Soil Water Balance Recharge Estimates for the Thurston County Groundwater Model

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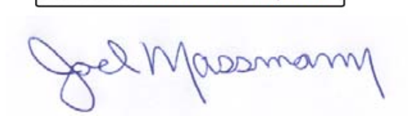

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A. INTRODUCTION AND OVERVIEW

The purpose of this study is to calculate a daily time series of ground water recharge in the area included in the Thurston County Groundwater Model. This time series can be used as an input to the Thurston County Model to estimate how groundwater levels and groundwater flows vary through time over seasons and years. The area included in the study is shown in Figure 1. The study area covers approximately 980 mi^2 in Thurston County, Washington and includes the Deschutes River watershed, which drains an area of approximately 160 mi^2. Estimates of daily recharge rates over the model area were developed for the period October 1, 1990 through September 30, 2014 using the USGS Soil Water Balance (SWB) model.

Results from the modeling effort described in this report include the following:

- The estimated average recharge rate for modeled area for the period October 1, 1990 through September 30, 2014 is 20.2 inches per year or 1,455 cfs.
- Long-term averages of simulated recharge from the SWB model are similar on a model-wide scale to previous estimates based on regressions between recharge and annual precipitation (Bidlake and Payne, 2001). The average rate over the model area from the Bidlake-Payne estimates is 21.18 inches, which is approximately 4.7% higher than the SWB estimates.
- The SWB and Bidlake-Payne recharge estimates show generally similar patterns in terms of the spatial distribution of recharge. The largest differences occur in the extreme southeast part of the model and in the northwest part of the model near the Black Hills. The SWB estimates are considerably higher in the Black Hills area and are considerably lower in the southeast part of the model (outside the Deschutes basin).
- The total wastewater recharge in the model area based on data provided by Thurston County equals 27 cubic feet per second (cfs). This is equivalent to approximately 2% of the total estimated recharge.
- The SWB estimates of recharge and runoff have been compared with streamflow data collected by the USGS on the Deschutes River. The comparison is made at two locations: the gauge near Rainier (USGS gauge 12079000) and the gauge the E Street Bridge (USGS gauge 12080010).
- The stream flow variables that are most directly comparable are the long-term average streamflow values from the USGS gauges versus the sum of baseflow and runoff from SWB. The SWB results are approximately 2.6% higher for the Rainier gauge and 0.9% higher for the E-Street gauge. These differences are quite small, considering the uncertainty and variability associated with the SWB input parameters.

- Additional comparisons of streamflow data and SWB results could be made for smaller streams to further check and calibrate the SWB results. These comparisons were beyond the scope of the current project.
- The SWB results were developed using 2006 landcover data. The effects of changes in landcover could be evaluated using available data for 2010 and 2016.

B. METHODS

Groundwater recharge was calculated using the Soil-Water-Balance (SWB) code developed by the U.S. Geological Survey (Westenbroek et al., 2010). This code was developed explicitly for calculating spatially- and temporally-varying ground water recharge. Input to the model includes land-use type, soil type, surface-water flow direction[1], temperature, and precipitation. The model employs a water-balance approach to calculate recharge. The approach used in the SWB model is summarized in the paragraphs that follow. Details of the methodology are described in Westenbroek et al. (2010).

The SWB model assumes that rain falling as precipitation (P) can be:

1. Intercepted by vegetation. Each land use type has a unique value for the maximum amount of precipitation that can be intercepted, for both the growing season and non-growing seasons.

2. Partitioned to flow out of the grid-cell as runoff. Runoff is calculated using the Natural Resources Conservation Service (NRCS) curve number rainfall-runoff relationship (Cronshey, 1986). This relationship varies the amount of precipitation that is partitioned to runoff according to land-use, soil type, and recent precipitation history.

3. Evapotranspired to the atmosphere. Evapotranspiration (ET) is the sum of water evaporated from bare soil and transpired from plants. Under well-watered conditions (i.e., when $P > ET$), ET is calculated using the approach described in Hargreaves and Samani, 1985). When there is a deficit between evapotranspiration and precipitation (i.e., when $P < ET$), ET is calculated using the change in soil moisture following Thornthwaite and Mather (1957).

4. Stored in the soil column as soil moisture. Any remaining precipitation that was not intercepted, partitioned to runoff, or evapotranspired, is stored in the soil column.

[1] Surface-water flow direction is defined for each model grid cell as the direction excess surface runoff would flow. This direction can be any of the 8 grid cells neighboring a given grid cell, and is calculated from a digital elevation model.

5. Sent to the groundwater aquifer as recharge. Each soil column has a maximum water capacity. Once soil water storage reaches this maximum water capacity, any additional water entering the soil column will leave as groundwater recharge.

In addition to the above processes, the model also moves runoff water among grid cells according to a surface water flow direction map defined at each grid-cell. Water is sent from uphill grid cells to downhill grid cells. This water can be either stored in the soil column or sent to the aquifer as recharge in the case that soil moisture is at its maximum water capacity. Finally, each grid cell has a maximum recharge amount, which is a function of land-use and soil type. Water in excess of this maximum recharge amount is partitioned to runoff.

Annual average recharge rates calculated from the monthly recharge rates derived using SWB are compared to the steady-state values used in the Thurston County Model. These steady-state values were calculated using regression equations described in Bidlake and Payne (2001). The Bidlake and Payne regression is the most commonly-used approach for estimating steady-state recharge for regional groundwater flow models developed in the western Washington by the U.S. Geological Survey and other agencies (e.g., Frans and Olsen, 2016; Frans et al., 2011; Johnson et al., 2011; Jones et al., 2011).

C. INPUT DATA

The SWB model incorporates meteorological data, land-use data, soil survey data, and a digital elevation model to derive groundwater recharge estimates. These data are summarized below. Attachment A includes maps showing the spatial distribution of input data derived from land-use data, soil survey data, and the digital elevation model.

C.1. Model grid

Figure 1 shows the active model grid outline for the MODFLOW model. The model contains grid cells with dimensions 200 ft x 200 ft. There are 681,021 active cells. The origin for the model grid is set at X=915,200,Y=485,000 (units are feet). The projected coordinate system used is NAD83 Washington South ft US. The geographic coordinate system is GCS North American 1983

The SWB grid covers the same area as the MODFLOW grid but is comprised of cells with dimensions 600 ft x 600 ft. This results in 417 rows and 477 columns and a total of 198,909 cells. The number of active cells in the SWB grid is 75,669.The origin for the SWB grid is the same as the MODFLOW model.

Land surface elevations were obtained from the MODFLOW model and represent the elevation in the model that corresponds to the X and Y coordinate for the SWB cells. (Note: Each SWB cell contains 9 MODFLOW cells. The elevations assigned to the SWB cell is the elevation of the MODFLOW cell at the center of the SWB cell.) Elevations for cells in the inactive model area are set to -9999.

C.2. Meteorological data: temperature and precipitation

Meteorological input data to the model include daily maximum and minimum temperature and daily precipitation values. Estimates of these meteorological variables over the model grid were derived using data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM 2021). PRISM generates a daily data product, but at relatively coarse 4km resolution. To account for variability at smaller spatial scales, the coarser resolution daily estimates were downscaled using PRISM 30-year climate normals (800 m resolution). Finally, these higher resolution data were re-sampled to the model grid using a cubic spline (GDAL 2020), providing smoothly varying meteorological fields consistent with topography-induced variability at relatively high spatial resolution.

C.3 Landcover

Landcover data were downloaded from NOAA's Coastal Change Analysis Program (NOAA, 2016).[1] Data were downloaded for 2006, 2010, and 2016. These are the only datasets available in the model area. The 2006 data were used for the SWB model. Table 1 summarizes the number of active cells in which the landcover changed between 2006 and 2016.

Figure 2 illustrates the distribution of these landcovers. The NOAA landcover classifications do not always correspond directly to land-use classifications used in SWB (Westenbroek et al., 2010; Cronshey, 1986), so classifications are adjusted to best match those used by SWB, as described in Table 2.

C.4 Soils

SWB requires information on the National Resources Conservation Service (NRCS) hydrologic soil type and the maximum water capacity. Data describing soils in the active model area were downloaded from the U.S. Department of Agriculture's (USDA) National Cooperative Soil Survey (NCSS) website.[2] The following soils data were extracted for the active model area: 1) soil type, 2) drainage descriptor, and 3) available water storage. These are described below.

Soil type. Table 3 lists the soil type included in the USDA's database and the percentage of the model area in which these soils occur. Locations with water were assigned a soil type "0." A small number of the model cells (289 cells or 0.3%) did not have a USDA soil type. For these locations where there were no soil type data in the database, the soil

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[1] Data were downloaded April 27, 2020 from https://catalog.data.gov/dataset/noaas-coastal-change-analysis-program-c-cap-2016-regional-land-cover-data-coastal-united-stateb5489

[2] Data were downloaded April 28, 2020 from https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

type was assigned based on the description of the soil (e.g., "river wash" was assigned a soil type A). The distribution of soil types over the active model area is shown in Figure 3.

Drainage descriptor. The drainage descriptor values are derived from the USDA database and are summarized in Table 4 and are shown in Figure 4. These descriptors were used to modify the NRCS soil type, as described in Table 4. As an example, if the NRCS soil group was assigned a value of "B" but the USDA drainage description was listed as "poorly drained," the NRCS soil group was shifted to a value of "C." Similarly, if the NRCS soil group was assigned a value of "C" but the USDA drainage description was listed as "somewhat excessively drained," the NRCS soil group was shifted to a value of "B." This approach was used to reduce discrepancies between the drainage descriptors and the soil group identifiers.

Available water storage. The available water storage (AWS) value is defined as the volume of water that the soil, to a prescribed depth, can store that is available to plants. AWS is calculated from available water capacity (AWC), which is commonly estimated as the difference between the water contents at 1/10 or 1/3 bar (field capacity) and 15 bars (permanent wilting point) tension. AWS is computed as AWC times the thickness of the soil. For example, if AWC is 0.15 cm/cm, the available water storage for 25 centimeters of soil would be 0.15 x 25, or 3.75 centimeters of water. AWS is reported as the weighted average of all components in the map unit, and is expressed as centimeters of water.

Available water storage values are derived from the USDA database. For locations where there were no descriptors in the USDA database (0.4% of the model cells), the AWS parameter was assigned based on the description of the soil. These descriptions included primarily rock outcrops. A drainage descriptor of "0" was assigned to these locations.

Four AWS values are given for each location, corresponding to the available water storage to a depth of 25, 50, 100, and 150 cm. The percentiles for the various depths are listed in Table 5. These percentiles are calculated over the full active model grid. Figure 5 shows the distribution of the 25-cm AWS values over the active model area. The 25-cm values were used in the SWB input.

C.5 Flow direction

The SWB model allows over-land flow routing to direct surface runoff to particular locations. Runoff from individual cells is assumed to infiltrate in downslope cells or be routed out of the model domain on the same day in which it originated as rainfall or snowmelt.

Flow directions were calculated using 1-arc second (30 meter) tifs downloaded from the USGS website.[1] (Directions were initially calculated using 1/3-arc second tifs, but this

[1] https://viewer.nationalmap.gov/basic/#productSearch.

higher level of resolution resulted in very slow computations and file sizes that exceeded 2GB). The flow directions were calculated using the Flow Direction tool under ArcMap's Spatial Analyst Tools/Hydrology menu. The resulting flow direction raster was sampled at the X and Y points corresponding to the center of the model grid cell.

The SWB results that are discussed below did not include the flow routing option because the resolution of this model (600 ft grid cells) was too large to adequately represent routing of surface water. Surface runoff that leaves a cell is assumed to immediately leave the model area. As a result, the estimated recharge estimated may be underestimated by the model because surface runoff did not have an opportunity to recharge within downstream cells.[1]

C.6 Recharge from reclaimed water and septic systems

Estimates of recharge from reclaimed water and septic systems within the Thurston County Model were provided in an Excel file by Thurston County (Kevin Hansen, personal communication[2]). The Excel file includes wastewater recharge rates in units of ft/day for 31,998 MODFLOW model cells. The recharge rates in ft/day were multiplied by the area of each MODFLOW cell (200 ft x 200 ft) to obtain recharge rates in ft3/day for each cell. The recharge rates were then assigned to the SWB model grid (600 ft x 600 ft) by summing the values for the nine MODFLOW cells that correspond to each SWB cell. Figure 6 illustrates the spatial distribution of the wastewater recharge.

The total wastewater recharge in the steady-state model equals 27 cubic feet per second (cfs). This is equivalent to approximately 2% of the total estimated recharge. Because the wastewater recharge is a relatively small fraction of the total recharge, it is assumed the recharge rates from precipitation are not affected by the recharge from wastewater. Total recharge estimates for individual model cells can be obtained by directly adding the wastewater recharge to the SWB results. The SWB results that are described below do not include the wastewater values.

D. RESULTS AND COMPARISON TO PREVIOUS WORK

The SWB model was used to develop estimates of daily recharge over the model area for the period October 1, 1990 through September 30, 2014. The results are described below using several different metrics.

D.1. Annual average recharge rates

[1] It should be noted that flow routing was also not used in the recent work by the USGS in the Chehalis River Basin because of the grid size (Gendaszek and Welch, 2018). The study area in the Chehalis River study was divided into 500-ft grid cells consisting of 378 rows and 546 columns, which is similar to the current Thurston County SWB model.

[2] The file name is "Wastewater_ONLY_recharge_2020-06-25 kh.xlsx."

Figure 7 shows the spatial distribution of recharge rates averaged from October 1, 1990 through September 30, 2014. The average rate is 20.21 inches per year which is equivalent to 1,455 cfs. The highest rates occur in the higher elevation areas, including the northwest part of the model near the Black Hills and in the upper reaches of the Deschutes watershed in the southeast part of the model. Maps showing the calculated mean monthly recharge rates and the mean monthly evapotranspiration rates derived using SWB are presented in Attachment A.

Recharge is greatest during the wet season, from November to March. As the wet season subsides and solar heating increases, evapotranspiration increases. By June and July, evapotranspiration is limited by water availability, as evidenced by increasing spatial heterogeneity of ET (e.g. Figure A7). Soils with large water holding capacity can maintain evapotranspiration, while soils with lower water holding capacity cannot. This large-scale drying of soils results in almost no groundwater recharge across the model domain, until September when the likelihood of pre-wet-season storms increases. Recharge steadily increases through November, while ET decreases with decreasing solar heating and energy availability.

