance error in cubic meters [Balance]
13. Actual evapotranspiration in mm [AET_mm]
14. Reference evapotranspiration in mm [RefET_mm]
15. Transpiration water stress coefficient Ks [K_s]
16. Basal Transpiration coefficient Kcb [Kcb]
17. Evaporation water stress coefficient Kr [K_r]
18. Evaporation coefficient Ke [Ke]
19. Maximum Kc [Kcmax]
20. Vegetation canopy cover fraction [fc]
21. Kcb for full vegetation cover [Kcb_full]
22. Minimum relative humidity [RH_min]
23. Precipitation in mm [Precp_mm]
24. Irrigation in mm [Irr_mm]
25. Net infiltration in mm [Infil_mm]
26. Runoff in mm [Roff_mm]
27. Runoff due to saturation of model cells in mm [ROsat_mm]
28. Runoff due to exceedances of soil saturated hydraulic conductivity in mm [RO_Ks_mm]
29. Runon in mm [Ron_mm]
30. Transpiration in mm [Trans_mm]
31. Evaporation in mm [Evap_mm]
32. Cumulative maximum actual evapotranspiration in mm [MaxAETmm]
33. Snow in mm [Snow_mm]
34. Change in snowpack in mm [dSnow_mm]
35. Snowmelt in mm [Smelt_mm]
36. Sublimation in mm [Sub_mm]
37. Change in soil water storage in mm [dWlvl_mm]

38. Ra_hor -- extraterrestrial radiation on a horizontal surface for a 24-hr period (MJ m^{-2} d^{-1}) [Ra_hor]
39. Rso_hor -- clear sky solar radiation over the 24-hr period (MJ m^{-2} d^{-1}) [Rso_hor]
40. Rsm_hor -- estimated 'measured' solar radiation on a horizontal surface using Hargreaves' method (MJ m^{-2} d^{-1}). [Rsm_hor]
41. Rsm_inc -- total radiation received by the inclined surface (MJ m^{-2} d^{-1}) [Rsm_inc]
42. Rs_eqhor -- horizontal projection (equivalent) of total radiation received by surface (MJ m^{-2} d^{-1}) [Rs_eqhor]
43. Rns -- horizontal equivalent for net short wave radiation on the incline (MJ m^{-2} d^{-1}) [Rns]
44. Rnl -- net outgoing long wave radiation (MJ m^{-2} d^{-1}) [Rnl]
45. Rn -- net radiation on the inclined surface projected to a horizontal projection (input to the Penman-Monteith equation). (MJ m^{-2} d^{-1}) [Rn]
46. Reference precipitation in mm (multiple columns if more than one reference station) [Pref_mm]
47. Daily minimum reference air temperature (ºC) [TminRefC]
48. Daily maximum reference air temperature (C) [TmaxRefC]
49. Reference wind speed (m/s) [WindRef]
50. Reference elevation (m) [ElevRef]
51. Dew point offset (C) [DewOff_C]
52. Wind speed at cell (m/s) [WindCell]
53. Dew point temperature at cell (C) [TdewCell]
54. Daily minimum air temperature at cell (C) [TminCell]
55. Daily average air temperature at cell (C) [TavgCell]
56. Daily maximum air temperature at cell (C) [TmaxCell]
57. Dew point temperature for watershed (C) [TdewWS]
58. Daily minimum air temperature for average elevation in watershed (C) [TminWS]
59. Daily average air temperature for average elevation in watershed (C) [TavgWS]
60. Daily maximum air temperature for average elevation in watershed (C) [TmaxWS]
61. Elevation of cell in meters [CellElev]
62. Slope of land surface at cell (degrees) [Slope]

63. Azimuth of land surface at cell [Azimuth]
64. k_Rs – Hargreaves' coefficient [k_Rs]
65. Average latitude of watershed (degrees) [Lat_WS]
66. Albedo of cell [Albedo]
67. Mean leaf resistance (s/m) at cell [rl_Cell]
68. Adjustment to Kcb from stomatal resistance [Fr]
69. Leaf area index at cell [LAI]
70. Evapotranspiration fraction [EToF]
71. Root zone water level for interwash in mm [ARWlvlmm]
72. Relative saturation of root zone [Sroot]
73. Average root zone water content where transpiration begins reduction due to water stress [Qp]
74. Average water content in the root zone [Qroot]
75. Depletion water level in the evaporation layer in mm [De_Cell]
76. Depletion water level in the root zone in mm [Dr_Cell]
77. Growing degree days (ºC) [GDD]
78. Root zone water level for wash in mm. Water level for interwash given if wash is not present. [RWlvlmm]
79. Total cell area in square meters. [TotalArea]
80. Interwash area for cell in square meters. [IWashArea]
81. Wash area for cell in square meters. [WashArea]
82. Area of cell with impervious surface in square meters [IpvArea]
83. Fraction of cell area with impervious surface (unitless) [IpvFrac]
84. Runoff from impervious surface in mm [RO_Ipvmm]
85. Net infiltration on impervious surface in mm [NI_Ipvmm]
86. Transpiration from wash in mm [TP_Wash]
87. Transpiration from interwash in mm [TP_IWash]
88. Evaporation from wash in mm [EP_Wash]
89. Evaporation from interwash in mm [EP_IWash]
90. Net infiltration on wash in mm [NI_Wash]
91. Net infiltration on interwash in mm [NI_IWash]

92. Change in water level in wash in mm [dWlevel_Wash]
93. Change in water level in interwash in mm [dWlevel_IWash]
94. Index for reference precipitation station selected for cell [SelectStation]

2.3.4 Output Watershed Annual Mass Balance (OWA)

This file has the water balance for the entire lumped watershed on an annual basis. Columns are as follows:

- Water year [Year]
- Total annual precipitation on watershed in acre-feet [Precip]
- Total annual irrigation on watershed in acre-feet [Irr]
- Total into watershed (Precipitation + Irrigation) in acre-feet [Total In]
- Total annual actual evapotranspiration for watershed in acre-feet [AET]
- Total net infiltration (e.g., recharge) for watershed in acre-feet [Infil]
- Ratio of net infiltration over precipitation [Infil/Precip%].
- Total annual runoff from watershed in acre-feet [ExitRO]
- Total annual sublimation in acre-feet [Sublim].
- Total out of watershed in acre-feet [Total Out]
- Difference between total in and total out to watershed in acre-feet [In - Out].
- Change in water storage for year over watershed in acre-feet [dStorage]
- Change in snow pack storage for year over watershed in acre-feet [dSnow].
- Mass balance error for watershed in percent [MBE%]

Previous versions of DPWM gave results in cubic meters for each water year with the average reported on the last line. The output was repeated at the bottom of the file in units of acre-feet.

2.3.5 Output All Cells at Specified Times (OCT)

This file contains output for all cells for the days specified in the IOT file. Columns are as follows:

1. CellID - Cell ID [ID]
2. Year - Water year [Year]
3. Month - Month [Month]

4. Day - Day of month [Day]
5. UTM83_Xm - UTM easting for zone 11 and NAD83 in meters [UTM83_Xm]
6. UTM83_Ym - UTM northing for zone 11 and NAD83 in meters [UTM83_Ym]
7. Area_m2 - Area of cell in square meters [Area_m2]
8. Precp_mm - Precipitation in mm
9. Irr_mm - Irrigation in mm
10. Infil_mm - Net infiltration in mm
11. Roff_mm - Runoff in mm
12. ROSat_mm - Runoff from saturation of cell profile in mm
13. RO_Ks_mm - Runoff from exceedances of soil saturated hydraulic conductivity in mm
14. Ron_mm - Runon in mm
15. Trans_mm - Transpiration in mm
16. Evap_mm - Evaporation in mm
17. Snow_mm - Snow in mm
18. dSnow_mm - Change in show pack in mm
19. Sub_mm - Sublimation in mm
20. dStor_mm - Change in storage in mm
21. refETmm - Reference evapotranspiration in mm
22. RHmin - Minimum relative humidity (%)
23. EToF - Evapotranspiration fraction
24. LAI - Leaf area index
25. Kc - Crop coefficient
26. Balance - Mass balance
27. Ra_hor - Ra_hor -- extraterrestrial radiation on a horizontal surface for a 24-hr period (MJ m^{-2} d^{-1})
28. Rso_hor - Rso_hor -- clear sky solar radiation over the 24-hr period (MJ m^{-2} d^{-1})
29. Rsm_hor - Rsm_hor -- estimated 'measured' solar radiation on a horizontal surface using Hargreaves' method (MJ m^{-2} d^{-1}).
30. Rsm_inc - Rsm_inc -- total radiation received by the inclined surface (MJ m^{-2} d^{-1})

31. Rs_eqhor - Rs_eqhor -- horizontal projection (equivalent) of total radiation received by surface (MJ m^{-2} d^{-1})
32. Rns - Rns -- horizontal equivalent for net short wave radiation on the incline (MJ m^{-2} d^{-1})
33. Rnl - Rnl -- net outgoing long wave radiation (MJ m^{-2} d^{-1})
34. Rn - Rn -- net radiation on the inclined surface projected to a horizontal projection (input to the Penman-Monteith equation). (MJ m^{-2} d^{-1})
35. windcell - Wind speed at cell (m/s)
36. T_dew - Dew point temperature (C)
37. T_min - Daily minimum air temperature at cell (C)
38. T_avg - Daily average air temperature at cell (C)
39. T_max - Daily maximum air temperature at cell (C)
40. elev - Elevation of cell (meters)
41. rl_Cell - Mean leaf resistance (s/m)
42. Fr - Transpiration coefficient for stomatal resistance
43. Dr - Root zone depletion water level (Dr) in mm
44. Sroot - Root zone relative saturation (Sroot)
45. SelectStation - Selected reference climate station

2.3.6 Output Runoff (ORO)

This output file contains monthly total runoff in acre-feet for the observation cells. The first column of the file has the Cell_ID for the observation cell. The remaining columns have the simulated monthly total runoff for each month of the simulation. The rows are ordered in the same order as found in the IOB file.

2.3.7 Output soil moisture (OSM)

The OSM file contains the relative root zone saturation (ranges 0 to 1) for each cell at each observation time specified in the file IOT. The columns are:

- Cell_ID number
- UTM easting coordinates in meters

- UTM northing coordinates in meters
- Relative Root zone saturation [n_obsTimes columns]

Groups are unique combinations of soil, rock and vegetation type. The OSM file will calculate the total number of groups as nGroups. If the maxNgroups specified in the code (in defin.h) is greater or equal to the number of nGroups, average values of relative root zone saturation for the groups at each observation time are given at the bottom of the file. The columns are:

- SoilID
- RockID
- VegID
- Group Number
- Average relative root zone saturation [n_obsTimes columns]

2.3.8 Output simulation averages for each cell (OCS)

This file gives the average water balance components for each cell averaged over the simulation period. The columns are:

1. Cell_ID number
2. UTM easting coordinates in meters
3. UTM northing coordinates in meters
4. Elevation of cell in meters
5. Average precipitation in mm/yr
6. Average irrigation in mm/yr
7. Average actual evapotranspiration in mm/yr
8. Average net infiltration in mm/yr
9. Average runoff in mm/yr
10. Average runon in mm/yr
11. Average change in soil moisture storage (mm/yr)
12. Average change in snow pack (mm/yr)
13. Average sublimation (mm/yr)
14. Average snowmelt (mm/yr)

15. Average portion of precipitation occurring as snowfall (mm/yr)
16. Available water in mm/yr -- average quantity of water available for surface infiltration (mm/yr) calculated as precipitation + runon – runoff.
17. Percent net infiltration computed as mean net infiltration / available water.
18. Area (square meters)
19. Reference evapotranspiration in mm/yr
20. Riparian evapotranspiration in mm/yr. Riparian evapotranspiration is estimated using the reference evapotranspiration and the crop coefficient for Cottonwood estimated with the growing degree day method. Riparian evapotranspiration is not used in the DPWM water balance calculations but is provided for use in the MODFLOW evapotranspiration package.

