Appendix B
Recharge and Evapotranspiration

1.0 Purpose

The purpose of this appendix is to document and present the methods used to estimate recharge and evapotranspiration (ET) flux inputs to the South Platte Decision Support System (SPDSS) alluvial groundwater flow model. These fluxes include the following:

1. *Estimated recharge from precipitation and irrigation*
2. *Estimated recharge from reservoir seepage*
3. *Estimated evapotranspiration from groundwater*

Recharge from precipitation and irrigation and from reservoir seepage comprises a majority of the recharge in the South Platte Basin. Additional recharge to the system occurs in managed recharge operations. The recharge associated with managed recharge areas is described and presented in Appendix M. The ET component includes both native area ET from phreatophytes, primarily in riparian areas, and sub-irrigation ET from meadows and alfalfa crop areas that were mapped as potentially sub-irrigated.

The recharge and ET datasets were prepared for the model study period 1950 through 2006 at a monthly time scale on a cell-by-cell basis within both the active and inactive model domain. Recharge occurring in the inactive model domain was used to determine estimates the lateral boundary inflows, flow entering the active model domain from inactive cells. The development of lateral boundary inflows is discussed in further detail in Appendix D Boundary Conditions. For the steady-state simulation period, average values for the 1991 – 1994 time period were extracted from the overall dataset, while for the transient simulation period (1999 – 2005), the appropriate sub-set of the dataset was extracted. The entire dataset is utilized for the validation period simulation. Section 2 describes the sources, processing, and results for native, irrigation-based, and reservoir seepage based components of recharge. Section 3 provides similar information for phreatophyte and sub-irrigated ET.

2.0 Recharge from Precipitation and Irrigation

Precipitation-based recharge occurs throughout the basin and is a function of the precipitation quantity, timing, and the land use. This precipitation-based recharge is estimated for both native and irrigated lands. Irrigation-based recharge is a function of the irrigation method, quantity, and timing of applied water. Also included is irrigation-related recharge associated with canal seepage and water applied for irrigation that is not consumed by crops and recharges the aquifer.

2.1 Data Sources

2.1.1 Precipitation-Based Recharge

Precipitation-based recharge is the recharge that originates from precipitation and infiltrates into the aquifer. Precipitation over the study period was developed by the Consumptive Use contractor in the SPDSS Task 64 Memorandum (SPDSS 2007). Estimates of precipitation-based recharge for non-irrigated lands and irrigated lands outside of the irrigation season were modified by CDM in consultation with the Consumptive Use contractor to a constant value of 3 percent of precipitation. Table B-1 (see end of section) provides the recharge percentages that were applied to estimate recharge for both the irrigation and non-irrigation season. Figure B-1 provides the distribution of soil types through the model area by hydrologic class, where soil A is the highest permeability, ranging to soil D, which represents the lowest permeability. The hydrologic class was obtained from the Statewide Soils coverage developed as part of Task 57 of the SPDSS (SPDSS 2008). Figure B-2 shows the land use classification for 2001 developed as part of Task 89.2 (SPDSS 2006). This land use was used for all years in the study period, as this is the only land use snapshot available during the development of SPDSS. These figures show the dominant soil type and land use within the model area; however, detailed model calculations consider the proportion of each model cell that is occupied by an individual land use and soil type classification. The soil types and land use classification information is used to determine the amount of precipitation recharging the aquifer within *proc_rainfall*, a data processing tool developed for the SPDSS (SPDSS Task 50 Memorandum; SPDSS 2012).Table B-1 provides the precipitation recharge factors for each land use and soil type combination.

Table B-1 Precipitation Recharge as Percentage of Total Precipitation

Land Use Category	Irrigation Season % April through October	Non-Irrigation Season % November through March
ALFALFA_SOILA	23%	3%
ALFALFA_SOILB	14%	3%
ALFALFA_SOILC	4%	3%
ALFALFA_SOILD	2%	3%
CORN_SOILA	23%	3%
CORN_SOILB	14%	3%
CORN_SOILC	4%	3%
CORN_SOILD	2%	3%
DRY_BEANS_SOILA	23%	3%
DRY_BEANS_SOILB	14%	3%
DRY_BEANS_SOILC	4%	3%
DRY_BEANS_SOILD	2%	3%
FOREST_SOILA	3%	3%
FOREST_SOILB	3%	3%
FOREST_SOILC	3%	3%
FOREST_SOILD	3%	3%
GRASS_PASTURE_SOILA	23%	3%
GRASS_PASTURE_SOILB	14%	3%
GRASS_PASTURE_SOILC	4%	3%
GRASS_PASTURE_SOILD	2%	3%
NATIVE_VEGETATION_SOILA	3%	3%
NATIVE_VEGETATION_SOILB	3%	3%
NATIVE_VEGETATION_SOILC	3%	3%

Table B-1 Precipitation Recharge as Percentage of Total Precipitation

Land Use Category	Irrigation Season % April through October	Non-Irrigation Season % November through March
NATIVE_VEGETATION_SOILD	3%	3%
ORCHARD_WO_COVER_SOILB	14%	3%
ORCHARD_WO_COVER_SOILC	4%	3%
ORCHARD_WO_COVER_SOILD	2%	3%
PHREATOPHYTE_SOILA	3%	3%
PHREATOPHYTE_SOILB	3%	3%
PHREATOPHYTE_SOILC	3%	3%
PHREATOPHYTE_SOILD	3%	3%
SMALL_GRAINS_SOILA	23%	3%
SMALL_GRAINS_SOILB	14%	3%
SMALL_GRAINS_SOILC	4%	3%
SMALL_GRAINS_SOILD	2%	3%
SOD_FARM_SOILA	23%	3%
SOD_FARM_SOILB	14%	3%
SOD_FARM_SOILC	4%	3%
SUGAR_BEETS_SOILA	23%	3%
SUGAR_BEETS_SOILB	14%	3%
SUGAR_BEETS_SOILC	4%	3%
URBAN_SOILA	3%	3%
URBAN_SOILB	3%	3%
URBAN_SOILC	3%	3%
URBAN_SOILD	3%	3%
VEGETABLES_SOILA	23%	3%
VEGETABLES_SOILB	14%	3%
VEGETABLES_SOILC	4%	3%
WATER_SOILA	0%	0%
WATER_SOILB	0%	0%
WATER_SOILC	0%	0%
WATER_SOILD	0%	0%
WATER_*ResWDID*_SOILA	0%	0%
WATER_*ResWDID*_SOILB	0%	0%
WATER_*ResWDID*_SOILC	0%	0%
WATER_*ResWDID*_SOILD	0%	0%

2.1.2 Irrigation-Based Recharge

The amount, timing, and spatial distribution of irrigation-based recharge is calculated within *StatePP*, a pre-processor developed by the state for preparing groundwater model inputs for DSS groundwater models, based on the applied water and the type of irrigation (sprinkler or flood). Applied water is calculated within *StatePP* and is based on consumptive use demands and available water for irrigation by structure (SPDSS Task 53.3 Memorandum; SPDSS 2006b). *StatePP* uses the information provided for each structure to determine the portion of water reaching the aquifer. It is important to note the consumptive use analysis is performed on a structure by structure basis not an individual parcel of irrigated land. For areas that are flood irrigated, 40 percent of the applied water is assumed to return to groundwater, while for sprinkler irrigated areas, 20 percent is assumed to percolate back to groundwater (SPDSS Task 56 Memorandum; SPDSS 2007). Estimates utilized in this analysis of canal seepage and excess surface water diversions were also estimated and discussed in detail in SPDSS Task 56

Memorandum (SPDSS 2007). Figure B-3 shows a schematic of the water balance components for irrigated lands during the irrigation season.

