EFFECTS OF PROJECTED LAND USE CHANGE ON WATER RESOURCES IN THE CALIFORNIA CENTRAL VALLEY

A Thesis

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in

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Hydrology/Hydrogeology Option

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by

Cab M. Esposito

Spring 2019

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DEDICATION

This thesis is dedicated to my daughter; whose contributions, both pre- and post-natal, where invaluable. And to my wife who reminded me to keep moving forward.

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ABSTRACT

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With the recent California legislation, SB 1168 (Pavley), SB 1319 (Pavley), and AB 1739 (Dickinson) creating the Sustainable Groundwater Management Act (SGMA), (California Groundwater, 2015) groundwater must be managed sustainably in the future. To accomplish this, a great deal of attention is focused on how groundwater is used, how those uses may change in the future, and what impact climate change and climate variation have on groundwater resources. This research provides a first step into coupling groundwater modeling with land use projections to examine how future water requirements may vary and their corresponding impacts to groundwater and surface water resources.

Land use projections from the United States Geological Survey (USGS) are incorporated into the Central Valley Hydrologic Model (CVHM) while controlling for climate. Projected land use from 2090 is compared to land use from 2010 with large shifts to urban areas and agricultural areas shifting from annual to perennial crops. The influence of projected land use change is evaluated through changes in water demand and changes in groundwater elevations. In the Sacramento Valley and Delta regions moderate climate variability is introduced to investigate how both land use and climate change could interact in these regions.

This study modeled a decrease of 27% in Annual Agriculture, 17% increase in Perennial Agriculture, and a 10% increase in Urban areas across the entire Central Valley study area. These land use projections were examined over two different climate scenarios, an average and a slightly dry of average. In an average climate these land use projections decreased the total required water demand by 13%, with reductions of 6% in surface water demand and 25% reduction in groundwater demand. The groundwater level response in an average climate was variable across the Central Valley with small increases in the northern study area and decreases in the southern study area. When controlling for regional changes in groundwater levels, this study shows that urbanization causes the largest decline in groundwater levels and agricultural expansion into native areas causes the largest increase in groundwater levels. When a dry-of-average climate was modeled in the Sacramento Valley, land use projections caused similar responses in groundwater level changes in some areas as the average year while other areas exhibited higher land use change associated groundwater levels.

CHAPTER I

INTRODUCTION

Motivation

Questions surrounding the future demand of water are complex and intriguing. Many studies have examined climate change and climate variability effects on projected water demand and water availability. Both climate change and climate variability introduce multiple sources of uncertainty in any analysis due to the number of unknowns. Some future stressors of water availability are less complex but have the potential to introduce equal amount of change in a systems, one such stressor is land use change. Studies have shown that in arid to semi-arid environments land use change can have a comparable effect compared to climate change and variability (Vorosmarty et al., 2004), but few groundwater studies include it. The motivation for this study comes from the lack of available research into how groundwater systems react to land use change stressors.

Purpose

Groundwater systems are dynamic and the effects of different stressors are oftentimes difficult to predict. Investigating groundwater systems through models gives researchers a greater understanding of the modeled system. Conjunctive use models allow for the coupling of climate, surface water, land use, groundwater availability and groundwater systems. The purpose of this research is to investigate the impact of projected land use change on water resources in the California Central Valley with conjunctive use models.

Scope

This study utilizes the Central Valley Hydrologic Model (CVHM) (Faunt et al., 2009), a United States Geological Survey (USGS) conjunctive use MODFLOW model (Schmid et al., 2006). The CVHM considers both surface-water and groundwater allocation and demand for a given region. This study uses the CVHM to examine effect land use changes have on surface-water allocations and groundwater demand and levels within the Central Valley. Land use changes are taken from a study conducted for the State of California's 4th Climate Change Conference. Two model years were analyzed, representing model year 2010 and 2090. This represents 80 years of projected land use change within the Central Valley. Each CVHM model held annual climate constant and was run for 40 years to allow for annual equilibrium to be reached. An average climate scenario and a slightly dry of average climate scenario were used.

The changes in total water demand and surface-water and groundwater demand are examined. Groundwater levels within the upper aquifers of the Central Valley were used to estimate total impact of land use change for both regional change and change by cell.

CHAPTER II

BACKGROUND

Study Area and Characteristics

The California Central Valley is a large sedimentary basin extending from Redding to Bakersfield and bounded by the Sierra Nevada and Coast Range. The Central Valley is approximately 650 kilometers (km) long and 80 km wide. In some areas the sedimentary basin consists of 20 km of sedimentary rocks. The sedimentary sequence, named the Great Valley sequence, consist of Mesozoic and Cenozoic aged rocks consisting of sandstone, shale, and conglomerates. The surficial material of the Central Valley is sediments eroded from the Sierra Nevada that were deposited during floods (Harden, 2004).

The Central Valley can be split into four distinct regions, these are the Sacramento Valley, Delta, San Joaquin Valley, and Tulare Basin (Figure 1). The Sacramento Valley includes the north to south flowing Sacramento River beginning at Lake Shasta near Redding and emptying into the San Francisco Bay Delta. Major tributaries to the Sacramento River come from mountain rivers that provide snowmelt flows during the spring and summer. These mountain front rivers include the Feather, Yuba, and American Rivers. The San Joaquin River is found in the San Joaquin Valley and Tulare Basin. The San Joaquin River flows south to north with major tributaries consisting of the Calaveras, Tuolumne, and Merced Rivers.

Precipitation within the Central Valley typically decreases from north to south. The Sacramento Valley experiences 330 millimeters (mm) to 660 mm of rainfall and 1,150 mm of reference evapotranspiration (ET) per year. The San Joaquin Valley experiences 125 mm to 450 mm of rainfall and 1,400 mm of reference ET per year (Faunt, 2009).

Groundwater and Conjunctive Use Models

The interconnectedness of surface water and groundwater has slowly been acknowledged through both legislation and modeling programs. Conjunctive use groundwater modeling incorporates surface water and groundwater to better understand holistic water use. Multiple open-source programs developed by the United States Geological Survey (USGS) can address conjunctive use modeling. The USGS conjunctive use models include GSFLOW (Markstrom, et al., 2008), which couples MODFLOW-2005 (Harbaugh, 2005) with the USGS Precipitation Runoff Modeling System, PRMS (Markstrom et al., 2015) and the One Water Hydrologic Flow Model (OWHM; Hanson et al., 2014). OWHM is a hydrologic model that aims to incorporate every aspect of water use, including landscape and anthropogenic processes.

The Central Valley Hydrologic Model (CVHM; Faunt et al., 2009) is a MODFLOW model developed by the USGS. The CVHM utilizes the Farm Process, FMP1 (Schmid et al., 2006) within MODFLOW to simulate the surface water demand and usage while coupling the surface-water process with groundwater flow. The FMP1 code uses a mass balance approach for each water balance region ("Farm") to estimate all surface demand gains and losses, shown in Figure 2. The CVHM is divided into 21 Farms which were previously identified by the California Department of Water Resources as water-balance subregions (herein referred to as “Subregion”). The surface-water balance is coupled with a finite-difference groundwater model that estimates groundwater flows.

The CVHM has been used in multiple regional scale studies within the Central Valley including nitrate loading (Ransom et al., 2018), effects of rice fallowing (Anderson et al., 2017), and effects of potential climate change (Hanson et al., 2012).

Land Use Change and Hydrology

Land use is a main driver for both recharge and groundwater withdrawals. Changes of land use at a fine scale can include irrigation type, such as line, wheel, or flood, or increasing impervious surfaces such as installing a paved road. At a coarse scale land use change includes urbanization or agricultural expansion. Incorporating land use changes into hydrologic analysis is typically done in surface water balances (Bhaduri et al., 2000; Tang et al., 2005; Kumar, 2018) which assess runoff, potential contaminants, and ET. The effects of urbanization have been linked to groundwater models (Reeves and Zellner, 2010) mainly through the projected increases in municipal pumping. Incorporation of land use change between irrigated land uses has not been fully investigated but can be used to evaluate potential growth scenarios and understand future water availability (Dams et al., 2008; Domingo-Pinillos et al., 2018).

Land use changes which incorporate agricultural growth and urbanization have the greatest impact to groundwater in semi-arid and arid environments (Domingo-Pinillos et al., 2018) though the effects of land use change can be seen in other climatic areas. The change in water use and ET rates from agricultural expansion and urbanization have affected precipitation patterns at a regional scale (Wada et al., 2017).

Land use change has numerous drivers ranging from climatic, such as desertification, to economic, such as agriculture expansion. These factors can be incorporated into models to predict future land use changes, such as the Land Use and Carbon Scenario Simulator (LUCAS) developed by the Land-Use and Climate Change Team within the USGS Western Geographic Science Center. The LUCAS model is a state and transition model and was utilized for Land Use and Land Cover Projections for California's 4th Climate Assessment (Sleeter et al., 2017). These studies include examining future soil organic carbon (Flint et al., 2018), changes in extreme wildfire events (Westerling et al., 2018), wildfire impacts on the electricity grid and insurance market (Dale et al., 2018; Dixon et al., 2018) and to assess crop and livestock adaptation (Medellín-Azuara et al., 2018).

The LUCAS model uses historic changes in land use, a backcast, to predict future changes, a forecast or project change. The potential pathways each land use can change to is presented in Figure 3. The LUCAS model accounts for the 12 ecological regions in California, 58 counties, and 11 land use classes creating 1,540 state classes within the model. Protected natural areas, as defined by the USGS Protected Area's Database (USGS, 2016), are also accounted for ensuring areas such as the Sacramento National Wildlife Refuge do not get converted to agriculture or urban areas.

The land cover projections examine land use and population change scenarios for all of California. Both the land use and population projections use a historical backcast from 1970 to 2001. Annual projections were created from 2001 to 2101 at a 1-km^2 spatial scale. To represent potential variability, 10 Monte Carlo simulations were run for both the backcast and projections. The projections from 2001 to 2101 were created for four different scenarios, a business-as-usual (BAU) and high, medium, and low projections based on the high, medium and low growth rate scenarios provided by the California Department of Finance population projections (Sharygin, 2016). Land use changes in the high, medium and low growth rate scenarios diverge from the BAU scenario only with respect to the rate of urbanization. The projected changes of agricultural classes and native areas remains constant throughout the four scenarios.

California Water Law

The Sustainable Groundwater Management Act (SGMA) is comprised of three bills including AB 1739 (Dickinson), SB 1168 (Pavley) and SB 1319 (Pavley). SGMA provides California legislation to manage groundwater sustainably. Through SGMA, local agencies and groundwater basins are required to manage their groundwater resources. Groundwater Sustainability Plans (GSP), created and implemented by local Groundwater Sustainability Agencies (GSA), are required to address how “undesirable results” will be avoided. There are six undesirable results which include (SGMA, Section 10721(x)):

1. Chronic lowering of groundwater levels.
2. Significant and unreasonable reduction of groundwater storage.
3. Significant and unreasonable seawater intrusion.
4. Significant and unreasonable degraded water quality.
5. Significant and unreasonable land subsidence that substantially interferes with surface land uses.

6. Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water.

The requirements of a GSP include a description of the basin, groundwater uses, surface water supply, types of monitoring, and incorporation of county and city general plans, just to name a few. An additional requirement of a GSP is (SGMA, Section 10727.4 (k)):

“Processes to review land use plans and efforts to coordinate with land use planning agencies to assess activities that potentially create risks to groundwater quality or quantity.”

Land uses is detailed in the Best-Management Practices (BMP) (California DWR, 2016) for creating hydrogeologic frameworks and water balances. Furthermore, the BMP for modeling include evaluating uncertainty in changes in local land use planning, population, and climate. Land use changes at a local scale can include changes to agricultural practices including irrigation type and crop rotation.

CHAPTER III

METHODOLOGY

This study incorporates land use change projections for the Central Valley of California within an integrated hydrologic modeling framework. The goal of this research is to evaluate the impact of these land use change projections on surface water and groundwater resources within the Central Valley.

Central Valley Hydrologic Model (CVHM)

The CVHM is an integrated hydrologic model based on MODFLOW that covers 20,334 square miles of the Central Valley with active model area extending from Redding to Bakersfield and bounded by the Coast Range and the Sierra Nevada. The CVHM was built and calibrated using data from 1961 through 2003. The spatial resolution is 2.56-square km cells (1 square mile) with monthly stress periods and bimonthly timesteps. The CVHM is comprised of 10 layers which correspond to different geologic layers of the Central Valley (Faunt et al., 2009). Spatially the CVHM is divided into four regions (Section II) and subdivided into 21 subregions (Figure 1).

This research modifies the CVHM to investigate how changing land use affects both surface water and groundwater usage and corresponding impacts on groundwater levels. To isolate the impact of land use change from climate variability, the CVHM was modified to repeat a climatic year. The climatic variables that are repeated include reference ET rates, precipitation, and stream flows. The model was run for 40 years to allow the changes in land use and repeated climate to propagate through the model. Annual dynamic equilibrium was typically reached within 20 years. Figure 4 shows root zone uptake for the extent of the CVHM. Root zone uptake is extremely sensitive to groundwater elevation and can be used as a proxy for groundwater levels through the model. Reaching dynamic equilibrium occurs when the proxy for groundwater elevation, root zone uptake, is continually repeated, in this case after approximately 20 years. The results presented in this research are taken from the last year of the model run to minimize effects of initial conditions.

The MODFLOW Package used to solve the finite difference equations of the CVHM is the Preconditioned Conjugate-Gradient (PCG; Hill, 1990) Package. The PCG Package in the original CVHM sets the head change criterion for convergence (HCLOSE) to 0.25 meters and a relaxation parameter (RELAX) of 0.97. HCLOSE is the maximum change at all nodes during an iteration before the PCG Package considers the solution to the groundwater flow equations acceptable. The RELAX parameter is used to reduce the number of iterations required for convergence to the solution. Modifying the CVHM to use an annually repeated input allowed for the HCLOSE parameter to decrease to 0.20 meters and the RELAX parameter set to 1.0 to achieve a more precise solution.

Stream flows within the CVHM uses the Stream-Flow Routing Package (SFR1; Prudic et al., 2004) to estimate stream flows and stream leakage. The SFR1 Package calculates stream-aquifer interactions as well as gains and losses from precipitation, ET, and runoff. The SFR1 uses the depth of the stream to calculate leakage into or out of the aquifer systems; the precision of this value is controlled by the DLEAK parameter. The original CVHM uses a DLEAK value of 100 which was modified for this research to 10^{-5}

to achieve a more precise solution. The typically recommended value for DLEAK is 10^{-4} when units of feet or meters are used (Prudic et al., 2004).

The precipitation and reference ET variables are examined for the active region of the CVHM. Figure 5 shows the percent of normal for both precipitation and reference ET by water year (WY). Large yearly variation is evident in the precipitation, ranging from less than 50% to over 150% in multiple years. WY 2003 is notable for being approximately average in both precipitation and reference ET. WY 2001 is slightly drier than average with lower than average precipitation and higher than average reference ET. WY 2003 was chosen as the average climatic year (herein referred to as the “average year”) while WY 2001 is chosen as the dry climatic year (herein referred to as the “dry year”). The difference, by subregion, between precipitation in the average and dry year (Figure 6) becomes negligible in the San Joaquin Valley and Tulare Basin with Subregions 12, 13, 14, and 19 having increased precipitation in the dry year. For this reason, any analysis between average and dry years is limited to the Sacramento Valley and Delta regions.

The reference ET by Subregion is shown as Figure 7. The differences between the average and dry year are minimal but consistently show higher reference ET in the dry year. The small differences in reference ET is largely due to the method with which it was calculated. The CVHM calculates reference ET with the Hargreaves-Samani equation which is a simple empirical equation based mainly on the maximum and minimum daily temperatures but compares well with more robust equations at the monthly timescale (Hargreaves and Allen, 2003).

The average and dry years were chosen to investigate the relationship between land use and an idealized “climate change” scenario. It is important to note that the variable intra-year climate signal in the dry and average year provide a glimpse into how climate variation can also play a role. For Subregions 1 through 9 the reference ET is between 0.8% and 3.2% higher in the dry year overall (Figure 7). When the reference ET is examined by both subregion and month (Figure 8) for the Sacramento Valley and Delta, the intra-year variations become evident. The dry year typically has higher rates of reference ET in January, March, April, and May. The average year has a higher reference ET in July, October, and November.

Depending on the land use type and crop coefficients in a given subregion, this can lead to higher total ET in an average year even though the overall the reference ET is higher in the dry year. This variability is also evident in the precipitation pattern shown in Figure 9. The dry year has more precipitation in January, February, and October even though the overall yearly precipitation average is less.

Land Use and Carbon Scenario Simulator

The land use change projections were taken from the Land Use and Land Cover Projections for California (LUCAS) (Sleeter et al., 2017). Analysis of LUCAS projections were conducted within ArcGIS 10.4 (ESRI, 2017) and R (R Core Team, 2017) via RStudio (RStudio Team, 2016). LUCAS files were trimmed to only include the active CVHM area and were resampled from the 1-km^2 spatial scale to the 2.56-km^2 scale of the CVHM. To investigate a large shift in land use change, model years 2010 (herein referred to as “current land use”) and 2090 (herein referred to as “future land use”) were chosen. To capture the variability of the ten iterations of Markov-Chain modeling (Section II), all ten replications were used and a majority calculation was conducted for every element. When a majority could not be calculated from equal number of land use projected classes in that element, e.g. five urban and five perennial classes, the land use class was randomly chosen between the two land use classes. This occurred for less than 5% of the cells within the model domain.

Land Use Class Designation

Land use classes within the LUCAS model are the 12 major classifications from the United States Department of Agriculture which include water, snow/ice, developed, transportation, barren, forest, mining, grassland, wetlands, shrublands, annual agriculture, and perennial agriculture. Mining is not used within the LUCAS model. Land use categories for the CVHM include 13 classes including water, urban, idle, native, rice, field crops, pasture, grain and hay, cotton, nursery and berry, vineyards, citrus, and deciduous fruits and nuts.

The transition groupings (Table 1) show that when going from LUCAS to CVHM, three types of transitions were required, a one-to-one transition, a many-to-one transition and a one-to-many transition. The one-to-one transitions including water to water and barren to idle, going from LUCAS to CVHM. The many-to-one transitions included developed and transportation in LUCAS going to urban in the CVHM as well as forest, grassland, wetlands and shrublands in LUCAS going to native in the CVHM. Both the one-to-one and many-to-one transitions were taken from LUCAS without any further modifications.

