RGDSS Memorandum
Phase 6 – Review and Enhancement of Climate Station Weighting
Final

TO: File
FROM: Kelley Thompson, P.E. and James R. Heath, P.E.
SUBJECT: RGDSS Groundwater Model – Phase 6: Review and Enhancement of Climate Station Weighting
DATE: 7/17/2012

1. Introduction

A review was completed of the methodology to compute the climate station to structure weights used within StateCU (a preprocessor to the Rio Grande Decision Support System (RGDSS) groundwater flow model). This review was completed as part of the Phase 6 efforts of the RGDSS Technical Advisory Committee (a/k/a Peer Review Team (PRT)) to review and update the RGDSS groundwater modeling.

This memorandum describes the review and enhancements to the methodology used to compute the climate station-to-structure weights used for structures in the RGDSS StateCU analysis. The objectives of this task were to:

1. *Identify alternative methods to the County/HUC combination method climate station weighting method implemented in previous Phases of the RGDSS modeling.*
2. *Evaluate the ease of implementation and validity of the identified methods.*
3. *Implement the most appropriate method.*

2. Previous Efforts

Climate weights used in previous Phases of the RGDSS modeling are documented in the RGDSS Subtask 3.2 memorandum *Assign Climate Stations to Irrigated Parcels* dated September 21, 1999, attached. This memorandum describes the procedure used to develop the County/HUC combination assignments used for previous phases of the RGDSS modeling.

As part of the South Platte Decision Support System (SPDSS) alternative methods were reviewed in the development of climate weights for structures and is described in the SPDSS Task 53.3 memorandum *Assign Key Climate Information to Irrigated Acreage and Reservoirs* dated September 1, 2005 (Revised February 1, 2006), attached.

3. Approach

Through the PRT's meeting process, it was discovered that some of the climate station to structure assignments were not a physical representation of the nearest climate stations to the irrigated lands under some structures. The cause of this was the County/HUC method used to define climate station to structure weights and the use of the structure headgate to define the County/HUC for that structure. There are several structures within the San Luis Valley (Valley) that have irrigated lands a significant distance from their headgates. Some examples are shown in Figure 1 and Table 1 below.