2.2 Data Processing

2.2.1 Precipitation-Based Recharge

Recharge from precipitation is calculated on a monthly basis using several individual processing packages. The total precipitation quantity is calculated in program *Proc_rainfall* (SPDSS Task 50 Memorandum; SPDSS 2012) to develop the recharge quantity that is provided to *StatePP* as an input file.

Precipitation-based recharge is processed separately from irrigation-based recharge to calculate of its contribution to recharge in the model domain. Precipitation-based recharge is calculated in three steps. First, *StateDGI* determines the contribution of each climate station for each model cell. The result is a spatially weighted contribution factor for each model cell. The second step calculates the monthly precipitation in each model cell using historical precipitation data and the spatially weighted contribution factors from each climate station. The third step applies the percentage of precipitation that contributes to recharge which ranges from 3 percent on native land to 23 percent on irrigated land during the irrigation season, as shown on Table B-1.

2.2.2 Irrigation-Based Recharge

The recharge quantities associated with irrigation activities are calculated within *StatePP*, using information developed separately as reported in *Historic Crop Consumptive Use Analysis, SPDSS* (SPDSS 2010). These recharge quantities are estimated by structure as the inefficient portion of the applied irrigation water. For example, irrigation efficiencies are assumed to be 80 percent for sprinkler irrigated lands and 60 percent for flood irrigated lands. Therefore, recharge to groundwater is estimated to be 20 percent of the applied water for sprinkler irrigated areas and 40 percent of the applied water for flood irrigated areas.

In the consumptive use analysis referenced above, lands that are irrigated with groundwater or with a combination of surface water and groundwater are assumed to have sufficient water delivered to meet consumptive use demands, if sufficient pumping capacity is available from wells supplying individual parcels. Areas that are irrigated solely by surface water also use consumptive use estimates to determine recharge rates. Surface water delivered to parcels within the structure first meet the consumptive use demand, accounting for the irrigation efficiency. If all demands are met for a structure and there is any excess water available, it is applied uniformly across all irrigated parcels served by the structure as recharge.

Canal seepage losses are estimated in the Task 56 Memorandum (SPDSS 2007) and are used as an input file to *StatePP*. Canal seepage is uniformly distributed along the length of each canal. An exception to this uniform distribution was made in the Pawnee Creek area where modifications to the seepage distribution on the North Sterling Canal were

made based on discussions with the Consumptive Use contractor and the State. In this case, the total seepage remained unchanged but the allocation along the canal was adjusted in specific areas where higher seepage rates were apparent. The recharge quantity from canal seepage is calculated in *StatePP* for each model cell based on the length of the canal or ditch within that cell.

In *StatePP*, each of the recharge components are summed for each cell and each stress period and assembled into a *MODFLOW* recharge package file for the time period being simulated.

2.3 Model Input

The following sections summarize the recharge estimates for the steady state, transient calibration, and model validation time periods implemented in the model. The precipitation and irrigation-based recharge rates are presented here.

2.3.1 Steady State Period

The steady state model period represents average annual conditions for 1991 through 1994. The basis for selecting this period is described in the *SPDSS Phase 4 Task 48.2 Development of Calibration Targets and Criteria Technical Memorandum* (SPDSS 2008).

The steady state model input represents the average annual precipitation and irrigation-based recharge for 1991 through 1994. The model input value is shown in Table B-2. Figure B-4 shows the monthly recharge from precipitation and irrigation sources.

Table B-2 Average Annual Precipitation & Irrigation-Based Recharge, 1991-1994 (AFY)

Model Input	Rate (AFY)
Precipitation Recharge, 1991-1994	98,000
Irrigation-Based Recharge, 1991-1994	877,000
Total Precipitation and Irrigation-Based Recharge, 1991-1994	975,000

2.3.2 Transient Calibration Period

The transient model calibration period represents monthly conditions for the period 1999 through 2005. The basis for selecting this period is described in the *SPDSS Phase 4 Task 48.2 Development of Calibration Targets and Criteria Technical Memorandum* (SPDSS 2008).

The transient calibration period model inputs consist of 84 monthly data groups that simulate precipitation and irrigation-based recharge from January 1999 through December 2005. The monthly values are shown on Figure B-5. The simulated precipitation-based recharge rates vary from month to month depending on climate while irrigation-based recharge rates vary based upon irrigation practices and the quantity of applied water. The average annual recharge from precipitation during this period was 101,000 acre-feet (AF), while the average annual recharge from irrigation was

840,000 AF. The total average annual recharge was slightly lower during the transient calibration period, compared to the steady state period.

2.3.3 Model Validation Period

The model validation period represents monthly conditions for the full study period of 1950 through 2006.

The model validation period model inputs consist of 684 monthly records that simulate irrigation and precipitation-based recharge from January 1950 through December 2005. Figure B-6 provides the monthly recharge from precipitation, while Figure B-7 provides the monthly recharge from irrigation. The average annual recharge from irrigation is 860,000 AF, while the average annual recharge from precipitation is 101,000 AF. Table B-3 provides the average monthly recharge rates for both precipitation and irrigation over the study period.

Table B-3 Average Monthly Precipitation and Irrigation-Based Recharge, 1950-2006 (AF)

Time Period	Average Precipitation-Based Recharge Rate (AF/month)	Average Irrigation-Based Recharge Rate (AF/month)
January	1,477	12,419
February	1,404	12,526
March	3,879	15,851
April	11,492	37,840
May	19,210	98,693
June	15,658	143,208
July	15,187	189,390
August	12,249	169,134
September	9,276	99,595
October	7,006	45,300
November	2,451	20,623
December	1,523	15,883

3.0 Recharge from Reservoir Seepage

Seepage from reservoirs is an additional source of spatially distributed recharge. The reservoirs included in the model are based upon the SPDSS Task 5 Memorandum (SPDSS 2006) identifying key reservoirs in the South Platte Basin. The reservoirs identified in the memo are spatially distributed throughout the basin. In the case where a reservoir is located within the active domain, seepage from the reservoir was included in the *MODFLOW* recharge package. In the case where either a portion or the entire area of the reservoir area is located outside the active model domain, the reservoir seepage was used to compute lateral boundary inflows. Reservoir seepage is not directly measured, so it was estimated for use in the model.

3.1 Data Sources

The locations of reservoirs were obtained from GIS coverages for the SPDSS, and 12 reservoirs within the active model domain were identified, which included:

- Bijou No. 2 Reservoir
- Riverside Reservoir

- Empire Reservoir
- Jackson Reservoir
- Barr Lake
- Lower Latham Reservoir
- Milton Reservoir
- Boxelder Reservoir No. 3
- North Poudre Reservoir No. 4
- Chatfield Lake
- Cherry Creek Reservoir
- Prewitt Reservoir

The locations of these reservoirs are shown on Figure B-8. The areal extent of each reservoir was assumed to remain the same over the entire study period. This may result in some overestimation of reservoir seepage for times prior to construction of several of the reservoirs, such as Chatfield and Cherry Creek, which were constructed during the early part of the validation period.