The one-to-many transitions includes annual agriculture in LUCAS corresponding to field crop, pasture, grain and hay, cotton, and nursery and berry in the

CVHM as well as perennial agriculture in LUCAS corresponding to vineyards, citrus, and deciduous fruits and nuts in the CVHM (Table 1). The methodology of the one-to-many transitions is to examine the surrounding 8 cells to find an applicable majority class or to find the nearest applicable cell. An example is provided as Figure 10 for three different cells transitioning to perennial land use. When cell 1 of Figure 10 changes to perennial the surrounding 8 cells are examined for any of the three CVHM perennial land use classes. In this case five cells are not applicable and three cells are characterized as vineyard, therefore cell 1 would transition to vineyard. Of the eight surrounding cells of cell 2, 6 are not applicable, one is vineyard and one is fruit and nut. In this case the land use would be randomly assigned to cell 2, this occurred in less than 5% of the transition samples. Cell 3 has no applicable cells surrounding it. In this case the nearest applicable cell would be taken, which is citrus and subtropical.

The final land use transition presented on Table 1 is rice. Rice is technically an annual agricultural land use and is not directly modeled within the LUCAS framework. Rice is considered an economically desirable crop as well as contributes a large amount of water into the groundwater system due to the flood irrigation growing method. For that reason, any rice cell that was modeled as rice in the CVHM was kept as rice unless it was projected to change to urban.

To examine how land use is projected to change in the Central Valley, land use change vectors (LUC-V) were created. A LUC-V is a descriptor of how a cell has changed from the current to the future land use by combining the land use classes. For example, a cell that was a native land use in the current scenario and changed to urban in the future scenario is classified as a “Native-Urban” LUC-V. Table 2 is a distribution of LUC-V by subregion. There are two simplifying assumptions made when creating LUC-V, these are: (1) Perennial and Annual Agriculture are lumped into a single Agriculture class when going to or from Native or to Urban and (2) when a LUC-V happened less than 20 times within the CVHM it is lumped into the Other LUC-V and is generally ignored in the analysis. The LUC-V that are included in the Other category include shifts from Urban, Perennial-Annual, and going to or transitioning from Idle. Additionally, Table 2 presents the total change within each subregion.

Head Results

Hydraulic head is a state variable within MODFLOW. In this analysis heads are considered the main measure of how groundwater in a cell is affected by the change in land use. The output format for MODFLOW are four-dimensional arrays with row, column, layer and stress period. A FORTRAN script was run to extract each two-dimensional array into a separate text file resulting in a file for every layer-stress period combination (Mehl, 2017). An R-script was created (Appendix A) that reads in each file to a table with the unique identifiers of row, column, layer and stress period.

Heads are first analyzed at the individual cell levels by taking the future groundwater head and subtracting the current land use groundwater head, producing a change in head caused by future land use change. A positive change in head value corresponds to the future land use having higher groundwater levels whereas a negative change in head value corresponds to the future land use having a lower groundwater head. Groundwater heads are examined for the upper three layers of the CVHM which have thicknesses of 15 meters (50 feet), 30 meters (100 feet), and 46 meters (150 feet), respectively.

Head changes are examined by subregion and LUC-V. To investigate head changes at the subregion level, head changes are grouped by subregion and the mean of the upper three layers is taken then. To remove the seasonal variability the change in head is averaged over the final 12 stress periods, or model year, of the CVHM. Head changes were similarly grouped and analyzed at the LUC-V level. Head was largely observed to be controlled by subregion, therefore, when investigating how LUC-V effects individual cells, the local change of the subregion was considered. This is done by mean-centering every cell by subregion before analyzing cells for LUC-V effects. To mean-center, the mean of every subregion and layer was found and then was subtracted from each cell in that subregion and layer. For instance, if a subregion had a mean increase of 3 meters and Native-Urban cells in that subregion had a mean increase of 2.7 meters then Native-Urban cells had a mean-centered change of -0.3 meters. If another subregion had a mean decrease of 2 meters and Urban-Native cells had a decrease of 2.5 meters, their mean-centered change is -0.5 meters. If both subregions had an equal number of Native-Urban cells then the average Native-Urban change would be 0.1 but the mean-centered average would be -0.4 meters. Through mean-centering the subregional influence is accounted for allowing a more precise analysis of how specific LUC-V are influencing the groundwater.

Linear models are relied upon to explain how much variance is accounted for by grouping variables. This research uses linear interaction models between subregion and LUC-V to create prediction intervals of changes in groundwater levels. When linear interaction models are used with factor or categorical variables every combination of those factor variables is run through a linear regression (Ott and Longnecker, 2001). For this research, that means a linear model was run for every LUC-V per subregion. For example if there is a sample population defined by colors including red, green, and blue, and size including large, medium, and small, a linear interaction model will calculate a linear model for the subgroups including red-large, green-large, blue-large, red-medium, green-medium, etc. Then those linear models are aggregated into a single linear model.

Volumetric Results

The CVHM, through the FMP1, uses both a surface water balance and groundwater model to solve for the demand for applied water. The surface water balance calculates the total water demand required to support the land use (e.g. irrigate crops) based on land use, soil type, farm efficiencies, and reference evapotranspiration. The CVHM requires that the total water demand be met for every stress period within the model. There are four values that are used to meet the total water requirement; (1) water from precipitation is available regardless of land management and is accounted for first, (2) groundwater that is within the rooting depth of the vegetation is available next, typically this is groundwater that is within a few meters of the ground surface, (3) surface water deliveries are taken next, this is water that is dependent on reservoir operations, water rights, and delivery systems such as the canals in California, and (4) groundwater is taken last, if the water requirements in a farm cannot be met through precipitation, groundwater root uptake, and surface water, the CVHM will pump groundwater to account for any deficiency. These calculations are performed every stress period and are aggregated to the subregion level with the CVHM.

The first two terms in determining water demand, available precipitation and groundwater root uptake, are the only water that is available for non-irrigated regions. There are four non-irrigated land use classes within the CVHM including water, urban, native, and pasture (Table 1) with urban and native classes consisting of the majority of non-irrigated area. The final two terms, surface-water deliveries and groundwater pumping are the Total Farm Delivery Requirement (TFDR).

To evaluate the impact of land use change on both surface water and groundwater resources, the changes in the total water demand and how that demand is met from current land use are compared to the future land use.

CHAPTER IV

RESULTS

The purpose of this study is to quantify the impact of future projected land use changes on surface water and groundwater resources within the California Central Valley. The following are the results of groundwater head and flow changes based on projected land use changes. Groundwater head changes are examined within the top three layers of the CVHM.

Land Use Change

Land use within the CVHM shows the general trends of decreasing Annual Agriculture, increasing Perennial Agriculture, increasing Urban and relatively constant Native (Figure 11). When examined on a regional level the trend of decreasing Annual Agriculture, increasing Perennial Agriculture and increasing Urban remains similar. Native classes show small growth in the Sacramento Valley, decreases in Delta and San Joaquin Valley, and increasing in the Tulare Basin (Figure 12). At the subregion level the trends of decreasing Annual Agriculture, increasing Perennial Agriculture and increasing Urban areas are also observed.

When examined by LUC-V the largest land use shifts come from Annual-Perennial (14%), Ag-Native (7%), Ag-Urban (7%), Native-Ag (5%), Native-Urban (2%), and Rice-Urban (<1%) (Figure 13). Land use changes account for approximately 36.5% of the total CVHM area; 63.5% of the area does not change. The LUC-V for unchanged cells consist of Native-Native (20%), Perennial-Perennial (18%), Annual-Annual (12%), Urban-Urban (7%), Rice-Rice (5%) and Water-Water (1%).

Figure 14 shows the same LUC-V by region. The Sacramento Valley changed in 26% of the area with Annual-Perennial (9%), Ag-Native (6%) and Ag-Urban (4%) making up the majority. The Delta changed in 42% of the area with Ag-Native (14%), Annual-Perennial (9%) and Native-Ag (8%). The San Joaquin Valley changed in 39% of the area with Annual-Perennial (18%), Native-Ag (10%) and Ag-Urban (8%). The Tulare Basin changed in 41% of the area with Annual-Perennial (17%), Ag-Native (11%) and Ag-Urban (7%).

Head Changes Under Average Climate Scenario

Figure 15 shows the mean head change by cell across the CVHM for layers 1, 2 and 3. Mean head changes by subregion shows the largest decline in Subregion 21 with a mean decline of 5.1 meters. The subsequent largest declines are in Subregions 6, 9, and 7 with a mean decline of 1.5, 1.4, and 1.0 meters, respectively. The largest head rise is in Subregion 16, with an increase of 4.0 meters. The next three largest increases are seen in Subregion 17, 8, and 11 with head increases of 3.8, 3.3, and 1.8 meters, respectively.

Grouping by LUC-V the largest decreases across the entire CVHM are Rice-Urban and Ag-Native with an average decrease of 1.65 and 1.54 meters. When the cells are mean-centered on the Subregion level the three largest declines are Native-Urban, Ag-Urban, and Rice-Urban with 1.14, 0.98, and 0.88 meters decrease, respectively. The largest increases in head are Native-Ag and Perennial-Perennial with an average increase of 3.56 and 1.50 meters. After mean-centering the largest increases are seen by Native-Ag, Water-

Water, and Perennial-Perennial with 2.43, 0.96, and 0.62 meters, respectively. The estimates for mean head changes by LUC-V and associated variances are presented in Table 3. Of note is the variance, which is typically much larger than the estimated values, emphasizing the range within the grouping.

Linear regressions were used to examine the explanatory value of both the Subregions and the LUC-V. By grouping the head change observations by subregion, linear regression explains 44% of the variance. When grouped by LUC-V 15% of the variance is explained throughout the CVHM. When both subregion and LUC-V are incorporated in a linear regression interaction model 64% of the variance is explained. The linear regression interaction model is further used to create prediction estimates for LUC-V by subregion. Figure 16 presents the estimated changes with the 95% confidence interval shown. Figure 16 shows both the aggregated impact for an entire subregion when all points are examined but also what the LUC-V impact is with the region.

Head Changes Under Dry Climatic Scenario

The dry climatic scenario is only applicable in the Sacramento and Delta Regions which encompass Subregions 1 through 9. Head changes presented here are due solely to the change in land use and cannot be directly compared to changes from an average climatic year.

When grouped by subregion, Subregions 1, 2 and 5 have a decrease of approximately 1.1 meters. Subregions 3, 4 and 7 have increases of 0.4 meters. Subregions 6 and 9 have an increase of 2.4 and 2.9 meters, respectively and Subregion 8 increases by 5.8 meters. Figure 17 shows the mean head change for layers 1, 2 and 3 in dry climatic year and Table 4 shows the average head for each Subregions 1 through 9 and layers 1 through 3 for all four land use and climate scenarios. This table illustrates the fact that even when heads increase during the dry climatic scenario, the heads in the dry climatic scenario are never greater than the heads in the average climatic scenario for Subregions 1 through 9.

Grouping by LUC-V the largest decreases across in the Sacramento Valley and Delta are Rice-Rice with a mean decrease of 0.24 meters. When cells are mean-centered on the subregion level the three largest declines are Native-Urban, Water-Water, and Urban-Urban with 1.5, 1.2, and 0.8 meters decline, respectively. The largest increases in head are Native-Ag and Ag-Urban with 5.6 and 2.3 meters, respectively. After mean-centering the three largest increases are Native-Ag, Perennial-Perennial and Annual-Perennial with 2.4, 0.6 and 0.4 meters, respectively.

Figure 18 presents the predicted changes in head due to land use change for an average year as compared to a dry year. Subregions 1 and 2 show lower predictions in head from land use change while Subregions 6, 8 and 9 have much higher predictions in head from land use change across the climatic models.

Total Water Requirements – Average Year

Figure 19 shows the change in water demand and source by subregion and Table 5 shows the percent change in each water source. Within the entire CVHM, there is a decline of 13% for total required water when comparing current to future land use. This reduction expresses itself with a 6% reduction in surface water requirements and a 25% reduction in groundwater pumping requirements.

Table 5 shows how the projected demand in a year is met from groundwater pumping, surface water deliveries, root uptake of groundwater and precipitation. The final two columns show the change in total farm delivery requirement (TFDR) and total water demand.

In an average year, the CVHM calculates that Subregion 4 can meet demand just on water available from precipitation and root zone groundwater. Subregion 1, 3, 4, 5, 7 and 10 are calculated as not requiring any groundwater pumping.

The Sacramento Valley experienced subregion specific changes in surface water deliveries and groundwater pumping, ranging from decreases of 76% (Subregion 1) to increases of 56% (Subregion 5) for surface water deliveries and 55% decrease (Subregion 6) to 55% increase (Subregion 2) in groundwater pumping. Water requirements met by non-delivery sources, i.e. precipitation and groundwater root uptake, increased between 1.3 to 15.3% for subregions in the Sacramento Valley. The Delta experienced decreases in surface water deliveries and groundwater pumping with Subregion 9 increasing water from non-delivery sources and Subregion 8 decreasing. Subregions in the San Joaquin Valley experienced increases in surface water deliveries ranging from 0.3% (Subregion 13) to 16% (Subregion 12) and increases in groundwater pumping ranging from 3% (Subregion 13) to 307% (Subregion 12). In general, the Tulare Basin saw decreases in surface water and groundwater pumping deliveries. Surface water deliveries changed between 3% increase (Subregion 15) to 51% decrease (Subregion 21).

Large declines in TFDR can be generally associated with the total amount of irrigated land use. Figure 20 shows the amount of irrigated and non-irrigated land by subregion for the Current and Future land use scenarios. Subregions 6, 9, 15 and 21, with

TFDR decreases of 30%, 57%, 36% and 59%, respectively all have declines in irrigated land use. Subregion 1 has an increase of irrigated land use from four irrigated cells to 8 irrigated cells out of 613 but a decrease in TFDR of 76.5%. This decrease can be attributed to two factors, one is the total TFDR demand is small and therefore a small volumetric change causes a large percentage decline. The second factor is that the land use changes allowed more water to be available for root zone uptake (16.5%) and more precipitation could be utilized (0.8%) because of the shift in the timing of demand.

Total Water Requirements – Dry Year

Figure 21 shows the change in water demand and source by subregion for both average and dry years. Table 6 shows the percent change in each water source for the dry climatic year. Subregion 1 is not dependent on groundwater pumping and saw a 79% decrease in surface water deliveries. Subregion 2 increased deliveries by 29%. Subregion 3 increased surface water deliveries by 16% and pumped groundwater to meet demand. Subregion 4 met demand by increasing surface water deliveries by 759%, this increase in surface water deliveries is an increase of 700,000 cubic meters per day out of a total of 38 million cubic meter per day demand. Subregion 5 increased surface water deliveries and groundwater pumping decreased, though the total amount pumped was negligible. Subregion 6, 8 and 9 decreased demand by 17% to 67% which propagated through both surface water and groundwater pumping deliveries. Subregion 7 increased demand by 18% and was met by increased surface water deliveries.

Subregions 6 and 9 show large declines in TFDR, 49% and 67%, respectively. Both Subregion 6 and Subregion 9 also have less irrigated land uses in the Future land use scenario. Subregion 8 has a decline in the TFDR while having an increase in irrigated land use. Figure 22 shows the yearly demand for Subregion 8 across all four climate and land use scenarios. The land use changes in Subregion 8 are largely shifts to Vineyards and Urban classes coming from Native and Annuals, where Urban is a non-irrigated land use and Vineyards have lower demands than other irrigated land uses. By comparing the Current to Future scenarios, for both average and dry climatic years, the yearly signal remains almost identical with the Future scenario being slightly, consistently lower. The land use scenarios do not cause large yearly shifts, such as the change in climate signal, but incremental changes in demand which are easier to see in yearly comparisons.

Total Water Requirements – Cross Comparison

By comparing the average to dry years for the Sacramento Valley and Delta (Figure 21) a moderate climate effect is observed. Table 7 presents the percentage change in water demand from an average to a dry year when holding either the current land use or future land use constant. The TFDR is the sum of the groundwater pumping and surface-water deliveries and the total water demand is a sum of all four water terms. In Subregion 1 and Subregion 8 the total water demand declines under both current and future land use scenarios. Subregion 6 has a decline in total water demand for future land use. All other subregions show increases in total demand for both land use scenarios. The TFDR increases across all subregions and land use scenarios. This indicates that under any conditions the dry climate will increase the water deliveries, which are realized as groundwater or surface-water deliveries.

In general, root zone uptake decreases when comparing average to dry climatic years with the exception being Subregion 4 which has an increase of 4% in root zone uptake for both current and future land uses. Figure 22 shows the water demand for the final water year differentiated by source for Subregion 8. Examining Current - Average to Current - Dry and Future – Average to Future – Dry, the changes from changing the climatic scenario are observed. In general, the lower heads in the dry scenario cause a much lower Root Zone Uptake throughout the year. The Total Water Demand shows the difference between the yearly ET, where the dry climatic year has a generally higher yearly reference ET but not a consistently higher reference ET (Section III). The Total Water Demand shows the dry climatic years have larger demand in the fall and winter, but the spring and summer show a similar demand, where the average climatic year occasionally has a larger total demand. Figure 23 shows the water demand for the final water year differentiated by source for Subregions 1 through 7 and Subregion 9. Changes in monthly demand is shown across both the average to dry climatic years and across the Current to Future land use scenarios.

CHAPTER V

DISCUSSION

Discussion of Results

This research utilizes the conjunctive use properties of the CVHM to estimate the impacts of projected land use shifts on water resources. The use of an average climatic year is idealized to understand impacts. Under an average year the Sacramento Valley and Delta regions are minimally impacted with subregional mean heads shifting between 3.3 meters increase to 1.5 meters decrease. The San Joaquin Valley is impacted less with subregional mean heads shifting between 1.8 meters increase to 0.1 meters decrease. The Tulare Basin underwent the largest mean head shifts of 4.0 meters increase to 5.1 meters decrease.

The water available for root uptake, a non-delivery source, is dependent on two factors, the depth or rooting and the water table level. Increases or decreases in root uptake can be from either, or both, of these factors.

Discussion of Comparable Studies

A 2008 study (Dams et al., 2008) coupled four different land use scenario projections with groundwater model for a basin in Belgium. The maximum head change experienced when the 20-year land use projections were incorporated were 0.025 meters to 0.009 meters decreases. Two major differences within this study is that all four land use scenarios included decreases in agricultural land and this area experiences an average of

800 mm of rainfall per year. The Sacramento Valley experiences 330 mm to 660 mm and the San Joaquin Valley experiences 125 mm to 450 mm of rainfall per year (Faunt et al., 2009).