2.3.9 Water balance tracking file (BAL)

This file tracks the water balance of the cell with the maximum mass balance error. The columns are:

1. CellID - Cell ID
2. Year - Water year
3. Month - Month
4. DOM - Day of month
5. DOWY - Day of water year
6. dWlevel - Daily change in water level in mm (area weighted for wash and interwash)
7. dSnowlvl - Daily change in snow level in mm
8. PPT_Cell - Daily precipitation in mm
9. Irr - Daily irrigation in mm
10. Transp - Daily transpiration in mm
11. Evap - Daily evaporation in mm
12. Infil - Daily net infiltration in mm
13. Sublim - Daily sublimation in mm
14. Runon - Daily run-on in mm
15. Runoff - Daily runoff in mm
16. MBE_m3 - Mass balance error in cubic meters
17. Runoff_Sat - Runoff from saturation excess

18. Runoff_Ks - Runoff from exceeding soil infiltration capacity
19. f_c - canopy coefficient
20. Wlevel_1 - Current water level in interwash in node 1 (mm)
21. WlevelOld1 - Previous water level in interwash in node 1 (mm)
22. Wlevel_2 - Current water level in interwash in node 2 (mm)
23. WlevelOld2 - Previous water level in interwash in node 2 (mm)
24. Wlevel_3 - Current water level in interwash in node 3 (mm)
25. WlevelOld3 - Previous water level in interwash in node 3 (mm)
26. Wlevel_4 - Current water level in interwash in node 4 (mm)
27. WlevelOld4 - Previous water level in interwash in node 4 (mm)
28. Snowlvl - Current snow level in mm
29. SnowlvlOld - Previous snow level in mm
30. K_s - Transpiration soil-water stress coefficient

2.3.10 Echo of Input and Output of Calculated Input Values (CHK)

This file echoes input data and outputs calculated input values. The file will flag errors in the run

2.3.11 Monthly and Quarterly Mean Net Infiltration (OIO and OQO)

The oio output file gives the mean monthly net infiltration for each grid cell in units of meters per day. The oqo output file gives the mean quarterly net infiltration for each grid cell in units of meters per day. The quarters are defined for the calendar year and not the water year.

The oio file has a header on the first line. The remainder of the file is NCELLS in lines in length and NMONTHS columns in width. The first column is the cell identification number. The remaining columns are the mean monthly infiltration rates in units of meters per day. The header gives the column label including month and calendar year.

The oqo file has a header on the first line. The remainder of the file is NCELLS in lines in length and NQUARTERS columns in width. The first column is the cell identification number. The remaining columns are the mean quarterly infiltration rates in units of meters per day. The header gives the column label including the quarter and calendar year.

2.3.12 Land Use Change Output File (OLC)

If land use changes are implemented with the ILC file, DPWM creates the OLC file. The OLC file gives detailed water balance information for cells where the rooting depth has changed due to a change in vegetation type. The columns include:

1. j - Cell index
2. i - Day Index
3. js - Soil Index (0 origin)
4. jv - Vegetation Index (0 origin)
5. Wlevelold_IW_IN[0] - Water level in node 1 (layer 1) in the interwash for the prior vegetation type
6. Wlevelold_IW_IN[1] - Water level in node 2 (layer 1) in the interwash for the prior vegetation type
7. Wlevelold_IW_IN[2] - Water level in node 3 (layer 2) in the interwash for the prior vegetation type
8. Wlevelold_IW_IN[3] - Water level in node 4 (layer 3) in the interwash for the prior vegetation type
9. Wlevelold_W_IN[0] - Water level in node 1 (layer 1) in the wash for the prior vegetation type
10. Wlevelold_W_IN[1] - Water level in node 2 (layer 1) in the wash for the prior vegetation type
11. Wlevelold_W_IN[2] - Water level in node 3 (layer 2) in the wash for the prior vegetation type
12. Wlevelold_W_IN[3] - Water level in node 4 (layer 3) in the wash for the prior vegetation type
13. Wlevelold_IW_OUT[0] - Water level in node 1 (layer 1) in the interwash for the new vegetation type.
14. Wlevelold_IW_ OUT [1] - Water level in node 2 (layer 1) in the interwash for the new vegetation type.
15. Wlevelold_IW_ OUT [2] - Water level in node 3 (layer 2) in the interwash for the new vegetation type.
16. Wlevelold_IW_ OUT [3] - Water level in node 4 (layer 3) in the interwash for the new vegetation type.
17. Wlevelold_W_ OUT [0] - Water level in node 1 (layer 1) in the wash for the new vegetation type.

18. Wlevelold_W_ OUT [1] - Water level in node 2 (layer 1) in the wash for the new vegetation type.
19. Wlevelold_W_ OUT [2] - Water level in node 3 (layer 2) in the wash for the new vegetation type.
20. Wlevelold_W_ OUT [3] - Water level in node 4 (layer 3) in the wash for the new vegetation type.
21. SumWlevelold_IW_IN - Sum of water levels in all nodes in the interwash for the prior vegetation type. This sum is for mass balance tracking and does not account for the canopy cover fraction of node 2 versus node 1.
22. SumWlevelold_IW_OUT - Sum of water levels in all nodes in the interwash for the new vegetation type. This sum is for mass balance tracking and does not account for the canopy cover fraction of node 2 versus node 1.
23. SumWlevelold_W_IN - Sum of water levels in all nodes in the wash for the prior vegetation type. This sum is for mass balance tracking and does not account for the canopy cover fraction of node 2 versus node 1.
24. SumWlevelold_W_OUT - Sum of water levels in all nodes in the wash for the new vegetation type. This sum is for mass balance tracking and does not account for the canopy cover fraction of node 2 versus node 1.
25. Qs_sl[0] - Saturated soil-water level (mm) for node 1
26. Qs_sl[1] - Saturated soil-water level (mm) for node 2
27. Qs_sl[2] - Saturated soil-water level (mm) for node 3
28. Qs_sl[3] - Saturated soil-water level (mm) for node 4
29. FC_layer[0] - Field capacity soil-water level (mm) for node 1
30. FC_layer[1] - Field capacity soil-water level (mm) for node 2
31. FC_layer[2] - Field capacity soil-water level (mm) for node 3
32. FC_layer[3] - Field capacity soil-water level (mm) for node 4
33. Wilt_layer[0] - Wilting point soil-water level (mm) for node 1
34. Wilt_layer[1] - Wilting point soil-water level (mm) for node 2
35. Wilt_layer[2] - Wilting point soil-water level (mm) for node 3
36. Wilt_layer[3] - Wilting point soil-water level (mm) for node 4
37. Nlayer - Number of layers
38. Nnodes - Number of nodes
39. soiltype - Soil index (1 origin)
40. vege_type - Vegetation Index (1 origin)
41. Zr_Cell - New rooting depth for cell (mm)

42. oldZr - Prior rooting depth for cell (mm)
43. Ze_Cell - Evaporation layer thickness (mm)
44. Zr - New rooting depth for vegetation (mm)
45. Vindex - Vegetation index for bare rock
46. Ze_rock - Bare rock depression storage (mm)
47. Thick[0] - New thickness for node 1 in layer 1 (mm)
48. Thick[1] - New thickness for node 2 in layer 1 (mm)
49. Thick[2] - New thickness for node 3 in layer 2 (mm)
50. Thick[3] - New thickness for node 4 in layer 3 (mm)
51. OldThick[0] - Prior thickness for node 1 in layer 1 (mm)
52. OldThick[1] - Prior thickness for node 2 in layer 1 (mm)
53. OldThick[2] - Prior thickness for node 3 in layer 2 (mm)
54. OldThick[3] - Prior thickness for node 4 in layer 3 (mm)
55. TEW - New total evaporable water (mm)
56. TAW - New total available water (mm)
57. TEW_old - Prior total evaporable water (mm)
58. TAW_old - Prior total available water (mm)
59. depth - Soil depth (mm)

2.3.13 Duration Output File (DUR)

If Ndur is greater than 1, DPWM creates the DUR output file. The DUR file contains a matrix [NCELL rows by NDAY columns) of the duration of precipitation for every day and every cell.

2.3.14 Binary File Output

If CellPrint in the IPM file is set to 2, DPWM generates output files containing daily values for every grid cell. The binary files generated are:

- Precipitation (mm) with file extension OPPT.
- minimum air temperature (°C) with file extension OTMIN.
- maximum air temperature (°C) with file extension OTMAX.
- average air temperature (°C) with file extension OTAVG.
- Reference evapotranspiration (mm) with file extension ORefET.
- Net radiation (Rn) on the inclined surface projected to a horizontal projection (MJ m^{-2} d^{-1}) with file extension ORn.

- Extraterrestrial radiation on a horizontal surface (Ra_hor) for a 24-hr period projection (MJ m^{-2} d^{-1}) with file extension ORa_hor.
- Clear sky solar radiation (Rso_hor) over the 24-hr period projection (MJ m^{-2} d^{-1}) with file extension ORso_hor.
- 'Measured' solar radiation (Rsm_hor) on a horizontal surface projection (MJ m^{-2} d^{-1}) with file extension ORsm_hor.
- Rs_equiv_hor - reproject Rsm_inc (total radiation received by the inclined surface) to a horizontal projection (equivalent) projection (MJ m^{-2} d^{-1}) with file extension ORs_equiv_hor.
- Basal crop coefficient (Kcb; unitless) with file extension OKcb.
- Evaporative crop coefficient (Ke; unitless) with file extension OKe. The reported Ke assumes that the evaporation reduction coefficient (Kr) is equal to one.
- Crop coefficient (Kc, unitless) with file extension OKc.

The values in the binary files are of float size (4 bytes) and are ordered by grid cell and then day (e.g., NCELL values are output for day one, then NCELL values are output for day two, etc.).

2.4 Initializing Routines

After DPWM loads the input data and opens the output files for writing, the *initialize* subroutine is called to calculate additional parameters. Input file units are converted to units of mm and days. The cdepth_fcn is called for each cell to calculate the thicknesses of the nodes from the total soil depth, as follows:

$$Thick_{1-4} = cdepth\_fcn(Depth, Ze, Zr_{veg}) \tag{1}$$

where $Thick_{1-4}$ = the thickness of Nodes 1 through 4 (mm)
Depth = the soil depth specified for the soil type of the cell converted to mm
Ze = the evaporation layer thickness (mm)
Zr = the rooting depth of the vegetation at the cell (mm)

If the vegetation index indicates that the cell is bare rock, the depth is set to the evaporation depth (Ze) to allow for surface storage and evaporation and the soil hydraulic conductivity is set to the bedrock hydraulic conductivity. For cells that are washes, the hydraulic properties of the soil are set to those specified for washes.