3.2 Data Processing

The location of each selected reservoir was overlain on the model grid cells to obtain an area within each cell that was within the reservoir footprint. The hydrologic soil type was identified within each reservoir footprint on a cell-by-cell basis from soil type files derived from NRCS STATSGO data (SPDSS Task 57 Memorandum; SPDSS 2006). Since no detailed analysis was done for each reservoir, effective seepage rates for each soil type were estimated based on typical percolation rates and an efficiency factor of 0.01 to account for loss of percolation capacity from sedimentation in the reservoir, and to account for times when the reservoir may not have been full. The effective percolation rates for each of the hydrologic soil classes are:

- Hydrologic Soil A (Sand, loamy sand, or sandy loam)– 0.006 ft/day
- Hydrologic Soil B (Silt loam or loam)– 0.004 ft/day
- Hydrologic Soil C (Sandy clay loam)– 0.002 ft/day
- Hydrologic Soil D (Clay loam, silty clay or clay)– 0.0005 ft/day

For each of the cells with an overlying reservoir, the area and soil class were used to develop the recharge rate within the cell. This rate was assumed to be constant across all stress periods.

Table B-4 Average Annual Reservoir Seepage Rates

Reservoir Name	Average Annual Reservoir Seepage (AFY)
Bijou No 2 Reservoir	950
Riverside Reservoir	5,690
Empire Reservoir	4,700
Jackson Reservoir	4,380
Barr Lake	3,290
Lower Latham Reservoir	480
Milton Reservoir	2,990
North Poudre Reservoir No. 4	170
Boxelder Reservoir No. 3	910
Chatfield Lake	2,100
Cherry Creek Reservoir	1,490
Prewitt Reservoir	4,250

3.3 Model Input

The reservoir seepage information was formatted for a *MODFLOW* Recharge package file and merged with other components of recharge for use in the model. The total annual seepage from t reservoirs within the active model is 31,400 AF. This rate remained constant through all time periods. A portion of this recharge occurs outside of the active groundwater model area, and is incorporated in the lateral boundary process, described in Appendix D.

4.0 Groundwater Evapotranspiration

ET from groundwater represents the removal of water from the aquifer by either direct evaporation from soils or the consumption of groundwater by plants. This process is dynamic and calculated within the model as a function of depth to water in identified phreatophyte areas and in crop areas that have been identified as sub-irrigated.

4.1 Data Sources

Data used to estimate evapotranspiration in the alluvial groundwater model were developed in an investigation of evapotranspiration from phreatophyte areas in the South Platte Basin. As a result of this investigation, the State's Consumptive Use contractor provided CDM with an ET curve and estimates of where ET from phreatophytes is expected (Figure B-9). The phreatophyte ET curve for the study area is based on one developed for the San Luis Valley and modified for the South Platte River Basin using data from field stations in Ft. Lupton, Ft. Collins, Greeley, and Holyoke (SPDSS Task 65 Memorandum; SPDSS 2007). The ET curves for sub-irrigated meadows and alfalfa were based on information originally developed for the Rio Grane Decision Support System (RGDSS); these ET curves were adopted for the SPDSS. The relative rate coefficients used in StatePP for each of these vegetation categories are shown in Table B-5. The temporal adjustment factor used in StatePP is shown on Table B-6.

Table B-5 Evapotranspiration Coefficients

Depth to groundwater (ft)	Phreatophyte Relative Rate (ft/day)	Sub-Irrigated Meadows Relative Rate (ft/day)	Sub-Irrigated Alfalfa Relative Rate (ft/day)
0.0	0.007415	0.009035	0.007940
2.0	0.004642	0.009035	0.007940
3.3	0.002668	0.002033	0.007630
3.4	0.002527	0.002033	0.007527
4.0	0.001631	0.001848	0.006836
8.0	0.000531	0.000614	0.002279
10.0	0.000378	0.0	0.0
15.0	0.0	0.0	0.0

Table B-6 ET Monthly Adjustment Factor

Month	ET Adjustment Factor
January	0.4537
February	0.5374
March	0.8630
April	1.065
May	1.286
June	1.593
July	1.734
August	1.457
September	1.140
October	0.8451
November	0.5195
December	0.4800

The maximum evapotranspiration would result if the water table were at the land surface. These maximum rates for each of the land use categories, using the coefficients noted above are:

- Phreatophyte: 32.5 in/year
- Sub-Irrigated Meadows: 39.6 in/yr
- Sub-Irrigated Alfalfa: 34.8 in/yr

4.2 Data Processing

ET inputs for the alluvial groundwater model were developed using *StatePP*. *StatePP* input files were prepared using the parameters defining the evapotranspiration curves for areas where ET from phreatophytes and sub-irrigated crops is expected. *StatePP* creates a composite ET function for each cell by accounting for the portion of the cell area covered by each sub-irrigated crop and combines it with the phreatophyte group and the shape of the function for each vegetative group. A detailed description of how the monthly ET is determined is presented in the following sections for phreatophytes and sub-irrigated crops.

4.2.1 Phreatophytes

ET of groundwater by native (non-agricultural) phreatophytes is simulated in the model using the *MODFLOW* ETS package. The ET surface is estimated to equal the ground surface elevation determined from the DEM data for each cell.

4.2.2 Sub-Irrigation

Sub-irrigation was estimated by structure using a time-dependent function that varies in a nonlinear fashion from a maximum at ground surface to zero at an extension depth. The time-dependent value is estimated for each structure and sub-irrigated crop as follows:

$$Etsub(i) = min\ (IWR(i),\ UnmetDemand(i))$$

Where

Etsub(i) = evapotranspiration by sub-irrigated crop i

IWR(i) = the irrigation water requirement of crop i (irrigated meadowlands or alfalfa)

UnMetDemand(i) = the unmet structure demand associated with sub-irrigated crop i. Estimated to be the total structure demand times the fraction of acreage associated with each sub-irrigated crop.

The above equation limits sub-irrigation to the consumptive potential of the sub-irrigated crop and the total unmet structure demand. This approach insures the potential consumptive use of sub-irrigated land is not exceeded while recognizing that the allocation of water supplies (surface water, groundwater, and sub-irrigation) by a structure is generally not known.

The irrigation water requirement term (*IWR*) and unmet demand (*UnMetDemand*) were provided for irrigated meadow and alfalfa by month for each structure by *StateCU*.

4.2.3 ET Surface

The ET surface is estimated to equal the ground surface elevation determined from the DEM data for each cell.

4.3 Model Input

Three separate ETS input files corresponding to the steady state, transient calibration, and validation periods were developed by *StatePP* using the parameters described in Section 4.1, along with the ground surface elevation for each cell. Since the ETS file is used to simulate the evapotranspiration in the model based upon simulated depth to water, the amount of evapotranspiration occurring in the model is presented in the Alluvial Groundwater Model Report.

4.0 References

SPDSS, 2012, SPDSS Task 50 – Documentation of Miscellaneous Data Management Interface Programs, Prepared by CDM for the Colorado Water Conservation Board and Colorado Division of Water Resources. (In Preparation)

SPDSS, 2010. *SPDSS Historic Crop Consumptive Use Analysis.* Prepared by LRE for the Colorado Water Conservation Board and Colorado Division of Water Resources. March 2010.

SPDSS, 2008. *SPDSS Phase 4 Task 48.2 Development of Calibration Targets and Criteria Technical Memorandum*. Prepared by CDM for the Colorado Water Conservation Board and Colorado Division of Water Resources.