The use of LUC-V and evaluating changes on a cell-by-cell basis is not currently found in the literature. Using the framework of LUC-V can illuminate regional patterns. Examining heads by LUC-V showed Ag-Native had a negative impact on heads and mean-centered heads with -1.54 and -0.84 meters, respectively. The top three head declines for mean-centered heads are Native-Urban, Ag-Urban and Rice-Urban. The effects of urbanization to surface water are well documented (Praskievicz and Chang, 2009) with increased impervious surfaces leading to decreased infiltration and potential nonpoint source pollution. The effects of urbanization without municipal pumping on groundwater are not fully investigated in this work. Considering that municipal water demand was kept constant through this analysis the effects of urbanization could potentially be exacerbated by increasing municipal pumping to keep up with population demand (Zellner and Reeves, 2012).

The Sacramento Valley and Delta generally saw less groundwater pumping when projected land use changes were incorporated. When total water demand increased it could generally be met with increased root zone uptake and surface water deliveries. Even when groundwater pumping contributed a large portion, such as Subregions 6 and 8, groundwater pumping requirements decreased with future land use projections. In Subregion 6 this decrease in pumping demand is from an overall increase in non-irrigated land uses in the future projections, even though this leads to higher total demand. Subregion 8 experiences a decrease in total demand based on the land use projections which propagates throughout every water source. The San Joaquin Valley saw very little change. The Tulare Basin is the most dependent on groundwater of the four regions. In general, decreases in total water demand are seen in the Tulare Basin, which is met by a decrease in groundwater pumping.

Land use water demand was investigated in 2016 (Wilson et al., 2016), with similar land use scenarios as this research, that spans from 1992 to 2062. While their study area consisted of the Central Valley and the surrounding Oak Woodlands, their analysis concluded that land use related water demand would increase by 4.1% but agricultural water demand would decrease by 7.8%. This investigation found that in an average year, the total water requirements for the entire CVHM decreased by 5.8% and water deliveries decreased by 13.4%.

Examining the Sacramento and Delta regions, incorporating Future land use scenario increased total water demand by 2.7% in an average year and decreased water demand by 5.9% in a dry year. Water deliveries decreases by 11.8% and 26.1% in the average and dry years, respectively. The research done by Wilson et al. (2016) included increases in industrial water usage as determined by the increase in developed land use. Those changes only consider the change in water requirements based on land use shifts and not any differences in climate.

Comparing the average to dry years within the Sacramento Valley and Delta regions, total water demand increases by 19% and 70% for the current and future land uses, respectively. The Total Farm Delivery Requirement increased by 113% and 78% in the current and future land uses, respectively. While a drier climatic year will increase water demands, incorporating the projected future land use changes could decrease the water that is required to be allocated to grow healthy crops. While the total demand increased going from average to dry, the monthly demand does not necessarily follow that trend in all areas. The yearly climate variability is an important factor in projecting future water demands. Understanding how seasonal demands could be changing will provide light onto how the demand is met. For instance, a slight increase in potential ET in the spring could probably be met by precipitation and root zone uptake, but a similar increase in the fall when groundwater is at a seasonal low and precipitation has not started could see larger increases in groundwater pumping to meet demand. The timing of demand and source water location both play important roles in projecting water demands.

The CVHM was coupled with climate models to investigate how water resources could respond to potential climate change (Hanson et al., 2012). The groundwater pumping deliveries were shown to increase over the next 100 years (Figure 24). The results of this study show that the predicted pumping increases may be tempered with the incorporation of land use change, specifically in the Sacramento Valley and Delta regions.

Conclusion

Changing land use will play a role in future water availability. This influence could be from large agricultural shifts, through climate change or economic drivers, growth of urban areas with the associated increase in municipal water demand, or more aggressive native area conservation efforts. These changes will most likely be determined at a local level but they will have regional effects. It is important to use modeling techniques such as the ones used in this study to gain a better understanding of how a system will react.

This research provides a framework for looking at how land use changes can be incorporated into conjunctive use models. The regional impacts of these changes will need to be considered in the creation of Groundwater Sustainability Plan especially when the administrative boundaries do not conform to flow boundaries. Sustainability plans need to look at both the near- and long-term impacts to groundwater resources including from a changing climate and changing demand. Changing land use will influence the total water demand and the timing of the demand while climate change will influence the total water demand and climate variability will influence the timing of that demand. The interaction between climate change, climate variability, and land use change are complicated. By focusing solely on climate or land use it is possible to miss the compound effects, which can be beneficial or detrimental to an area. Understanding that interaction could prove important for future planning.

CHAPTER VI

LIMITATIONS AND FUTURE WORK

Limitations

This research has been built on multiple assumptions.

1. This work did not account for the population increases that were coupled with the land use changes. To explore the effect of land use municipal pumping was held to 2003 levels. Preliminary analysis was conducted by coupling the population projections associated with LUCAS with the municipal pumping in the CVHM. Linear regression on a subregion level fit the historic data but provided large prediction intervals when projected to 2090.
2. Reservoirs in California provide a significant portion of stream flows into the Central Valley. This research assumed that reservoir releases would remain the same for each of the climate scenarios, at the 2001 or 2003 year.
3. Multiple assumptions were made and documented in transitioning from LUCAS to CVHM land use types (Section III).
4. All limitations documented in the LUCAS development (Sleeter et al., 2017) and CVHM development (Faunt et al., 2009) are carried over into this analysis.

Future Work

This research incorporates future land use projections into groundwater models. This work has shown how variable different regions are within the Central Valley.

Current work (Zipper et al., 2018) have used statistical methods to separate out the influences of land use change and climate change using least-mean-squared regressions. This separation is done on a continuous basis and could be used for the original 1961 to 2003 CVHM model run. In addition, coupling land use projections with climate projections (Hanson et al., 2012) could provide insight into how water resources will need to be managed in the future.

This research can be modified to study the sensitivity of which changes in land use are causing changes in simulated groundwater levels and water demands. This can be done by running separate scenarios that only look at a single LUC-V. The individual LUC-V effects can be compared against the cumulative effect, presented in this research, to investigate interactions.

The effect of urbanization on groundwater systems is interesting and is worth exploring further. Potentially using water balances for sites that have increased urbanization or modeling efforts to look at total amount of infiltration and recharge from urban areas.

This research focused exclusively on the upper three layers of the CVHM aquifer system. The upper three layers are considered the “shallow” groundwater system, but there are thousands of feet of additional aquifer that make up the deep groundwater system. Additional work on examining how land use changes are changing the deeper system is another avenue of research.

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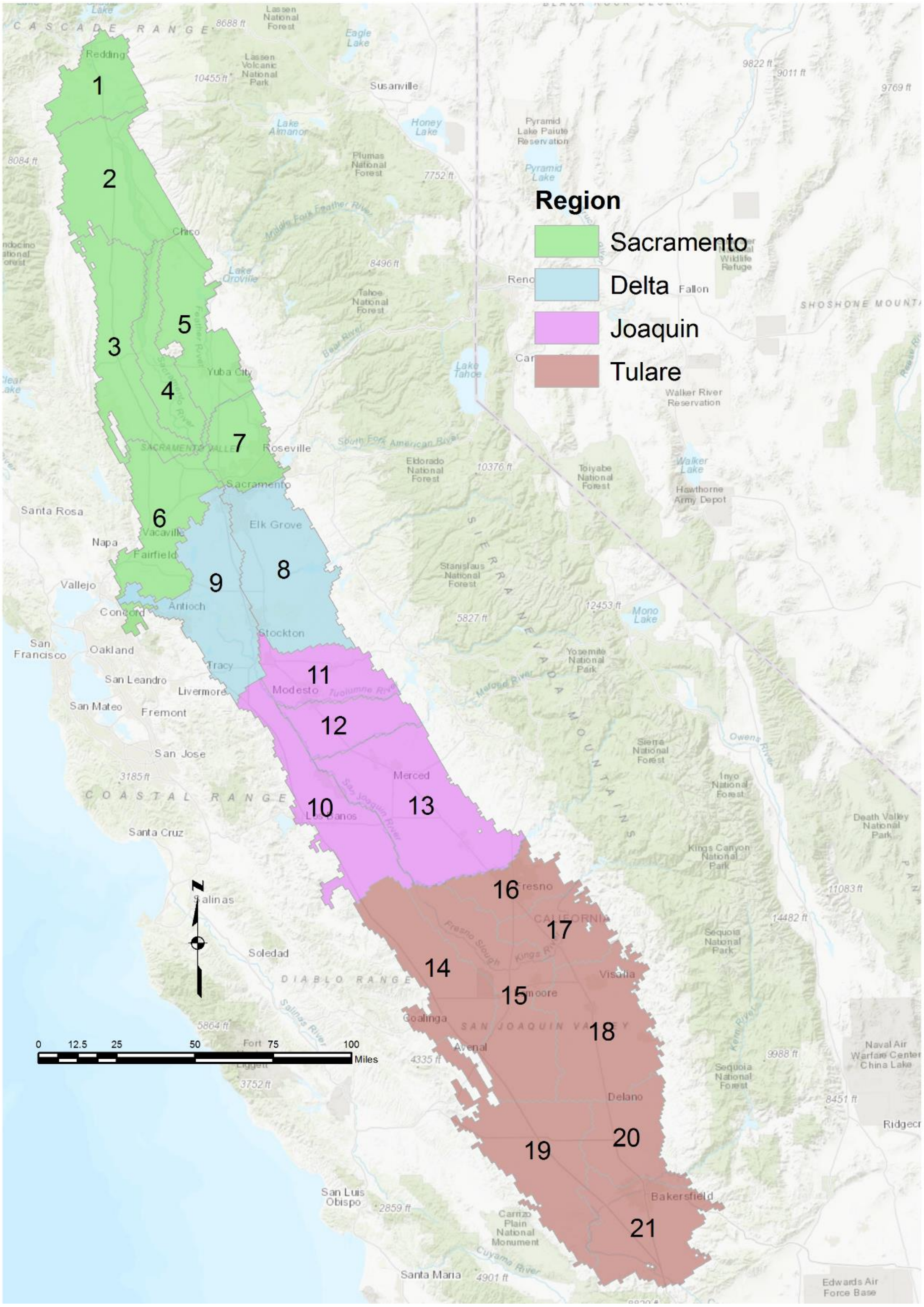

Figure 1: Study Area Map of the Central Valley Hydrologic Model. The main regions, Sacramento Valley, Delta, San Joaquin Valley, and Tulare Basin are shaded and labelled by subregion.

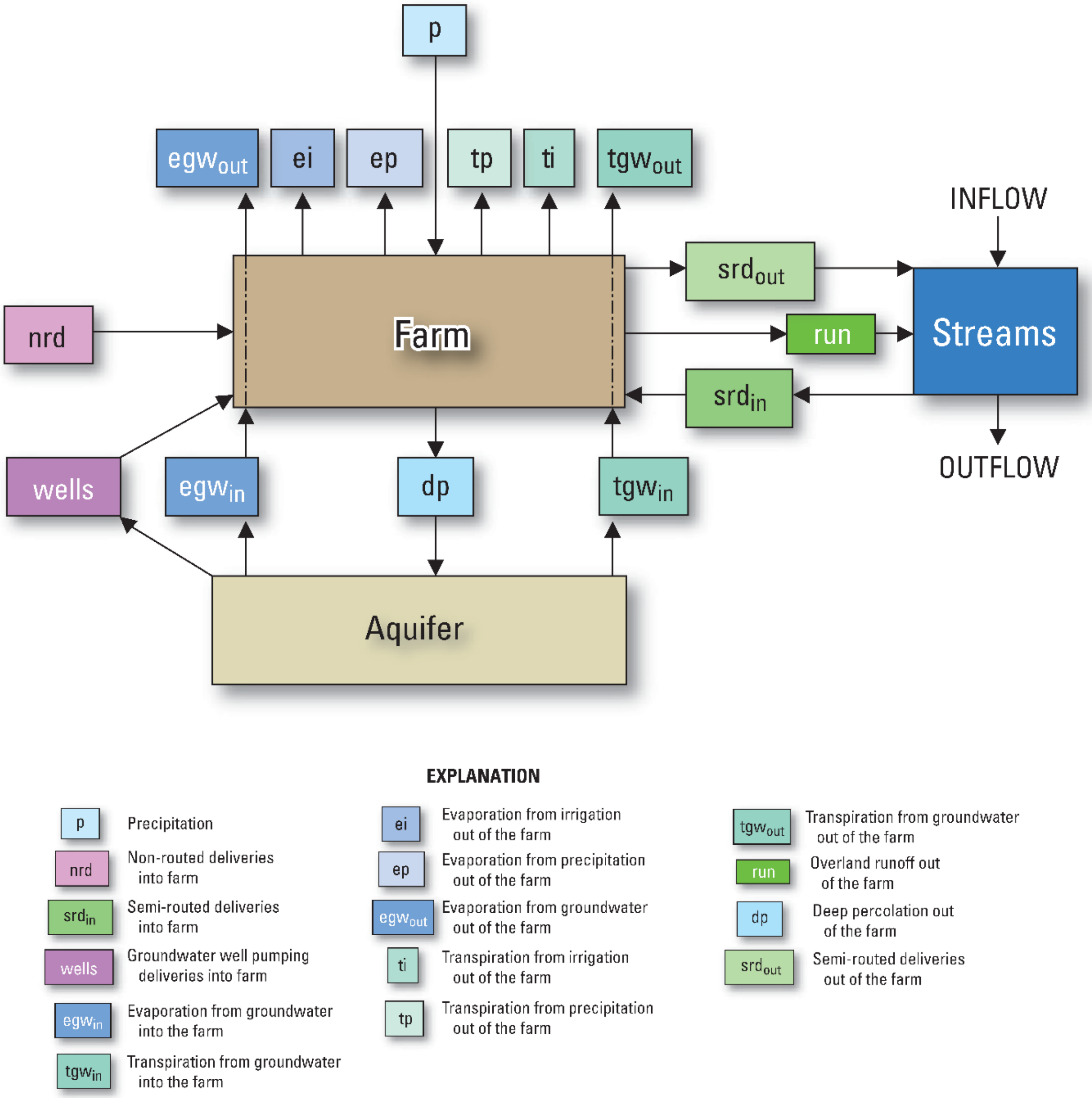

Figure 2: Flow chart of computed inputs and outputs for the surface water mass balance equation conducted by the CVHM. Modified from Faunt, 2009.

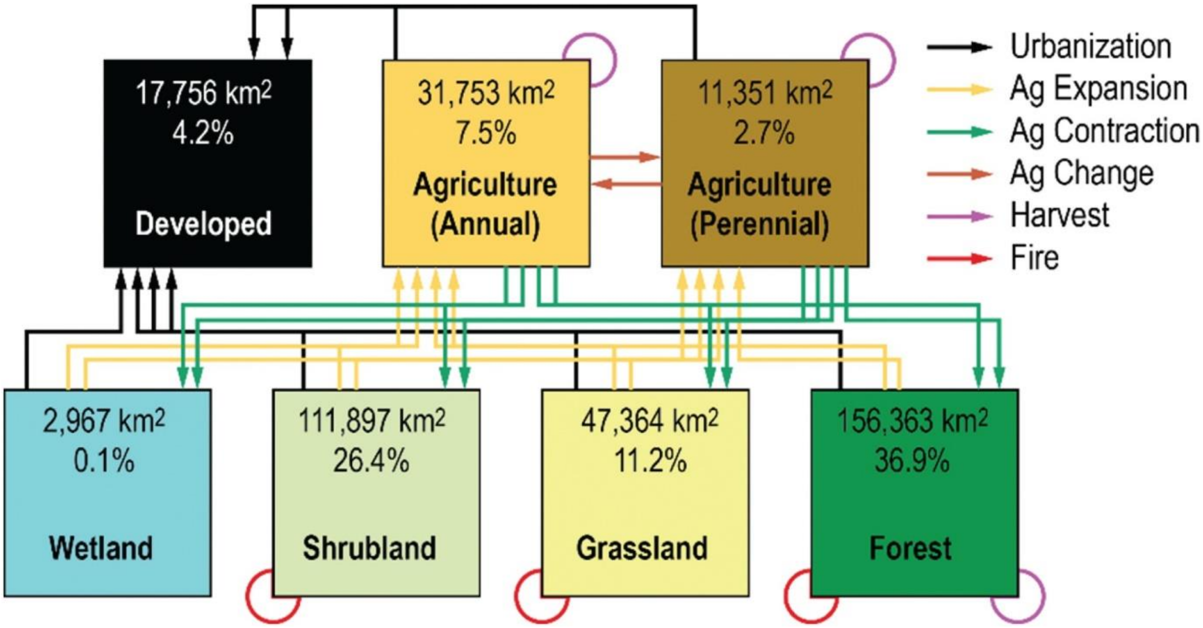

Figure 3: LUCAS pathways which describe how cells can change within the LUCAS model. The area and percentages are the total land for each land cover type and the percent of the total model in 2001 when the model was initiated (modified from Sleeter et al., 2017).