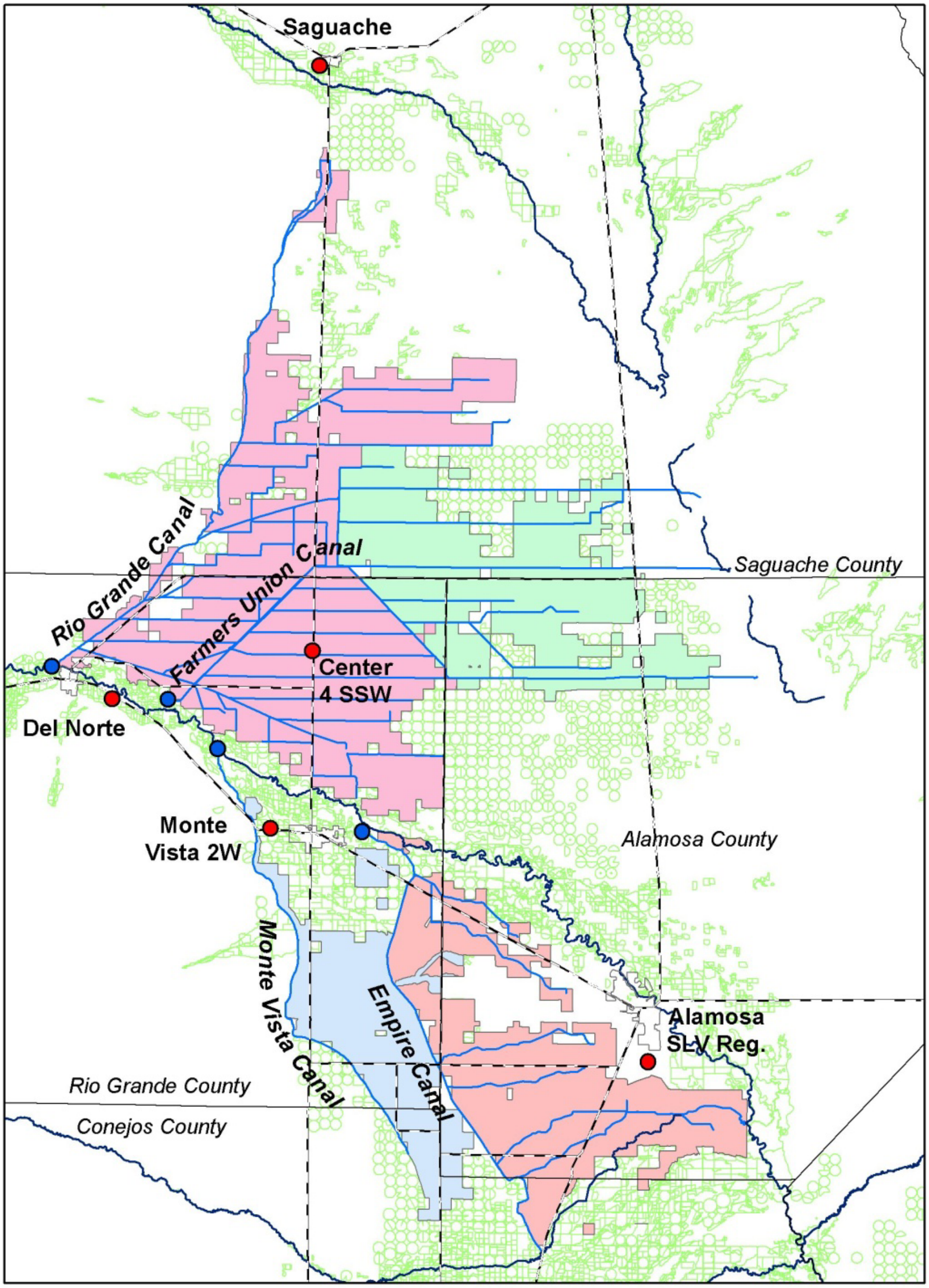

Figure 1. Locations of Selected Climate Stations, Ditch Headgates, and Service Areas

Table 1. Phase 5 Climate Station Weighting for Selected Structures

		Phase 5 - Climate Station Assignments (%)				
WDID	**Structure**	**Alamosa**	**Del Norte**	**Monte Vista**	**Saguache**	**Center**
200812	Rio Grande Canal	0	10	0	80	10
20MS02	Empire Canal	100	0	0	0	0
200631	Farmers Union	60	0	0	0	40
200753	Monte Vista	0	20	40	0	40

3.1. Methodology Investigation

The PRT decided that is would be worthwhile to investigate alternative methods that were in use in other basins within Colorado's Decision Support Systems (CDSS). As part of the South Platte Decision Support System (SPDSS) a similar investigation was performed and documented in SPDSS Memorandum for Task 53.3. Of the methods described in SPDSS Task Memo 53.3, the Thiessen polygon and linear interpolation methods were reviewed for possible application within the RGDSS modeling.

The Thiessen polygon approach creates areas for each climate station identifying their regional influence. Thiessen (or Voronoi) polygons define the region that is closer to the associated point than any other point. Thiessen polygons can be constructed graphically by first drawing triangles between each point then drawing the perpendicular bisector to each triangle edge to define the Thiessen polygon as shown in the following figure.

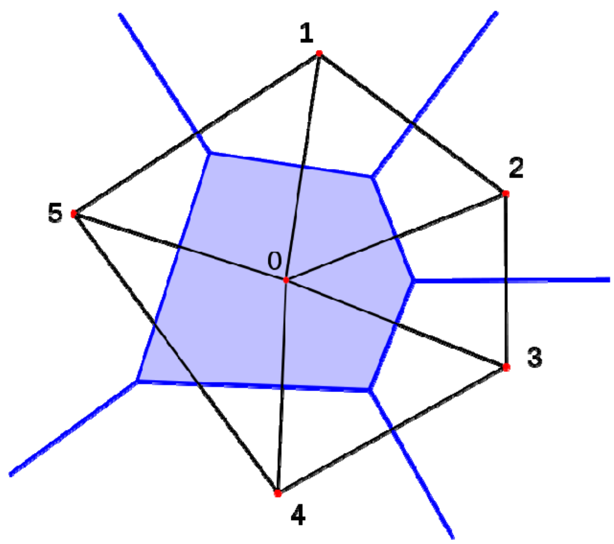

Figure 2. Construction of Thiessen polygon (blue) for point 0

Thiessen polygons can be generated in commonly available GIS software, and results are straightforward and repeatable. Within ESRI branded GIS software, Thiessen polygons can be generated using the 3D analyst extension for ArcView, ArcInfo packages, or an "Advanced" license within ArcGIS 10.