SPDSS, 2007. *SPDSS Task 56 Estimating South Platte Phreatophyte Groundwater Evapotranspiration*. Prepared by D. Groeneveld and M. Prescott for the Colorado Water Conservation Board and Colorado Division of Water Resources. January 30, 2007.

SPDSS, 2006. *SPDSS Task 5 Key Reservoirs Technical Memorandum*. Prepared by LRE for the Colorado Water Conservation Board and Colorado Division of Water Resources. December 19, 2006.

SPDSS, 2006b. *SPDSS Task 53.3 Assign Key Climate Information to Irrigated Acreage and Reservoirs*. Prepared by LRE for the Colorado Water Conservation Board and Colorado Division of Water Resources. February 1, 2006.

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Figure B-1: Distribution of Soils by Hydrologic Classification

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State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

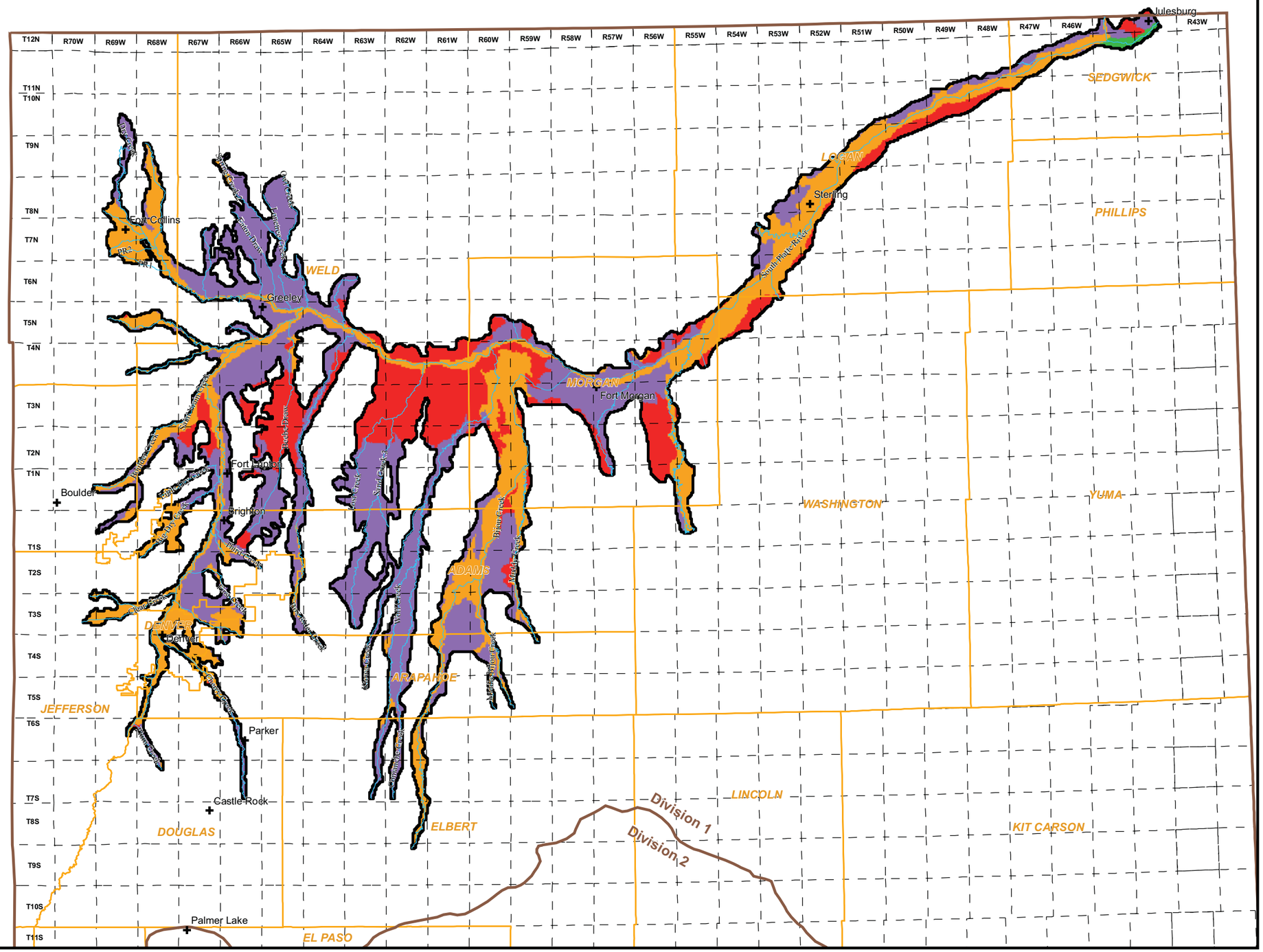
Legend

- City
- Stream
- County

Hydrologic Classification

- A - Sand, loamy sand, or sandy loam
- B - Silt loam or loam
- C - Sandy clay loam
- D - Clay loam, silty clay, or clay

Source Data:
Soil Classifications - SPDSS 2008 Task 57 Assign Soil Moisture Water Holding Capacities to Structures. Prepared by LRE for the Colorado Water Conservation Board and Division of Water Resources. March 2008



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NAD 1983 UTM Zone 13N

Prepared by: CDM

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Figure B-2: Land Use Distribution in 2001

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Legend

- City
- Stream
- County

Land Use Distribution 2001

- 1 Alfalfa
- 2 Corn
- 3 Dry Beans
- 5 Forest
- 6 Grass Pasture
- 7 Orchard
- 8 Phreatophyte
- 9 Small Grains
- 10 Sod Farm
- 11 Sugar Beets
- 12 Urban
- 13 Vegetables
- 14 Water

Source Data:
Land Use - SPDSS 2006 Task 89.2 Crop & Land Use Classification Procedures for 2001. Prepared by Riverside Technology Inc. for the Colorado Water Conservation and Division of Water Resources. September 29, 2006.

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Scale
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Miles