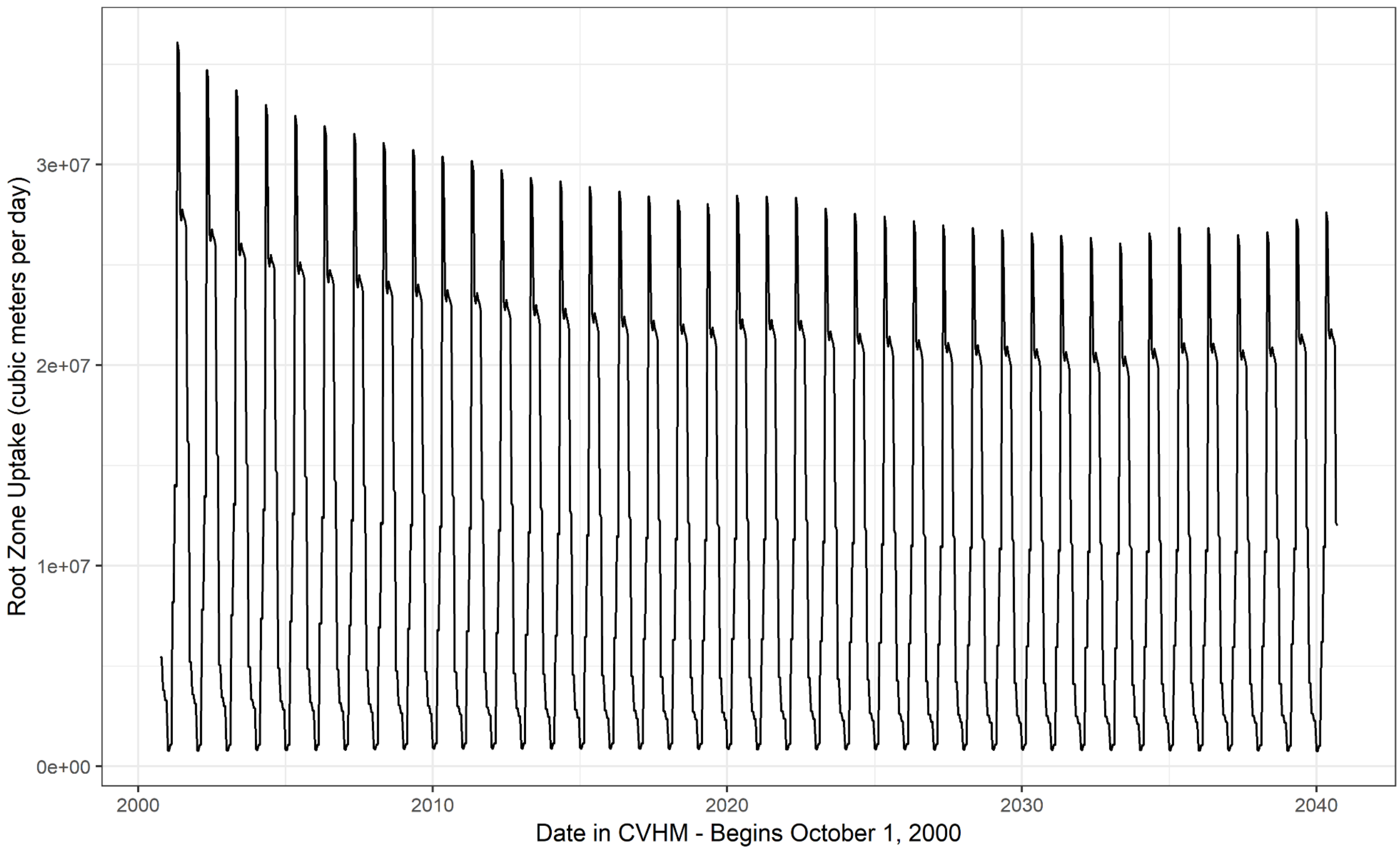

Figure 4: Root zone uptake over time for the entire CVHM. Equilibrium with the yearly flows is typically reached after 15 years in the model.

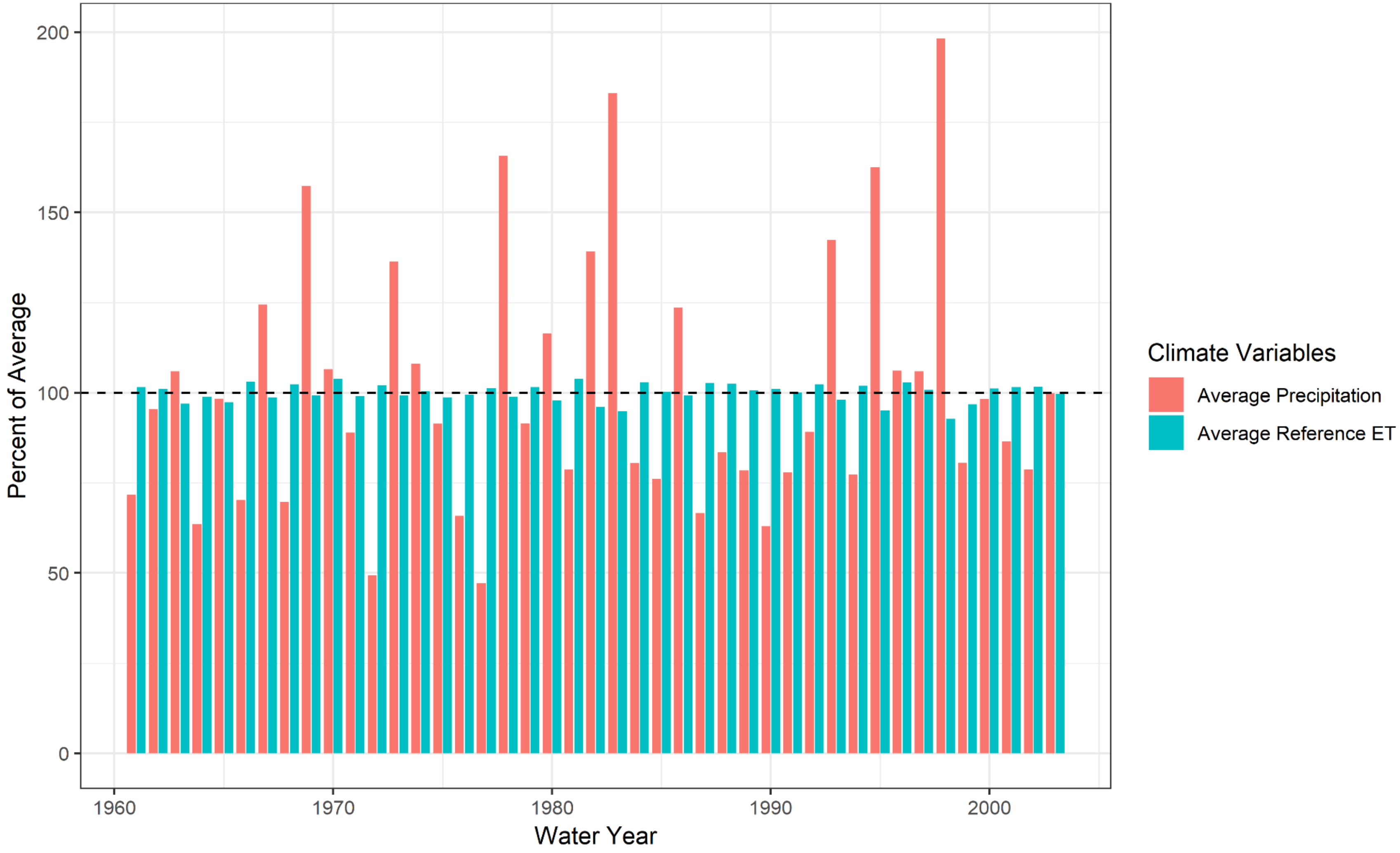

Figure 5: Annual reference ET and precipitation as percent of average.

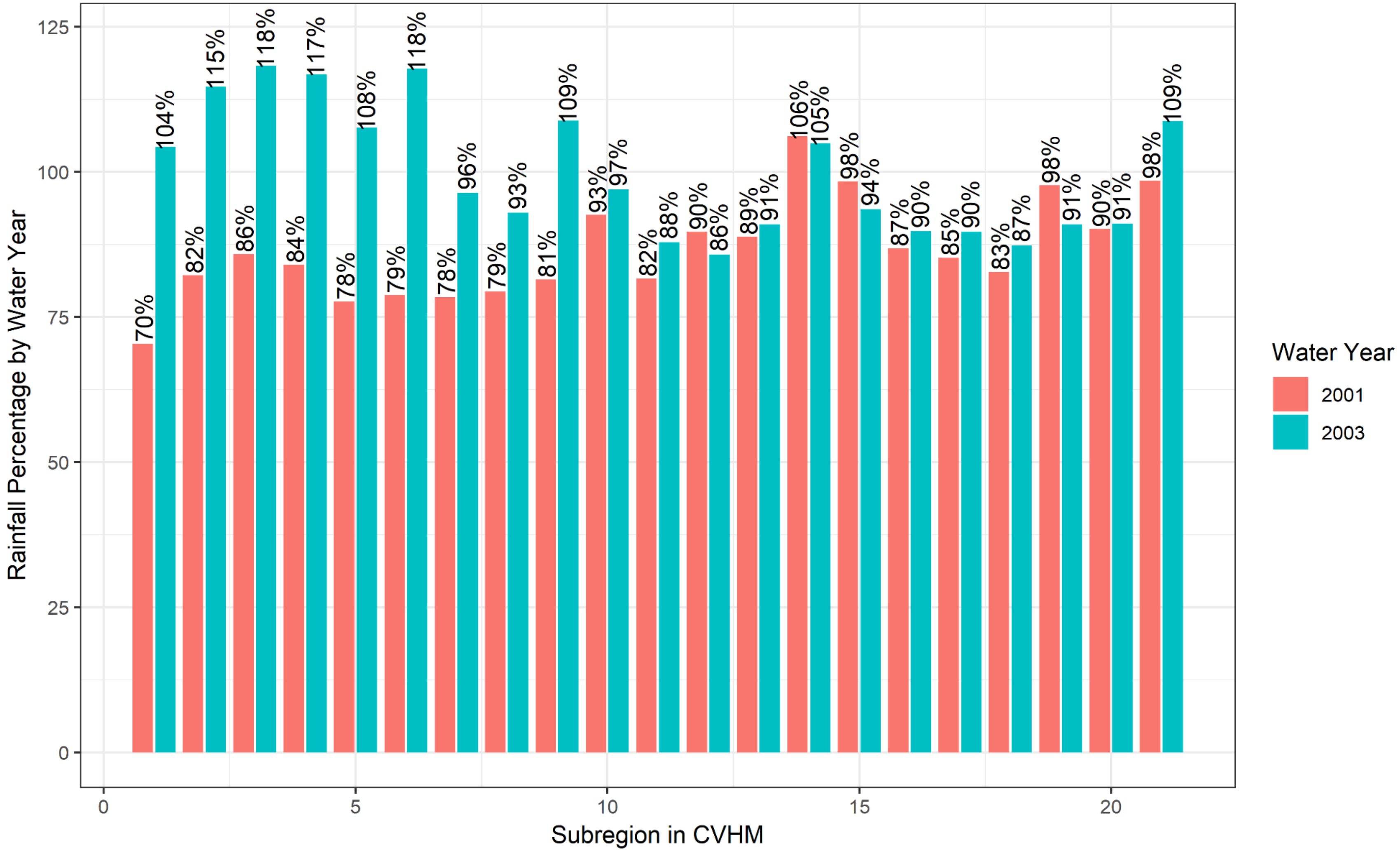

Figure 6: Annual precipitation by CVHM subregion for water year 2001 and 2003. Examining the “dry” and “average” year respectively.

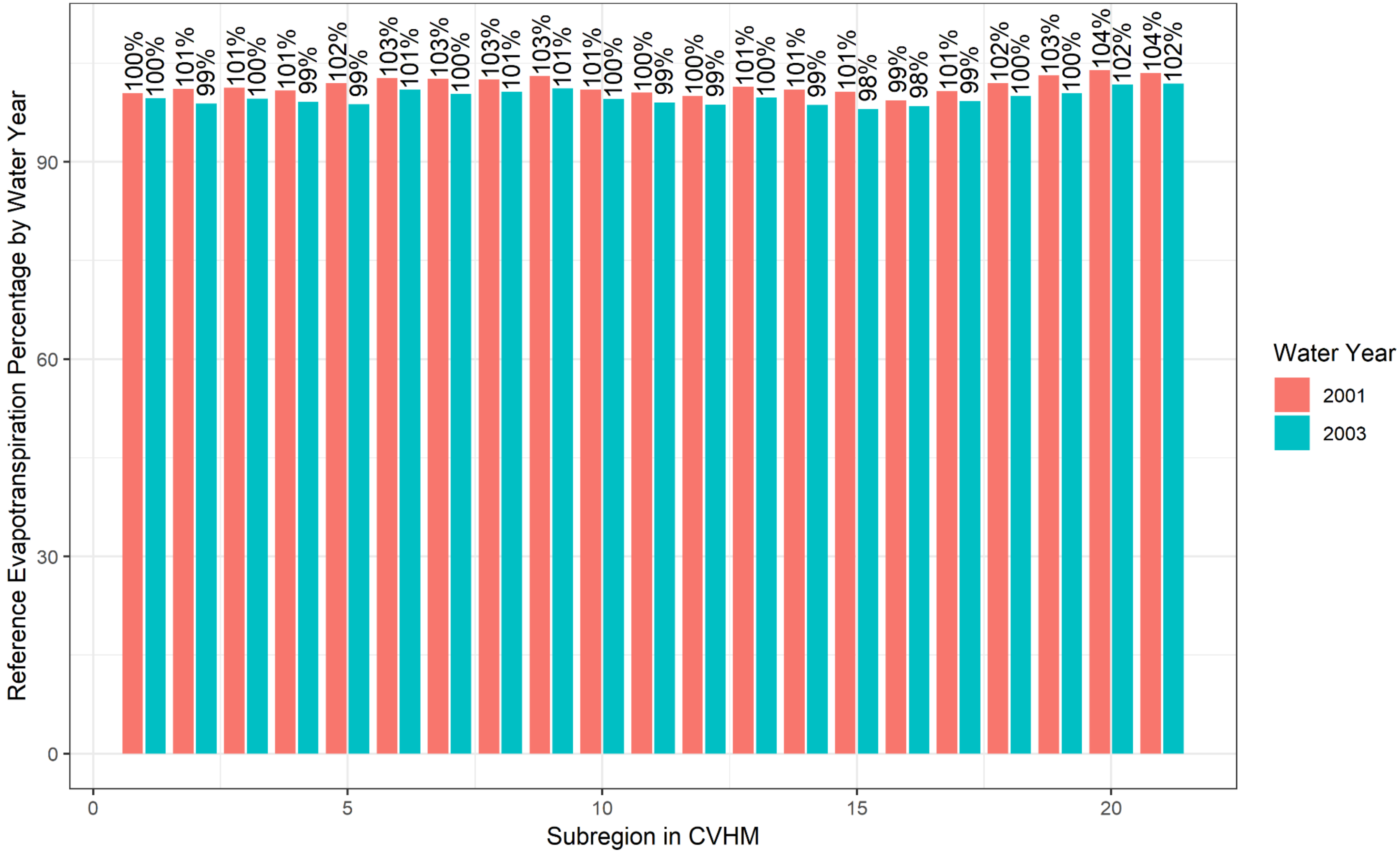

Figure 7: Annual ET by CVHM subregion for water year 2001 and 2003. Examining the “dry” and “average” year respectively.

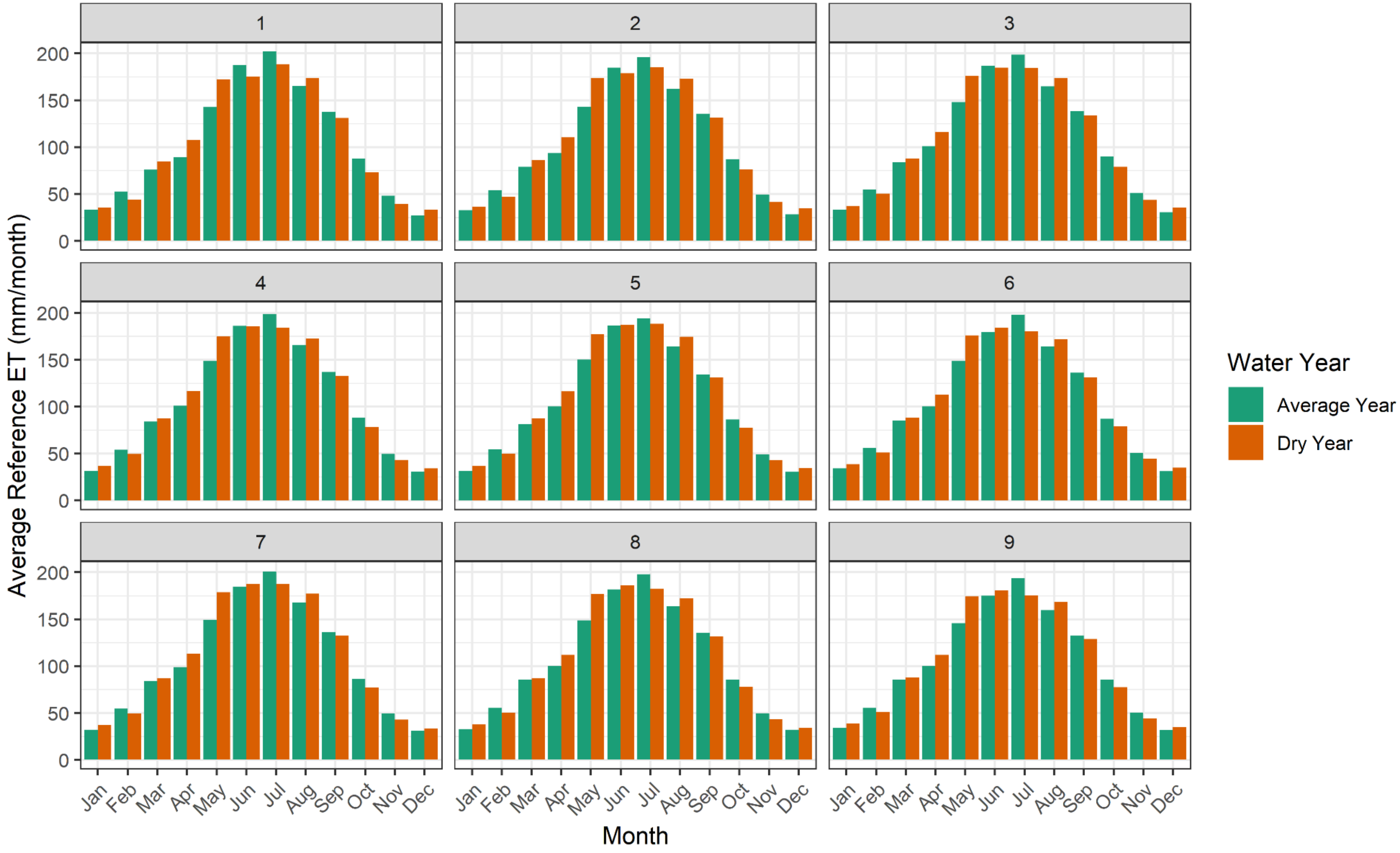

Figure 8: Monthly reference ET for the Sacramento Valley and Delta Regions.