D.2. Comparison with recharge values from steady-state MODFLOW model

Recharge rates from the steady-state MODFLOW model are shown in Figure 8. These rates are estimated using regressions described in Bidlake and Payne (2001).[1] The average rate over the model area from the Bidlake-Payne estimates is 21.18 inches, which is approximately 4.7% higher than the SWB estimates.

A comparison of Figures 7 and 8 show generally similar patterns in terms of the spatial distribution of recharge. Figure 9 illustrates differences between annual average recharge rates calculated from the SWB model and the steady-state rates from the Bidlake-Payne regression. Positive values indicate areas where SWB rates are greater than Bidlake-Payne rates. The largest differences occur in the extreme southeast part of the model and in the northwest part of the model near the Black Hills. The SWB estimates are considerably higher in the Black Hills area and are considerably lower in the southeast part of the model (outside the Deschutes basin).

The differences shown in Figure 9 perhaps reflect the utility of using a model such as SWB which more directly accounts for the processes impacting recharge. The Bidlake and Payne regressions are useful for generating first-order estimates of recharge given geological information and precipitation data. Linear relationships between annual precipitation and recharge are assumed, with a different relationship for fine grained soils, urban land, and forested and non-forested vegetation over coarser grained soils. SWB improves on this approach primarily in two ways: 1) it accounts for a much broader

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[1] The steady-state recharge estimates were extracted from the Thurston County MODFLOW model entitled "TC_GW_Model_135_PEST." The rates from the model include wastewater recharge from septic systems and reclaimed water facilities, as described in Section C.6 above. The wastewater recharge values were subtracted from the MODFLOW rates to obtain estimates of average or steady-state recharge due to precipitation.

spectrum of soil types and land-use types, and combinations of the two, and 2) it uses physically-based calculations to determine the relationship between recharge and precipitation, which we expect may not be exactly linear with annual precipitation amount. If recharge is viewed from a water balance perspective, it is given as:

$$R = P - (ET + RO)$$

where R is recharge, P is precipitation, ET is evapotranspiration, and RO is runoff.

Assuming a linear relationship between R and P assumes that the varying portion of ET plus RO are some fraction of annual precipitation. However, both quantities have more complicated relationships with precipitation. In the case of ET, ET is energy-limited during the wet season (November-March) when water is abundant but solar energy is not. So for the wet season, ET will be more a function of energy availability than precipitation. For the dry season, ET is limited by water. However, this water availability will be largely determined by water holding capacity of the soil, and the timing of late wet-season storms, or the frequency of anomalous dry season rains, all of which are explicitly accounted for in SWB, and might not be directly correlated with total annual amount of precipitation. Similarly, the fraction of precipitation that becomes surface runoff might vary with the frequency and intensity statistics of precipitation rather than just the absolute annual amount of precipitation. Years characterized by a few closely-bunched, high-intensity storms should have a higher fraction of runoff because saturated soils have lower infiltration rates and high intensity storms are more likely to exceed these infiltration rates. Conversely, years characterized by many but well-spaced, low-intensity events should have a smaller fraction of runoff, as antecedent soil moisture conditions should be drier and lower rainfall rates are more likely to be below infiltration rates. SWB can account for these effects: larger daily events (higher intensity) will have a larger fraction of runoff, and closely bunched events (within a 5 day period) will also have a higher fraction of runoff.

The NRCS rainfall-runoff curves that parameterize these effects use their own simplifications with inherent weaknesses, but they still capture the general relationships between runoff and precipitation. By incorporating additional physical processes, estimates of ground water recharge derived using SWB represent a likely improvement over simpler regression methods such as those used in Bidlake and Payne (2001).

D.3. Comparison with streamflow data

The SWB estimates of recharge and runoff have been compared with streamflow data collected by the USGS on the Deschutes River. The comparison is made at two gauge locations: the gauge near Rainier (USGS gauge 12079000) and the gauge the E Street Bridge (USGS gauge 12080010). The drainage areas for these two gauges are 89.8 square miles for Rainer and 162 square miles for E Street. Streamflow data collected between October 1, 1990 and September 30, 2014 were used. This time period corresponds with the period used in the SWB model. These two locations were chosen for the comparison because data are available for the full simulation period and the .

Estimates of baseflow were derived directly from USGS data collected using the BFLOW algorithm (Arnold et al., 1995; Arnold and Allen, 1999). The BFLOW algorithm uses multiple passes to estimate baseflow. The authors indicate that, in general, the fraction of water yield contributed by baseflow should fall somewhere between the value for the first and second pass.

Baseflow estimates for these two gauge locations are also included in a 1999 Ecology study (Sinclair and Pitz, 1999). Although the period used in the Ecology study largely pre-dates the period used for the SWB modeling work, the results are included to illustrate base flow estimates for an earlier time period and an alternative base-flow separation approach.[1]

Table 6 provides a comparison of annual and seasonal values for several streamflow and SWB variables. Variables from the USGS data include total streamflow, baseflow, and runoff. The baseflow and runoff estimates represent the average values from the first and second pass using the BFLOW algorithm. Variables from the SWB model include runoff and infiltration.

The variables that are most directly comparable are the annual streamflow values from the USGS gauges versus the sum of baseflow and runoff from SWB. Table 6 shows that the SWB results are approximately 2.6% higher for the Rainier gauge and 0.9% for the E-Street gauge. These differences are quite small, considering the uncertainty and variability associated with the SWB input parameters. The comparison of seasonal values shows larger differences, as might be expected, given the time lag between when infiltration occurs and when that infiltration arrives at the stream as baseflow.

Figure 10 compares monthly average baseflows and SWB recharge estimates for the Rainier and E Street gauges. The graph shows that recharge is nearly zero during July and August, while baseflow is between approximately 0.5 and 1 inches. Recharge rates during November and December are significantly larger than baseflow values as water levels in aquifers are refilled after the dry season.

E. SUMMARY AND CONCLUSIONS

The USGS model SWB was used to estimate monthly groundwater recharge from October 1, 1990 and September 30, 2014. Simulated ET and runoff compare favorably with streamflow observations. SWB resolves fine-scale spatial variability in recharge induced by topography, soil, and land-use variability. Additionally, SWB simulates the strong seasonal cycle in recharge, runoff and ET associated with wet and dry seasons in the Pacific Northwest.

[1] Data are available for the period 1949-2021 for the Rainier gauge and 1945-2021 for the E Street gauge. The Ecology study uses data collected prior to 1999 and uses the HYSEP algorithm for baseflow separation.

Long-term averages of simulated recharge are similar to previous estimates based on regressions between recharge and annual precipitation (Bidlake and Payne, 2001) on a model-wide scale. There are significant differences in the spatial distribution of recharge estimates, particularly for the higher elevations in the northwest and southeast parts of the model area. These differences may highlight the strengths of SWB as an intermediate complexity model for estimating ground water recharge. SWB captures general relationships between precipitation, runoff, ET and recharge that simpler regression-based approaches fail to account for. Through judicious use of simplifications and parameterizations, SWB avoids the pitfalls of more sophisticated land surface models: the model is transparent and the output is understandable, and computational costs are relatively low.

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Table 1. Changes in landcover from 2006 to 2016.

	2006 to 2010	2010 to 2016	2006 to 2016
Number of cells changed	6801	7888	11454
% of area changed	9.0%	10.4%	15.1%

Table 2. Land-use classifications provided by NOAA and how they are adapted to land-use classifications used in SWB.

GRIDCODE	Land use from NOAA	Land use from SWB
2	High Intensity Developed	Developed/High Intensity
3	Medium Intensity	Developed/Medium Intensity
4	Low Intensity Developed	Developed/Low Intensity
5	Developed Open Space	Developed/Open Space
6	Cultivated Land	Cultivated Crops (SR+CR
7	Pasture/Hay	Pasture/Hay (fair)
8	Grassland	Grass/Pasture
9	Deciduous Forest	Deciduous Forest
10	Evergreen Forest	Evergreen Forest
11	Mixed Forest	Mixed Forest
12	Scrub/Shrub	Shrubland
13	Palustrine Forested	Woody Wetlands
14	Palustrine Scrub/Shrub	Herbaceous Wetlands
15	Palustrine Emergent	Herbaceous Welands
16	Estuarine Forested Wetland	Woody Wetlands
17	Estuarine Scrub/Shrub	Herbaceous Wetlands
18	Estuarine Emergent	Herbaceous Wetlands
19	Unconsolidated Shore	Barren
20	Bare Land	Barren
21	Open Water	Open Water
22	Palustrine Aquatic Bed	Open Water
23	Estuarine Aquatic Bed	Open Water
24	Tundra	Barren
25	Snow/Ice	Barren

Table 3. Soil types within the active model area derived from the NRCS database.

Soil type	Description from the USDA Natural Resources Conservation Service	Percent of model area
A	Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.	24.4%
B	Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.	38.0%
C	Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.	27.1%
D	Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission	4.1%
0	Water	6.3%

Table 4. USDA drainage descriptions, and how they were used to modify NRCS soil water groups; -1 refers to a shift towards "A" soil group, and +1 refers to a shift towards "D" soil groups.

USDA Drainage Description	Percent of model area	NRCS Soil group shift
Very poorly drained	2.32%	+2
Poorly drained	5.63%	+1
Somewhat poorly drained	3.89%	+1
Moderately well drained	18.47%	0
Well drained	48.80%	0
Somewhat excessively drained	20.68%	-1
Excessively drained	0.22%	-1

Table 5. NRCS available water capacity values. All values are in units of cm of water.

	Soil depth			
Percentile	**25cm**	**50cm**	**100cm**	**50cm**
90	6.25	11.3	20	29.21
75	5.1	9.69	18.17	26.39
50 (median)	2.63	4.71	7.01	8.65
25	2.95	5.34	8.11	9.8
10	2.63	4.71	7.01	8.65

Table 6. Comparison of streamflow data and SWB simulation. Units in inches.

Variable	Source	Annual	Mar - May	Jun -Aug	Sep - Nov	Dec - Feb
Runoff	Rainier	15.39	1.22	0.13	1.05	2.73
Runoff	SWB	16.01	1.22	0.15	1.48	2.49
Difference		3.9%	-0.1%	11.4%	28.8%	-9.4%
Runoff	E-Street	11.06	0.87	0.11	0.72	1.98
Runoff	SWB	11.40	0.81	0.09	1.07	1.83
Difference		3.0%	-7.6%	-26.9%	32.3%	-8.0%
Baseflow	Rainier	23.12	2.54	0.69	1.06	3.42
Infiltration	SWB	23.54	2.37	0.27	1.71	3.50
Difference		1.8%	-7.2%	-151.5%	37.8%	2.2%
Baseflow	E-Street	23.85	2.64	0.97	1.11	3.24
Infiltration	SWB	23.84	2.05	0.17	1.85	3.88
Difference		-0.1%	-28.7%	-483.7%	40.2%	16.5%
Streamflow	Rainier	38.52	3.76	0.82	2.12	6.15
Baseflow+Runoff	SWB	39.55	3.58	0.42	3.19	5.99
Difference		2.6%	-4.8%	-94.7%	33.6%	-2.6%
Streamflow	E-Street	34.91	3.52	1.08	1.83	5.21
Baseflow+Runoff	SWB	35.24	2.87	0.25	2.92	5.71
Difference		0.9%	-22.7%	-324.8%	37.3%	8.7%

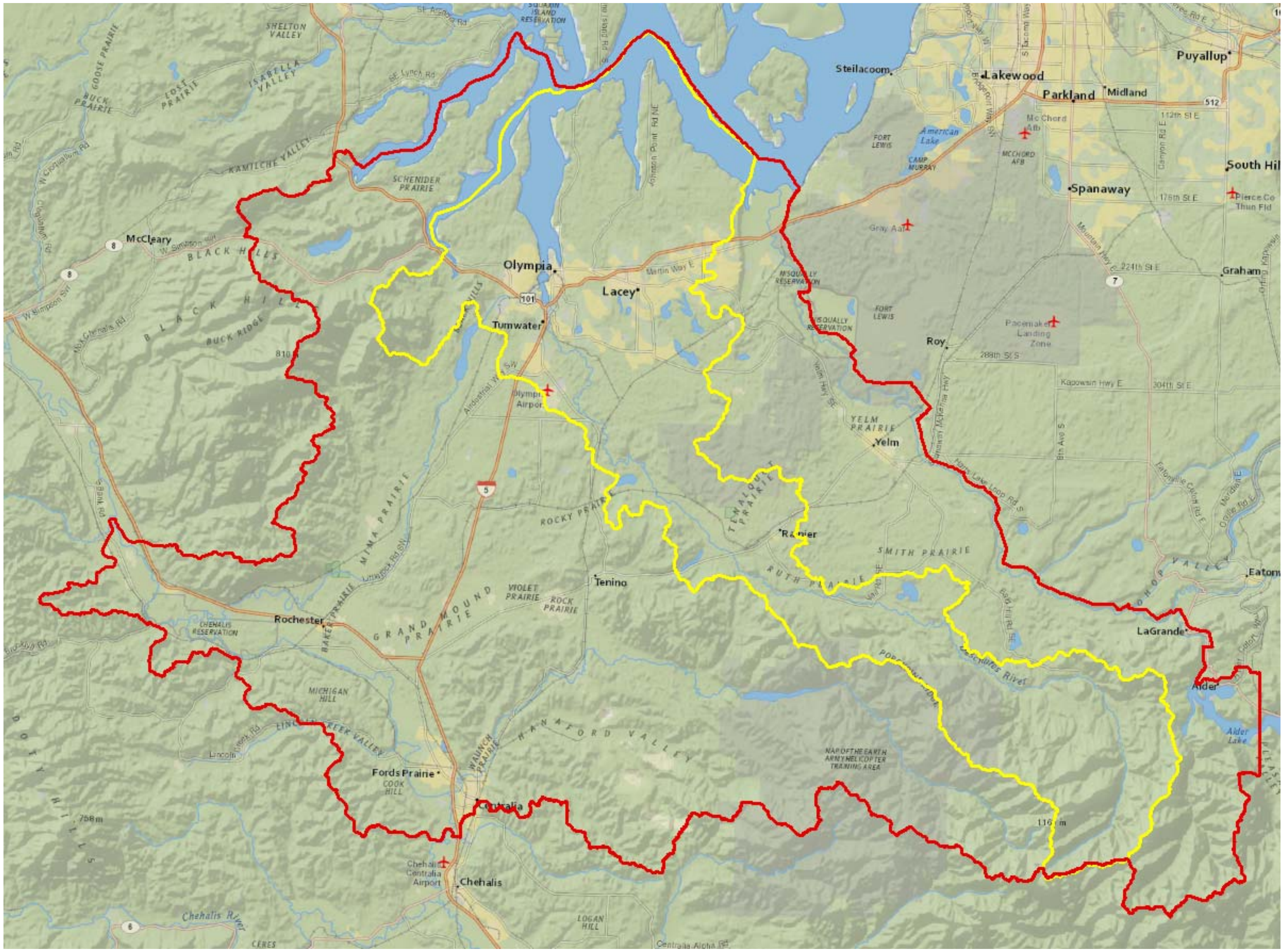


Figure 1. Model boundary is shown in red and WRIA 13 (the Deschutes River watershed) is shown in yellow.