NAD 1983 UTM Zone 13N

Prepared by: CDM

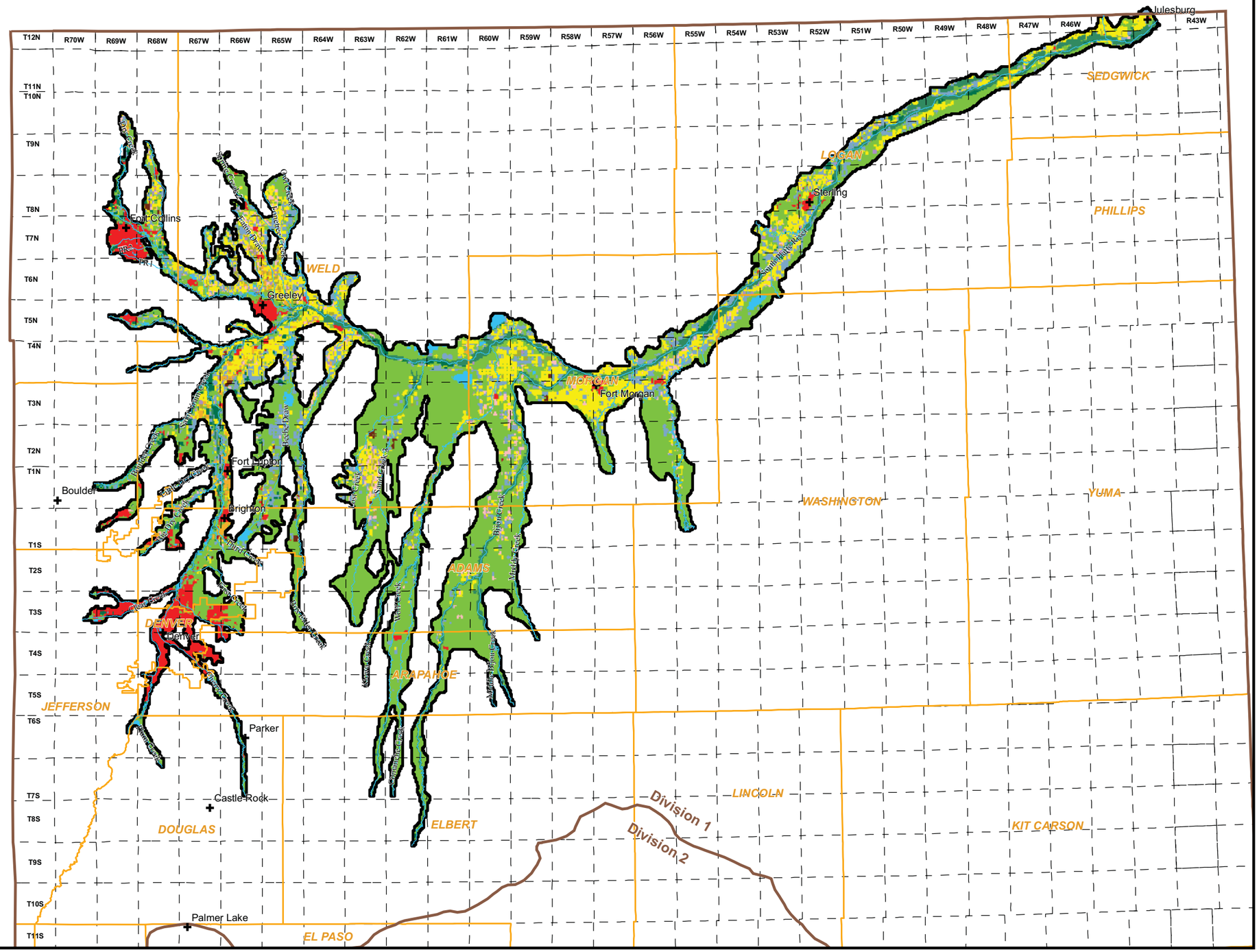

Figure B-3. Irrigated Lands Recharge Schematic

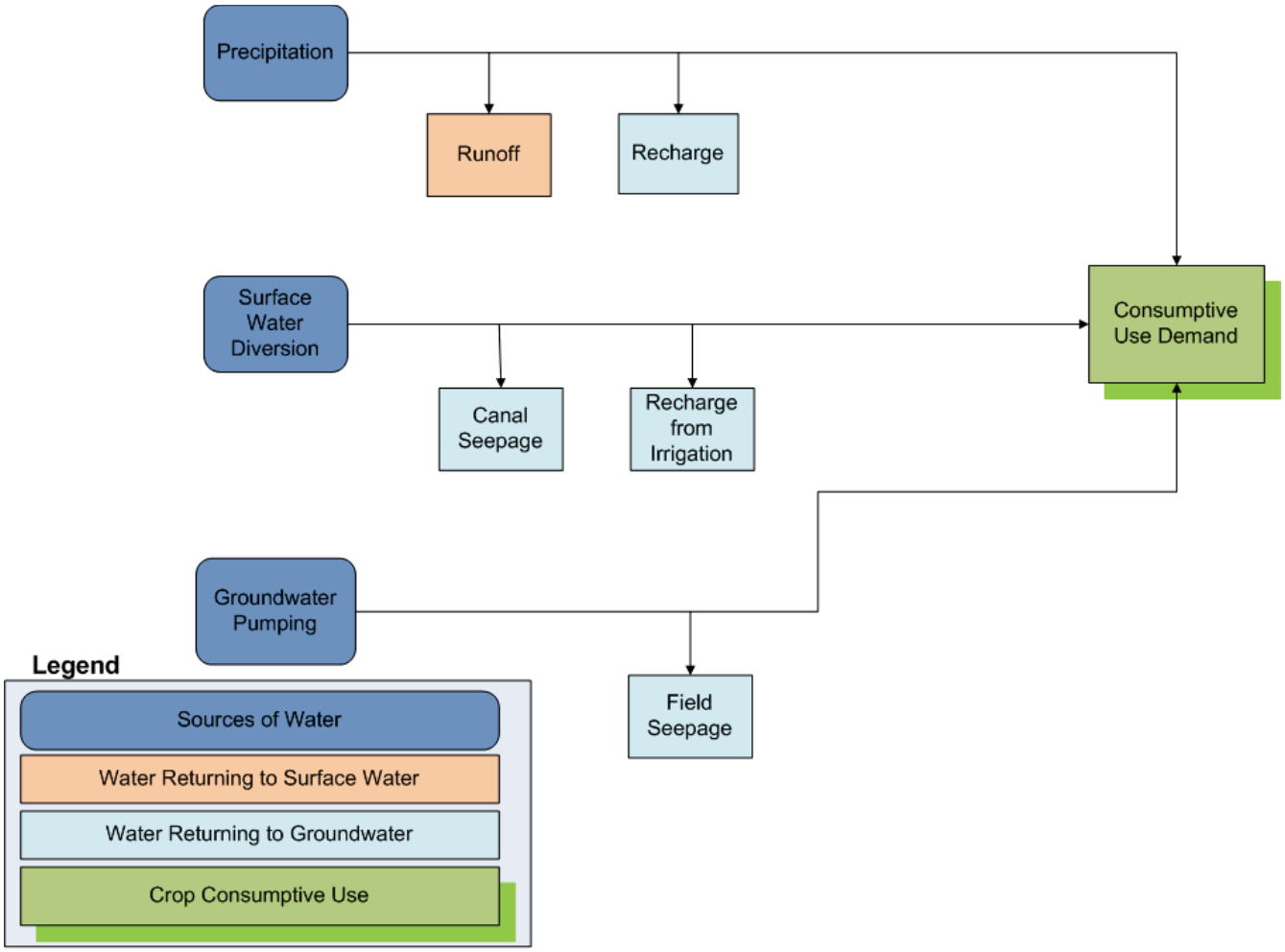

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Figure B-4. Monthly Recharge from Precipitation and Irrigation for Steady State Period (1991 - 1994)