The maximum water level in each cell node is set based on the saturated water content and node thickness, as follows:

$$\theta s\_level_{1-4} = \theta s \cdot Thick_{1-4} \tag{2}$$

where θs_level_{1-4} = the water level equivalent to saturation in the node (mm)
θs = the saturated water content from the soil type at the cell

The water contents associated with the field capacity and wilting point capillary pressure heads are computed, as follows:

$$\begin{aligned} \theta_{FC} &= vg\_head\_to\_wc(\theta r, \theta s, \alpha, n, h_{FC}) \\ \theta_{WP} &= vg\_head\_to\_wc(\theta r, \theta s, \alpha, n, h_{WP}) \end{aligned} \tag{3}$$

where θ_{FC} = the field capacity water content
θ_{WP} = the wilting point water content, θr is the residual water content
θs = the saturated water content
α and n = the van Genuchten curve fitting parameters
h_{FC} = the field capacity capillary pressure head (cm) specified by the user
h_{WP} = the wilting point capillary pressure head (cm) specified by the user

The water levels equivalent to the field capacity and wilting point water contents are calculated as follows:

$$\begin{aligned} FC_{1-4} &= Thick_{1-4} \cdot \theta_{FC} \\ WP_{1-4} &= Thick_{1-4} \cdot \theta_{WP} \end{aligned} \tag{4}$$

where FC_{1-4} = the water level equivalent to the field capacity water content for Nodes 1 through 4 (mm)
WP_{1-4} = the water level equivalent to the wilting point water content for Nodes 1 through 4 (mm)

The FAO-56 parameters for total evaporable water (TEW) and total available water (TAW) are computed for each cell based on the equations in Allen et al. (1998), as follows:

$$\begin{aligned} TEW &= (\theta_{FC} - 0.5 \cdot \theta_{WP}) \cdot Thick_1 \\ TAW &= (\theta_{FC} - \theta_{WP}) \cdot (Thick_1 + Thick_3) \end{aligned} \tag{5}$$

where θ_{FC} = the field capacity water content
θ_{WP} = the wilting point water content

$Thick_1$ = the thickness of Layer 1 from Node 1 (Nodes 1 and 2 in Layer 1 have the same thickness and either could have been used here)
$Thick_3$ = the thickness of Layer 2 from Node 3

The initial water levels in each node of each cell are set based on the user specified capillary pressure heads in each node, as follows:

$$\theta_{1-4} = vg\_head\_to\_wc(\theta r, \theta s, \alpha, n, h_{i,1-4})$$
$$Wlevel_{1-4} = \theta_{1-4} \cdot Thick_{1-4} \tag{6}$$

where θ_{1-4} = the water content in Nodes 1 through 4 in each cell
θr = the residual water content
θs = the saturated water content
α and n = the curve fitting parameters
$hi_{,1-4}$ = the initial capillary pressure head for Nodes 1 through 4 specified by the user

Typically, the initial water levels are set to the wilting point in Nodes 1 through 3 and to field capacity in Node 4. The water in Node 4 is stagnant (will not drain or evapotranspire) when set at or below the field capacity.

After the initial properties have been calculated, they are printed to the output file check.txt or *.chk for verification.

2.5 Main Program Routine

The main program routine is the daily water balance calculation for each cell and for each day. For each day of the simulation, the program loops through all of the cells as ordered in the watershed file. The cells in the watershed file must be ordered so that no cell is below a cell that is downstream (the program checks that the order is correct and if not correctly ordered will stop execution).

Before the cell calculations, the program calculates the dewpoint offset (Koffset) if not given in the ICL file by using a harmonic function fit (KdewOffset_fcn), maximum relative humidity (TdewFromRHmax_and_Tmin), or a constant offset in IPM.

The routine for each cell for the day is as follows:

- Estimate minimum, mean and maximum air temperatures at the cell and for the average elevation in the watershed using either the temperature lapse rate in IPM or based on PRISM (T_elev_PRISM or T_elev_cor_fcn).

- Estimate the Growing Degree Days as the cumulative difference for each day between the mean air temperature at the cell and the minimum threshold temperature (TETMIN).

- Correct the windspeed for the elevation of the cell from the reference station.

- Adjust precipitation from reference station to cell elevation and location based on the precipitation lapse rate (Precip_elev_cor_fcn), the mean annual PRISM estimates of precipitation (Precip_elev_PRISM), or using the monthly estimate of precipitation from PRISM (PPT_PRISM_Monthly_fcn).

- Calculate the evaporation and transpiration coefficients (e.g., "crop" coefficients) in the subroutine AET_Fraction.

- Estimate the reference evapotranspiration adjusted for the slope and azimuth of the cell (RefET_fcn).

- Estimate the snow hydrology components using either the MASSIF (Snow_MASSIF), MASSIF and HELP (Snow_MASSIFHELP) or INFIL and HELP (Snow_INFILHELP) methodologies. If the MFMIN and MFMAX factors are less than or equal to zero in the IPM file, the snow hydrology functions are not implemented.

- Add the cumulative runon from upstream cells to the water available at the surface. The volume of runon is adjusted for the cell area.

- Estimate the quantity of runoff resulting from exceeding the saturated hydraulic conductivity of the soil. The saturated hydraulic conductivity of the soil is adjusted downwards to account for the fraction of the day when precipitation or snowmelt occurs. If there is snowmelt, the fraction of day for water available at the soil surface is set to 12 hours.

- The water balance routine DPWM_FC is implemented to estimate changes in soil water storage, evaporation, transpiration, net infiltration and additional runoff from exceeding the storage capacity of the soil.

- The volume of runoff is transferred to the downstream cell

The main program stores the cell balances for the day and prints daily balances to OCD and OCT output files. At the end of the daily balance for all of the cells, balances are summed for the watershed and printed to the OWD output file. At the end of the simulation, annual and average output files OWA, ORO, OSM, OCS and OCA are generated.

2.6 Balance Functions

2.6.1 BalanceFC_Kcb_fcn

This function calculates water redistribution between nodes for a cell using the field capacity method, and computes runoff and net infiltration. If precipitation or snowmelt occurs on a particular day, BalanceFC_Kcb_fcn is called twice—first for the duration of the precipitation/melting event and then for the balance of the day. If no precipitation or melting occurs, water in excess of the field capacity may yet exist in one or more nodes due to precipitation or melting on a previous day. For this case, BalanceFC_Kcb_fcn is called once for the entire day.

The initial step in the function is to reduce the soil and bedrock saturated hydraulic conductivities for the fraction of the day for the calculation, as follows:

$$Ksoil_{frac} = Ksoil \cdot fracDt$$
$$Krock_{frac} = Krock \cdot fracDt \tag{7}$$

where $Ksoil_{frac}$ = the reduced soil hydraulic conductivity (mm)
$Ksoil$ = the soil saturated hydraulic conductivity (mm/d)
$fracDt$ = the fraction of the day for the balance calculation (day)
$Krock_{frac}$ = the reduced bedrock saturated hydraulic conductivity (mm)
$Krock$ = the bedrock saturated hydraulic conductivity (mm/d)

The next step is to calculate the amount of water that can drain from Node 1 if the water level in Node 1 exceeds field capacity. Drainage is the minimum of the difference between the water level and field capacity or the reduced soil hydraulic conductivity. The water level in Node 1 is reduced for any drainage that occurs from Node 1, as follows:

$$Drain_1 = \min(Ksoil_{frac}, Wlevel_1 - FC_1) \geq 0$$
$$Wlevel_1 = Wlevel_1 - Drain_1 \tag{8}$$

where $Drain_1$ = the drainage from Node 1 (mm)
$Ksoil_{frac}$ = the reduced soil saturated hydraulic conductivity (mm)
$Wlevel_1$ = the water level in Node 1 (mm)
FC_1 = the water level equivalent of field capacity (mm)

Next, the drainage from Node 2 is calculated if the water level in Node 2 is greater than field capacity. Drainage is the minimum of the water level and field capacity drainage or the adjusted soil hydraulic conductivity, as follows:

$$Drain_2 = \min(Ksoil_{frac}, Wlevel_2 - FC_2) \geq 0$$
$$Wlevel_2 = Wlevel_2 - Drain_2 \tag{9}$$

where $Drain_2$ = the drainage from Node 2 (mm)
$Ksoil_{frac}$ = the adjusted soil saturated hydraulic conductivity (mm)
$Wlevel_2$ = the water level in Node 2 (mm)
FC_2 = the water level equivalent of field capacity (mm)

If drainage from Node 2 is less than the adjusted soil hydraulic conductivity and there is water in Node 1 in excess of the saturated water content water level (θs_level1), the excess water in Node 1 is transferred to Node 2 and drainage from Node 2 is recomputed, as follows:

$$\begin{aligned}
&Wlevel_2 = Wlevel_2 + Drain_2\\
&\Delta Wlevel_\max_1 = Wlevel_1 - \theta s_level_1\\
&\Delta Wlevel_\max_2 = Ksoil_{frac} - \max(Wlevel_2 - FC_2, 0)\\
&\Delta Wlevel_2 = \min\left(\Delta Wlevel_\max_1 \frac{1-f_c}{f_c}, \Delta Wlevel_\max_2\right)\\
&Wlevel_2 = Wlevel_2 + \Delta Wlevel_2\\
&Drain_2 = Wlevel_2 - FC_2 \geq 0\\
&Wlevel_2 = Wlevel_2 - Drain_2\\
&Wlevel_1 = Wlevel_1 - \Delta Wlevel_2 \frac{f_c}{1-f_c}
\end{aligned} \tag{10}$$

Similarly, if there is excess water in Node 2 and drainage in Node 1 is not at the maximum, water is transferred from Node 2 to Node 1 and Node 1 drainage is recomputed, as follows:

$$\begin{aligned}
&Wlevel_1 = Wlevel_1 + Drain_1\\
&\Delta Wlevel_\max_2 = Wlevel_2 - \theta s_level_2\\
&\Delta Wlevel_\max_1 = Ksoil_{frac} - \max(Wlevel_1 - FC_1, 0)\\
&\Delta Wlevel_1 = \min\left(\Delta Wlevel_\max_2 \frac{f_c}{1-f_c}, \Delta Wlevel_\max_1\right)\\
&Wlevel_1 = Wlevel_1 + \Delta Wlevel_1\\
&Drain_1 = Wlevel_1 - FC_1 \geq 0\\
&Wlevel_1 = Wlevel_1 - Drain_1\\
&Wlevel_2 = Wlevel_2 - \Delta Wlevel_1 \frac{1-f_c}{f_c}
\end{aligned} \tag{11}$$

Then the drainage from Nodes 1 and 2 in Layer 1 is added to the water level in Layer 2 (Node 3), as follows:

$$Wlevel_3 = Wlevel_3 + (1 - f_c)Drain_1 + f_c \cdot Drain_2 \tag{12}$$

Water in excess of field capacity Layer 2 (Node 3) is added to Layer 3 (Node 4), as follows:

$$\begin{aligned} Drain_3 &= Wlevel_3 - FC_3 \geq 0 \\ Drain_3 &= \min\left(Drain_3, Ksoil_{frac}\right) \\ Wlevel_3 &= Wlevel_3 - Drain_3 \\ Wlevel_4 &= Wlevel_4 + Drain_3 \end{aligned} \tag{13}$$

Water in excess of field capacity in Layer 3 (Node 4) becomes net infiltration, as follows:

$$\begin{aligned} Drain_4 &= \min(Wlevel_4 - FC_4, Ksoil_{frac}, Krock_{frac}) \geq 0 \\ Wlevel_4 &= Wlevel_4 - Drain_4 \\ Infil &= Drain_4 \end{aligned} \tag{14}$$

After net infiltration has been computed, any water in excess of the saturated water content in the layers is passed back up to the overlying layer. If water is in excess of the saturated water content in Layer 3 (Node 4), the excess water is added to Layer 2 (Node 3), as follows:

$$\begin{aligned} Wlevel_3 &= Wlevel_3 + \left(Wlevel_4 - \theta s\_level_4\right) \\ Wlevel_4 &= \theta s\_level_4 \end{aligned} \tag{15}$$

If water is in excess of the saturated water content in Layer 2 (Node 3), it is passed back up to Layer 1 and is proportioned between Nodes 1 and 2 based on the original drainage, as follows:

$$\begin{aligned} \Delta Wlevel_3 &= Wlevel_3 - \theta s\_level_3 \\ Wlevel_3 &= \theta s\_level_3 \\ Wlevel_1 &= Wlevel_1 + \frac{Drain_1}{\left[(1 - f_c)Drain_1 + f_c \cdot Drain_2\right]} \cdot \Delta Wlevel_3 \\ Wlevel_2 &= Wlevel_2 + \frac{Drain_2}{\left[(1 - f_c)Drain_1 + f_c \cdot Drain_2\right]} \cdot \Delta Wlevel_3 \end{aligned} \tag{16}$$

If the water level of Node 1 is greater than the saturation limit and the water level of Node 2 is below the saturation limit, the excess water in Node 1 is transferred to Node 2 up to the capacity of Node 2 before computing runoff, as follows:

$$
\begin{aligned}
&\Delta Wlevel\_\max_1 = Wlevel_1 - \theta s\_level_1 \\
&\Delta Wlevel_2 = \min\left(\Delta Wlevel\_\max_1 \frac{1-f_c}{f_c}, \theta s\_level_2 - Wlevel_2\right) \\
&Wlevel_2 = Wlevel_2 + \Delta Wlevel_2 \\
&Wlevel_1 = Wlevel_1 - \Delta Wlevel_2 \frac{f_c}{1-f_c}
\end{aligned}
\tag{17}
$$

Similarly, if the water content in Node 2 is greater than the saturated water content and the water level in Node 1 is less than the saturated water content, the excess water in Node 2 is passed to Node 1 up to the saturated water content of Node 1 before computing runoff, as follows:

$$
\begin{aligned}
&\Delta Wlevel\_\max_2 = Wlevel_2 - \theta s\_level_2 \\
&\Delta Wlevel_1 = \min\left(\Delta Wlevel\_\max_2 \frac{f_c}{1-f_c}, \theta s\_level_1 - Wlevel_1\right) \\
&Wlevel_1 = Wlevel_1 + \Delta Wlevel_1 \\
&Wlevel_2 = Wlevel_2 - \Delta Wlevel_1 \frac{1-f_c}{f_c}
\end{aligned}
\tag{18}
$$

Water in excess of the saturated water content in Nodes 1 and 2 is transferred to runoff, as follows:

$$
\begin{aligned}
&Runoff = Wlevel_1 - \theta s\_level_1 (1 - f_c) \\
&Wlevel_1 = \theta s\_level_1 \\
&Runoff = Runoff + (Wlevel_2 - \theta s\_level_2) f_c \\
&Wlevel_2 = \theta s\_level_2
\end{aligned}
\tag{19}
$$

The function returns the water levels in each of the nodes, runoff, and net infiltration.