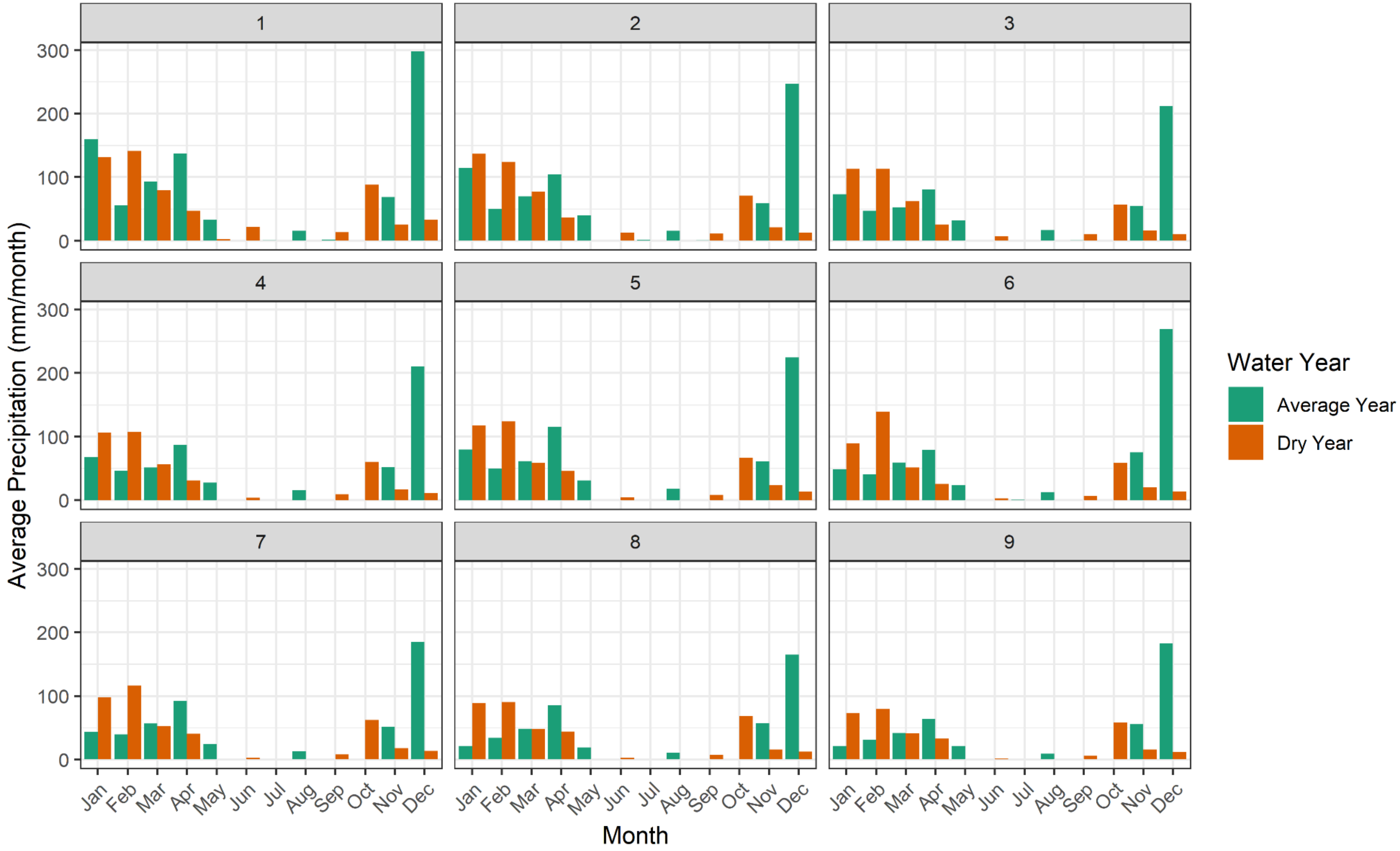

Figure 9: Monthly precipitation for the Sacramento Valley and Delta Regions.

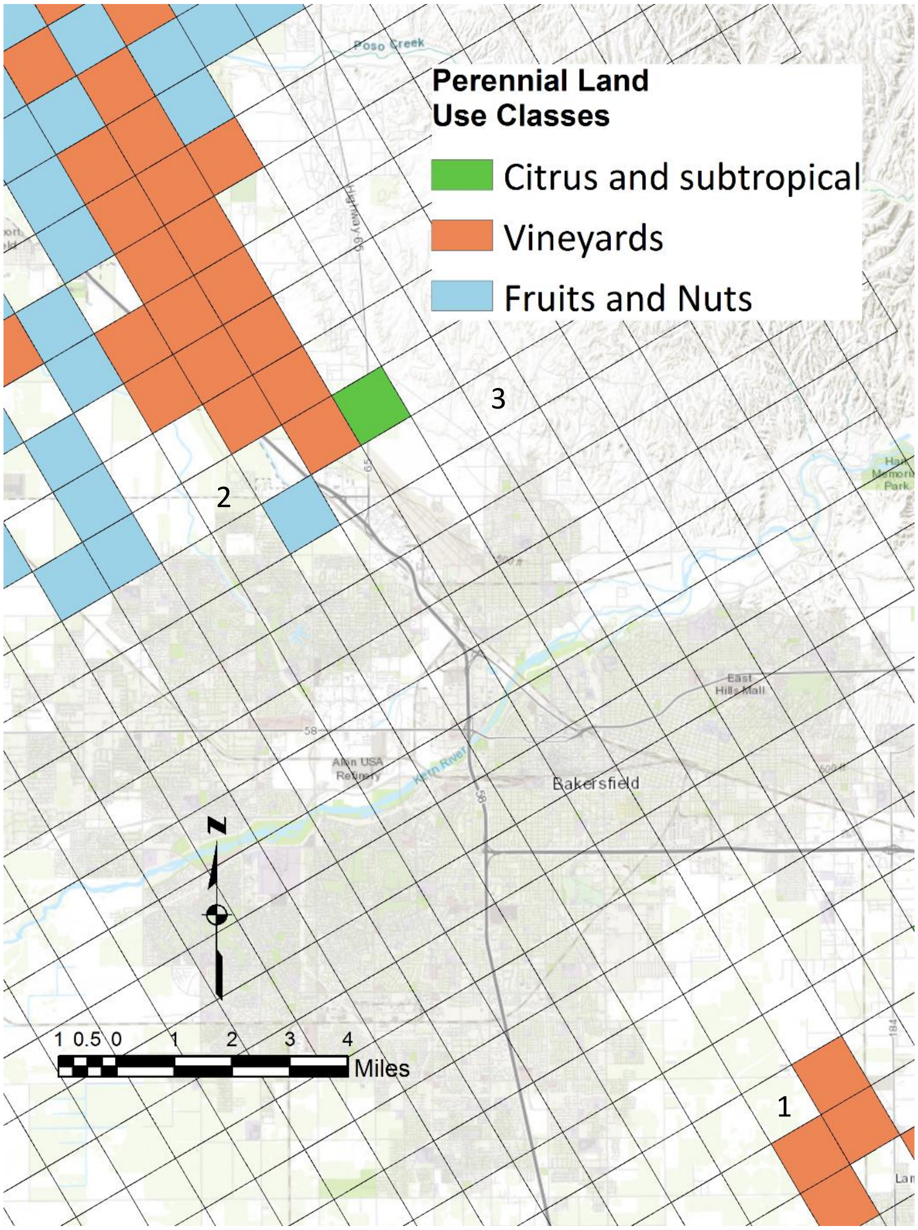

Figure 10: Example of land use change. When cell 1 changes to perennial the surrounding 8 cells are examined for any of the three CVHM perennial land use classes. In this case five cells are not applicable and three cells are characterized as vineyard, therefore cell 1 would transition to vineyard. Of the eight surrounding cells of cell 2, 6 are not applicable, one is vineyard and one is fruit and nut. In this case the land use would be randomly assigned to cell 2, this occurred in less than 5% of the transition samples. Cell 3 has no applicable cells surrounding it. In this case the nearest applicable cell would be taken, which is citrus and subtropical.

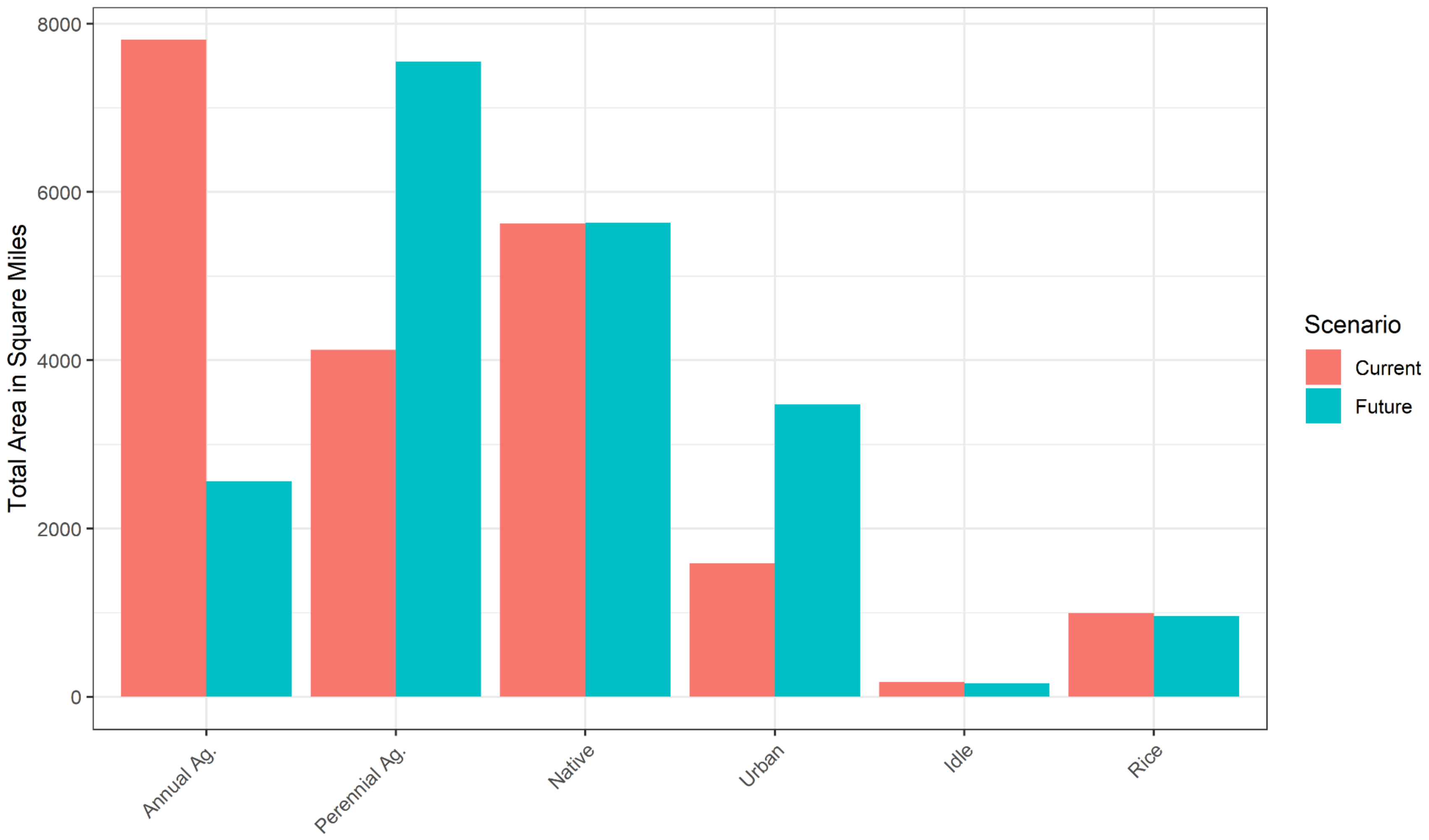

Figure 11: Current and Future land use in the CVHM.

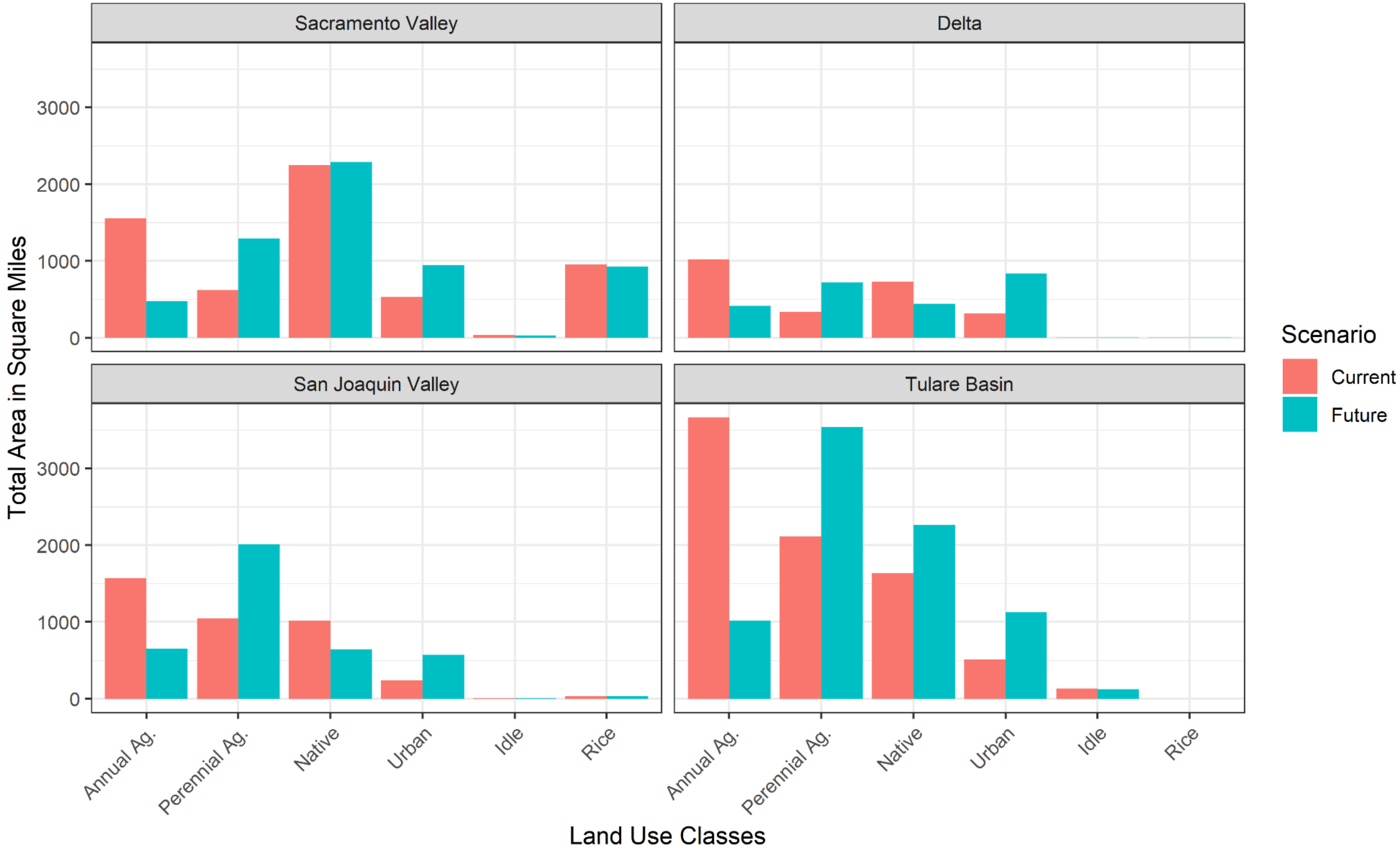

Figure 12: Current and Future land use in CVHM Regions.

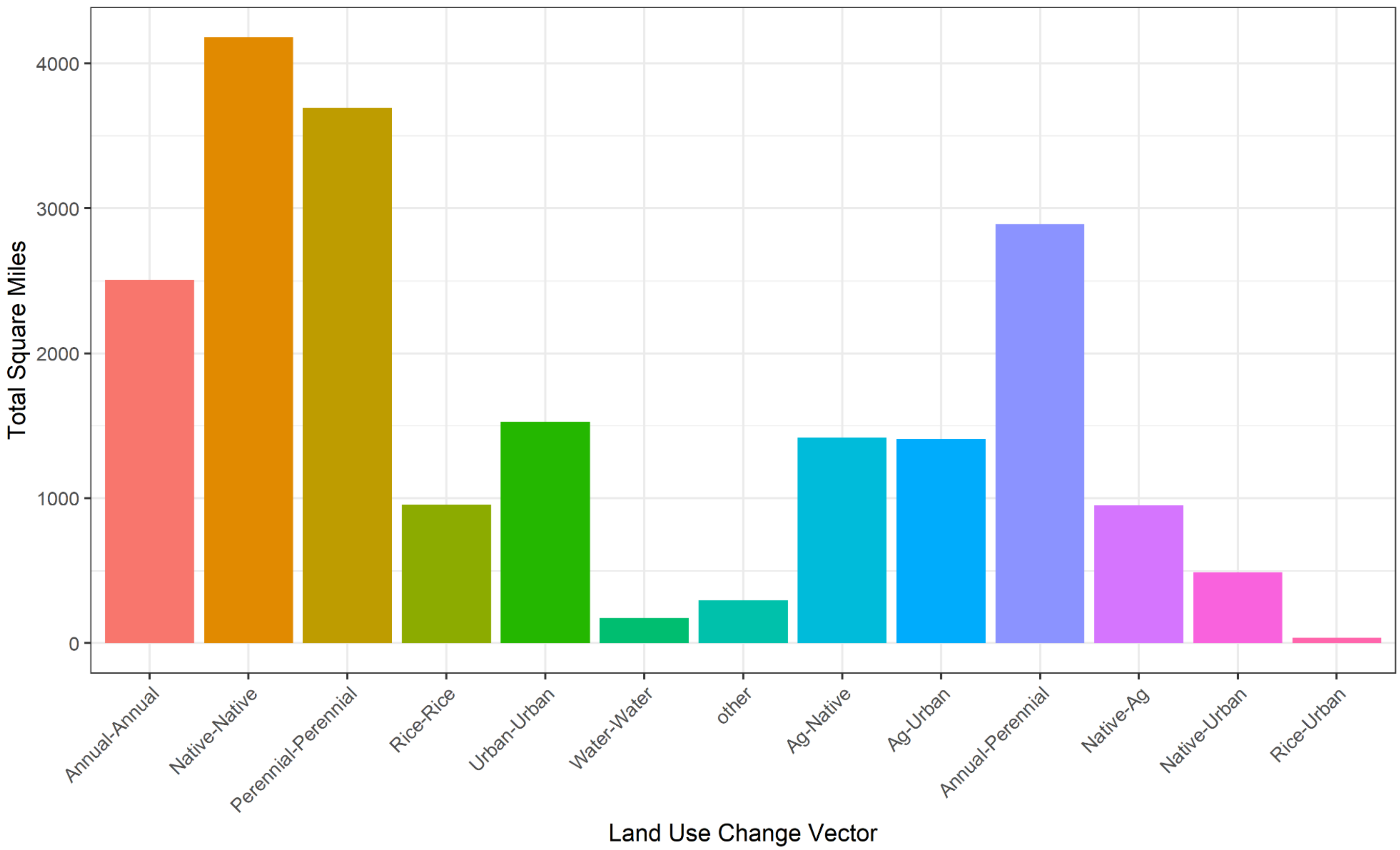

Figure 13: Land Use Change Vector (LUC-V) for CVHM.