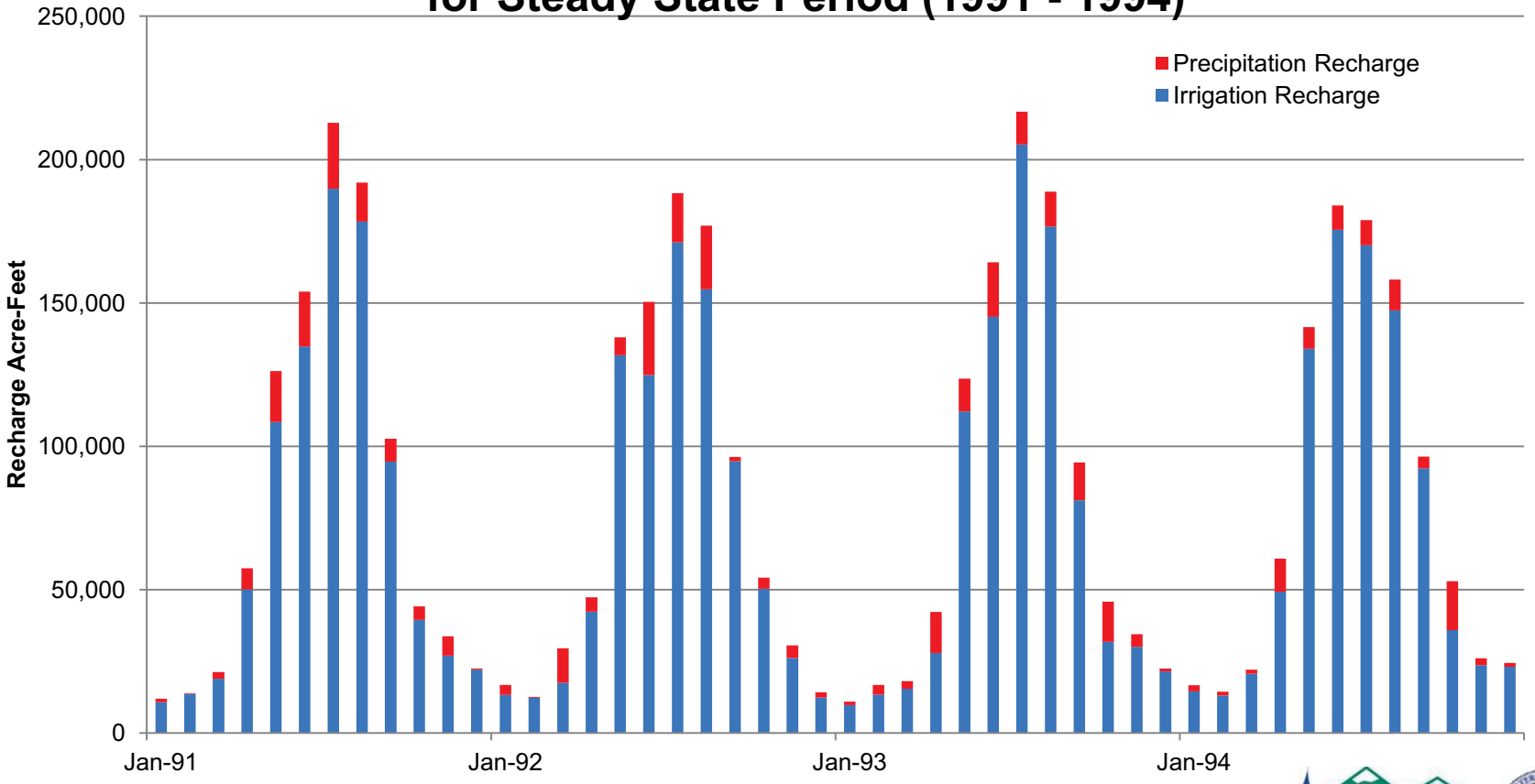

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Figure B-5. Monthly Recharge from Precipitation and Irrigation for Transient Calibration Period (1999 - 2005)

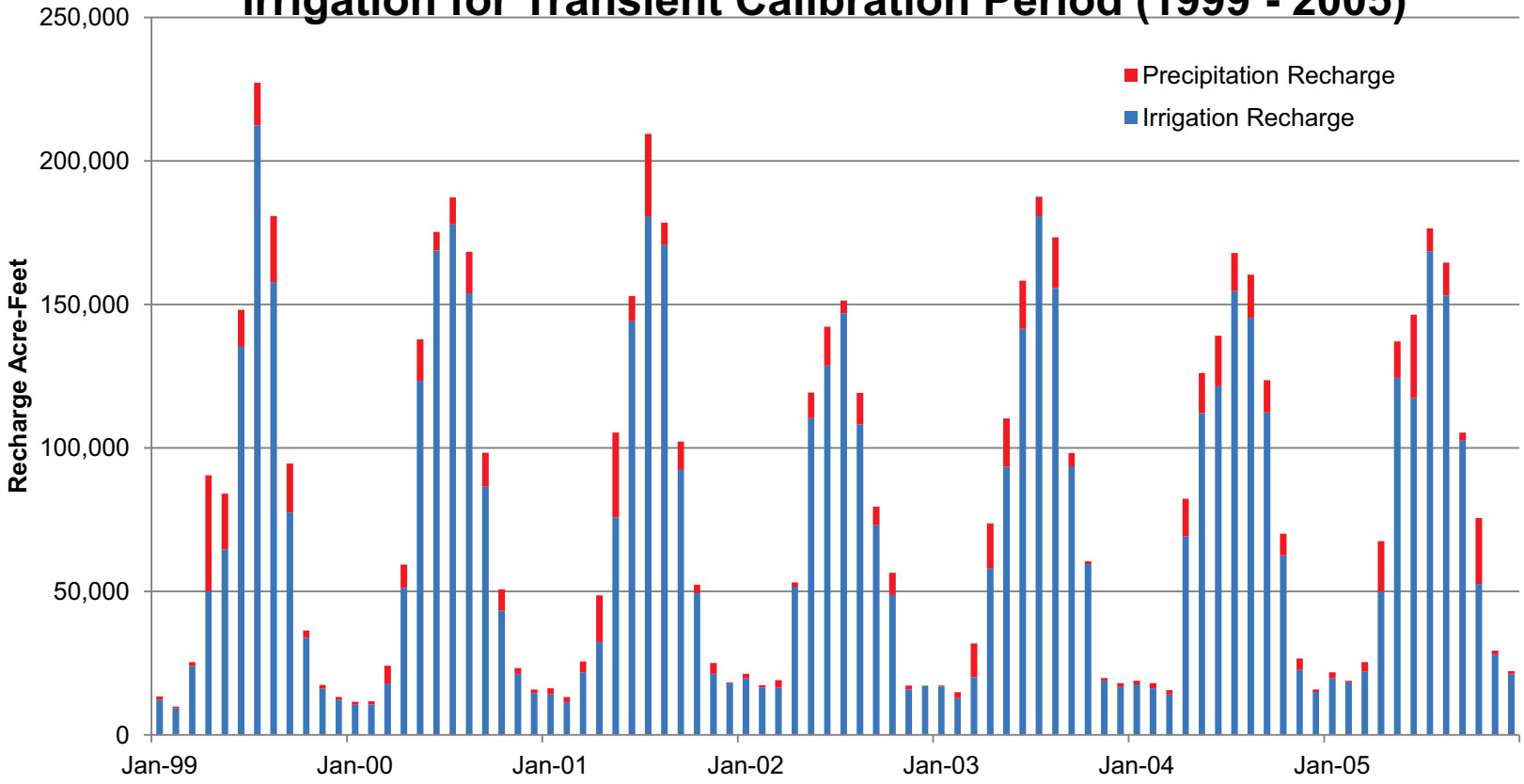

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Figure B-6. Monthly Recharge from Precipitation for Model Validation Period (1950 - 2006)