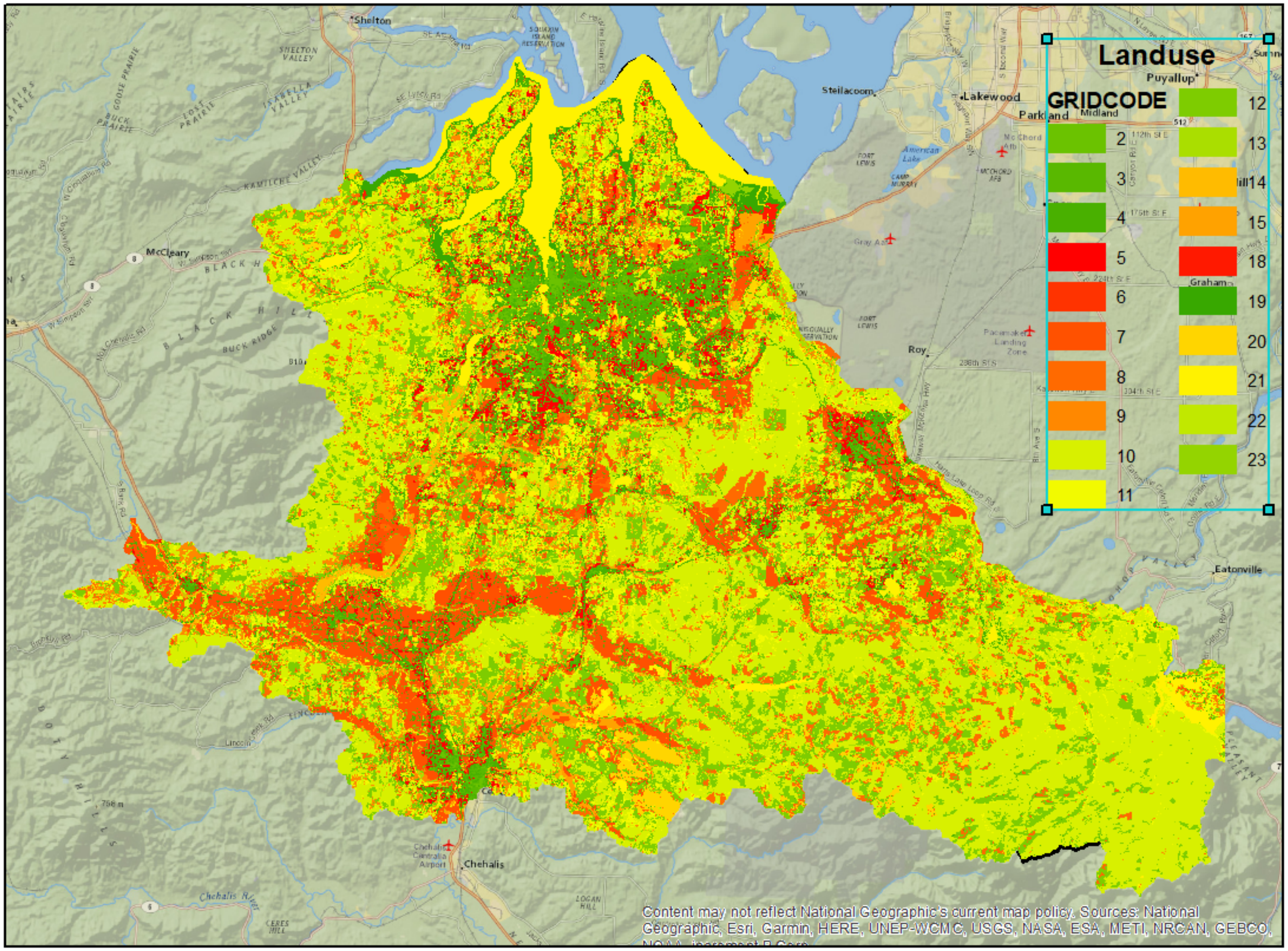


Figure 2. Landcover distribution from the NOAA Coastal Change Analysis Program. GRIDCODE descriptors are included in Table 2.

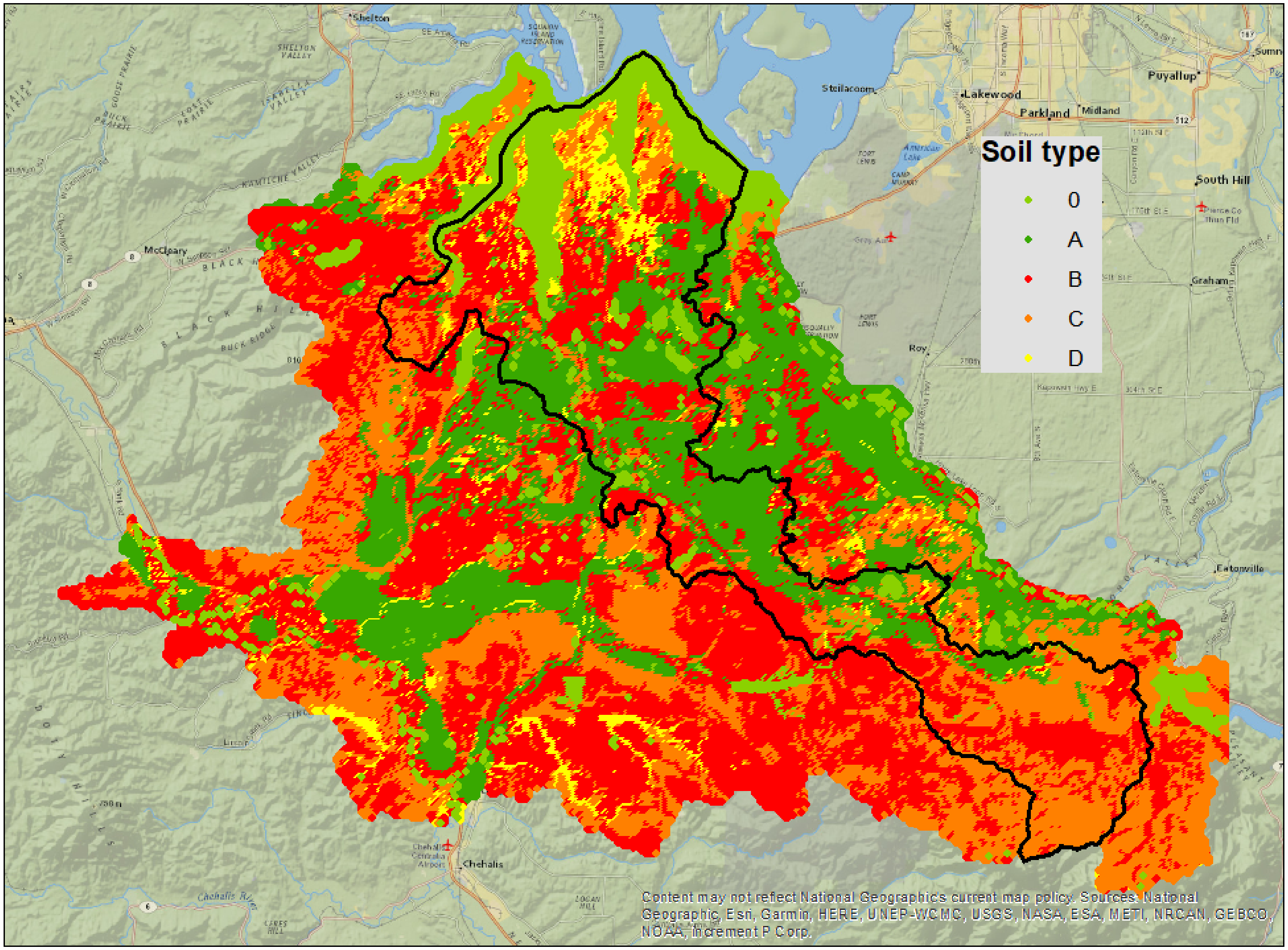


Figure 3. NRCS soil type.

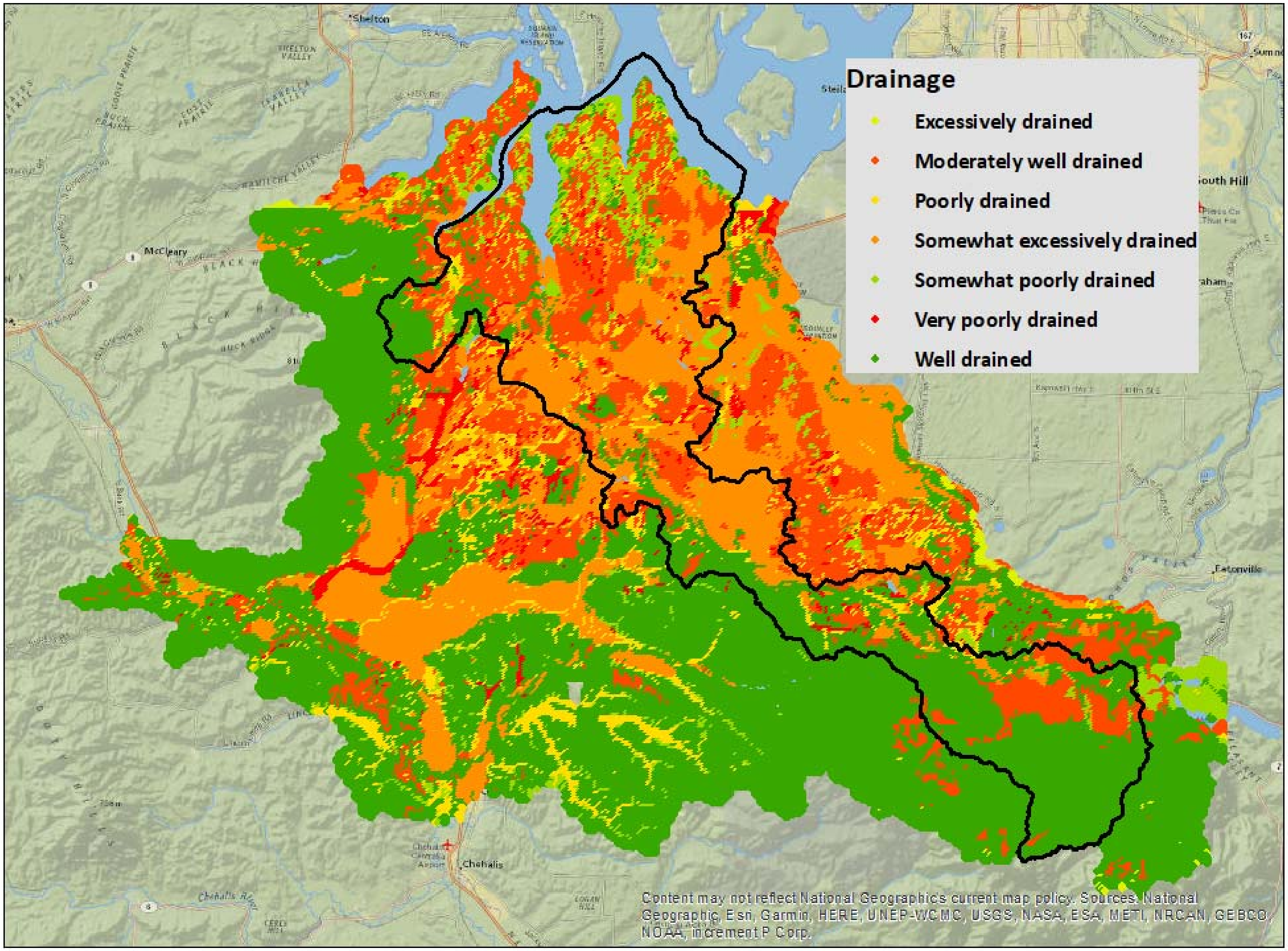


Figure 4. USDA drainage descriptions.