The methodology for assigning climate station weights to structures is:

- Ditches with service areas that are fully within one Thiessen polygon will be assigned to only one climate station.

- For ditches with service areas that overlap more than one Thiessen polygon, an area weighting of the service area within each Thiessen polygon will be used to assign weights for each of the climate stations.
- For ditches without service areas, the location of the headgate will be used to define the one climate station.
- Groundwater only structures are assigned climate weights based on an area weighted intersection between the response area and the Thiessen polygons.

The Thiessen polygon approach was determined to be appropriate for the Valley because the geometry of the Valley along with the distribution of the climate stations throughout the Valley yield Thiessen polygons that are reasonable representations of similar climatic regions.

A linear interpolation method was also investigated. GIS can be used to find the closest climate station to the centroid of each irrigated parcel in an irrigated lands snapshot. Within a ditch service area, the areas of parcels associated with each climate station can then be used to calculate the weight of each climate station based on the areas. The areas of parcels served by multiple structures must be appropriately fractioned during the accounting process to avoid overweighting parcels with overlapping water sources. However, different irrigated lands snapshots yield slightly different area weightings for several of the larger ditch service areas, and this temporal change in station weighting complicates modeling in StateCU.

3.2. Methodology Choice

The Thiessen polygon method is easier to implement than the linear interpolation method for the following reasons:

- Less calculations needed by using the ditch service area rather than individual parcels,
- Does not need multiple analyses (for each irrigated lands snapshot), and
- Does not require a complex algorithm to area weight climate stations to structures by parcels that are served by multiple ditches.

For these reasons the Thiessen polygon approach was chosen for implementation in the RGDSS modeling.

3.3. Additional Investigations and Modifications to Thiessen Polygons

Through initial PRT review of the Thiessen polygons, questions arose about the cloud effects on the west side of the Valley near Del Norte and Monte Vista. Agro Engineering was tasked with investigating this further and completed the following investigation into possible modifications to the Thiessen polygons.

Agro Engineering maintains its own network of climate stations in the Valley. Currently, the network consists of five Campbell Scientific ET-106 stations. Agro Engineering has maintained a climate station near its office (“Agro Office” station) located between Monte Vista and Alamosa since the early 1990s and installed a station north and west of Monte Vista (“West” station) in 2004.

When Thiessen polygons are constructed for the climate stations used in the RGDSS, the Agro Engineering Office station lies within the area of the Monte Vista 2W NOAA climate station. The West station is located slightly within the Thiessen polygon area of Center 4 SSW NOAA station near the boundary of the Thiessen polygon for the Del Norte NOAA station. Both of the NOAA stations are located where there is some question of cloud effects and therefore were compared to the Agro stations to further evaluate the validity of the Thiessen polygon areas. The location of the Agro Office and West climate stations relative to the Thiessen polygons for the NOAA climate stations are shown in Figure 3.

For the RGDSS, StateCU uses temperature data to estimate potential crop evapotranspiration using calibrated crop coefficients. Precipitation data are used to estimate effective precipitation and irrigation water requirement. However, in the Valley where there is very little rainfall, temperature (with relationships to wind and solar through the calibrated coefficients) is typically a more predominant factor for overall water use than precipitation. Therefore, temperature data was used for comparison.

Daily temperature data files from the Agro Engineering climate stations were processed to monthly data for comparison with monthly temperature data from the nearby NOAA climate stations available in HydroBase. Average monthly temperatures were calculated as the average of the mean daily maximum temperature and mean daily minimum temperature for the month. Then, for each month, the mean average monthly temperature was compared between the Agro Engineering and NOAA climate stations for all months between 2004 and 2011, see Table 2.