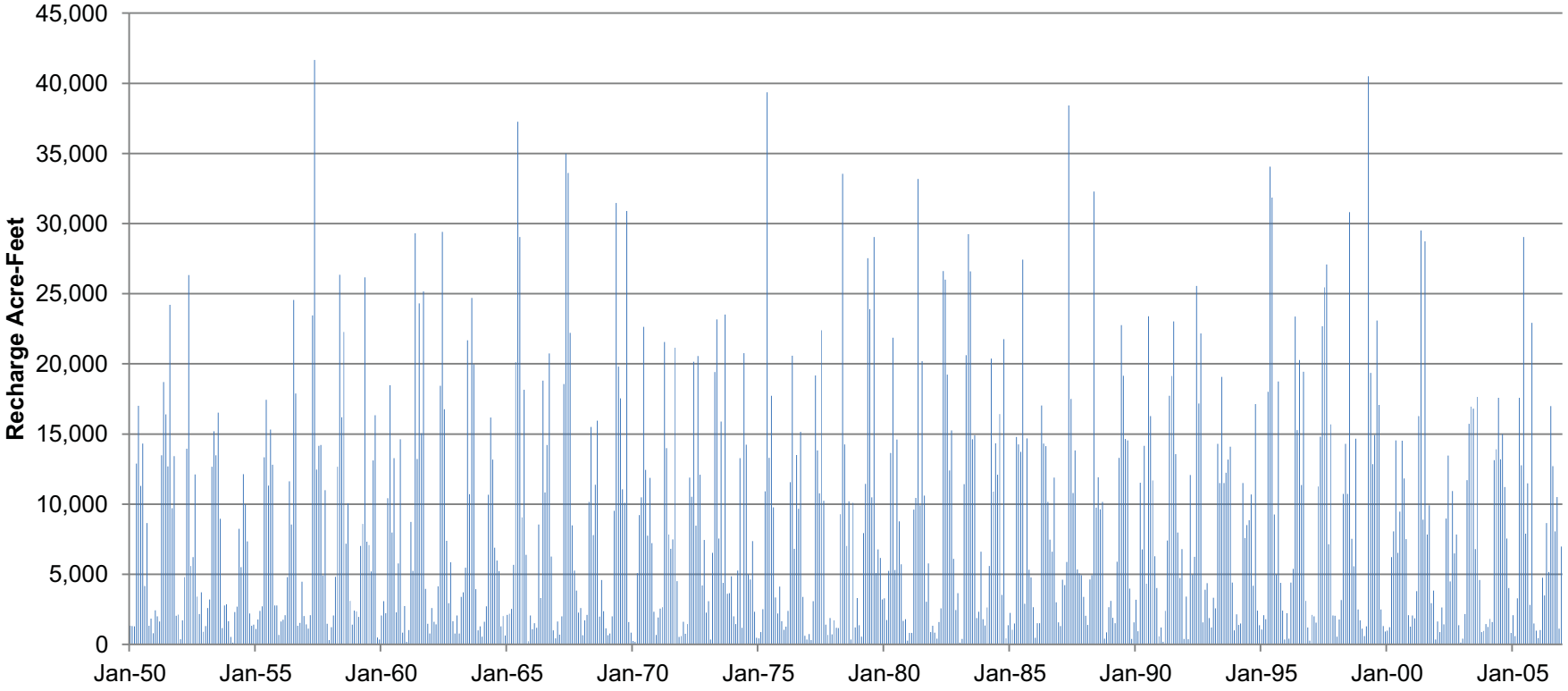

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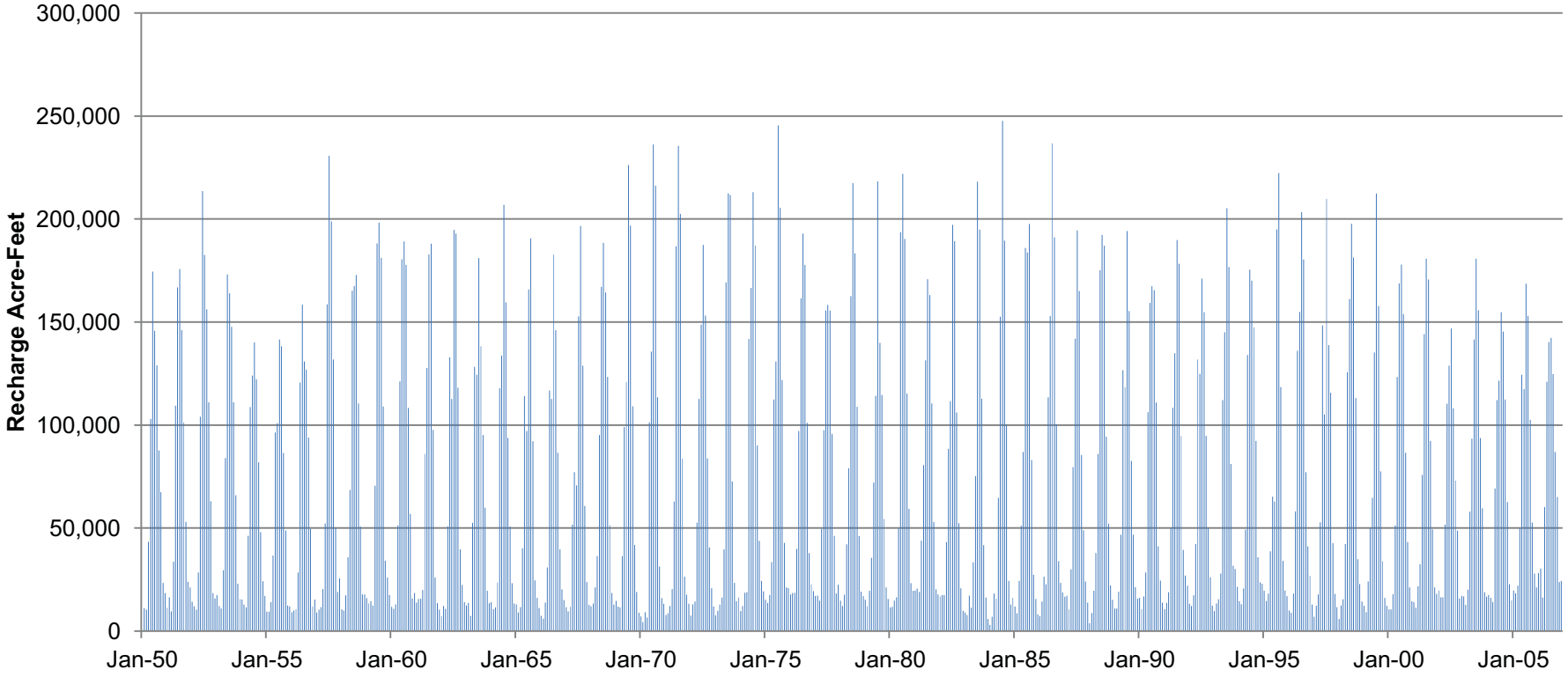
Figure B-7. Monthly Recharge from Irrigation for Model Validation Period (1950 - 2006)



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DEPARTMENT OF NATURAL RESOURCES

State of Colorado
Department of Natural Resources
Colorado Water Conservation Board
Division of Water Resources

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Figure B-8: Explicitly Modeled Reservoirs within Active Model Domain