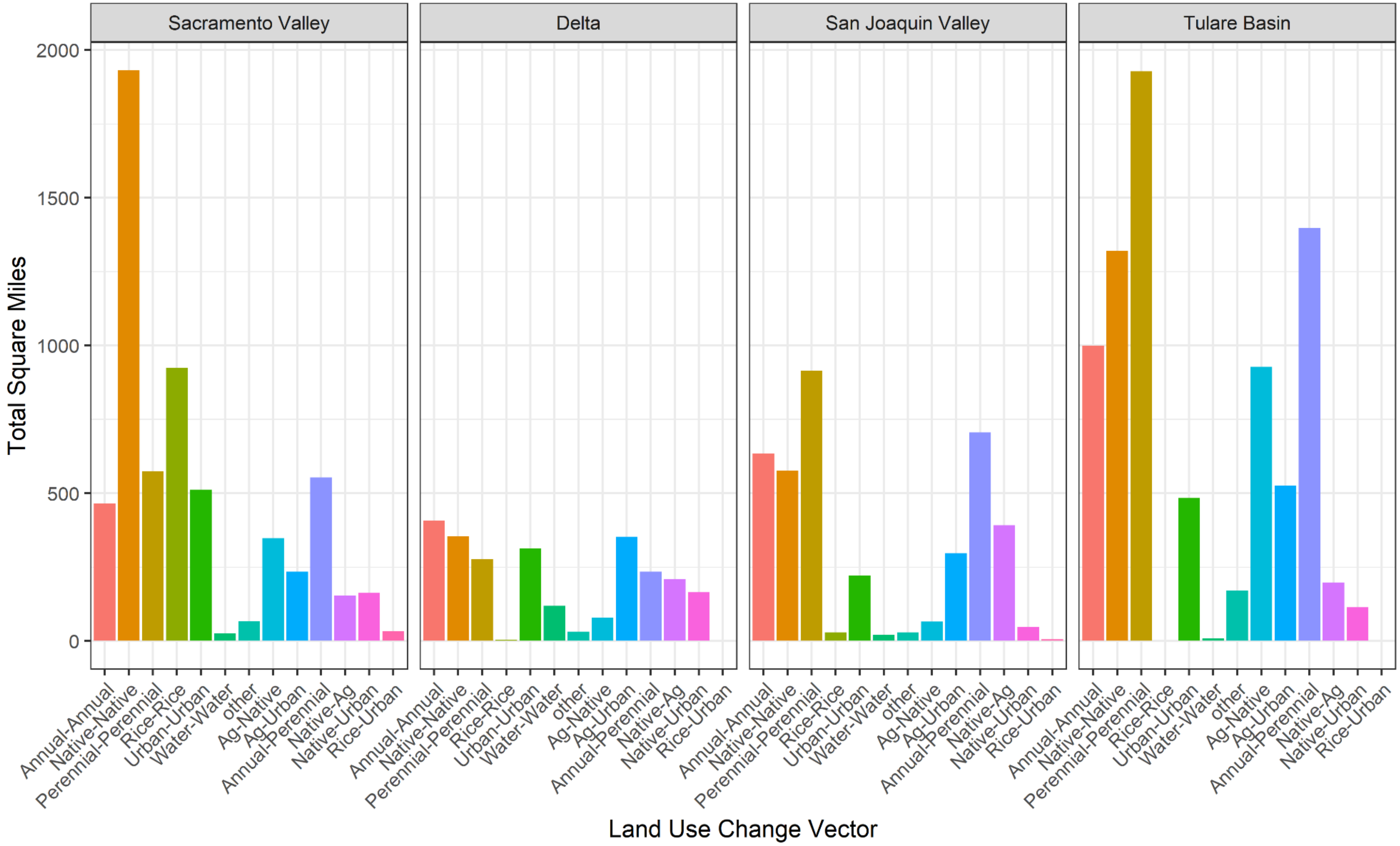

Figure 14: Land Use Change Vectors (LUC-V) for CVHM Regions.

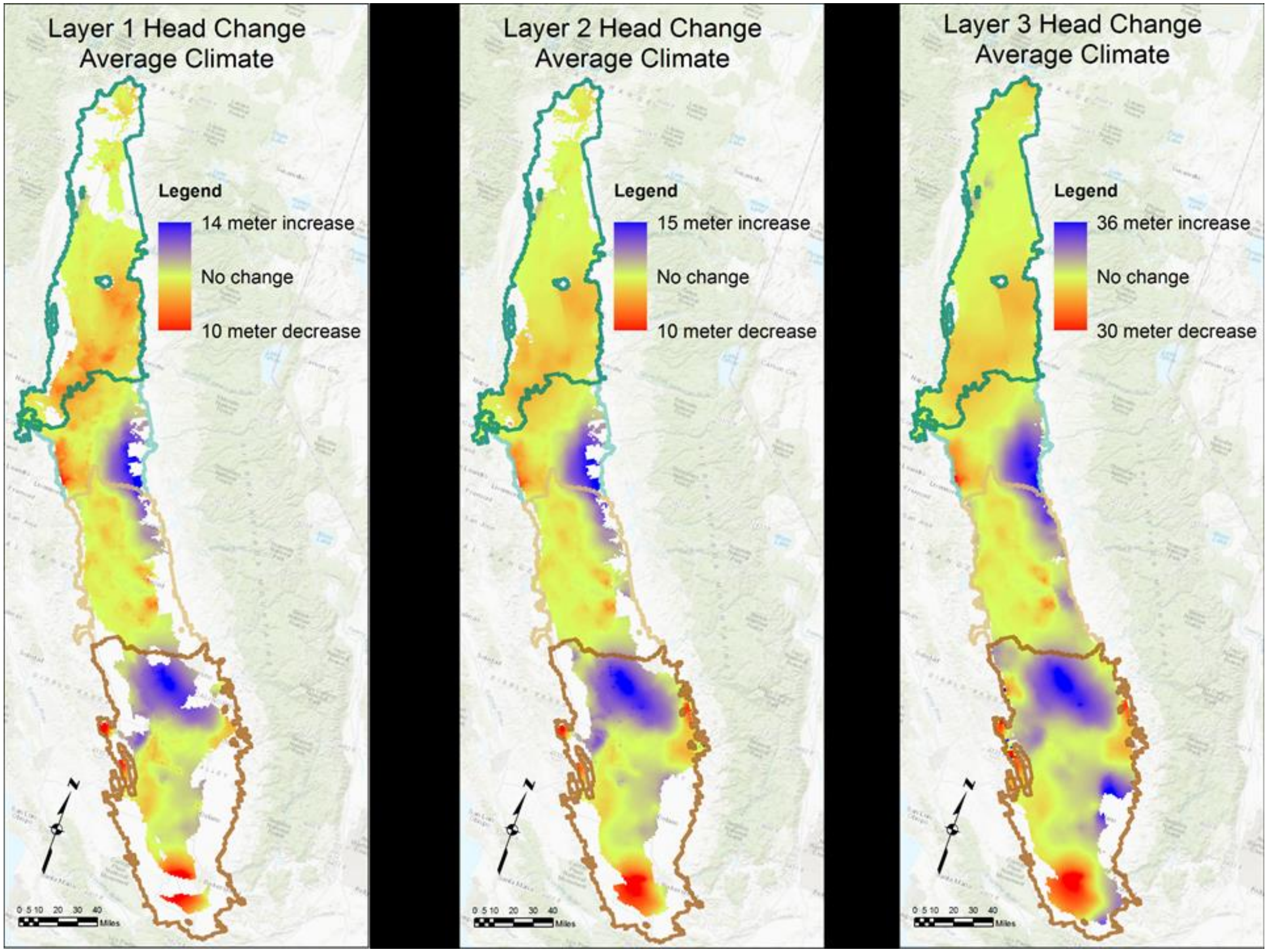

Figure 15: Head changes caused by land use change in an average climate.

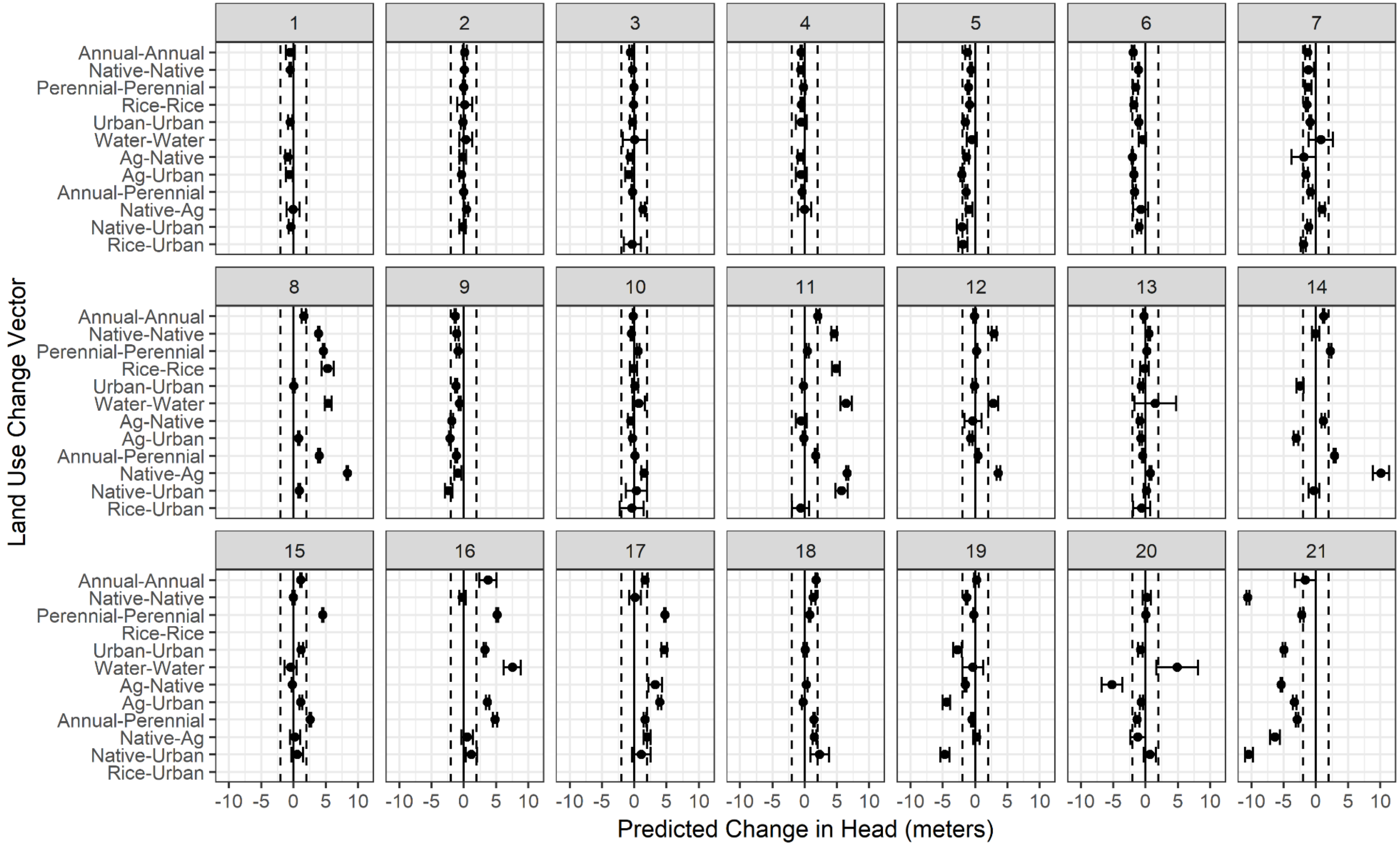

Figure 16: Predicted changes in head for an average year by LUC-V and subregion.

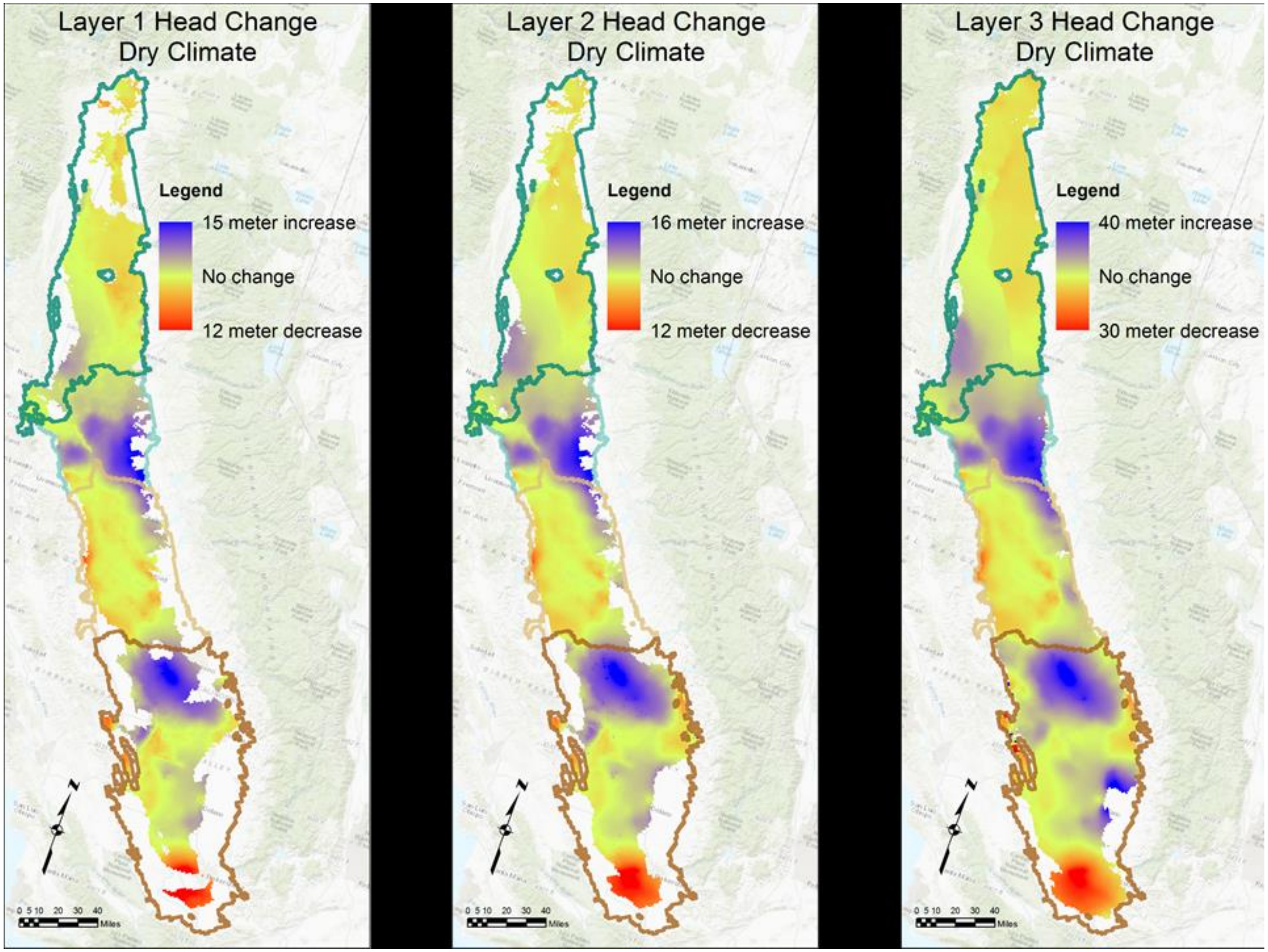

Figure 17: Head changes caused by land use change in a dry climate.

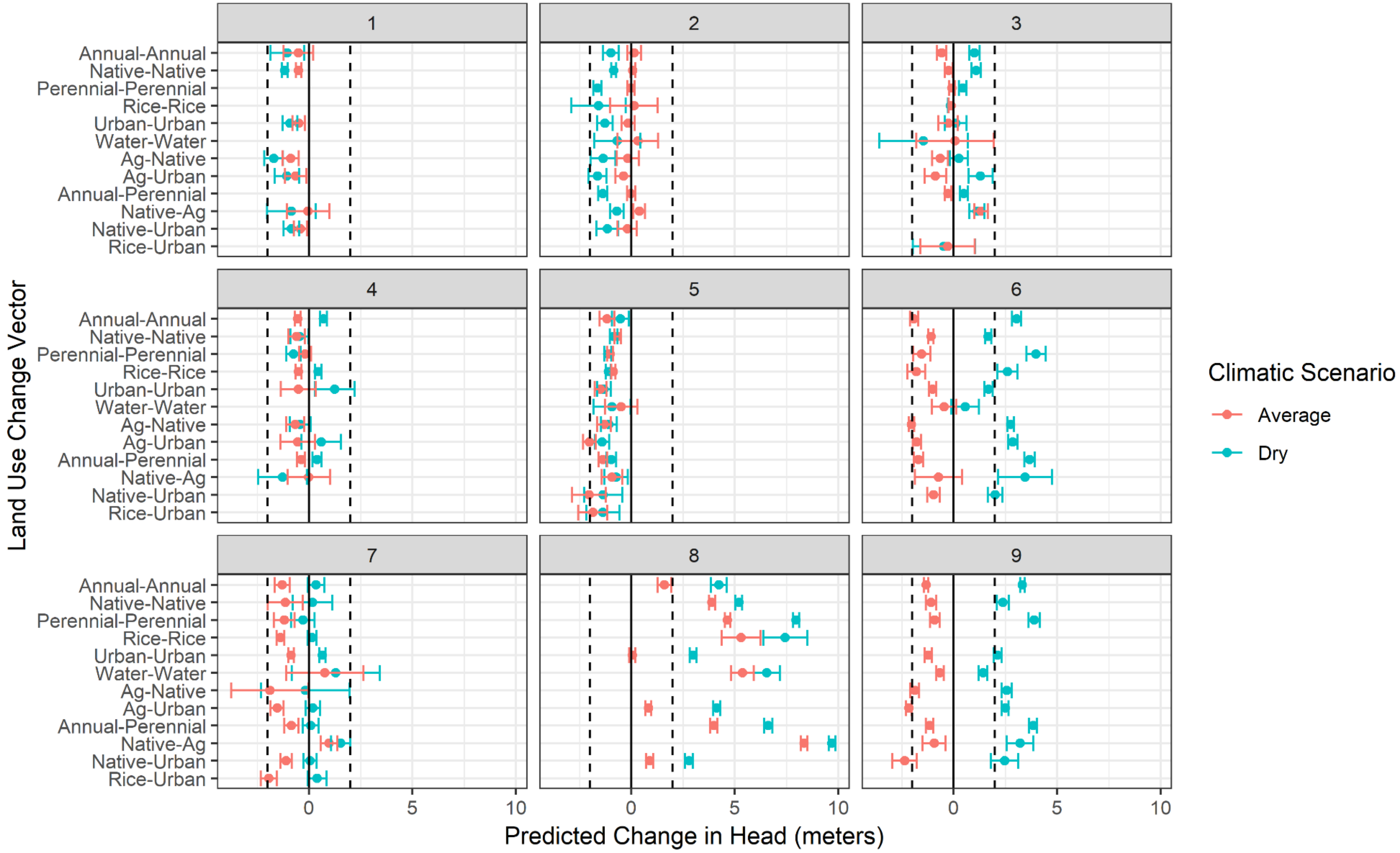

Figure 18: Predicted changes in head for a dry year by LUC-V and subregion.