2.6.2 DPWM_FC

The DPWM_FC function adds the water that infiltrates the soil surface to the water balances of the top layer of the cell (nodes 1 and 2). The function then calls the GroupBalance and ET_Kcb_fcn routines to compute the changes in soil water storage, net infiltration, runoff and evapotranspiration. DPWM_FC then tracks the total change in soil water storage and computes the relative root zone saturation (Sroot) that corresponds with METRIC. The Sroot computation is as follows:

If Kcb is greater than Kc_min, then transpiration is active and Sroot is computed based on the stress water level in the entire root zone thickness.

$$\begin{aligned} Root\_Wlevel &= Wlevel_1(1-f_c) + Wlevel_2 f_c + Wlevel_3 \\ MaxRoot\_Wlevel &= \theta s\_level_1 + \theta s\_level_3 \\ Stress\_Wlevel &= (FC\_Wlevel_1 + FC\_Wlevel_3) - \\ &\quad p[(FC\_Wlevel_1 + FC\_Wlevel_3) - (WP\_Wlevel_1 + WP\_Wlevel_3)] \end{aligned} \tag{20}$$

If Kcb is less than or equal to Kc_min, transpiration is inactive and only layer 1 is used for computing the stress water level:

$$\begin{aligned} Root\_Wlevel &= Wlevel_1(1-f_c) + Wlevel_2 f_c \\ MaxRoot\_Wlevel &= \theta s\_level_1 \\ Stress\_Wlevel &= (FC\_Wlevel_1) - p[(FC\_Wlevel_1 - WP\_Wlevel_1)] \end{aligned} \tag{21}$$

Where Root_Wlevel is the quantity of water available for transpiration or evaporation, MaxRoot_Wlevel is the saturated capacity of the layers 1 and/or 2, and the Stress_Wlevel is the water level in layer 1 and/or 2 where the transpiration begins reduction due to water stress. The water levels are converted to average water contents and the relative saturation (Sroot) is computed:

$$\begin{aligned} \theta_p &= Stress\_Wlevel / MaxRoot\_Wlevel * \theta s \\ \theta_{root} &= Root\_Wlevel / MaxRoot\_Wlevel * \theta s \\ \theta wp &= Wilt\_Layer_1 / \theta s\_Wlevel_1 * \theta s \\ S_{root} &= \frac{\theta_{root} - \theta_{wp}}{\theta_p - \theta_{wp}} \end{aligned} \tag{22}$$

Sroot is limited to values between 0 and 1. The output of Sroot is limited to be no less than the minimum reported by METRIC (~0.09).

2.6.3 GroupBalance

The *GroupBalance* function calls the balance model for the fraction of the day where precipitation, if any, occurs and for the non-precipitation fraction of the day. The function returns the total net infiltration and runoff for the cell for the day and updates the water levels in each node based on the balance model results.

2.6.4 WATERSHED_TABLE

This function linearly interpolates values of LAI from given values over the water year.

2.6.5 Balance_LUC

This function calculates changes in soil-water storage from a change in the vegetation type. This function calculates changes in the soil-water storage when the following conditions are all true:

- Land use changes are implemented (the ILC file is present)
- The day of the run matches a day for land use change specified in the ILC file
- The vegetation type in the ILC file is different from the current vegetation type.
- The cell has a change in rooting depth. In some case, the soil thickness may control the rooting depth and the change in vegetation type has no effect on the rooting depth at the cell.

The routine for updating the soil-water content in the root zone is as follows:

1. Calculate the rooting depth of the cell as the minimum of the soil depth or the new vegetation rooting depth
2. Calculate sum of water levels for all of the nodes in the interwash (SWlevelold_IW[0]) and the wash (SWlevelold_W[0]) using the prior water contents.
3. Calculate the water contents corresponding to field capacity, wilting point, and saturated water contents.

4. Calculate the new layer thicknesses using the cdepth_fcn function.
5. Calculate previous water content for node 4 (layer 3). Apply water content to new thickness of node 4.
6. The change in water level in node 4 (layer 3) is added to node 3 (layer 2).
7. Calculate previous water content for node 3 (layer 2). Apply water content to new thickness of node 3.
8. The change in water level in node 3 (layer 2) is added to node 4 (layer 3).
9. The saturated, field capacity and wilting point water levels are updated for all nodes based on the new thicknesses.
10. Total Available Water (TAW) and Total Evaporable Water (TEW) are updated based on the new root zone thickness.
11. Calculate sum of water levels for all of the nodes in the interwash (SWlevelold_IW[1]) and the wash (SWlevelold_W[1]) using the new water contents.
12. Check for mass balance errors where the difference between the prior and new sum of water levels is greater than 1e-03 mm.

Note that the thickness of layer 1 (nodes 1 and 2) does not change with a change in vegetation type.

2.7 Climate Functions

Code for the climate functions are contained in the file climate.cpp.

2.7.1 CellP_fcn

This function calculates the atmospheric pressure at a cell for a given elevation (Allen et al., 1998, Equation 7):

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{23}$$

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where P = the atmospheric pressure (kPa)
z = the elevation above sea level in meters

2.7.2 KdewOffset_fcn

This function calculates the dewpoint offset based on the day of the year. In arid climates, the dewpoint temperature is typically less than the daily minimum temperature. The DPWM allows for either a constant dewpoint offset from the daily minimum temperature or a harmonic fit to observed dewpoint offset from measurements of minimum relative humidity and temperature. The harmonic fit equation is as follows (after Boas, 1985, page 299):

$$Ko = \left(A \cdot \sin\left(\frac{2\pi}{L} (DOY - V) \right) \right) + C \qquad (24)$$

where A, L, V, and C = the fitted parameters of the harmonic function supplied by the user
DOY = the day of the year

If C is specified by the user as negative (or if A, L, and V are set to 1.0), the harmonic fit is not used and the absolute value of C is used as a constant offset.

2.7.3 PPT_PRISM_Monthly_fcn

This function uses the estimate of precipitation provided by PRISM for the month and year at the given cell (PPT_PRISM_Month). The monthly value is portioned into daily values based on the quantity of monthly precipitation that occurs at a reference station for the given day.

PPT_Cell = PPT_PRISM_Month * (PPT_Ref_Daily / PPT_Ref_Month) (25)

2.7.4 Precip_Elev_PRISM

This function uses the mean annual estimate of precipitation at the cell versus the reference station that is estimated by PRISM. The annual difference in precipitation between the two locations estimated by PRISM is divided into a daily value based on the quantities of daily and annual precipitation measured at the reference station. The quantity of precipitation cannot be less than zero.

PPT_Cell = (PPT_Ref_Daily + (PPT_Ref_Daily / PPT_Ref_Annual) * (PPT_PRISM_Cell - PPT_PRISM_Ref) (26)

Where PPT_Cell is the daily total precipitation at the cell (mm), PPT_Ref_Daily is the daily total precipitation at the reference station, PPT_Ref_Annual is the annual total precipitation at the reference station, PPT_PRISM_Cell is the mean annual precipitation estimated by PRISM for the cell, and PPT_PRISM_Ref is the mean annual precipitation estimated by PRISM for the reference station. Mean annual estimates of precipitation from PRISM are converted from values of inches in the input file IPZ to mm.

2.7.5 Precip_elev_cor_fcn

This function is the MASSIF implementation for adjusting the daily rate of precipitation for elevation in the watershed. This function estimates the precipitation at a cell for a given elevation based on the reference precipitation value for the day supplied by the climate file. The correction to precipitation for elevation is based on the slope of the correlation between precipitation and elevation supplied by the user. The elevation correction for precipitation is as follows:

$$P_{cell} = P_{ref}\left(1 + \left(elev_{cell} - elev_{ref}\right)Cprecip\right) \qquad (27)$$

where P_{cell} = the daily precipitation at the cell (mm)

P_{ref} = the reference precipitation supplied in the user file (mm)

$elev_{cell}$ = the elevation of the cell (m) supplied in the watershed file

$elev_{ref}$ = the elevation of the reference precipitation supplied in the parameter input file (m)

Cprecip = the correlation between precipitation and elevation (mm/m)

Although negative values for daily precipitation are not expected, this function is set to zero if the result is negative. The value of Cprecip is estimated by linear regression of observed mean annual precipitation (MAP) at climate stations. The slope of the regression equation is used to predict the MAP at the reference location. Cprecip is then the linear regression slope divided by the predicted MAP. The standard error of the lapse rate is obtained by the standard error of the regression slope parameter divided by the predicted MAP at the reference location. The nominal lapse rate for Yucca Mountain was 6.3%/100m (6.28E-04) with a standard error of 0.7%/100m. If the predicted precipitation is negative, the precipitation for the day at the cell is set to zero.

2.7.6 Psych_fcn

This function calculates the psychrometric constant, as follows (Allen et al., 1998, Equation 8):

$$\gamma = \frac{c_p P}{\varepsilon \lambda} \tag{28}$$

where γ = the psychrometric constant (kPa/°C)

c_p = the specific heat at constant pressure (1.013 x 10^{-3} MJ/(kg°C))

P = the atmospheric pressure

ε = the ratio of molecular weight of water vapor to dry air (0.622)

λ = the latent heat of vaporization (2.45 MJ/kg)

2.7.7 RH_min_fcn

This function calculates the daily minimum relative humidity from the daily dewpoint and maximum temperatures, as follows (Allen et al., 1998, Equation 10):

$$RH_{\min} = \frac{e0(Tdew)}{e0(T\max)} \cdot 100 \tag{29}$$

where RH_{min} = the daily minimum relative humidity

e0 = the function described above

Tdew = the daily dewpoint temperature (°C)

Tmax = the maximum daily temperature (°C)

2.7.8 T_dew_fcn

This function calculates the daily dewpoint temperature from the daily minimum temperature:

$$Tdew = T\min - Ko \tag{30}$$

where Tdew = the daily dewpoint temperature

Tmin = the daily minimum temperature from the climate input file

Ko = the dewpoint offset calculated from KdewOffset_fcn

1.1.1 T_elev_PRISM

This function uses PRISM monthly estimates of mean minimum and maximum air temperature at the cell and reference location. The offset is:

Offset = Temp_PRISM_Cell – Temp_PRISM_Ref (31)

The offset applies to the minimum and maximum temperatures from the reference station to obtain the temperature at the cell. This function also returns the mean daily air temperature as the simple average of the minimum and maximum air temperature and returns the dew point temperature from T_dew_fcn. This function is only used if bPRISM_TEMP is true in the input file IPM.