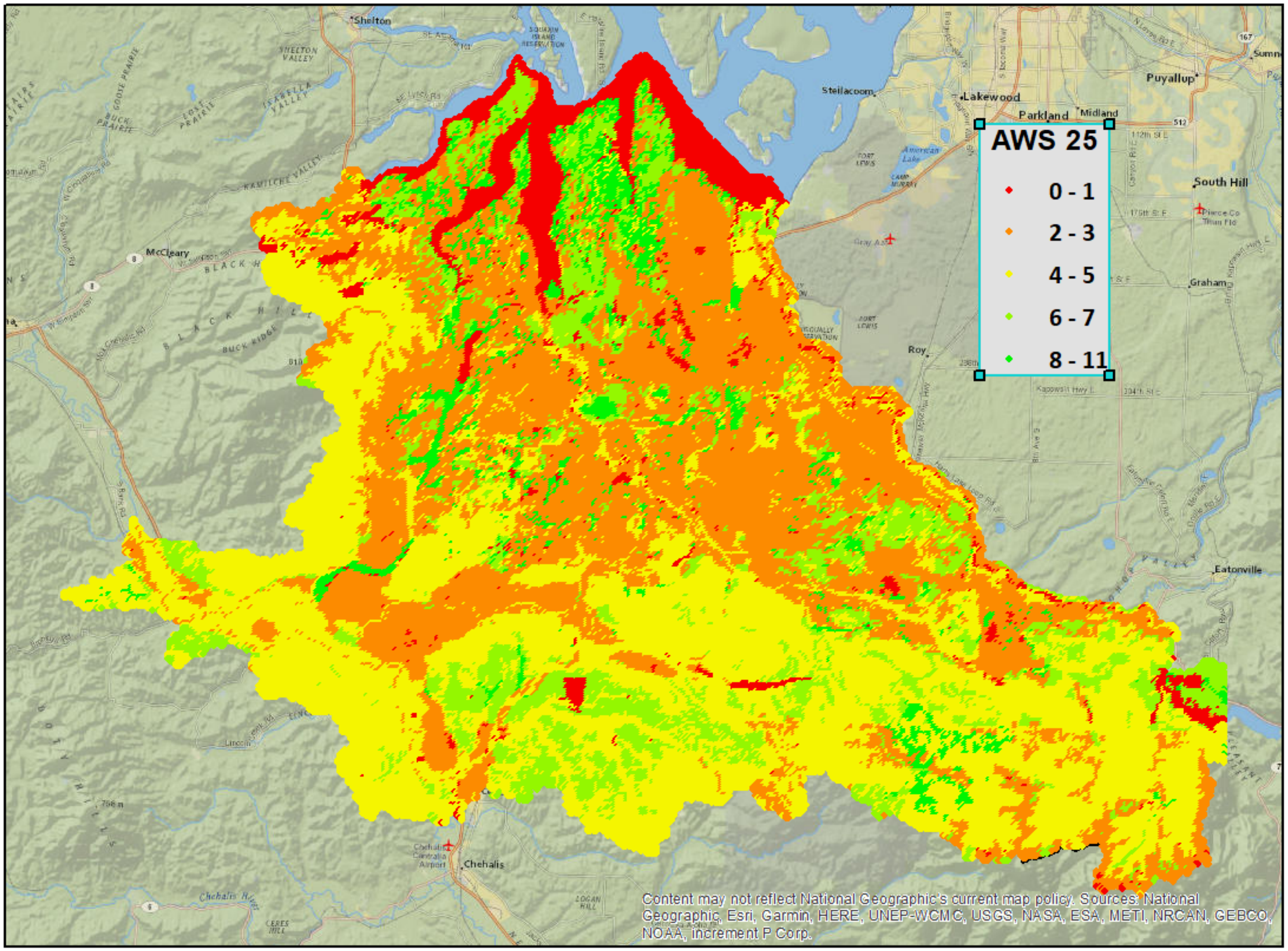


Figure 5. Available water capacity for 25 cm depth from NRCS. Units are centimeters.

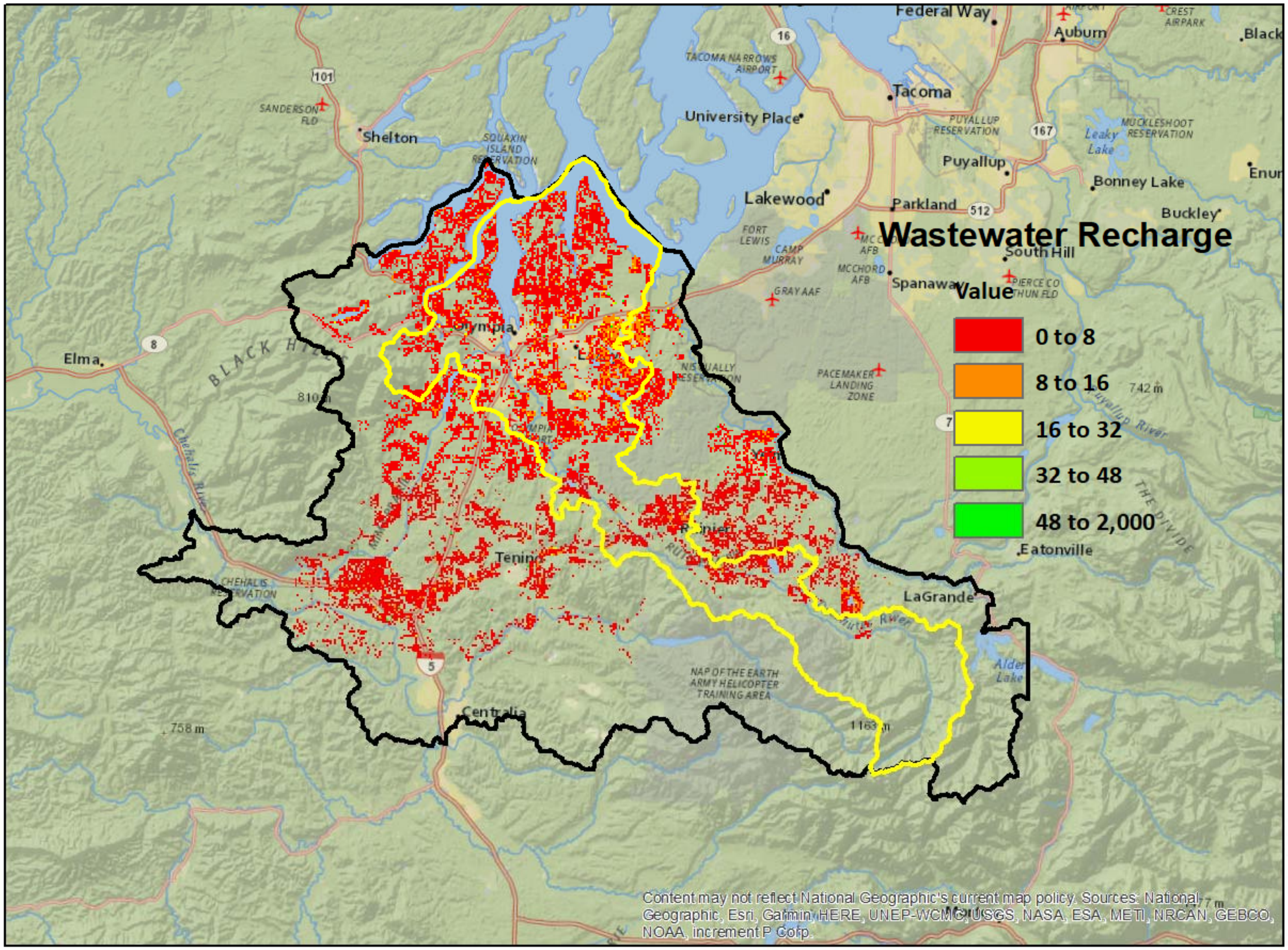


Figure 6. Recharge from septic systems and reclaimed water facilities. Units are inches per year.

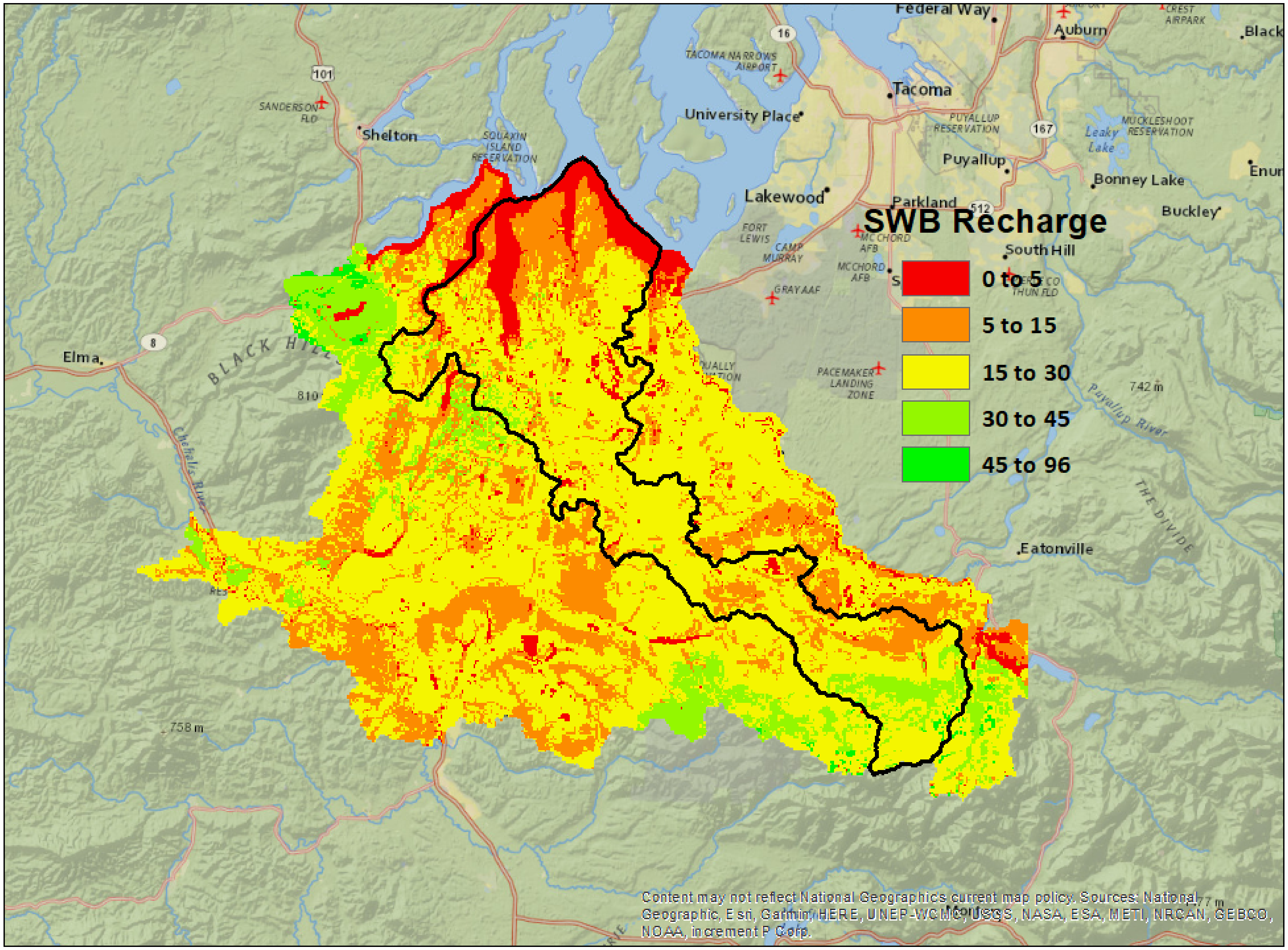


Figure 7. Average recharge from SWB. Units are inches per year.

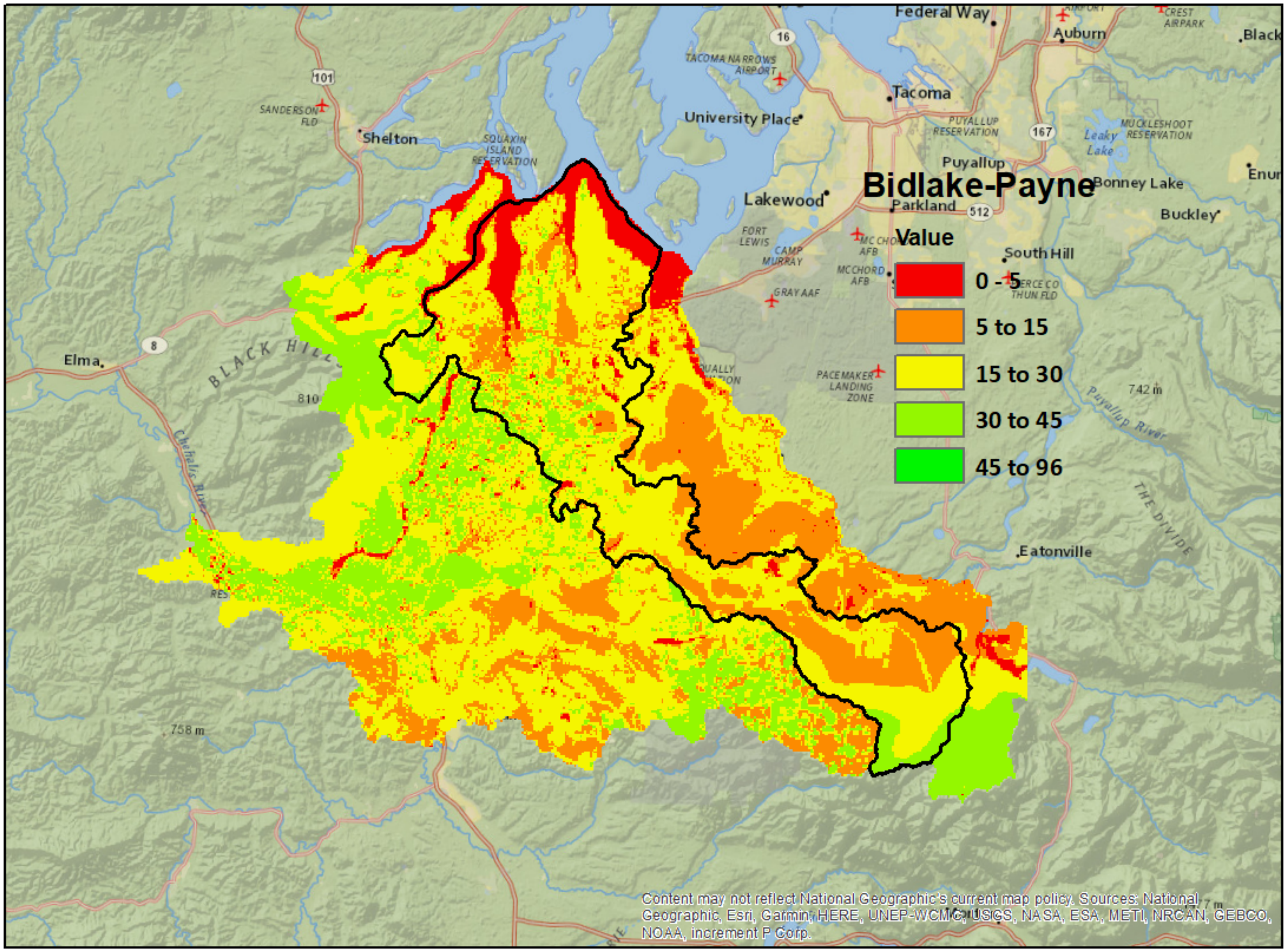


Figure 8. Steady-state recharge from Bidlake-Payne regressions. Units are inches per year.