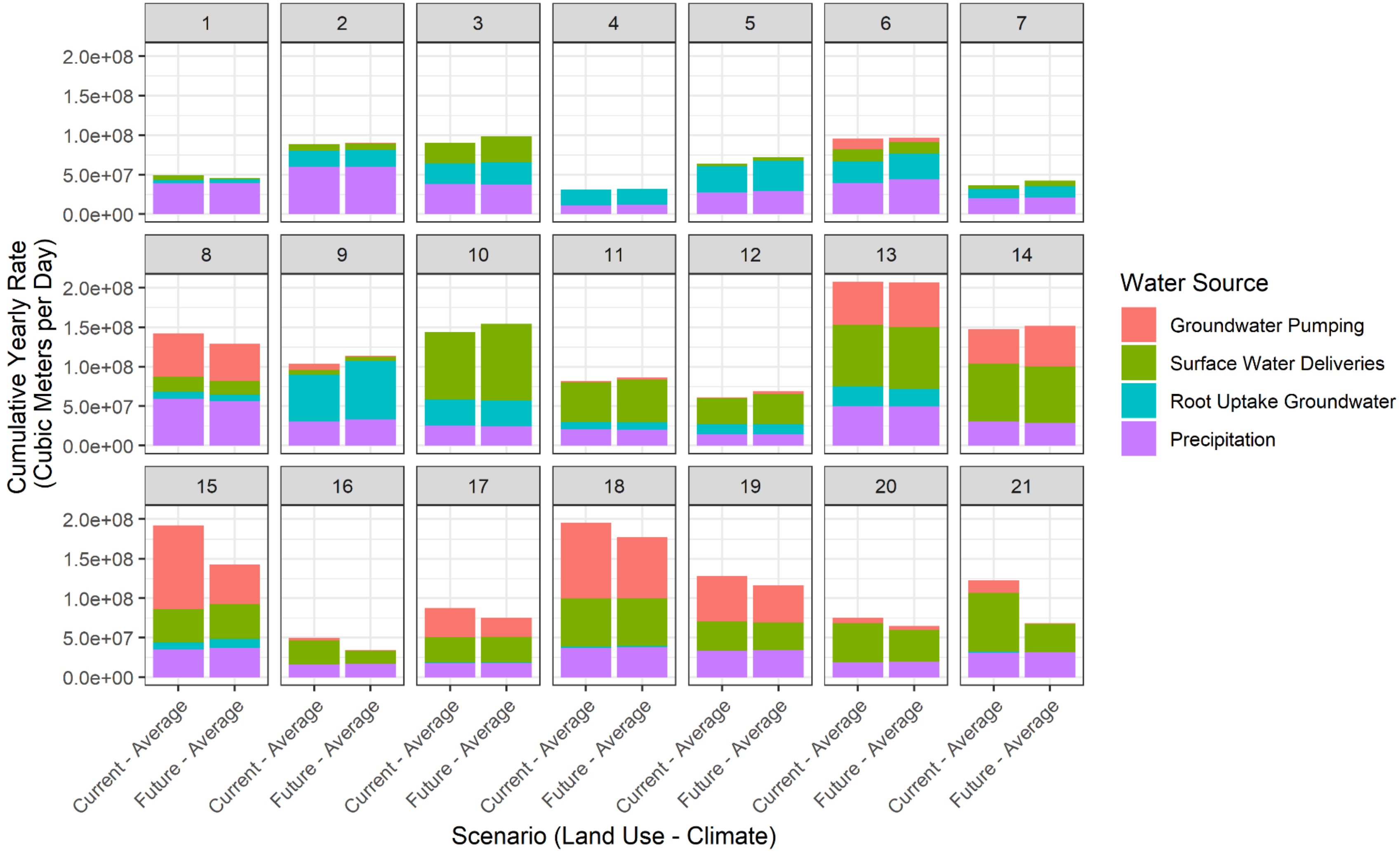

Figure 19: Total water demand differentiated by water source for an average year.

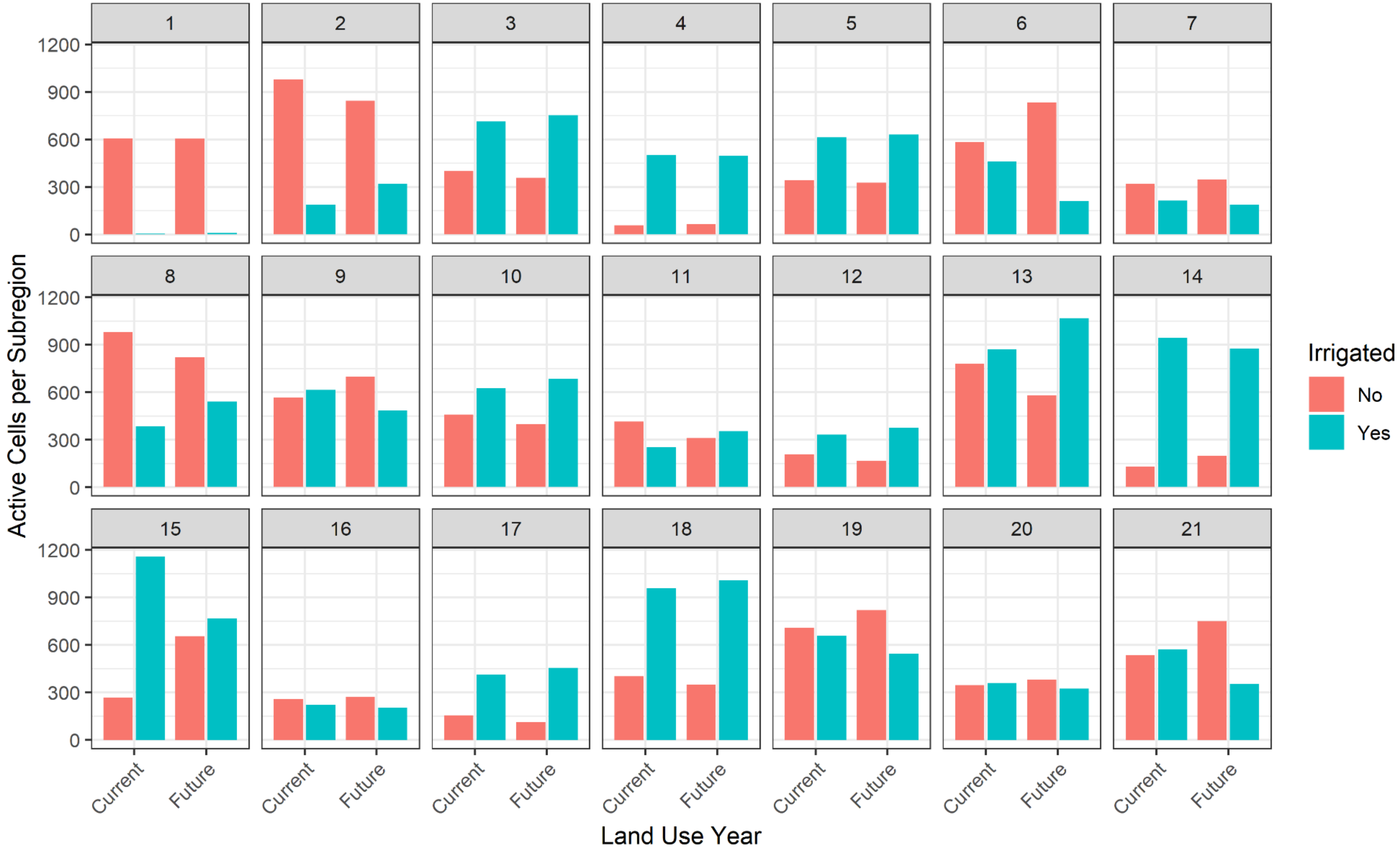

Figure 20: Current and Future irrigated and non-irrigated land use by subregion.

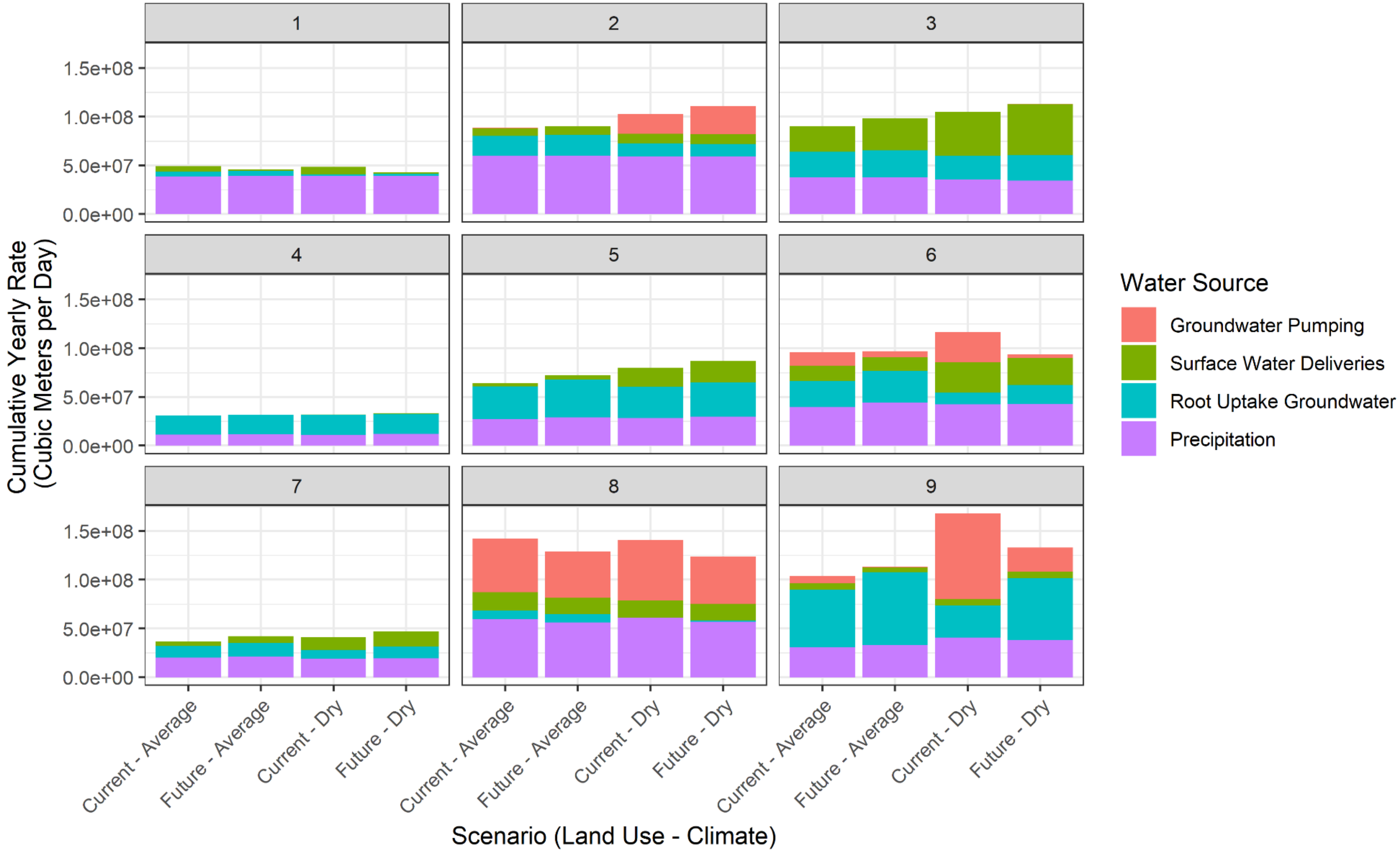

Figure 21: Total water demand differentiated by source for a dry year.

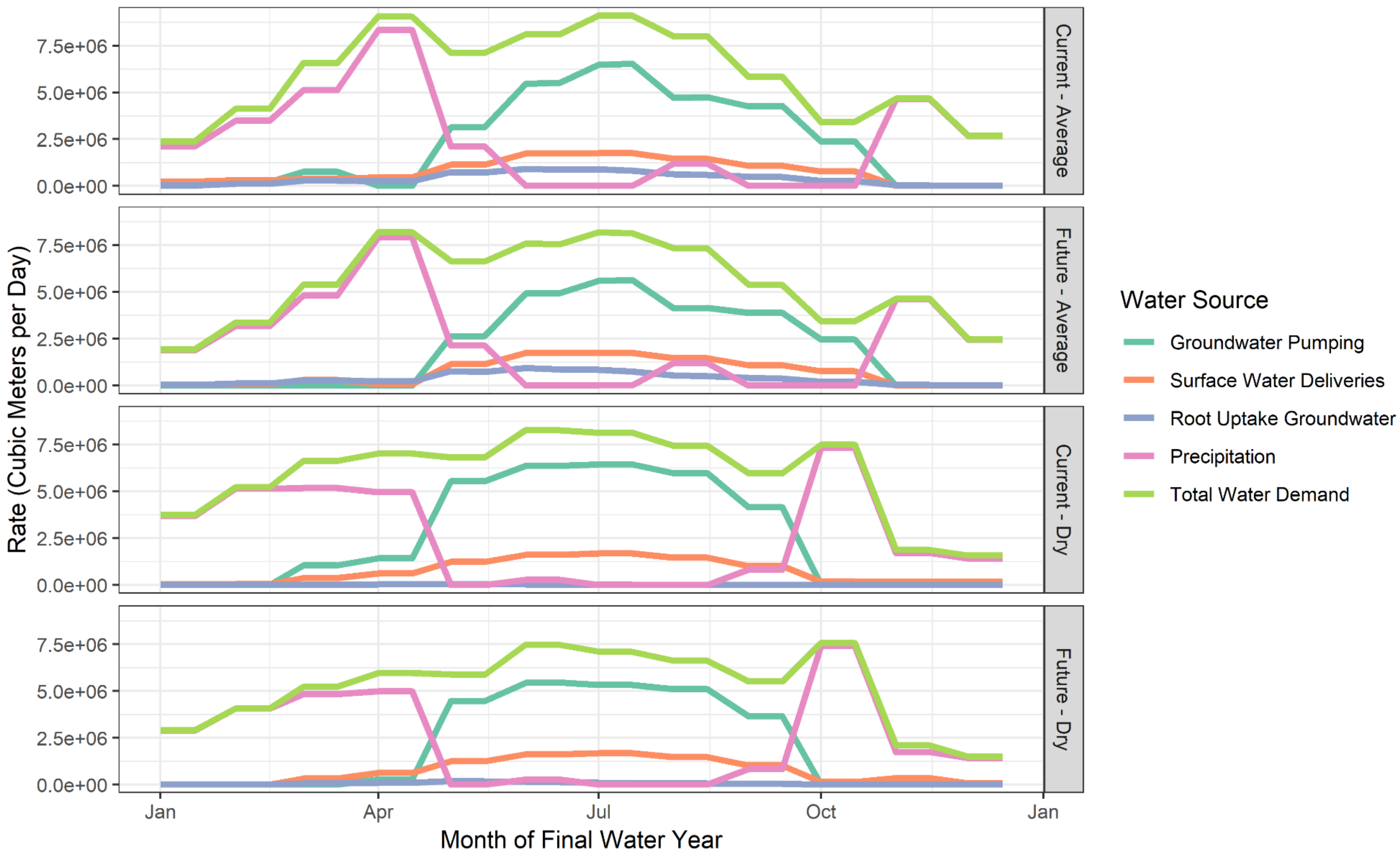

Figure 22: Monthly water demand for Subregion 8 across all four climate and land use scenarios.