2.7.9 T_elev_cor_fcn

This function returns the minimum, maximum, average, and dewpoint temperatures for a cell. The minimum and maximum temperatures are estimated for the elevation of the cell from the reference minimum and maximum temperatures, as follows:

$$Tcell = Tref - (elev_{cell} - elev_{ref})C\_Tcor \tag{32}$$

where Tcell = the minimum or maximum temperature for the cell (°C)
Tref = the corresponding minimum or maximum reference temperature (°C)
$elev_{cell}$ = the elevation of the cell (m)
$elev_{ref}$ = the elevation of the reference temperature (m)
C_Tcor = the correlation between temperature and elevation

The average daily temperature for the cell is the average of the minimum and maximum temperatures estimated. The dewpoint temperature is calculated from the minimum daily temperature using the function *T_dew_fcn*.

2.7.10 TdewFromRHmax_and_Tmin

This function returns the dew point temperature based on the daily maximum relative humidity (RHmax)and the daily minimum air temperature (Tmin; Allen et al 2005).

$$Tdew = \frac{237.3\log\left(\frac{RH_{\max}}{100}\exp\left(\frac{17.27T_{\min}}{237.3+T_{\min}}\right)\right)}{17.27-\log\left(\frac{RH_{\max}}{100}\exp\left(\frac{17.27T_{\min}}{237.3+T_{\min}}\right)\right)} \tag{33}$$

2.7.11 e0

This function calculates the mean saturation vapor pressure as a function of air temperature (Allen et al., 1998, Equation 11):

$$e0 = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \tag{34}$$

where e0 = the saturation vapor pressure at the air temperature T (kPa)
T = the air temperature (°C)

2.7.12 ea_RH

This function estimates the actual vapor pressure (ea) in units of kPa from relative humidity and/or air temperature. If the daily minimum relative humidity is available, the function returns (Allen et al 1998, eq. 17):

$$e_a = \frac{e0(T_{\min})\frac{RH_{\max}}{100} + e0(T_{\max})\frac{RH_{\min}}{100}}{2} \tag{35}$$

If the minimum relative humidity is not available, this function returns (Allen et al 1998, eq 18)

$$e_a = e0(T_{\min})\frac{RH_{\max}}{100} \tag{36}$$

2.8 Evapotranspiration Functions

The evapotranspiration functions are contained in the ET.cpp and RefET.cpp files.

2.8.1 AET_Fraction

This function computes the transpiration coefficients based on leaf area index (LAI), METRIC, or growing degree days (GDD). LAI data can be supplied for each vegetation stage in the IPM file by vegetation type or from satellite data at regular intervals for each cell in the IMT file. Intermediate values of LAI are linearly interpolated using the WATERSHED_Table function.

Prior to selecting the LAI, METRIC or GDD method, this function computes air pressure at the cell with CellP_fcn, the psycrometric constant with Psych_fcn, the saturation slope with slope_es, the minimum relative humidity with RH_min_fcn, and the Kcb coefficient for full vegetation with KcbFull_fcn. Next, adjustments for stomatal control are estimated by linearly interpolating the rl values from the DPWM input file IPM using the TABLE_linear function and then calling the function for the resistance correction factor in Fr_fcn. Finally, the daily adjustment to Kcb for wind speed, relative humidity and plant height is estimated (Allen et al 1998, eq 62 and 100):

$$adjust = \left[0.04(u_2 - 2) - 0.004 \cdot (RH_{\min} - 45)\right]\left(\frac{h_{plant}}{3}\right)^{1/3}$$

(37)

2.8.1.1 LAI by Cell

If leaf area index (LAI) data are supplied for each cell in the imt file and bLAI is true in the IPM file, the AET_Fraction function will compute the crop coefficients as follows:

- The LAI for the cell is linearly interpolated from the supplied LAI table in the IMT file. If the LAI value is missing for the cell (indicated by a value less than or equal to zero), the LAI is set to 1.0. If the vegetation type for the cell is indicated to be rock, the LAI is set to zero.
- The Kcb is estimated by calling the LAI_to_Kcb function
- The Kcb is adjusted for stomatal control.
- If the average daily air temperature is less than or equal to the minimum or maximums for transpiration set in the IPM file (TETMIN or TETMAX), the Kcb is set to the value of Kc_min.

- The maximum Kcb (Kc_max) is computed from equation 72 in Allen et al 1998
- If the Kcb is greater than Kc_max, then the Kcb is set to Kc_max.
- If the fraction of ground cover is not constant, the fraction of ground cover is computed with equation 76 in Allen et al 1998.
- The evaporative fraction coefficient (Ke) is computed by calling the Ke_fcn function
- The single crop coefficient (Kc) is computed as the sum of Kcb and Ke.

2.8.1.2 METRIC EToF

If the evaporative fraction is supplied in the imt file from METRIC data, the daily value of EToF is linearly interpolated between measurements for the cell using WATERSHED_TABLE function. The procedure for the computing the crop coefficients is then:

- Kc is set equal to EToF estimated for the day and cell.
- Kc_max is computed from equation 72 in Allen et al 1998.
- The evaporative fraction (Ke) is the difference between Kc_max and Kc.
- The basal transpiration coefficient (Kcb) is the difference between Kc and Ke.
- If the average daily air temperature is less than or equal to the minimum or maximums for transpiration set in the IPM file (TETMIN or TETMAX), the Kcb is set to the value of Kc_min.
- If the fraction of ground cover is not constant, the fraction of ground cover is computed with equation 76 in Allen et al 1998.

- There is no stomatal adjustment made so Fr is set to 1.0
- The LAI is set to -999 for printing purposes.

2.8.1.3 Growing Degree Days

The growing degree days method for the crop coefficients computes the maximum crop coefficient (Kc_max) and then calls the Kcb_GDD function. The fraction of ground cover is computed with equation 76 in Allen et al 1998 and the evaporative fraction is computed with the Ke_fcn.

2.8.1.4 LAI by Vegetation Type and Growing Season

The procedure for estimating LAI by vegetation type and growing season is the same as for LAI by Cell except that LAI is linearly interpolated from input data in the IPM file.

2.8.2 Dc_fcn

This function calculates the depletion depth of the evaporative layer covered by vegetation canopy (Layer 1, Node 2).

$$Dc = \min\left(FC_2 - Wlevel_2, TEW\right) \geq 0 \tag{38}$$

where Dc = the depletion depth (mm)
FC_2 = the field capacity in Node 2
$Wlevel_2$ = the water level in Node 2
TEW = the total evaporable water

Depletion depth is a measurement of how far the water level in the node is below field capacity. When the water level in the cell is at or above field capacity, the depletion depth is zero. When the water level is at one-half the wilting point, the depletion depth is at a maximum equal to the total evaporable water (e.g., De_{max} = TEW = (FC – ½WP) in units of mm).

2.8.3 De_fcn

This function calculates the depletion depth of the bare soil fraction of the evaporative layer (Layer 1, Node 1):

$$De = \min\left(FC_1 - Wlevel_1, TEW\right) \geq 0 \tag{39}$$

where De = the depletion depth (mm)
FC_1 = the field capacity in Node 1
$Wlevel_1$ = the water level in Node 1
TEW = the total evaporable water

2.8.4 Dr_fcn

This function calculates the root zone depletion depth:

$$\begin{aligned} Dr &= \left[FC_1(1-f_c)+FC_2 f_c + FC_3\right]-\left[Wlevel_1(1-f_c)+Wlevel_2 f_c + Wlevel_3\right] \geq 0 \\ Dr &= \min\left(Dr, TAW\right) \end{aligned} \tag{40}$$

where Dr = the root zone depletion depth
FC = the field capacity for the specified node
f_c = the vegetation canopy cover fraction
Wlevel = the water level in the specified node
TAW = the total available water for transpiration in the root zone

Dr is always greater than zero and less than or equal to TAW.

2.8.5 ET_Kcb_fcn

The ET_Kcb_fcn calculates the amount of transpiration and evaporation from the cell for the day. If there is no soil or evaporative layer thickness, the evaporation and transpiration are set to zero. Otherwise, the transpiration and evaporation are computed. The depletion depth is calculated using the De_fcn for the bare soil fraction of Layer 1 (Node 1):

$$De = De\_fcn\left(FC_1, Wlevel_1, TEW\right) \tag{41}$$

where De = the depth depletion depth

where De = the depletion depth
FC_1 = the water level equivalent to field capacity in Node 1
$Wlevel_1$ = the water level in Node 1
TEW = the total evaporable water

Next, if the water level in Node 1 is greater than one-half the wilting point and there is no snow present, the evaporation from Node 1 is computed:

$$\begin{aligned}
Kr &= Kr_fcn(De, REW, TEW) \\
Ke &= Ke_fcn(Kr, Kc_{\max}, Kcb, f_c) \\
Evaporation &= \min(Ke \cdot RefET, (Wlevel_1 - 0.5WP_1)(1 - f_c))
\end{aligned} \tag{42}$$

where Kr = the dimensionless evaporation reduction coefficient
REW = the readily evaporable water
Ke = the soil evaporation coefficient
Kc_{max} = the maximum basal transpiration coefficient
Kcb = the basal transpiration coefficient
f_c = the canopy cover coefficient
RefET = the potential reference evapotranspiration
WP1 = the water level equivalent to the wilting point in Node 1

The evaporation is subtracted from the water level in Node 1, as follows:

$$Wlevel_1 = Wlevel_1 - \frac{Evaporation}{1 - f_c} \tag{43}$$

Next, transpiration is computed for Layers 1 and 2 (Nodes 1 through 3). The maximum transpiration possible from each node is calculated as follows:

$$\begin{aligned}
Transpire_\max_1 &= Wlevel_1 - WP_1 \geq 0 \\
Transpire_\max_2 &= Wlevel_2 - WP_2 \geq 0 \\
Transpire_\max_3 &= Wlevel_3 - WP_3 \geq 0
\end{aligned} \tag{44}$$

where $Transpire\_max_1$ through $Transpire\_max_3$ = the maximum transpirations from Nodes 1 through 3
$Wlevel_1$ through $Wlevel_3$ = the water levels in Nodes 1 through 3

WP_1 through WP_3 = the water level equivalents for the wilting point in Nodes 1 through 3.

The total maximum transpiration (Transpire_max) from the model cell is:

$$Transpire\_\max = Transpire\_\max_1 (1 - f_c) + Transpire\_\max_2 \cdot f_c + Transpire\_\max_3 \quad (45)$$

Transpiration is not limited to the canopy covered fraction and occurs in Layers 1 and 2 (Nodes 1 through 3) over the entire area of the cell. If Transpire_max is greater than zero, the actual total transpiration is computed. First the depletion depth for the root zone is calculated:

$$Dr = Dr\_fcn(FC_{1-3}, Wlevel_{1-3}, TAW, f_c) \quad (46)$$

Next, the unadjusted evapotranspiration is computed as follows (Allen et al., 1998, Equation 69):

$$ET_c = (K_e + Kcb)\, RefET \quad (47)$$

The water stress coefficient is as follows:

$$Ks = Ks\_fcn(Dr, TAW, ET_c, p) \quad (48)$$

where Ks = the transpiration reduction coefficient due to water stress
p = the fraction of the total available water (TAW) for transpiration that is readily available

Actual total transpiration is as follows:

$$Transpiration = \min(Ks \cdot Kcb \cdot RefET, Transpire\_\max) \quad (49)$$

The transpiration is then proportioned between the nodes using the extension to FAO-56 described by Allen et al. (2005b). If the water level in Node 1 is above the wilting point, Node 1 transpiration coefficient (Ktp) is:

$$Ktp = Ktp\_fcn(De, Dr, TEW, TAW, Thick) \quad (50)$$

where Thick = the thickness of each node

The transpiration from Node 1 is:

$$Transpiration_1 = \min(Ktp \cdot Transpiration, Transpire\_\max_1) \quad (51)$$

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Similarly, the transpiration from the fraction of Layer 1 covered by the vegetation canopy (Node 2) is calculated as follows:

$$\begin{aligned} &Dc = Dc\_fcn(FC_2, Wlevel_2, TEW) \\ &Ktpc = Ktpc\_fcn(Dc, Dr, TEW, TAW, Thick) \\ &Transpiration_2 = \min(Ktpc \cdot Transpiration, Transpire\_max_2) \end{aligned} \tag{52}$$

The transpiration from the root zone (Layer 2, Node 3) is:

$$Transpiration_3 = \min\left(Transpiration - Transpiration_1(1 - f_c) - Transpiration_2 f_c, Transpire\_max_3\right) \tag{53}$$

Next, the total transpiration is recalculated:

$$Transpiration = Transpiration_1(1 - f_c) + Transpiration_2 f_c + Transpiration_3 \tag{54}$$

The water levels are adjusted for transpiration, as follows:

$$\begin{aligned} Wlevel_1 &= Wlevel_1 - Transpiration_1 \\ Wlevel_2 &= Wlevel_2 - Transpiration_2 \\ Wlevel_3 &= Wlevel_3 - Transpiration_3 \end{aligned} \tag{55}$$

The function returns the updated water levels, total transpiration, and total evaporation.