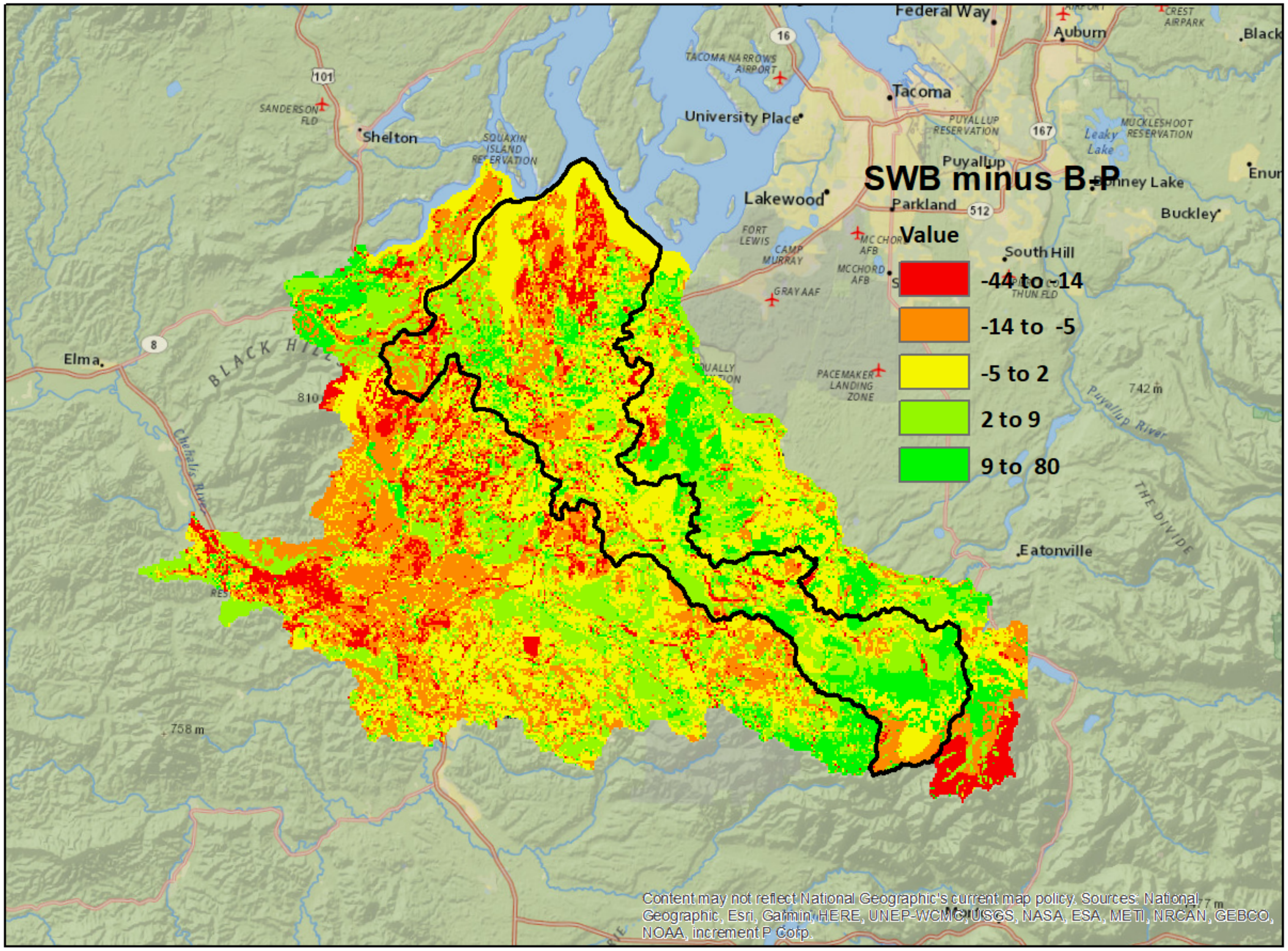
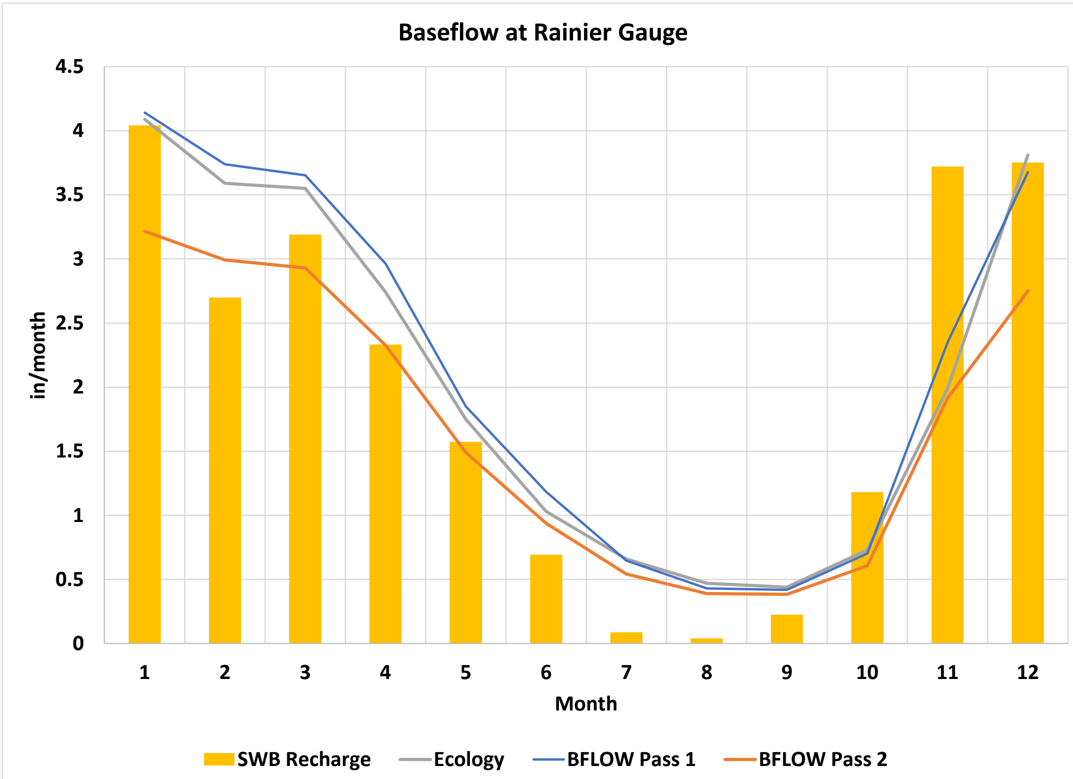
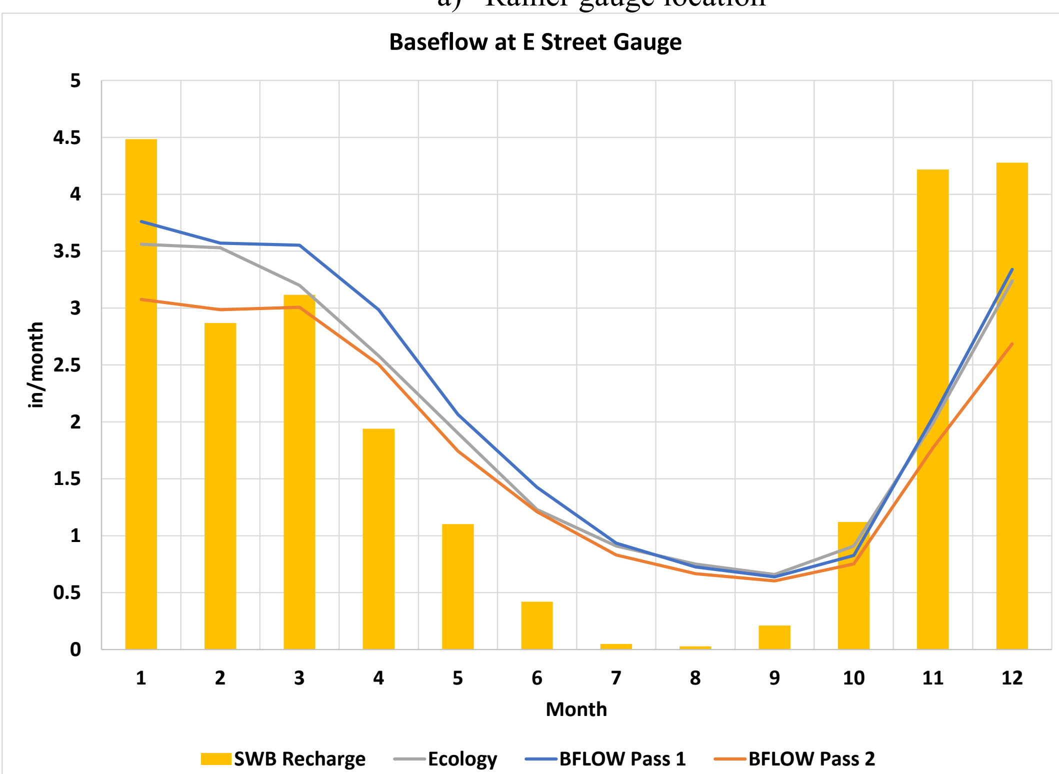


Figure 9. SWB recharge minus Bidlake Payne recharge. Units are inches per year.



a) Rainer gauge location

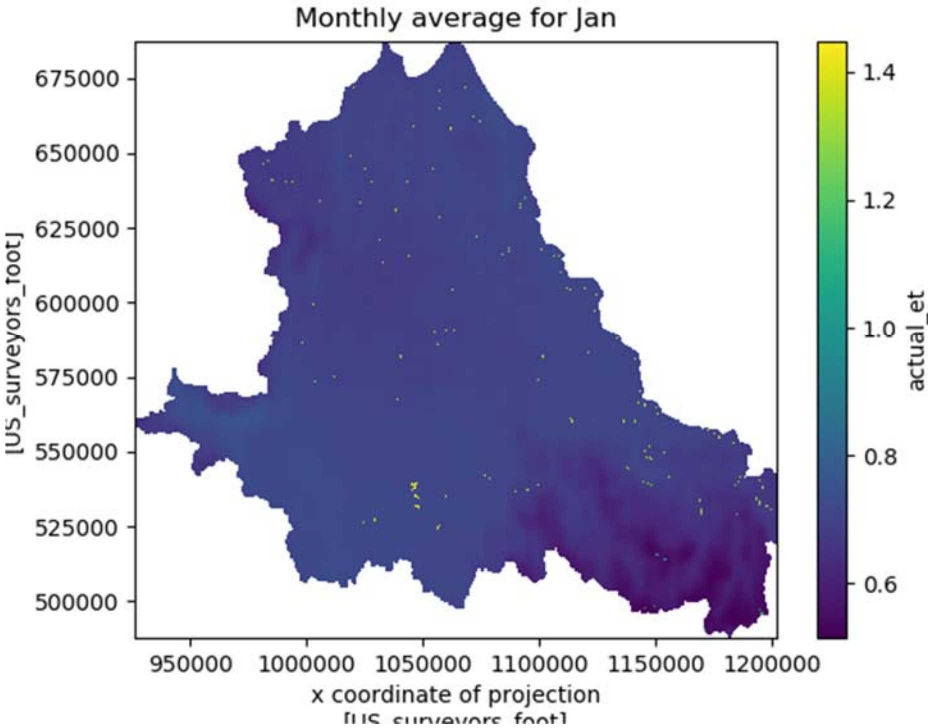


b) E Street gauge location

Figure 10. Comparison of SWB recharge with estimate baseflows.

ATTACHMENT A

Plots showing average monthly recharge rates and evapotranspiration rates from SWB