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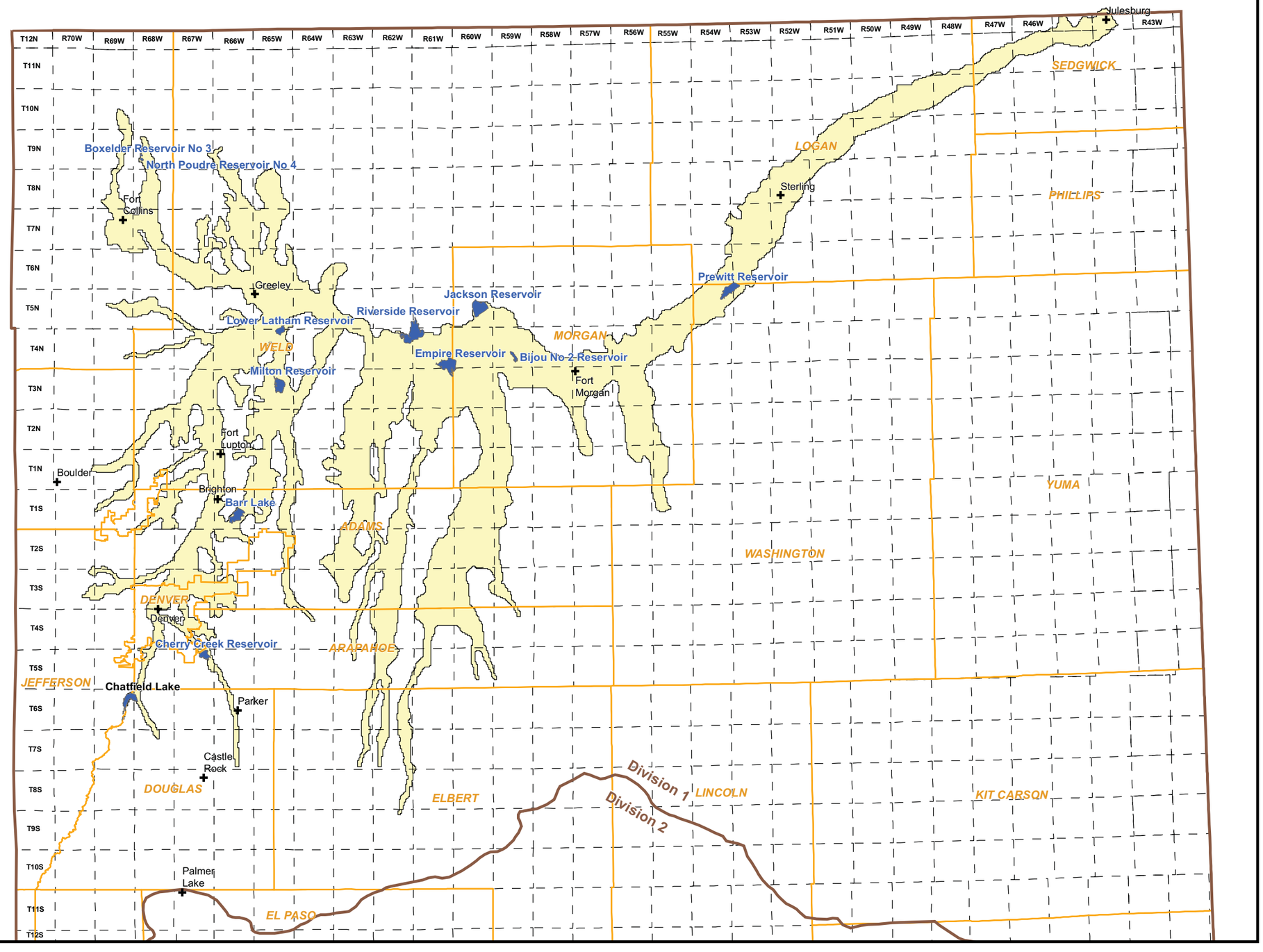
Legend

- Modeled Reservoirs
- City
- County



N
W E
S

Scale
1:1,000,000
0 5 10 20
Miles

NAD 1983 UTM Zone 13N

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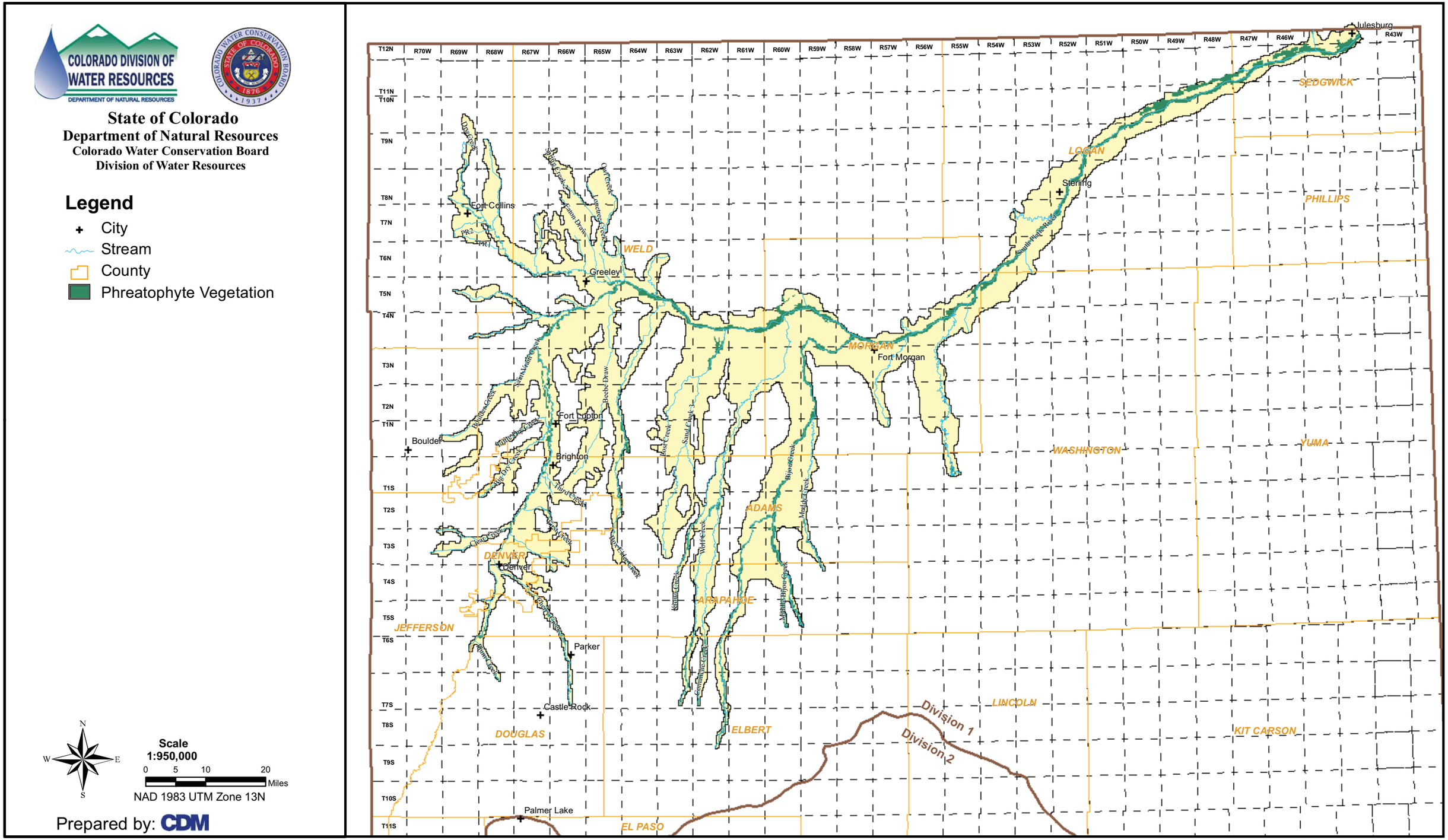
Figure B-9: Extent of Phreatophyte Vegetation Simulated in Groundwater Model