2.8.6 Fr_fcn

This function calculates the stomatal resistance correction factor, as follows (Allen et al., 1998, Equation 102):

$$Fr = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_l}{100}\right)} \tag{56}$$

where Fr = the resistance correction factor
Δ = the slope of the saturation vapor pressure temperature relationship (kPa/°C)
u_2 = the mean daily wind speed at 2 meters above ground (m/s)
γ = the psychrometric constant (kPa/°C)

r_l = the mean leaf resistance (s/m)

The mean leaf resistance for the ET_0 reference grass and many agricultural crops is 100 s/m (Allen et al., 1998).

2.8.7 KcbFull_fcn

This function estimates the transpiration coefficient for natural vegetation with full ground cover during the peak of the growing season (Kcb_{full}). The first step is to estimate Kcb for full cover vegetation under sub-humid and calm wind conditions (Kcb_h), as follows (Allen et al., 1998):

$$Kcb_h = 1.0 + 0.1h \leq 1.20 \quad (57)$$

where h = the plant height

For vegetation greater than 2 meters in height, Kcb_h is limited to a value of 1.20 (Allen et al., 1998). Kcb_{full} is then estimated for the site climate conditions using Allen et al. (1998), Equation 100, as follows:

$$Kcb_{full} = Kcb_h + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \quad (58)$$

where u_2 = the daily mean wind speed (m/s)
RH_{min} = the daily minimum relative humidity
h = the plant height

2.8.8 KcbLAI_fcn

The basal transpiration coefficient is estimated from LAI as follows (Allen et al., 1998, Equation 97):

$$Kcb = Kc_{min} + \left(Kcb_{full} - Kc_{min}\right)\cdot\left(1 - \exp(-0.7 \cdot LAI)\right) \quad (59)$$

where Kc_{min} = the minimum Kc for bare soil (user input)
Kcb_{full} = the basal Kcb for peak plant height and cover (calculated in *Kcbfull_fcn*)
Kcb = the basal transpiration coefficient

The function then adjusts Kcb using the stomatal resistance adjustment as follows (Allen et al., 1998, p. 191-193):

$$Kcb = Kcb \cdot Fr \qquad (60)$$

where Fr = the stomatal resistance correction factor (Allen et al., 1998, Equation 102) calculated in the function *Fr_fcn*

2.8.9 Kcb_GDD

This function computes the Kcb based on the number of growing degree days (GDD) in the season. The GDD is set to zero at the beginning of the year (January 1) and whenever the mean daily air temperature is above the minimum for transpiration (TETMIN), the difference is accumulated as the GDD value for the day. The Kcb is estimated from GDD data using a 5th order polynomial (Brower 2008):

$$Kcb = a_0 + a_1 GDD + a_2 GDD^2 + a_3 GDD^3 + a_4 GDD^4 + a_5 GDD^5 \qquad (61)$$

The coefficients a0 through a5 are supplied for each vegetation type in the IPM file.

2.8.10 Ke_fcn

This function calculates the reduction in evaporation as the soil dries in the evaporative layer (Allen et al., 1998, Equation 71):

$$Ke = Kr\left(Kc_{\max} - Kcb\right) \le f_{ew} Kc_{\max} \qquad (62)$$

where Ke = the soil evaporation coefficient
Kr = the dimensionless evaporation reduction coefficient (calculated outside of this function by *Kr_fcn*)
Kc_{max} = the maximum value of Kc following rain or irrigation
Kcb = the basal crop coefficient
f_{ew} = the fraction of the soil that is both exposed and wetted

2.8.11 Kr_fcn

This function calculates the dimensionless evaporation reduction coefficient for the evaporative layer. If all of the water that is available for evaporation (TEW) has been depleted, then Kr is equal to zero. If the soil water in the evaporative layer exceeds the amount of readily evaporable water (REW), then Kr is equal to 1. Otherwise, Kr ranges from 0 to 1 based on the following equation (Allen et al., 1998, Equation 74):

$$Kr = \frac{TEW - De}{TEW - REW} \tag{63}$$

where De = the cumulative depth of evaporation (depletion) in the evaporative layer
REW = the readily evaporable water equal to the difference between the field capacity and one-half the wilting point

2.8.12 Ks_expfcn

This function returns the reduction factor for transpiration based on water stress of the vegetation using an exponential rate of decrease rather than the linear rate of decrease given in FAO-56 (e.g., Allen et al 1998; eq. 84). If the level of water in the root zone is less than the quantity of readily available water (RAW), the relative saturation in the root zone is computed as:

$$S = \frac{TAW - Dr}{TAW - RAW} \tag{64}$$

where TAW = the total available water for transpiration
Dr = the root zone depletion
RAW = the readily available water for transpiration

The transpiration reduction coefficient is then

$$Ks = \exp(Ks\_\exp(S - 1)) \tag{65}$$

where Ks_exp = the transpiration stress coefficient given in the IPM file. Currently, the Ks_power function is activated in DPWM and the Ks_expfcn is not active. See the ET_Kcb_fcn function in ET.cpp to change between the Ks_power and the Ks_expfcn functions.

2.8.13 Ks_power

This function returns the reduction factor for transpiration based on water stress of the vegetation using an power-law rate of decrease rather than the linear rate of decrease given in FAO-56 (e.g., Allen et al 1998; eq. 84). If the level of water in the root zone is less than the quantity of readily available water (RAW), the relative saturation in the root zone is computed as:

$$S = \frac{TAW - Dr}{TAW - RAW} \tag{66}$$

where TAW = the total available water for transpiration
Dr = the root zone depletion
RAW = the readily available water for transpiration

The transpiration reduction coefficient is then

Ks = S^Ks_exp (67)

where Ks_exp = the transpiration stress coefficient given in the IPM file. The value of Ks is limited to range between 0 and 1.

2.8.14 Ks_fcn

This function calculates the reduction in transpiration due to the depletion in water content in the root zone. The transpiration reduction coefficient (Ks) is calculated as follows (Allen et al., 1998, Equation 84):

$$Ks = \frac{TAW - Dr}{TAW - RAW} \tag{68}$$

where TAW = the total available water for transpiration
Dr = the root zone depletion
RAW = the readily available water for transpiration

The root zone depletion (Dr) is the difference between the field capacity water level and the root zone water level (see Dr_fcn in section 2.8.4). The Dr ranges between TAW and zero. RAW is computed from TAW as follows (Allen et al., 1998, Equation 83):

$$RAW = p \cdot TAW \tag{69}$$

where p = the average fraction of TAW that can be depleted from the root zone before moisture stress reduces ET

The value of p depends on the plant and the climate and ranges from 0.30 for shallow rooted plants under high ET to 0.70 for deep rooted plants with low ET. If bPadj is true, the DPWM adjusts the user-supplied value of p depending on ET, as follows (Allen et al., 1998; p. 162):

$$p_{adj} = p + 0.04(5 - ET_c) \tag{70}$$

where p = the user-supplied value
ET_c = the potential ET for the given plant

The value of p_{adj} is constrained to be between 0.1 and 0.8. If bPadj is false or if the user supplied value of p is negative, the absolute value is used as a constant rather than adjusting p with equation 70.

2.8.15 Ktp_fcn

This function implements one of the extensions to the FAO-56 method described by Allen et al. (2005b) where transpiration is proportioned between the evaporative layer and root layer depending on the water contents of each layer and the rooting depth of the vegetation. The function Ktp_fcn is for bare soil node of Layer 1 (Node 1). The proportion of basal transpiration extracted from the evaporative layer is as follows (Allen et al., 2005b, Equation 29):

$$K_{tp} = \left(\frac{1 - \frac{De}{TEW}}{1 - \frac{Dr}{TAW}} \right) \left(\frac{Ze}{Zr} \right)^{0.6} \tag{71}$$

where De = the cumulative depletion in Node 1 (bare soil fraction of evaporative layer)
Dr = the cumulative depletion in Node 3 (root layer)
TEW = the total evaporable water
TAW = the total available water
Ze = the evaporation layer depth
Zr = the rooting depth

2.8.16 Ktpc_fcn

This function implements the extension to the FAO-56 method where transpiration is proportioned between the evaporative layer and root layer. This function is virtually the same as Ktp_fcn except that Ktpc_fcn is for the fraction of the evaporative layer that is covered by the plant canopy (Node 2). The proportion of basal transpiration extracted from the evaporative layer is calculated as follows (Allen et al., 2005b, Equation 29):

$$K_{tp} = \left(\frac{1 - \dfrac{Dc}{TEW}}{1 - \dfrac{Dr}{TAW}} \right) \left(\frac{Ze}{Zr} \right)^{0.6} \qquad (72)$$

where Dc = the cumulative depletion in Node 2 (canopy covered fraction of evaporative layer)

Dr = the cumulative depletion in Node 3 (root layer)

TEW = the total evaporable water

TAW = the total available water

Ze = the evaporation layer depth

Zr = the rooting depth

2.8.17 LAI_daily_fcn

This function returns the leaf area index (LAI) linearly interpolated from data provided for the vegetation type in the IPM file. If the day of the calendar year is less than the start of development (Develop_Start), the LAI is set to the initial value (LAI_ini). Between the start of development and the start of the mid-season, the LAI is linearly interpolated between LAI_ini and the mid-season LAI (LAI_mid). Between the start of the mid-season and the end of the mid-season, the LAI is constant and set to the mid-season LAI. Between the end of the mid-season and the start of vegetation decline, the LAI is linearly interpolated between LAI_mid and LAI_late. After the start of the late season, the LAI is constant at the LAI_Late value.

2.8.18 LAI_to_Kcb

This function calculates the Kcb from leaf area index using equation 97 in Allen et al 1998. If the value of LAI is greater than 3 or if the estimated Kcb is greater than Kc_max, the function returns Kc_max.

2.8.19 slope_es_fcn

This function estimates the slope of the saturation vapor pressure curve (Allen et al., 1998, Equation 13):

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \tag{73}$$

where D = the slope of the saturation pressure curve (kPa/°C)
T = the air temperature (°C)

2.8.20 TABLE_Linear

This function linearly interpolates between values similar to the method in LAI_daily_fcn.

2.8.21 Varying_f_c_fcn

This function maintains the water balance as the sizes of Nodes 1 and 2 change with changing canopy cover. Node 1 represents the bare soil area of the evaporative layer while Node 2 is the remaining area of the cell covered by vegetation canopy cover. As the canopy cover changes, the corresponding volumes of Nodes 1 and 2 change and water must be transferred to maintain the water balance.

If the canopy cover fraction (f_c) decreases, the water level in Node 1 increases, as follows:

$$Wlevel_1 = \frac{(1-f_{c\_old})Wlevel_{1\_old} + (f_{c\_old} - f_c)Wlevel_{2\_old}}{1-f_c} \tag{74}$$

where $Wlevel_1$ = the new water level in Node 1 (mm)
f_{c_old} = the old canopy cover fraction
$Wlevel_{1\_old}$ = the old water level in Node 1 (mm)
$Wlevel_{2\_old}$ = the old water level in Node 2 (mm)
f_c = the new canopy cover fraction

The water level in Node 2 does not need to be changed when the canopy cover decreases to maintain the water mass balance in Layer 1.