Table 2. Average Monthly Temperature during Growing Season 2004-2011 (°F)

Station	APR	MAY	JUN	JUL	AUG	SEP	OCT	Average
AGRO Office	41.7	50.9	58.7	63.7	61.5	54.4	43.1	53.4
AGRO West	42.2	51.0	59.4	64.5	63.2	56.0	44.8	54.5
CENTER 4 SSW	43.0	53.1	59.7	64.8	62.5	56.1	45.0	54.9
MONTE VISTA 2 W	41.0	50.5	57.7	63.4	60.9	54.1	42.7	52.9
DEL NORTE 2 E	39.8	49.2	57.0	61.8	59.5	53.6	42.2	51.9
ALAMOSA SLV Reg	42.5	51.8	60.2	65.8	63.0	55.3	43.6	54.6

The Agro Office climate station is located within the Thiessen polygon area of the NOAA Monte Vista station. For the Agro Office station, average monthly temperatures during the growing season from 2004 through 2011 were more similar to the NOAA Monte Vista station than the NOAA Center, Del Norte, or Alamosa stations.

The Agro West climate station is located within the Thiessen polygon area of the NOAA Center station although quite close to the area of the Del Norte station. For the Agro West climate station, average monthly growing season temperature is more similar to conditions at the Center climate station than the nearby Del Norte or Monte Vista stations.

Therefore, the Thiessen polygon representation appears appropriate in these particular locations. This also adds some support for use of the Thiessen polygon methodology in general given that the areas examined were among the most questionable.

The Thiessen polygons associated with climate station locations were used directly as generated with the exception of one modification. The boundary between the Manassa and Blanca NOAA station areas was modified by extending the north-south line generated between the Alamosa and Blanca stations to the south to the New Mexico stateline as shown in Figure 3. This boundary better represented the geographic separation of the San Luis Hills between Conejos and Costilla Counties. This also assigned the irrigated lands in water district 24 and the majority of the irrigated lands in Costilla County to the Blanca NOAA station and restricted irrigated lands represented by the Manassa NOAA station to Conejos County.