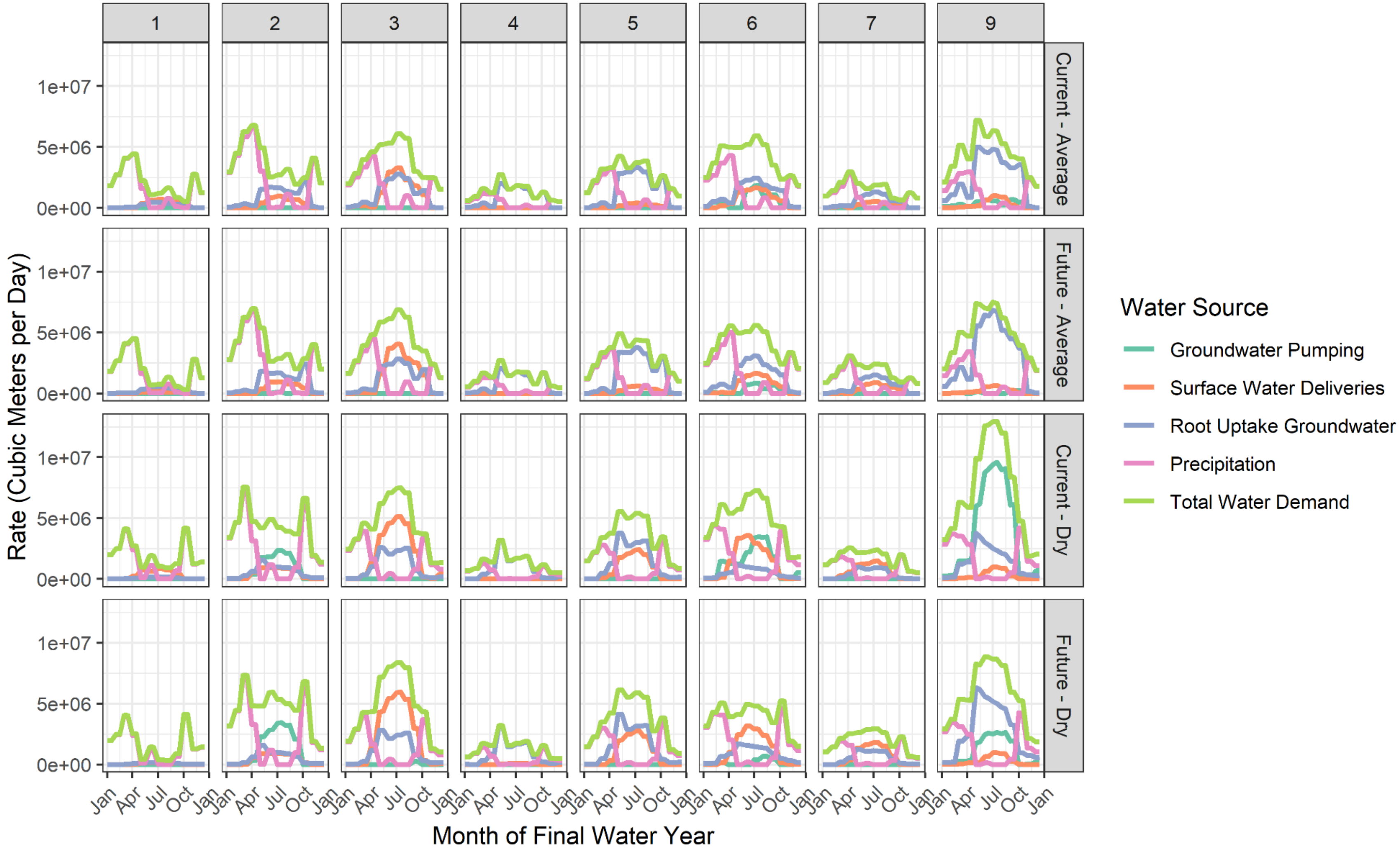

Figure 23: Monthly water demand for Subregions 1 through 7 and Subregion 9 across all four climate and land use scenarios.

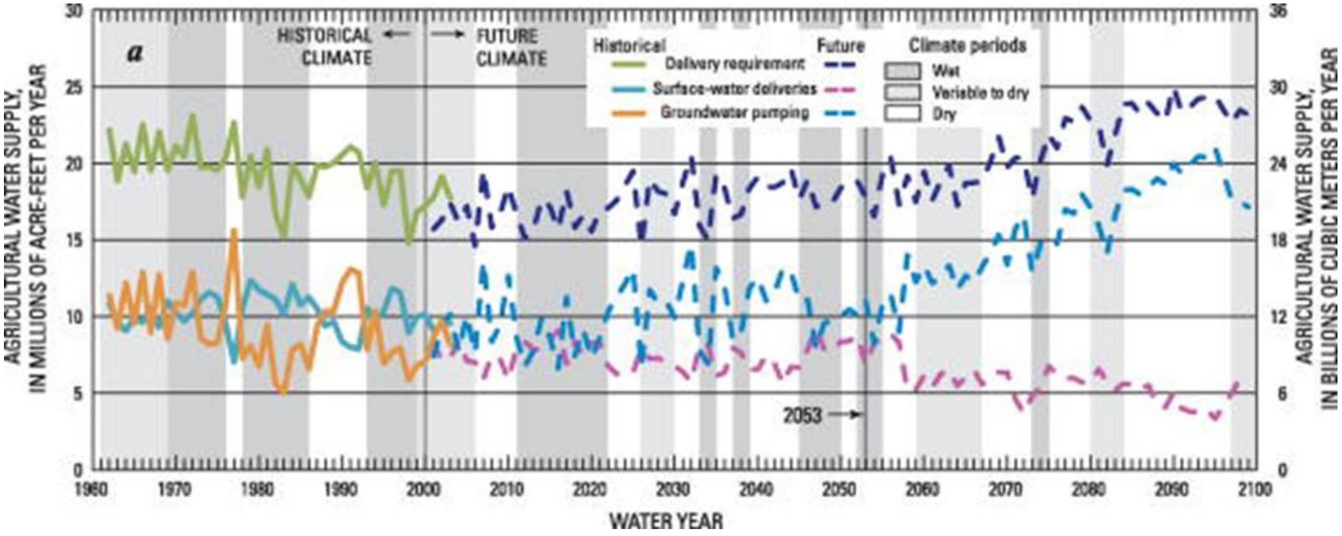

Figure 24: Water deliveries in the CVHM coupled with climate projections to show future surface water and groundwater deliveries (from Hanson et al., 2012).

Table 1: Transition groupings of land use classes when going from LUCAS to CVHM.

LUCAS	CVHM	Irrigated	Area (Percent)		
			2000	2010	2090
Water	Water	No	1%	1%	1%
Developed	Urban	No	7%	8%	17%
Transportation					
Barren	Idle/Fallow	Yes	2%	1%	1%
Forest	Native	No	32%	27%	27%
Grassland					
Wetlands					
Shrublands					
Annual	Field Crop	Yes	8%	9%	3%
	Pasture	No	7%	10%	3%
	Grain and Hay	Yes	4%	5%	1%
	Cotton	Yes	9%	9%	3%
	Truck, nursery, and berry	Yes	5%	4%	2%
Perennial	Vineyards	Yes	6%	7%	11%
	Citrus and subtropical	Yes	2%	2%	3%
	Deciduous fruits and nuts	Yes	11%	12%	23%
Rice	Rice	Yes	5%	5%	5%

Table 2: Distribution of LUC-V by subregion.

Subregions	Annual-Annual	Native-Native	Perennial-Perennial	Rice-Rice	Urban-Urban	Water-Water	other	Ag-Native	Ag-Urban	Annual-Perennial	Native-Ag	Native-Urban	Rice-Urban	No Change	Change
1	1%	76%	0%	0%	8%	0%	1%	5%	2%	0%	1%	6%	0%	85%	15%
2	4%	59%	12%	0%	4%	1%	1%	1%	2%	9%	5%	2%	0%	79%	21%
3	7%	26%	17%	27%	2%	0%	1%	2%	1%	14%	4%	0%	0%	78%	22%
4	33%	5%	8%	31%	1%	0%	1%	3%	1%	16%	1%	0%	0%	78%	23%
5	3%	18%	18%	33%	5%	1%	2%	3%	4%	9%	2%	1%	1%	78%	22%
6	9%	28%	2%	2%	13%	1%	1%	22%	9%	8%	0%	5%	0%	55%	45%
7	5%	1%	3%	19%	41%	0%	1%	0%	7%	6%	4%	9%	4%	69%	31%
8	2%	22%	16%	0%	13%	1%	0%	0%	12%	9%	14%	11%	0%	54%	46%
9	32%	4%	5%	0%	12%	9%	2%	7%	16%	10%	1%	2%	0%	62%	38%
10	36%	18%	11%	1%	2%	1%	1%	2%	4%	18%	6%	0%	0%	69%	31%
11	7%	8%	16%	2%	14%	1%	1%	1%	15%	17%	17%	1%	0%	48%	52%
12	14%	7%	23%	0%	8%	1%	1%	0%	11%	25%	10%	0%	0%	53%	47%
13	8%	18%	34%	0%	4%	0%	0%	2%	6%	16%	10%	2%	0%	63%	37%
14	35%	7%	17%	0%	2%	0%	1%	5%	4%	27%	1%	1%	0%	61%	39%
15	18%	7%	20%	0%	2%	0%	1%	28%	6%	17%	0%	0%	0%	47%	53%
16	1%	10%	33%	0%	27%	0%	0%	0%	17%	8%	2%	2%	0%	71%	29%
17	4%	2%	54%	0%	4%	0%	0%	1%	12%	19%	4%	1%	0%	64%	36%
18	22%	3%	28%	0%	5%	0%	1%	4%	6%	24%	6%	0%	0%	59%	41%
19	2%	40%	17%	0%	3%	0%	8%	13%	1%	12%	1%	2%	0%	62%	38%
20	1%	31%	34%	0%	7%	0%	0%	1%	11%	7%	4%	5%	0%	72%	28%
21	0%	26%	14%	0%	11%	0%	2%	22%	7%	15%	2%	1%	0%	51%	49%

Table 3: Estimates for mean head changes by LUC-V and associated variances

LUC-V	Head Change	Variance of Head Change	Subregion Centered Head Change	Variance of Subregion Centered Head Change
Annual-Annual	0.14	2.46	-0.12	1.30
Native-Native	-0.24	7.42	-0.10	3.41
Perennial-Perennial	1.50	9.68	0.62	5.41
Rice-Rice	-0.53	0.85	0.07	0.34
Urban-Urban	-0.43	4.76	-0.75	3.45
Water-Water	0.33	5.70	0.96	2.10
other	-0.23	6.78	0.13	3.86
Ag-Native	-1.54	5.03	-0.84	2.16
Ag-Urban	-0.40	7.07	-0.98	4.85
Annual-Perennial	0.63	6.62	0.21	4.11
Native-Ag	3.56	16.93	2.43	9.25
Native-Urban	-0.34	7.10	-1.14	4.81
Rice-Urban	-1.65	0.66	-0.88	0.51

Table 4: Average head (meters above mean sea level) for Subregions 1 through 9 and layers 1 through 3 for all four land use and climate scenarios.

Subregion	Layer	Current-Average	Future-Average	Current-Dry	Future-Dry
1	1	136.2	135.6	125.5	124.3
1	2	134.8	134.3	123.5	122.4
1	3	136.3	135.8	122.2	121.1
2	1	85.9	85.8	77.7	76.8
2	2	81.3	81.3	73	71.9
2	3	95.3	95.4	82.8	81.7
3	1	40.1	39.9	33.1	33.3
3	2	40.2	40	33	33.3
3	3	42	41.8	34.2	34.7
4	1	28.8	28.3	22.5	22.5
4	2	29.7	29.2	23.2	23.2
4	3	30.3	29.8	23.5	23.6
5	1	36.3	35.1	29	27.9
5	2	36.6	35.5	29.4	28.3
5	3	37.1	36.1	29.9	28.8
6	1	12	10.5	2.4	4.3
6	2	13.6	12.3	3	5.5
6	3	13.7	12.5	2.9	5.8
7	1	17	16	10.4	10.6
7	2	16.8	15.8	10.1	10.5
7	3	16.4	15.4	9.6	10
8	1	12.2	15.6	2.7	8.6
8	2	11.6	14.9	2.1	7.9
8	3	13.2	17	3.8	9.9
9	1	4.5	3.3	-3.6	-1.3
9	2	4.4	3.3	-4.2	-1.5
9	3	4.6	3.5	-4.5	-1.6

Table 5: Percent change in water demand and source for an average climatic year by subregion comparing current land use to future land use.

Subregion	Climate Year	Groundwater Pumping	Surface Water Deliveries	Root Uptake Groundwater	Precipitation	Farm Delivery Requirement	Total Water Demand
1	Average	--	-76.5	16.5	0.8	-76.5	-7
2	Average	55.5	7.3	3.6	0.5	9.4	2.1
3	Average	--	24.9	6.5	-0.5	24.9	8.9
4	Average	--	--	1.9	4.3	--	2.8
5	Average	--	55.6	14	7	55.6	13
6	Average	-55.7	-7.9	19.7	12.4		1.4
7	Average	--	55.2	19.7	4.1	55.2	15.5
8	Average	-13.8	-10	-8	-5.1	-12.8	-9.3
9	Average	-82.5	-27.5	26.5	7.4	-57.2	9.6
10	Average	--	13.9	-1.4	-2.3	13.9	7.5
11	Average	108.6	6.9	2.8	-2.1	9.2	5.6
12	Average	306.7	15.9	1.4	-1.5	21.9	12
13	Average	3.2	0.3	-9.4	-1.3	1.5	-0.5
14	Average	18	-2.9	-51.3	-5.5	4.9	2.7
15	Average	-52.3	3	31.7	5.9	-36.4	-25.7
16	Average	-72.8	-44.1	-1.6	3.2	-46.5	-30.3
17	Average	-34	-0.6	-15.2	3.3	-18.4	-14
18	Average	-18.9	-1.3	-10.3	3.1	-12	-9.1
19	Average	-18.3	-4.7	--	1.2	-13	-9.2
20	Average	-30.3	-17.6	--	1.4	-19.2	-14
21	Average	-96.8	-51.2	-95.5	1.8	-59.2	-44.4

Table 6: Percent change in water demand and source for the dry climatic year by subregion.

Subregion	Climate Year	Groundwater Pumping	Surface Water Deliveries	Root Uptake Groundwater	Precipitation	Farm Delivery Requirement	Total Water Demand
1	Dry	--	-79.2	14.9	0	-79.2	-11.7
2	Dry	43.3	1.4	-3.2	-0.1	29.3	8.1
3	Dry	Inf[1]	15.8	6.7	-2.6	17	8
4	Dry	--	758.9	0.6	7.8	758.9	5.2
5	Dry	-100	13.7	8	5.5	13.6	8.5
6	Dry	-88	-11.3	65.4	0.8	-49.4	-19.4
7	Dry	--	17.9	34	2	17.9	14.1
8	Dry	-21.7	-1.4	409.2	-6.9	-17.3	-11.9
9	Dry	-71.7	0[2]	92.4	-6.4	-66.9	-20.9

[1] Subregion 4 went from not pumping anything to pumping, causing the percent change to be divided by zero.

[2] Subregion 9 used the exact same surface water deliveries, causing a zero percent change.

Table 7: Percentage change in water demand from an average to a dry year when holding either the current land use or future land use constant

Subregion	Land Use	Groundwater Pumping	Surface Water Deliveries	Root Uptake Groundwater	Precipitation	Farm Delivery Requirement	Total Water Demand
1	Current	NA	28%	-59%	1%	28%	-2%
2	Current	5518%	27%	-37%	0%	263%	16%
3	Current	NA	72%	-8%	-6%	72%	16%
4	Current	NA	--	6%	-1%	--	3%
5	Current	--	542%	-4%	3%	543%	25%
6	Current	125%	101%	-56%	8%	112%	22%
7	Current	NA	187%	-25%	-5%	187%	12%
8	Current	13%	-8%	-97%	3%	7%	-1%
9	Current	1067%	0%	-44%	32%	576%	62%
1	Future	NA	13%	-59%	0%	13%	-7%
2	Future	5079%	20%	-41%	-1%	329%	23%
3	Future	--	60%	-8%	-8%	61%	15%
4	Future	NA	--	4%	2%	--	6%
5	Future	NA	370%	-9%	2%	370%	20%
6	Future	-39%	93%	-40%	-3%	54%	-3%
7	Future	NA	118%	-16%	-7%	118%	10%
8	Future	2%	1%	-83%	1%	2%	-4%
9	Future	1787%	38%	-15%	15%	424%	17%
Total	Current	162%	70%	-31%	4%	113%	19%
Total	Future	92%	70%	-21%	0%	78%	70%

APPENDIX A

```
#R file used to read in head values from MODFLOW
library("readr")
library("stringr")
library("dplyr")
#Create function to read in the two-dimensional matrix into a vector
cvhm.read <- function(x) {
  as.vector(t(as.matrix((read.table(x, quote="\"", comment.char="")))))
}
#insert new folder with the head data in it
all_head_files <- str_sort(unlist(list.files("/inputs_LUC50_18-0206/heads_test/",
full.names=TRUE)), numeric=TRUE)
#Read in the base file that specifies layer, row, and column
FMP <- read.csv("~/Research/Stats/R_heads/FMP_input_clean.csv")
#Read in heads by layer
FMP_lay1 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_1_")),
cvhm.read))
FMP_lay2 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_2")),
cvhm.read))
FMP_lay3 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_3")),
cvhm.read))
FMP_lay4 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_4")),
cvhm.read))
FMP_lay5 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_5")),
cvhm.read))
FMP_lay6 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_6")),
cvhm.read))
FMP_lay7 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_7")),
cvhm.read))
FMP_lay8 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_8")),
cvhm.read))
FMP_lay9 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_9")),
cvhm.read))
FMP_lay10 <- cbind(FMP,sapply(subset(all_head_files, str_detect(all_head_files, "_lay_10")),
cvhm.read))
#Remove head files
rm(all_head_files)
#Set the layers
FMP_lay1$LAYER <- 1
FMP_lay2$LAYER <- 2
FMP_lay3$LAYER <- 3
FMP_lay4$LAYER <- 4
FMP_lay5$LAYER <- 5
FMP_lay6$LAYER <- 6
FMP_lay7$LAYER <- 7
FMP_lay8$LAYER <- 8
FMP_lay9$LAYER <- 9
```

```
FMP_lay10$LAYER <- 10
#Column names are read in as long text strings, replace them with only the stress period.
colnames(FMP_lay1) <- sub('.*_ts_', "ts_", colnames(FMP_lay1))
colnames(FMP_lay2) <- sub('.*_ts_', "ts_", colnames(FMP_lay2))
colnames(FMP_lay3) <- sub('.*_ts_', "ts_", colnames(FMP_lay3))
colnames(FMP_lay4) <- sub('.*_ts_', "ts_", colnames(FMP_lay4))
colnames(FMP_lay5) <- sub('.*_ts_', "ts_", colnames(FMP_lay5))
colnames(FMP_lay6) <- sub('.*_ts_', "ts_", colnames(FMP_lay6))
colnames(FMP_lay7) <- sub('.*_ts_', "ts_", colnames(FMP_lay7))
colnames(FMP_lay8) <- sub('.*_ts_', "ts_", colnames(FMP_lay8))
colnames(FMP_lay9) <- sub('.*_ts_', "ts_", colnames(FMP_lay9))
colnames(FMP_lay10) <- sub('.*_ts_', "ts_", colnames(FMP_lay10))
#Rename file to proper scenario and combine them.
FMP_luc50 <-
rbind(FMP_lay1,FMP_lay2,FMP_lay3,FMP_lay4,FMP_lay5,FMP_lay6,FMP_lay7,FMP_lay8,FMP_lay9,FMP_lay10)
#Remove individual layer datasets
rm(FMP_lay1,FMP_lay2,FMP_lay3,FMP_lay4,FMP_lay5,FMP_lay6,FMP_lay7,FMP_lay8,FMP_lay9,FMP_lay10)
#Save the values as RData
Save(FMP_luc50, file = "~/Research/Stats/R_heads/head_change_luc50.RData”)
```