If the canopy cover fraction increases, the water level in Node 2 increases, as follows:

$$Wlevel_2 = \frac{f_{c\_old} \cdot Wlevel_{2\_old} + \left(f_c - f_{c\_old}\right) Wlevel_{1\_old}}{f_c} \tag{75}$$

where $Wlevel_2$ = the new water level in Node 2 (mm)
f_{c_old} = the old canopy cover fraction
$Wlevel_{1\_old}$ = the old water level in Node 1 (mm)
$Wlevel_{2\_old}$ = the old water level in Node 2 (mm)
f_c = the new canopy cover fraction

The water level in Node 1 does not need to be changed when the canopy cover increases to maintain the water mass balance in Layer 1.

2.8.22 RefET_fcn

This function calculates the reference evapotranspiration adjusted for the slope and azimuth of the cell. Values of latitude, slope, and aspect provided in units of degrees are converted to radians at the beginning of RefET_fcn. The procedure is the same as that described by Allen and Trezza (2006).

Step 1: The mean daily dewpoint temperature is set to the reference dewpoint temperature:

$$Tdew = Tdew_{ref} \tag{76}$$

Step 2: The general, actual vapor pressure (ea) is calculated for use in the Penman-Monteith equation and for estimating precipitable water (W) over the watershed, as follows (Allen et al., 1998, Equation 14):

$$e_{a\_general} = 0.6108 \cdot \exp\left[\frac{17.27 \cdot Tdew}{Tdew + 237.3}\right] \tag{77}$$

$e_{a\_general}$ is in units of kPa. It is assumed that the entire air mass over the watershed has this actual vapor pressure.

Step 3: The inverse square relative distance between the earth and the sun (d_r) is then calculated for use in the Ra calculation, as follows (Allen et al., 1998, Equation 23):

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}DOY\right) \tag{78}$$

where DOY = the calendar day of the year between January 1 and December 31

Step 4: The declination of the earth (δ) is then calculated as follows (Allen et al., 1998, Equation 24):

$$\delta = 0.409\sin\left[\frac{2\pi}{365}DOY - 1.39\right] \tag{79}$$

Step 5: The sunset hour angle (w_s) for a horizontal surface is then calculated as follows (Allen et al., 1998, Equation 25):

$$\omega_s = ar\cos[-\tan(Latitude)\tan(\delta)] \tag{80}$$

where latitude = the average latitude of the watershed

Step 6: Extraterrestrial radiation on a horizontal surface for a 24-hour period (Ra_hor) is calculated as follows (Allen et al., 1998, Equation 21):

$$R_{a\_hor} = \frac{12(60)}{\pi}G_{sc}d_r[\omega_s \cdot \sin(Latitude)\sin(\delta) + \cos(Latitude)\cos(\delta)\sin(\omega_s)] \tag{81}$$

where G_{sc} = the solar constant (0.0820 MJ/(m^{2}min))
Latitude = the average latitude of the watershed

Step 7: The sine of mean solar elevation over a 24-hour period weighted by extraterrestrial radiation is calculated as follows (Allen et al., 2005a, Equation D-5):

$$\sin\beta_{24} = \sin\left[0.85 + 0.3Latitude \cdot \sin\left(\frac{2\pi}{365}DOY - 1.39\right) - 0.42(Latitude)^2\right] \geq 0.001 \tag{82}$$

The value of $\sin\beta_{24}$ is limited to values greater than 0.001 for numerical stability in Step 10.

Step 8: The mean atmospheric pressure for the reference weather station is calculated using the elevation of the weather station, as follows (Allen et al., 1998, Equation 7):

$$P_{ref} = 101.3\left(\frac{293 - 0.0065 Elev_{ref}}{293}\right)^{5.26} \quad (83)$$

where $Elev_{ref}$ = the reference elevation of the weather station

Step 9: Precipitable water (W) at the reference location is calculated as follows (Allen et al., 2005a, Equation D-3):

$$W = 0.14 \cdot e_{a\_general} \cdot P_{ref} + 2.1 \quad (84)$$

where W = the precipitable water over the watershed

Step 10: The 24-hour transmissivity for beam radiation is calculated as follows (Allen et al., 2005a, Equation D-2):

$$K_{Bo\_hor} = 0.98 \exp\left[\frac{-0.00146 P_{ref}}{K_{c\ln} \cdot \sin\beta_{24}} - 0.075\left(\frac{W}{\sin\beta_{24}}\right)^{0.4}\right] \quad (85)$$

where P_{ref} = the atmospheric pressure at the reference location (kPa)
W = the precipitable water in the atmosphere (mm)
Kcln = the atmospheric clearness (turbidity) coefficient

K_{cln} ranges from less than 0.5 for extremely turbid, dusty or polluted air to 1.0 for clean air.

Step 11: The 24-hour transmissivity for diffuse radiation is calculated as follows (Allen et al., 2005a, Equation D-4):

$$\begin{aligned} K_{Do\_hor} &= 0.35 - 0.36 K_{Bo\_hor} \quad for\ K_{Bo\_hor} \geq 0.15 \\ K_{Do\_hor} &= 0.18 - 0.82 K_{Bo\_hor} \quad for\ K_{Bo\_hor} < 0.15 \end{aligned} \quad (86)$$

Step 12: Clear sky solar radiation over the 24-hour period is calculated as follows (Allen et al., 2005a, Equation D-1):

$$R_{so\_hor} = \left(K_{Bo\_hor} + K_{Do\_hor}\right) R_{a\_hor} \quad (87)$$

Step 13: "Measured" solar radiation on a horizontal surface is estimated using Hargreave's method, as follows (Allen et al., 1998, Equation 50):

$$R_{sm\_hor} = k_{rs}\sqrt{T\max_{ref} - T\min_{ref}}\,R_{a\_hor} \le R_{so\_hor} \tag{88}$$

where R_{sm_hor} = the estimated "measured" solar radiation (MJ/(m^{2}d))
k_{rs} = the adjustment coefficient (typically 0.16 to 0.19)
$Tmax_{ref}$ = the maximum daily temperature at the reference location (°C)
$Tmin_{ref}$ = the minimum daily temperature at the reference location (°C)

Step 14: The total short-wave transmissivity (also known as clearness index) associated with the "measured" R_s value is calculated as follows (Duffie and Beckman, 1980, Equation 2.9.2):

$$\tau_{sw\_hor} = \frac{R_{sm\_hor}}{R_{a\_hor}} \tag{89}$$

Step 15: The atmospheric transmissivity in Step 14 is partitioned into its diffusive and direct beam components. The procedure as described by Trezza and Allen (2006) is adapted from Duffie and Beckman (1980, 1991), who cite Orgill and Hollands (1977). Allen and Trezza (2006) rearranged the equations and made minor modifications to match measured transmissivity data at Yucca Mountain.

$$\begin{aligned} K_{D\_hor} &= 0.12\tau_{sw\_hor} \quad \text{for } \tau_{sw\_hor} \ge 0.78 \\ K_{D\_hor} &= 1.557\tau_{sw\_hor} - 1.84\left(\tau_{sw\_hor}\right)^2 \quad \text{for } 0.35 < \tau_{sw\_hor} < 0.78 \\ K_{D\_hor} &= \tau_{sw\_hor} - 0.249\left(\tau_{sw\_hor}\right)^2 \quad \text{for } \tau_{sw\_hor} \le 0.35 \end{aligned} \tag{90}$$

Step 16: The actual direct beam transmissivity is calculated as the difference between total transmissivity and diffuse transmissivity, as follows (Allen, 1996, Equation 7):

$$K_{B\_hor} = \tau_{sw\_hor} - K_{D\_hor} \tag{91}$$

Step 17: The direct beam radiation on the horizontal surface is calculated based on the measured R_{sm_hor}, as follows:

$$I_{b\_hor} = K_{B\_hor} \cdot R_{a\_hor} \tag{92}$$

Step 18: The diffuse component of measured R_{sm_hor} for a horizontal surface is calculated as follows:

$$I_{d\_hor} = K_{D\_hor} \cdot R_{a\_hor} \tag{93}$$

Step 19: The albedo (α_T) is the value specified by the user or estimated for snow cover:

$$\alpha_T = albedo \tag{94}$$

Step 20: The ratio of beam radiation R_b on an incline to the beam radiation on a horizontal plane is calculated. Allen and Trezza (2006) suggest making a lookup table for many slope-aspect-day of year combinations, but the DPWM calculates the ratio exactly for the given slope-aspect and day of year combination.

Step 20a: The effective latitude for a given slope and aspect is calculated as described by Revfeim (1976; Equation 2):

$$\varphi_{eff} = \arcsin\left[\cos(s)\sin(\varphi) + \sin(s)\cos(\gamma + \pi)\right] \tag{95}$$

where φ_{eff} = the effective latitude
s = the slope in radians
φ = the average latitude for the watershed in radians
γ = the surface aspect angle in radians

Step 20b: Check whether surface receives any direct beam radiation during the day. If the cell does not receive any direct beam radiation (i.e., during winter on extreme northerly slopes), Rb is zero and the remaining Step 20 sub-steps are skipped:

$$if\ \varphi_{eff} - \delta \geq \frac{\pi}{2} \quad then\ Rb = 0 \tag{96}$$

where δ = the declination from Step 4

Step 20c: Set up for the solution of daily integration limits for beam (direct) radiation using Duffie and Beckman (1991). Parameter A for the slope-aspect combination is calculated as follows:

$$A = \cos(s) + \tan(\varphi)\cos(\gamma)\sin(s) \tag{97}$$

where s = the slope in radians
φ = the latitude in radians
g = the surface aspect angle in radians

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Step 20d: Parameter B for the slope-aspect combination and day of the year is calculated as follows:

$$B = \cos(\omega_s)\cos(s) + \tan(\delta)\sin(s)\cos(\gamma) \tag{98}$$

where w_s = the sunset hour angle from Step 5
s = the slope in radians
d = the solar declination from Step 4
g = the surface aspect angle in radians

Step 20e: Parameter C for the specified slope-aspect combination is calculated as follows:

$$C = \frac{\sin(s)\sin(\gamma)}{\cos(\varphi)} \tag{99}$$

Step 20f: The 24-hour integration limits on w_{sr} and w_{ss} for the Rb equation are calculated assuming that the sun appears only once during a 24-hour period:

$$\begin{gathered}
|\omega_{sr}| = \min\left[\omega_s, ar\cos\left(\frac{A\cdot B + C\sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right)\right] \\
\omega_{sr} = \begin{Bmatrix} -|\omega_{sr}|\, if\ (A > 0\, and\ B > 0\ or\ A \geq B) \\ |\omega_{sr}|\ \ otherwise \end{Bmatrix} \\
|\omega_{ss}| = \min\left[\omega_s, ar\cos\left(\frac{A\cdot B - C\sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right)\right] \\
\omega_{sr} = \begin{Bmatrix} |\omega_{sr}|\, if\ (A > 0\, and\ B > 0\ or\ A \geq B) \\ -|\omega_{sr}|\ \ otherwise \end{Bmatrix}
\end{gathered} \tag{100}$$

The program checks that the square root term (A2 - B2 + C2) is positive and that the arcos terms are within the domain bounds of –1 to 1. If the square root term is negative, w_{sr} = –w_s and w_{ss} = w_s. If one of the arcos terms is out of bounds, the respective integration limit is w_{sr} = –w_s and/or w_{ss} = w_s. Another check is performed before calculating Rb to prevent negative values of Rb. Negative values for Rb may occur under conditions of very low sun angles during the day (e.g., winter) on north-facing slopes. Negative values of Rb are prevented by changing the signs for the integration limits:

$$\begin{aligned} & if\ (A < B)\ and\ \gamma > 0\ then\ \omega_{sr} = -\omega_{sr} \\ & f\ (A < B)\ and\ \gamma < 0\ then\ \omega_{ss} = -\omega_{ss} \end{aligned} \tag{101}$$

Step 20g: The beam adjustment ratio Rb is calculated as follows:

$$Rb = \frac{\begin{aligned} & \sin(\delta)\sin(\varphi)\cos(s)(\omega_{ss} - \omega_{sr}) \\ & -\sin(\delta)\cos(\varphi)\sin(s)\cos(\gamma)(\omega_{ss} - \omega_{sr}) \\ & +\cos(\delta)\cos(\varphi)\cos(s)(\sin(\omega_{ss}) - \sin(\omega_{sr})) \\ & +\cos(\delta)\sin(\varphi)\sin(s)\cos(\gamma)(\sin(\omega_{ss}) - \sin(\omega_{sr})) \\ & -\cos(\delta)\sin(s)\sin(\gamma)(\cos(\omega_{ss}) - \cos(\omega_{sr})) \end{aligned}}{2(\cos(\varphi)\cos(\delta)\sin(\omega_s) + \omega_s \sin(\varphi)\sin(\delta))} \tag{102}$$

Step 21: The direct beam on the inclined surface for a given slope-aspect combination is calculated using the Rb adjustment factor from Step 20:

$$I_b = I_{b\_hor} \cdot Rb \tag{103}$$

where I_{b_hor} is from Step 17. I_b and I_{b_hor} have units of MJ/(m^{2}d).