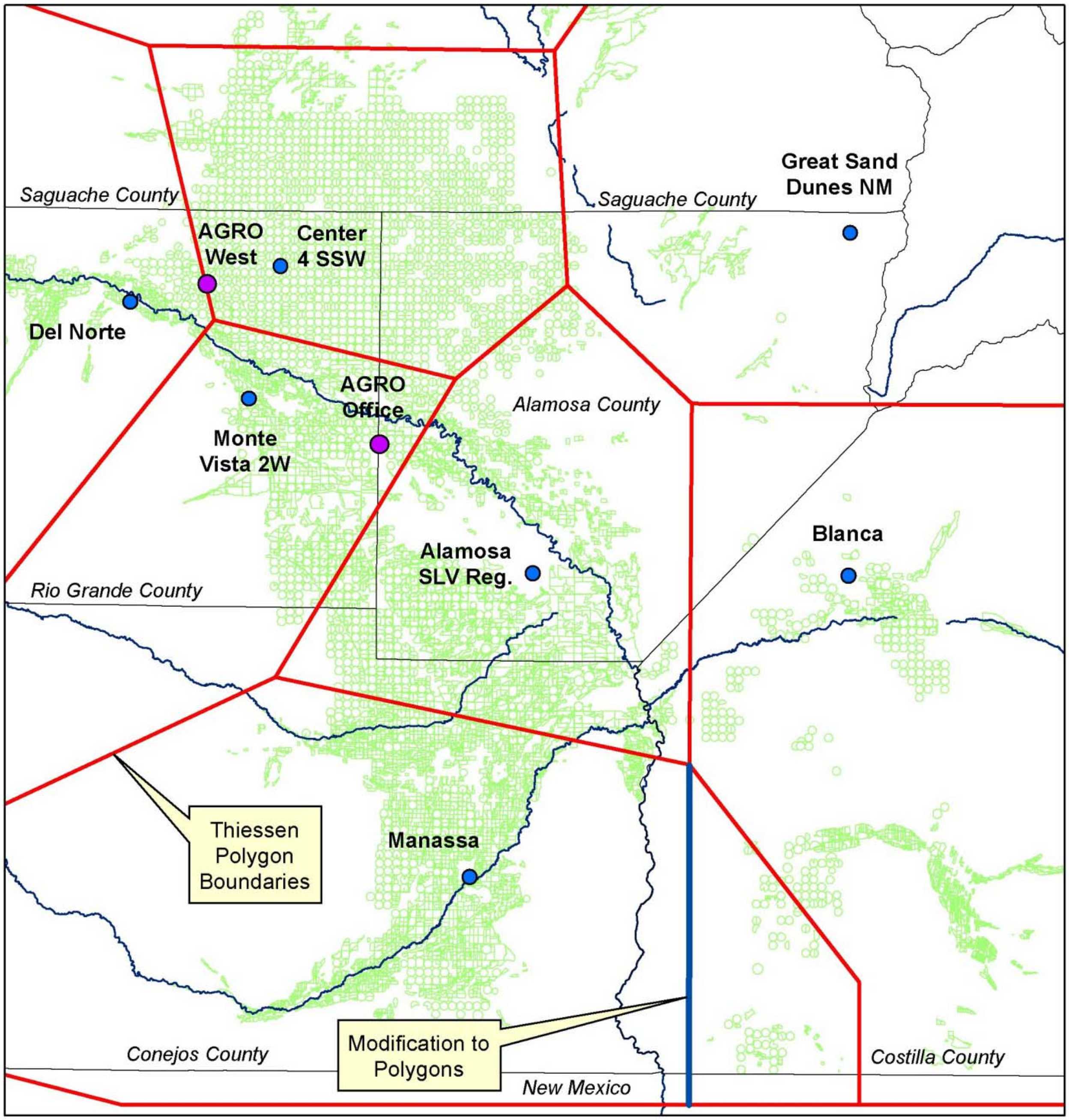

Figure 3. Location Map of Agro and NOAA Climate Stations along with Thiessen Polygons

3.4. <u>Application of Thiessen Polygon Method within StateCU Dataset</u>

Nine key climate stations were identified in RGDSS Subtask 2.1 and were previously assigned to structures as described in the 1999 memo for Subtask 3.2. Thiessen polygons were generated in GIS based on the location of these same nine climate stations. The polygon boundaries generated by GIS were only adjusted in the area between the Manassa and Blanca stations as described previously.

In GIS, the Thiessen polygon areas were spatially intersected with a) ditch service areas b) the location of ditch headgates, and c) response areas. For ditch or response areas divided between multiple Thiessen polygon areas, climate station weighting is calculated using an area weighting of the intersection polygons. Individual climate station weights were limited to a minimum of 5%. Climate station weights for ditches were based on the area weighting of their service area if it has been delineated or their headgate location if the service area has not been mapped. Ditches without mapped service areas are located primarily along upstream areas and have smaller service areas that are located relatively close to headgate locations. For ditch multistructures, climate station weights were based on area weighting of individual ditch service areas within the multistructure, if mapping for individual ditches were available. For groundwater only areas, climate station weighting was based on the area weighting of the mapped response areas.

For implementation in StateCU, a comma delimited file of station weights was exported from the spreadsheet used to calculate climate station weighting. This file was read in StateDMI which, in turn, creates the CU Location (STR) input file for StateCU. The STR file lists individual climate station weights for each structure that add to 100%.

4. Results

Use of Thiessen polygon areas for assignment of climate station weighting to structures in Division 3 was found to be a straightforward methodology that provides reasonable representations of climatic regions. The RGDSS peer review team felt that the Thiessen polygon methodology improved structure climate station weighting from the methodology used previously. The revised climate station weighting methodology was reviewed and approved by the RGDSS peer review team for use in the Phase 6 model.

A larger view of the climate station Thiessen polygons that were applied along with ditch service areas and irrigated parcels from 2005 is shown in Figure 4. The tables that follow compare the climate station weighting of the example ditch service areas between the Phase 5 and Phase 6 methodologies.