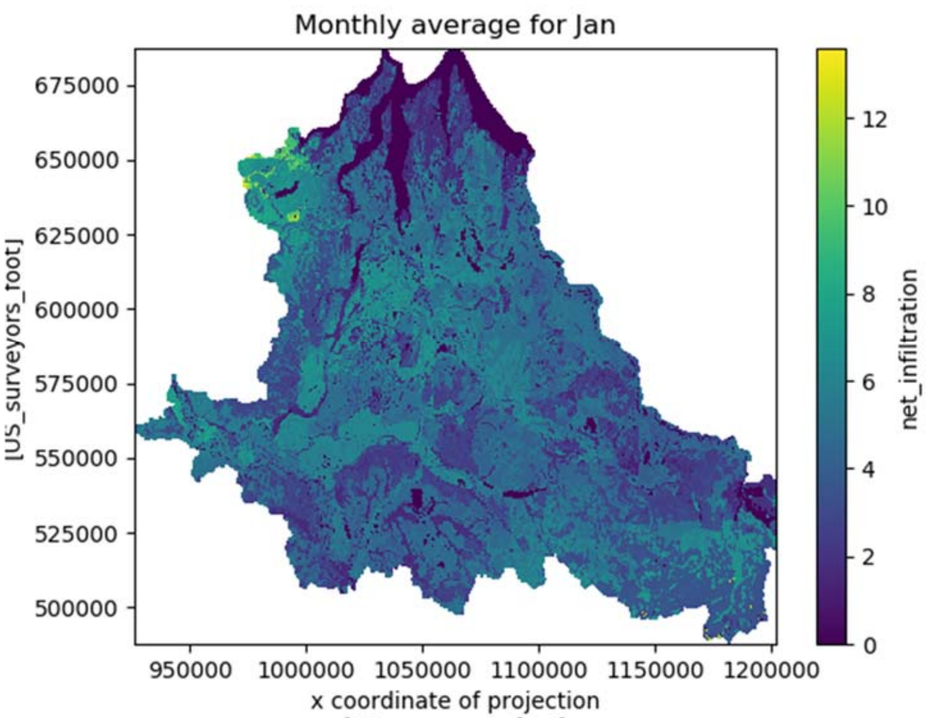


Figure A1. ET and SWB recharge for January

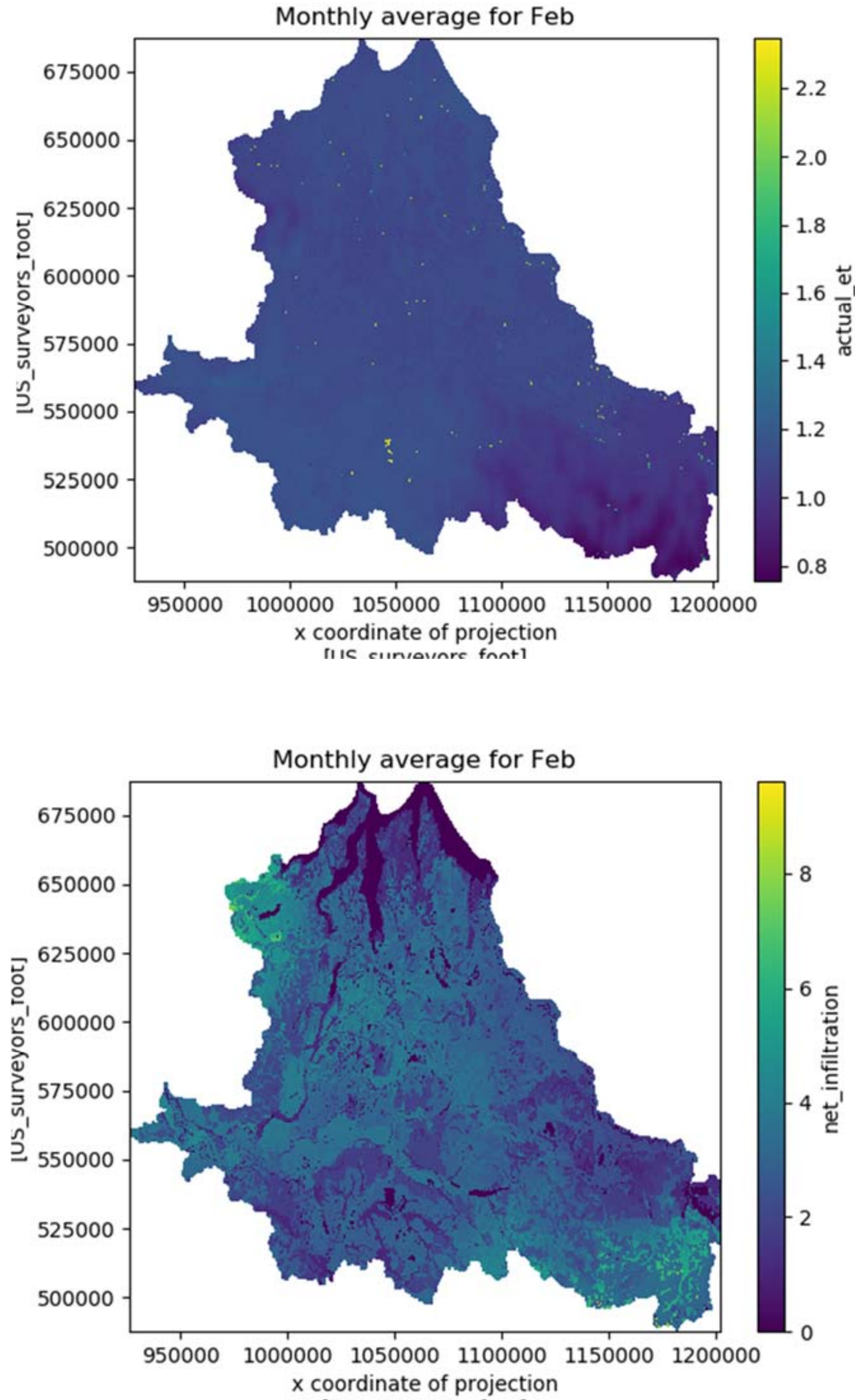
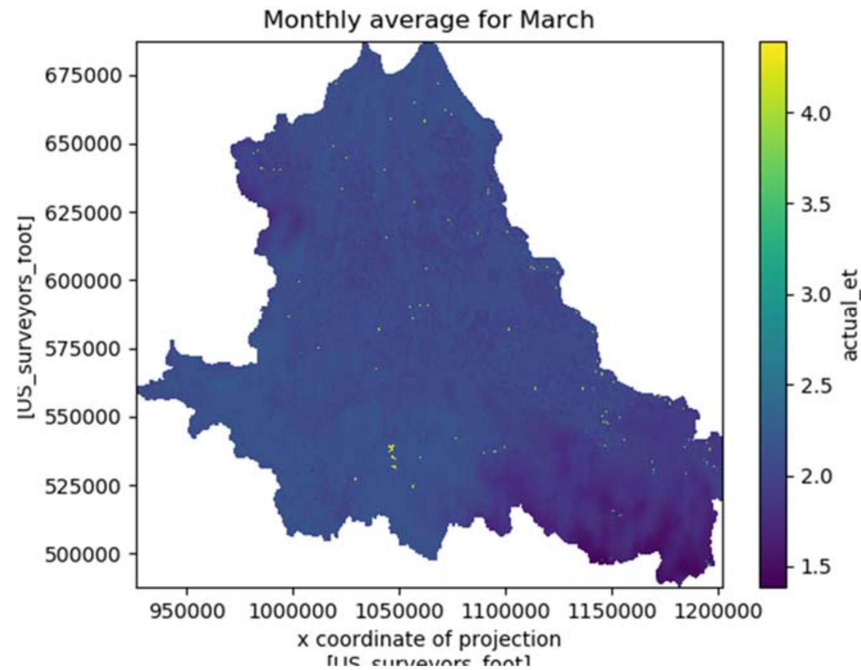