Step 22: The anisotropic index is equivalent to the actual direct beam transmissivity (K_{B_hor}):

$$A_t = K_{B\_hor} \tag{104}$$

where K_{B_hor} is from Step 16.

Step 23: The modulating function f is calculated as follows:

$$f = \sqrt{\frac{I_{b\_hor}}{R_{sm\_hor}}} \tag{105}$$

where I_{b_hor} is from Step 21 and R_{sm_hor} is from Step 13.

Step 24: The diffuse component for the inclined surface is calculated as follows:

$$I_d = I_{d\_hor}\left[(1 - A_t)\left(\frac{1+\cos(s)}{2}\right)\left(1 + f \cdot \sin^3(s/2)\right) + A_t Rb\right] \tag{106}$$

Step 25: The reflected radiation component for the inclined surface is calculated as follows:

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$$I_r = R_{sm\_hor} \cdot \alpha_T \cdot \left(\frac{1 - \cos(s)}{2} \right) \quad (107)$$

where α_T = the albedo of the terrain (Step 19)
s = the slope in radians

Step 26: The total radiation received by the inclined surface is calculated as follows:

$$R_{sm\_inc} = I_b + I_d + I_r \quad (108)$$

where I_b = the beam radiation on the incline (Step 21)
I_d = the anisotropic diffuse radiation on the incline (Step 24)
I_r = reflected radiation from lower-lying terrain (Step 25)

Step 27: Reproject R_{sm_inc} to a horizontal projection (equivalent), as follows:

$$R_{s(equiv)\_hor} = \frac{R_{sm\_inc}}{\cos(s)} \quad (109)$$

Step 28: The mean saturation vapor pressure associated with the lapsed daily extreme temperature for the cell is calculated as follows:

$$e_s = \frac{e0(T\max_{cell}) + e0(T\min_{cell})}{2} \quad (110)$$

where $Tmax_{cell}$ = the maximum temperature for the cell (°C)
$Tmin_{cell}$ = the minimum temperature for the cell (°C)
e0 = the function described above

Step 29: The actual vapor pressure of the cell is limited to a value equal or greater than e_a from Step 2:

$$e_a = \min\left(e_{a\_general}, e_s\right) \quad (111)$$

Step 30: The slope of the saturation vapor pressure curve is calculated as follows:

$$\Delta = slope\_es\_fcn(Tavg_{cell}) \quad (112)$$

Step 31: The atmospheric pressure at the cell is calculated as follows:

$$P_{cell} = CellP\_fcn(Elev_{cell}) \tag{113}$$

Step 32: The psychrometric constant is calculated as follows:

$$\gamma_c = Psych\_fcn(P_{cell}) \tag{114}$$

Step 33: The horizontal equivalent for net short wave radiation on the incline is calculated as follows (Allen et al., 1998, Equation 38):

$$R_{ns} = (1 - \alpha_T) \cdot R_{s(equiv)hor} \tag{115}$$

Step 34: The net outgoing radiation is calculated as follows (Allen et al., 1998, Equation 39):

$$R_{nl} = \sigma \left[\frac{T\max_{cell,K}{}^4 + T\min_{cell,K}{}^4}{2} \right] \left(0.34 - 0.14\sqrt{e_a}\right) \left(1.35 \frac{R_{sm\_hor}}{R_{so\_hor}} - 0.35\right) \tag{116}$$

where R_{nl} = the net outgoing longwave radiation (MJ/(m^{2}d)) on a horizontal equivalent projection

s = the Stefan-Boltzmann constant at 4.903 x 10^{-9} MJ K^{-4} M^{-2} day^{-1}

$Tmax_{cell,K}$ = the maximum absolute temperature at the cell (°K)

$Tmin_{cell,K}$ = the minimum absolute temperature at the cell (°K)

e_a = the actual vapor pressure at the grid cell (kPa)

R_{sm_hor} = the measured or calculated solar radiation on a horizontal surface (MJ m^{-2} day^{-1})

R_{sm_hor} = the calculated clear-sky radiation on a horizontal surface (MJ m^{-2} day^{-1})

The ratio of R_{sm_hor}/R_{so_hor} is limited to values less than or equal to 1.

Step 35: Net radiation on the inclined surface projected to a horizontal projection is calculated as follows (Allen et al., 1998, Equation 40):

$$R_n = R_{ns} - R_{nl} \tag{117}$$

Step 36: The reference evapotranspiration (ET_0) is calculated as follows (Allen et al., 1998, Equation 6):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma_c \frac{900}{Tavg_{cell} + 273} u_2 (e_s - e_a)}{\Delta + \gamma_c (1 + 0.34 u_2)} \quad (118)$$

where ET_0 = the reference evapotranspiration (mm/d) for an inclined surface but expressed on a horizontal basis

R_n = the net radiation at the incline (but horizontal projection) (MJ m^{-2} day^{-1})

G = the soil heat flux density, which is zero for daily time steps

$Tavg_{cell}$ = the average temperature at the cell (°C)

u_2 = the wind speed at a 2-meter height provided from user input (m/s)

e_s = the saturation vapor pressure (kPa)

e_a = the actual vapor pressure (kPa)

$e_s - e_a$ = the saturation vapor pressure deficit (kPa)

Δ = the slope of the vapor pressure curve (kPa/°C)

γ_c = the psychrometric constant (kPa/°C)

2.9 Snow Functions

In all of the snow functions, if the mean daily air temperature is below freezing and precipitation occurs, the precipitation occurs as snow and is added as its water equivalent to the snow pack on the cell. Since air temperatures vary with elevation in the model, it is possible for precipitation to occur as snow in the higher elevations on a given day and as rain in the lower elevations. Any sublimation or snowmelt that occurs is removed from the snowpack. The quantity of sublimation or snowmelt is limited by the quantity of snowpack available.

2.9.1 Snow_INFILHELP

This function uses the sublimation function from the INFIL model (USGS 2008) and the snowmelt function from the HELP model Schroeder et al 1994. The INFIL sublimation methodology uses a fraction of the potential (or reference) evapotranspiration as the daily quantity of sublimation. If the temperatures are below freezing, the sublimation factor is set to SUBPAR1. If the temperatures are above freezing the sublimation factor is set to SUBPAR2.

Snow melt occurs when the temperatures are above freezing (0 C) based on equation 40 in the HELP model (Schroeder et al 1994). The rate of snow melt varies from MFMIN on December 21 to MFMAX on June 21.

2.9.2 Snow_MASSIFHELP

This function uses the MASSIF method for computing sublimation where the entire seasonal quantity of sublimation is removed from the snowpack on the day that the snowfall occurs at a specified fraction given by SUBPAR1 in the IPM file. Snow melt occurs when the temperatures are above freezing (0 C) based on equation 40 in the HELP model (Schroeder et al 1994). The rate of snow melt varies from MFMIN on December 21 to MFMAX on June 21.

2.9.3 Snow_MASSIF

This function uses the MASSIF method for computing sublimation and snow melt (SNL, 2007). The sublimation is computed for the snowfall on the day that the snow occurs as a specified fraction of the snowfall (SUBPAR1). The snowmelt occurs at a constant rate (MFMIN) based on the mean daily air temperature.

2.10 Soil Functions

2.10.1 Krel_fcn

This function calculates the relative permeability (K_{rel}) using the van Genuchten–Mualem equation. If the water content is less than the residual water content, K_{rel} is set to zero. Otherwise the relative permeability is calculated as follows (Selker et al., 1999):

$$K_{rel} = \sqrt{\frac{\theta - \theta r}{\theta s - \theta r}}\left[1 - \left(1 - \left(\frac{\theta - \theta r}{\theta s - \theta r}\right)^{\frac{1}{m}}\right)^{m}\right]^{2} \tag{119}$$

where θ = the water content of the node (L^3/L^3)

θr = the residual water content (L^3/L^3)

θs = the saturated water content (L^3/L^3)

m = the dimensionless van Genuchten exponent

2.10.2 Ktheta_fcn

The *Ktheta_fcn* estimates the unsaturated hydraulic conductivity based on the relative permeability calculated by the function *Krel_fcn*. The unsaturated hydraulic conductivity as a function of water content [K(θ)] is estimated as follows:

$$K(\theta) = Ksat \cdot Krel\_fcn \tag{120}$$

where Ksat = the saturated hydraulic conductivity

If the water level is greater than the thickness of the layer, K(θ) is set to Ks. Assuming a unit gradient, the rate of drainage from the layer is equivalent to the unsaturated hydraulic conductivity. This function is used in the VGM balance model.

2.10.3 cdepth_fcn

This function calculates the depth of each layer in a cell based on the total thickness of the cell. If the total thickness of the cell is less than evaporation layer thickness (Ze, specified by user), the thickness of Layer 1 (Nodes 1 and 2) is set to the total thickness and the thicknesses of Layers 2 (Node 3) and 3 (Node 4) are set to zero. If the total thickness is greater than the evaporation layer thickness but less than the rooting depth, the thickness of Layer 1 is set to the evaporation layer thickness, the thickness of Layer 2 is set to the difference between the total soil thickness and the evaporation layer thickness, and Layer 3 thickness is set to zero. If the soil thickness is greater than the rooting depth, Layer 1 is set to the evaporation layer thickness, Layer 2 is set to the rooting depth minus the evaporation layer thickness, and Layer 3 is set to the total thickness minus the rooting depth. This function is called once for each cell during the calculation of initial properties.

2.10.4 vg_head_to_wc

This function calculates the water content for a given capillary pressure using the van Genuchten equation:

$$\theta = \frac{(\theta s - \theta r)}{\left(1 + [\alpha \cdot h_c]^n\right)^m} + \theta r \tag{121}$$

where θ = the water content (L^3/L^3)
θs = the saturated water content (L^3/L^3)

θr = the residual water content (L^3/L^3)

α and n = the van Genuchten curve fitting parameters (1/L and unitless, respectively)

m = the van Genuchten curve parameter calculated as m = 1 – 1/n

h_c = the capillary pressure (L)

This function is used to estimate water contents for the field capacity and wilting point pressure points.

2.10.5 vg_wc_to_head

This function calculates the capillary pressure for a given water content based on the van Genuchten equation. This equation is not directly used to calculate water balance components in the DPWM but is provided to output average capillary pressures associated with water contents in the cell nodes:

$$h_c = \frac{1}{\alpha}\left[\left(\frac{\theta - \theta r}{\theta s - \theta r}\right)^{-\frac{1}{m}} - 1\right]^{\frac{1}{n}} \qquad (122)$$

where hc = the capillary pressure

α and n = the van Genuchten curve fitting parameters

m = the van Genuchten curve parameter estimated from n as m = 1 – 1/n

θ = the water content

θr = the residual water content

θs = the saturated water content

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List of All Variables

x xxxx [units]