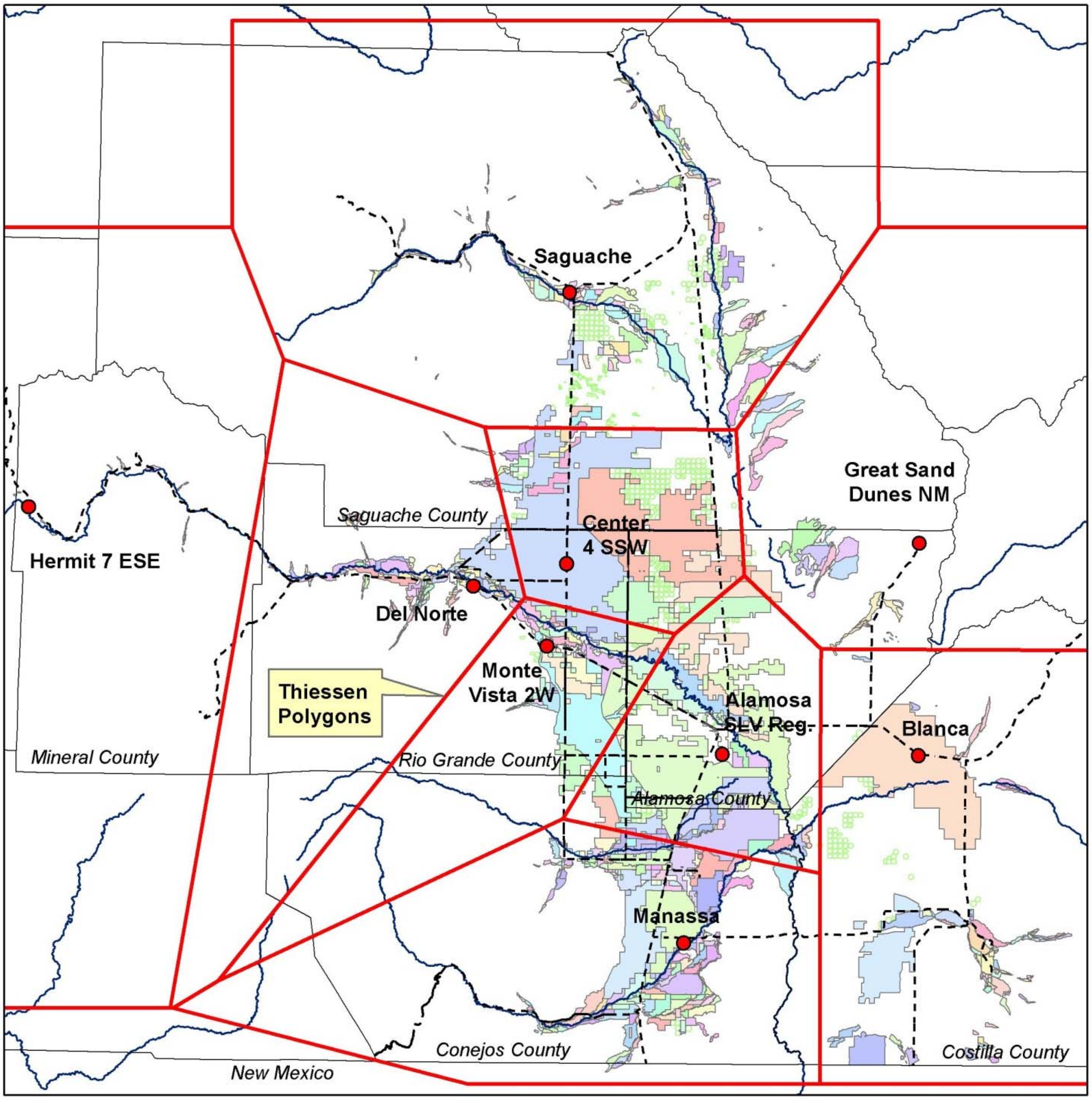

Figure 4. Thiessen Polygon Areas used for RGDSS Phase 6 Modeling

Table 1. Phase 5 Climate Station Weighting for Selected Structures (repeated)

		Phase 5 - Climate Station Assignments (%)				
WDID	**Structure**	**Alamosa**	**Del Norte**	**Monte Vista**	**Saguache**	**Center**
200812	Rio Grande Canal	0	10	0	80	10
20MS02	Empire Canal	100	0	0	0	0
200631	Farmers Union	60	0	0	0	40
200753	Monte Vista	0	20	40	0	40

Table 3. Phase 6 Climate Station Weighting for Selected Structures

		Phase 6 - Climate Station Assignments (%)				
WDID	**Structure**	**Alamosa**	**Del Norte**	**Monte Vista**	**Saguache**	**Center**
2000812	Rio Grande Canal	0	11	8	0	81
20MS02	Empire Canal	87	0	13	0	0
2000631	Farmers Union	0	0	0	0	100
20MS10	Monte Vista	37	0	63	0	0

5. Comments

The following files were produced for Phase 6 processing of structure climate station weighting. Assemblies of GIS shapefiles are noted as .shp.