Figure A2. ET and SWB recharge for February



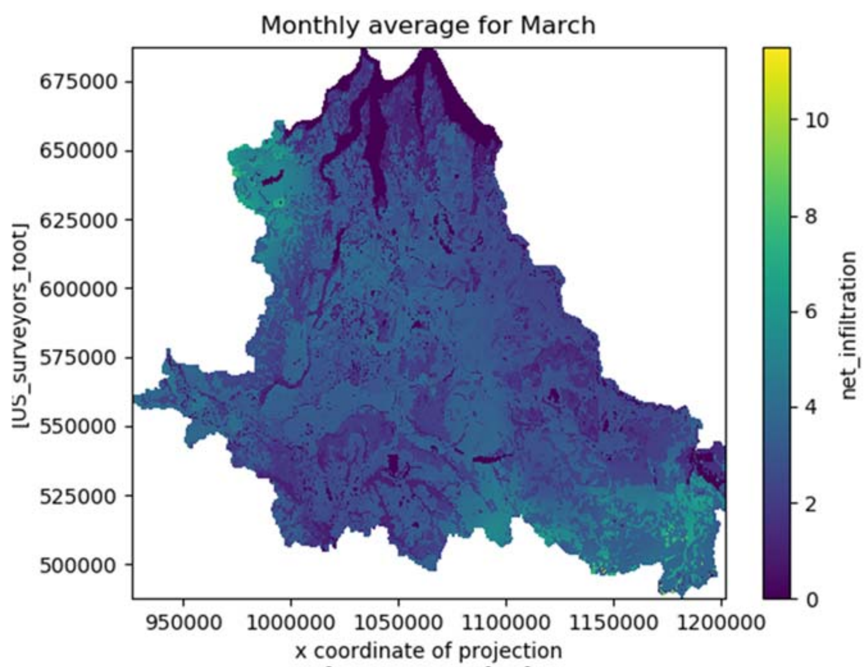


Figure A3. ET and SWB recharge for March

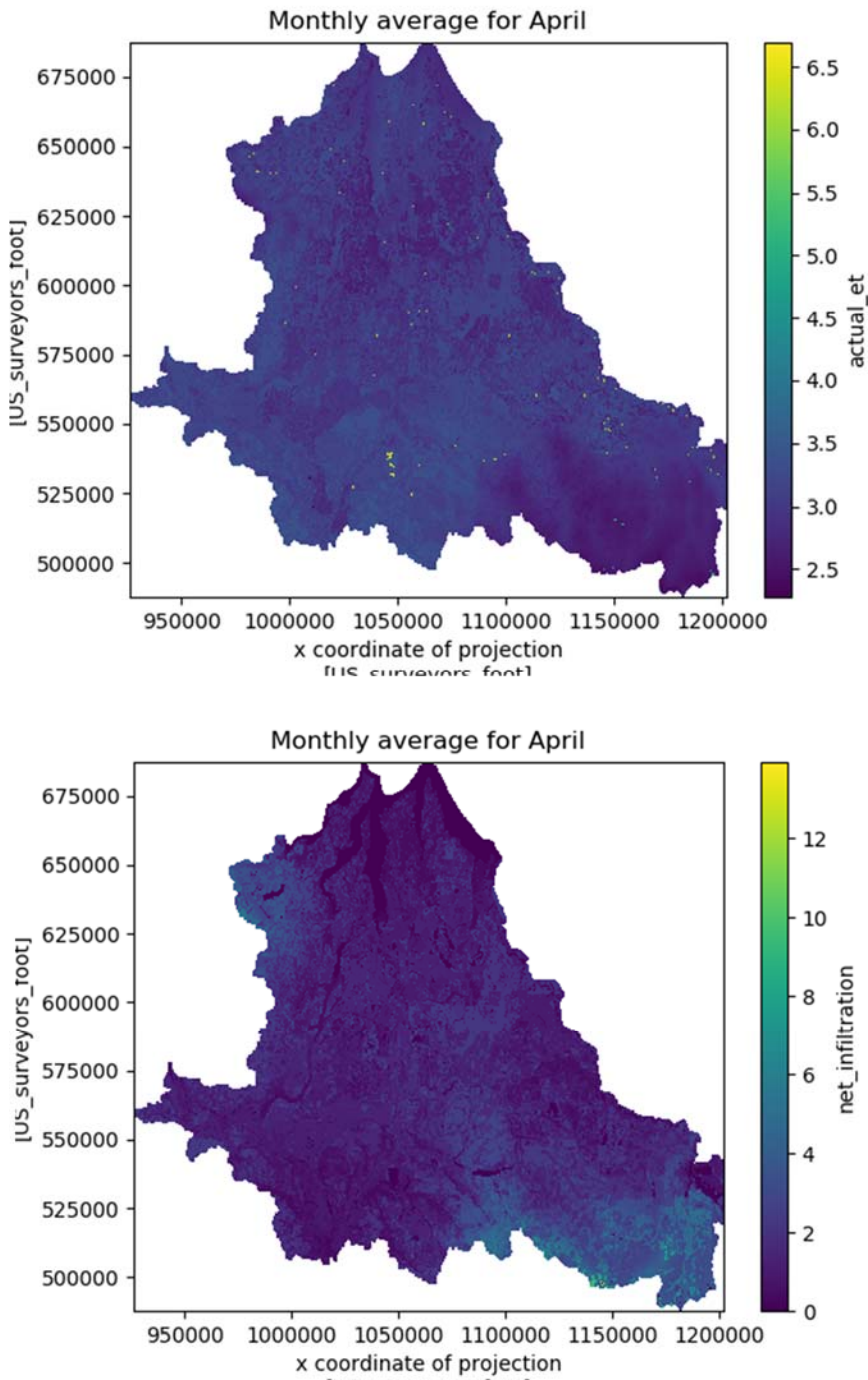


Figure A4. ET and SWB recharge for April

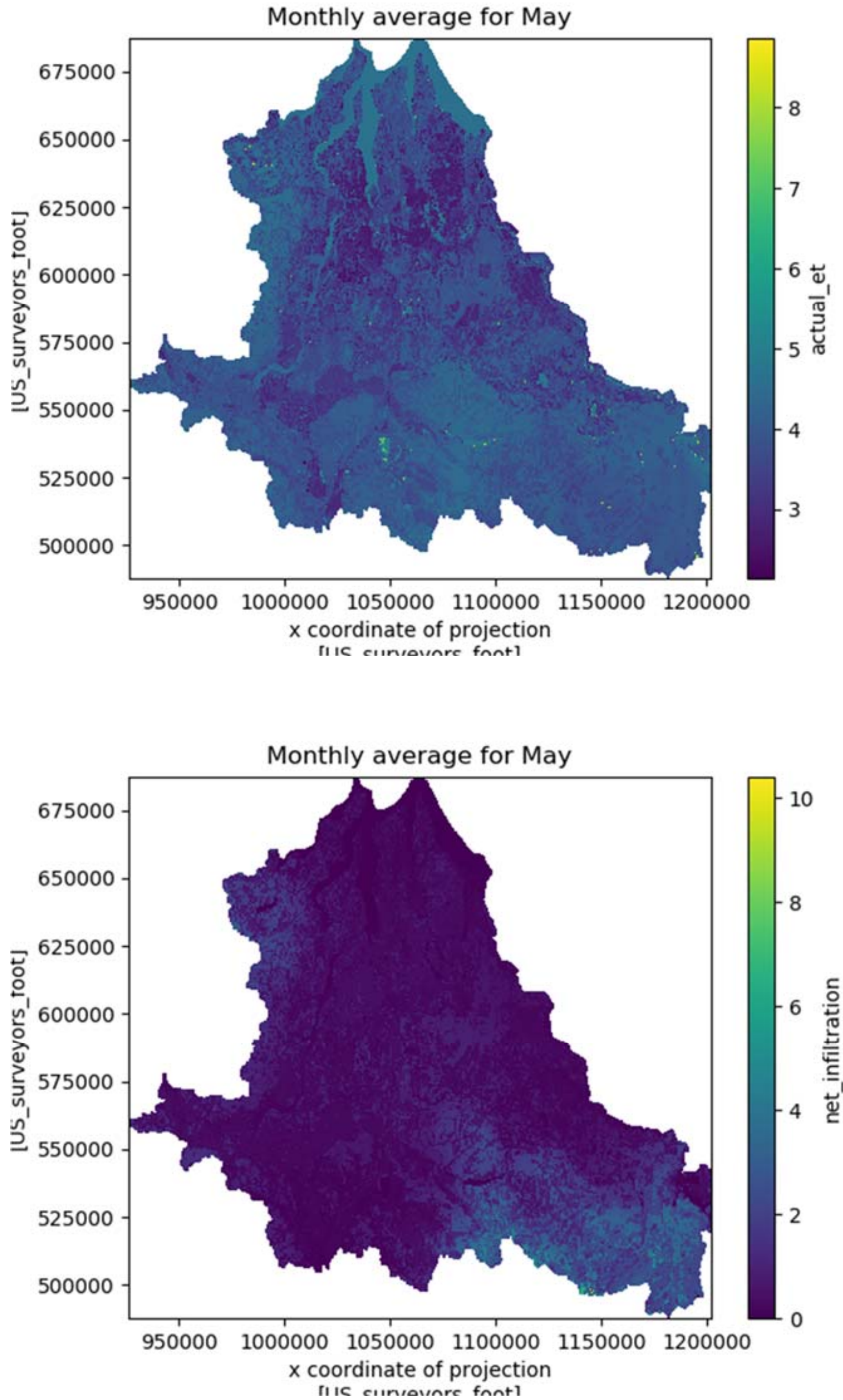
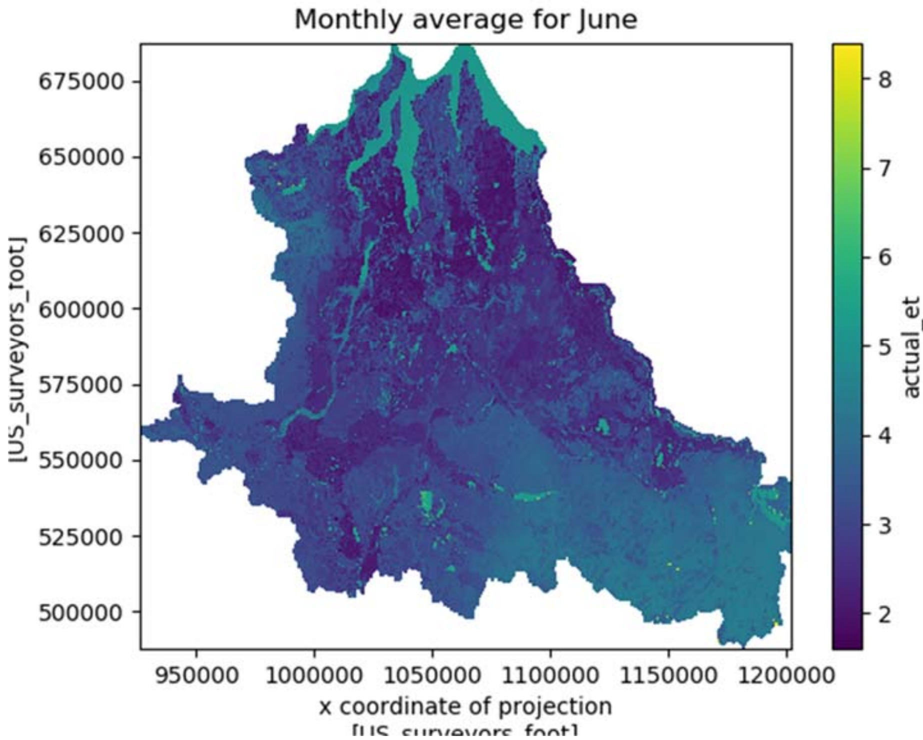


Figure A6. ET and SWB recharge for May



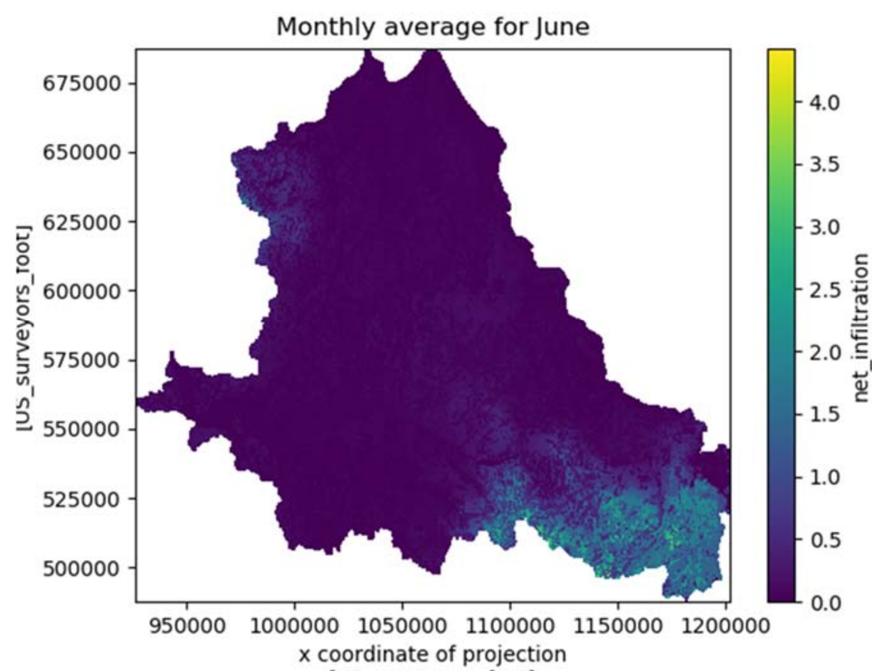
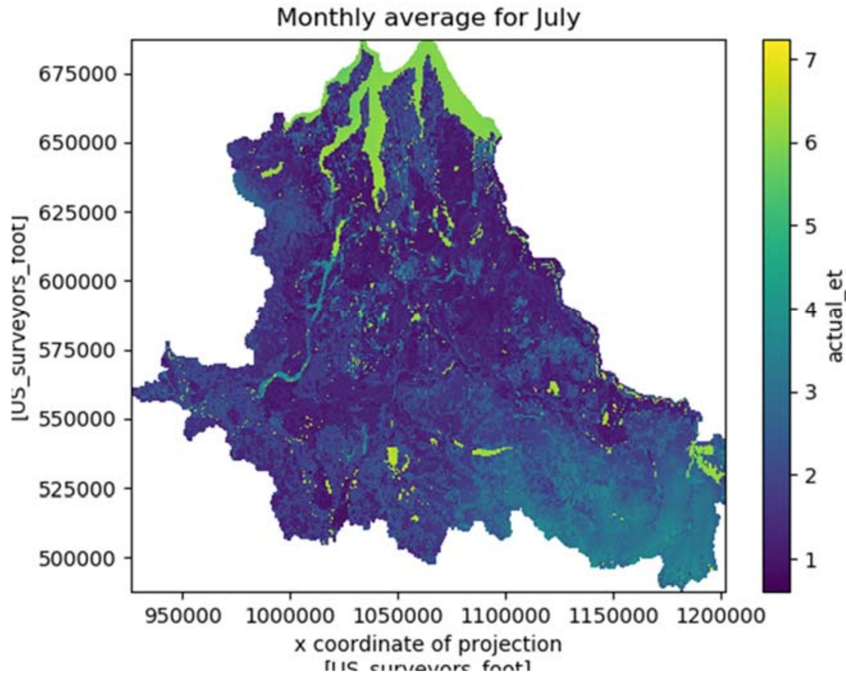


Figure A6. ET and SWB recharge for June



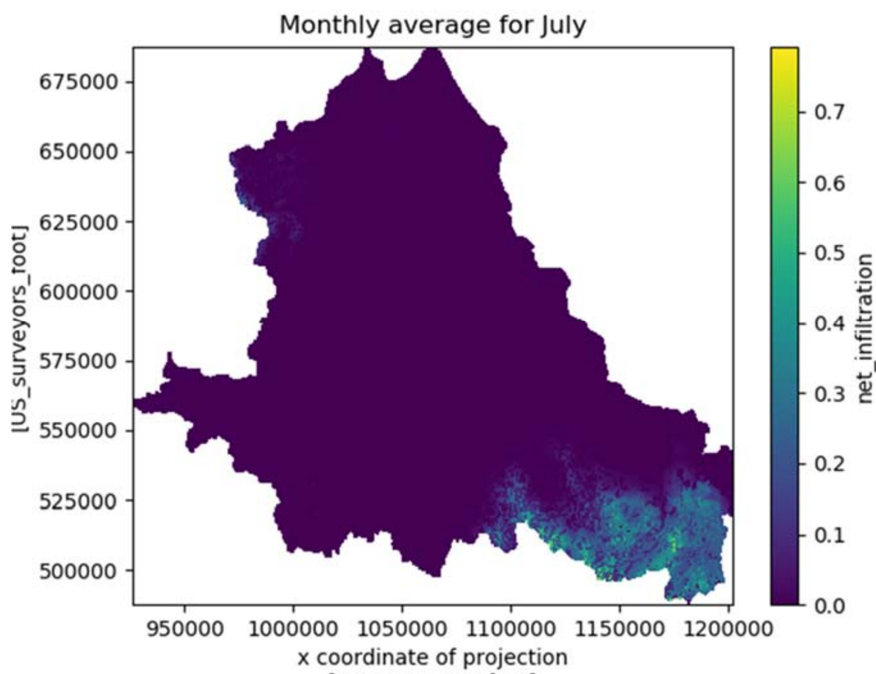
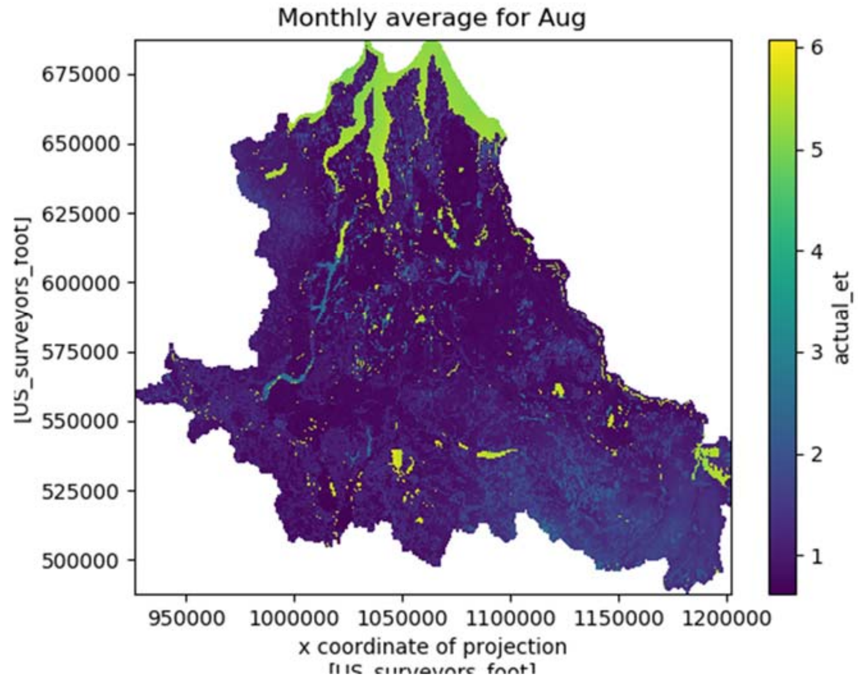


Figure A7. ET and SWB recharge for July



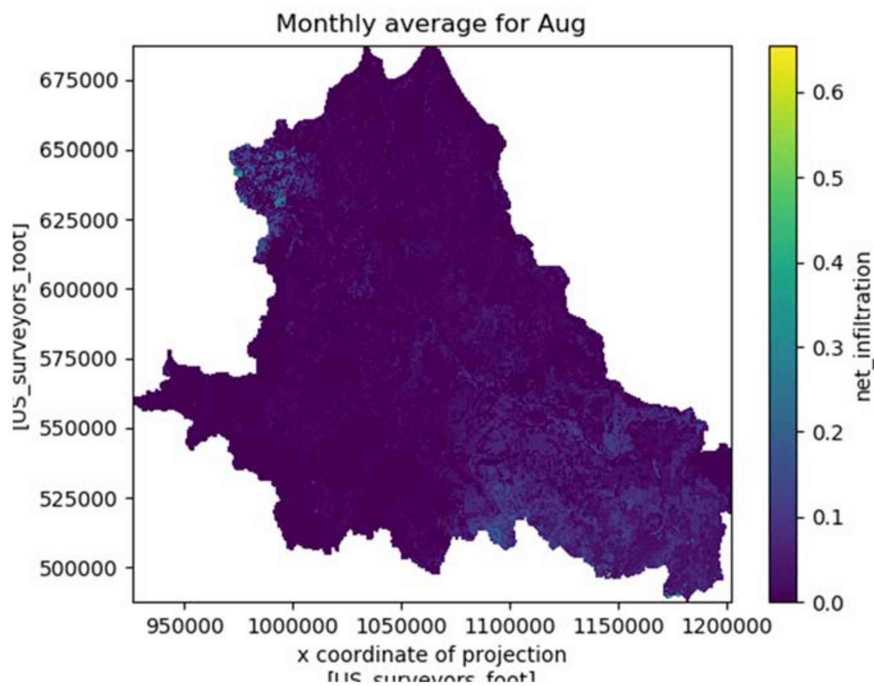
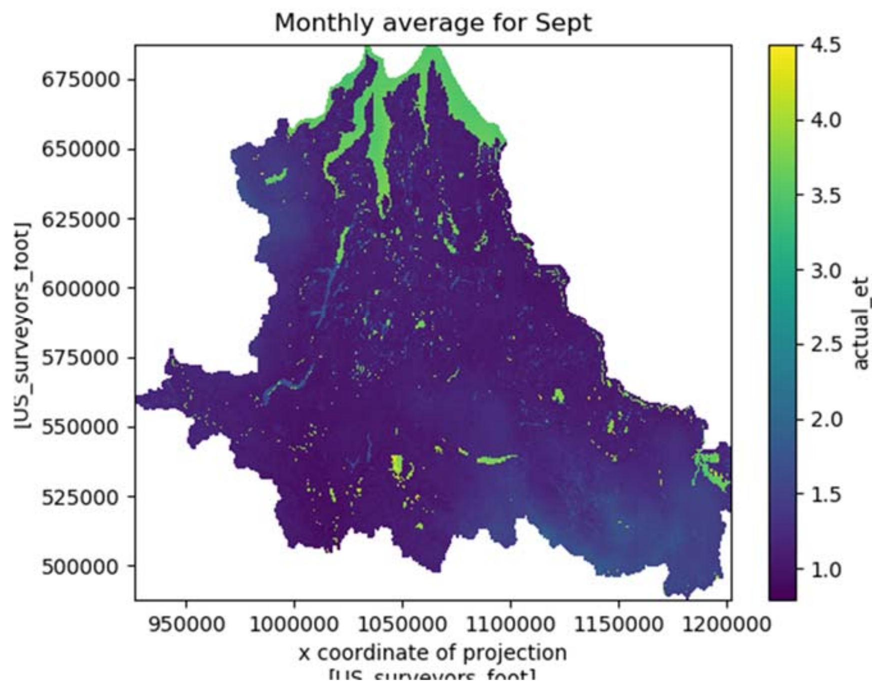


Figure A8. ET and SWB recharge for August



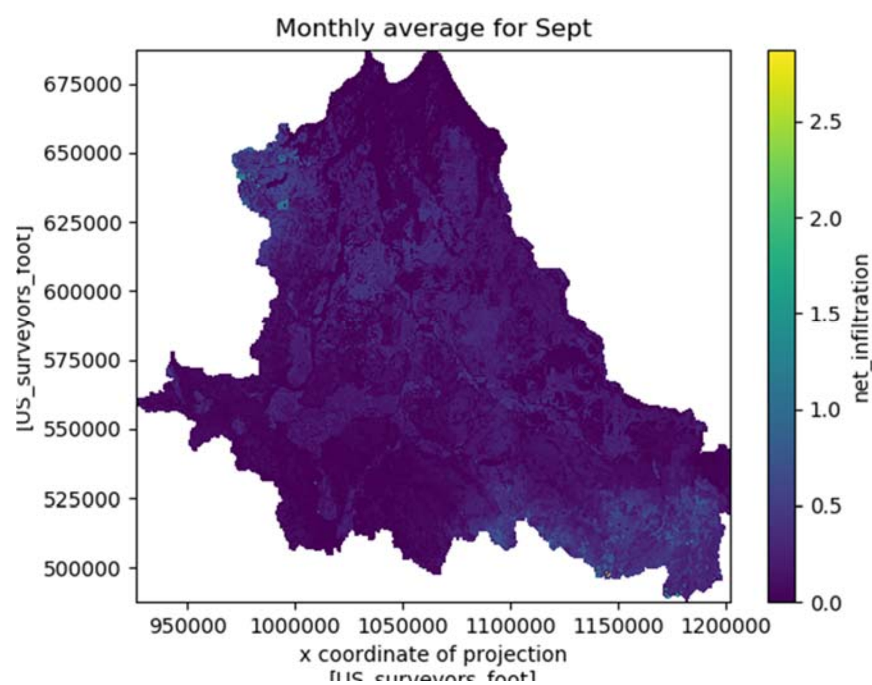
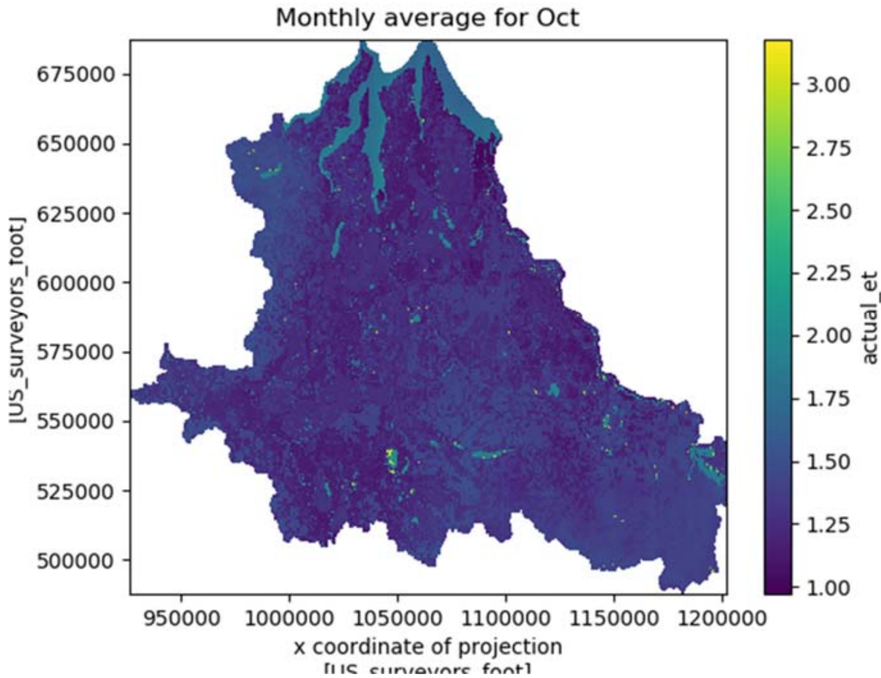


Figure A9. ET and SWB recharge for September



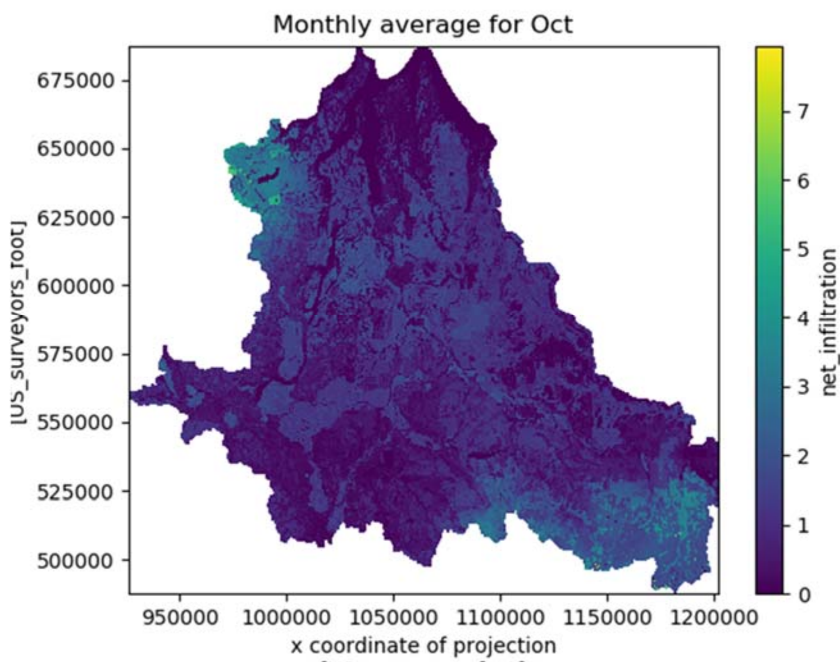
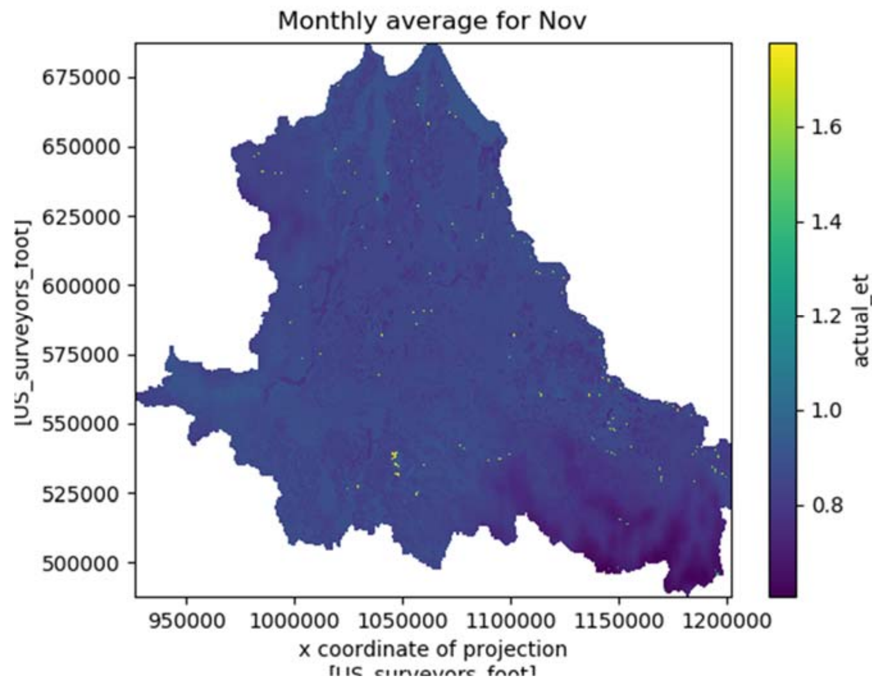


Figure A10. ET and SWB recharge for October



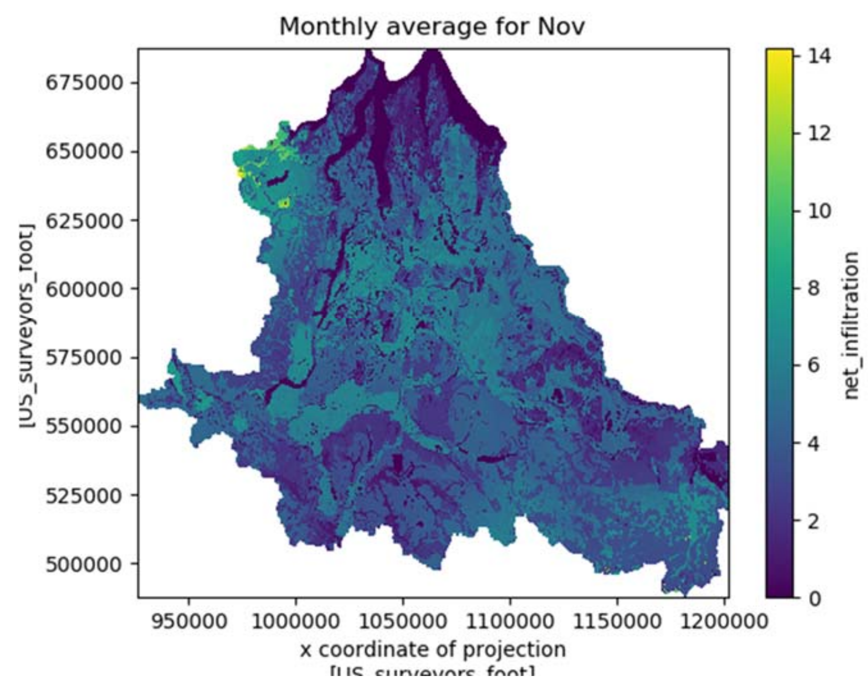


Figure A11. ET and SWB recharge for November

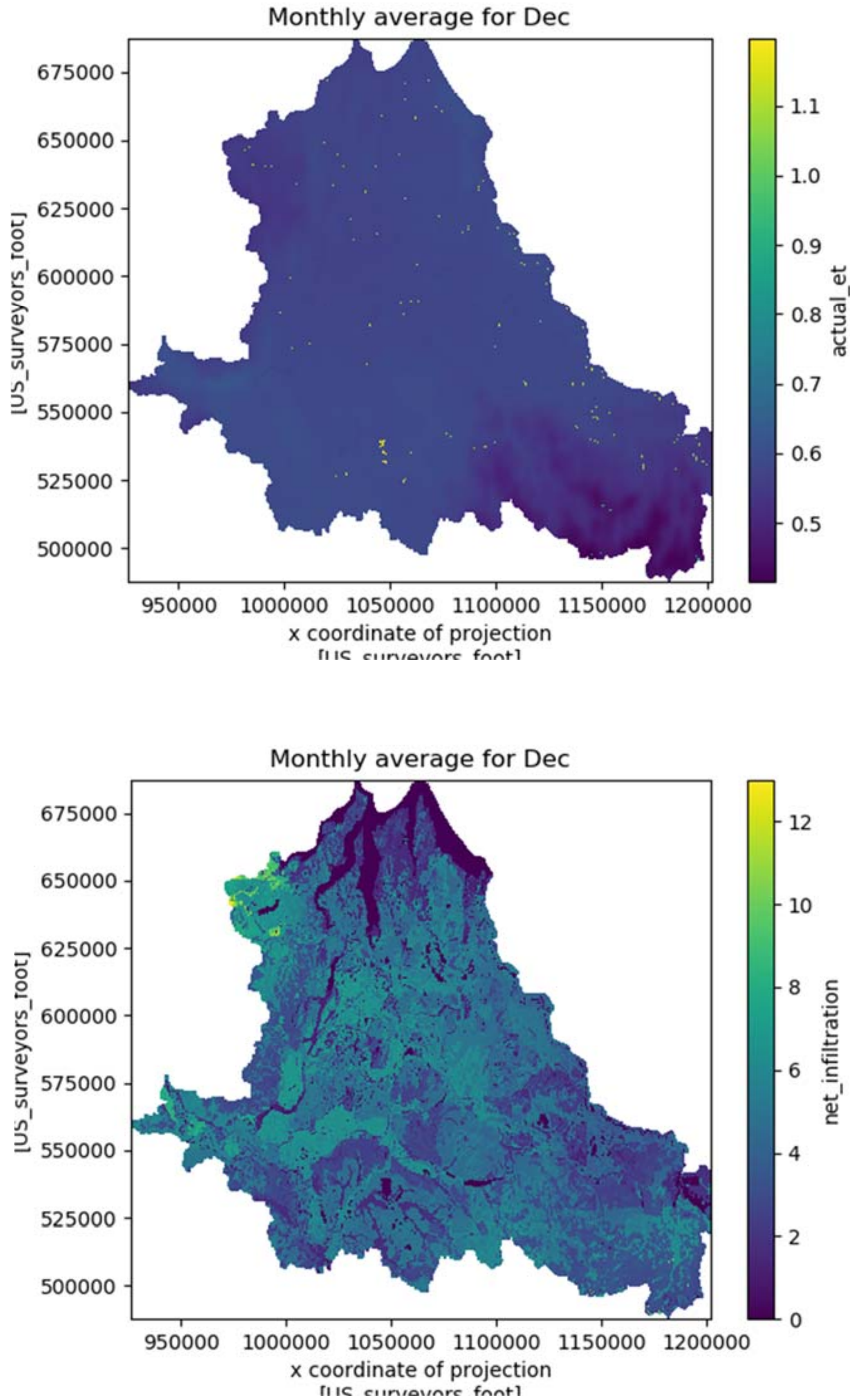


Figure A12. ET and SWB recharge for December

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