- *ClimateStationThiessenPolygons.shp* - Thiessen polygon areas
- *CS_DitchService_Pre99_Inter_Jan12_MP.shp* - intersection of polygons with ditch service areas
- *CS_DitchHG_Inter_Jan12.shp* - intersection of polygons with ditch headgates
- *CS_ModelZones_Inter_Jan12_MP.shp* - intersection of polygons with response areas
- *Climate Weights.xlsx* – spreadsheet for calculation of climate station weighting
- *rgdss.wts.csv* – comma delimited file read by StateDMI
- *rg2011_STR.StateDMI* – StateDMI command file that creates STR file
- *rg2011.str* – StateCU Location CU file

Attachments

RGDSS Memorandum – Assign Climate Stations to Irrigated Parcels RGDSS Subtask 3.2

SPDSS Memorandum – Task 53.3 – Assign Key Climate Information to Irrigated Acreage and Reservoirs

RGDSS Memorandum
Draft

To: Ray Bennett, Ray Alvarado, Andy Moore

From: LRCWE, Erin Wilson and Ross Bethel

Subject: Assign Climate Stations to Irrigated Parcels
RGDSS Subtask 3.2

Date: September 21, 1999

Introduction

This memorandum describes the approach and results obtained under Subtask 3.2, "Assign Climate Stations to Irrigated Parcels" for the Historic Crop Consumptive Use Determinations (Task 3).

Approach and Results

ArcView coverages were used to assign climate stations and associated weights to County/HUC combinations. In addition, default County/HUCs were assigned to water districts for use when County/HUC information is not available in HydroBase. The following procedure was followed in completing this task:

1. The key climate stations identified and filled in Subtask 2.1 where highlighted on the Climate Station ArcView coverage. Their elevations where added to the associated ArcView database. Table 1 shows the climate stations and the corresponding unfilled period of record, elevation, and average annual temperature and precipitation for the period of record.
2. The County and HUC ArcView coverages where combined to determine the County/HUC combinations in the Rio Grande basin. These County/HUC combinations are the basis for climate station assignments.
3. The GIS coverage showing irrigated acreage for identified service areas, and the GIS coverage of diversion structure locations where both added to the GIS project. These coverages were used to represent the probable location of irrigated acreage both within and outside of identified service areas.
4. Based on the coverages from Step 3, coupled with topographic and land ownership information from 1:50,000 USGS County maps and engineering judgement, the likely centroid of irrigated acreage was identified for each County/HUC combination and placed on a layer in the GIS project. Figure 1 shows the location of these centroids, the County and HUC outlines, the GIS irrigated acreage, the GIS diversion structure locations, and the location of the climate stations in the basin.

5. The elevation of the centroids of irrigated acreage where identified from the USGS County maps. The distance from the centroid of irrigated acreage to the nearest climate stations was determined from the GIS coverages. This information is summarized in Table 2.
6. Based on centroid elevations, distance to climate stations, and engineering judgement, climate stations and a corresponding appropriate weight were assigned to each County/HUC combination. The results of this analysis are presented in Table 3.
7. All nine climate stations included in the analyses have both temperature and precipitation data. Therefore, the same weights were assigned to both temperature and precipitation data.
8. The Water District Boundary GIS coverage was brought into the GIS project. Based on the location of most irrigated acreage within water district, a default County/HUC combination was assigned to the water districts as shown in Table 4.

Table 1
Key Climate Stations

Station Name	Station ID	County	Elevation (feet)	Period of Record	Average Annual Temperature (Deg F)	Average Annual Precipitation (inches)
Alamosa WSO AP	0130	Alamosa	7534	1948-1999	41.3	7.11
Center 4 SSW	1458	Saguache	7668	1948-1999	40.8	7.14
Del Norte	2184	Rio Grande	7880	1948-1999	43.1	9.99
Hermit	3951	Mineral	9001	1948-1999	34.2	15.32
Monte Vista 2W	5706	Rio Grande	7665	1948-1999	41.0	7.51
Manassa	5322	Conejos	7710	1948-1999	42.3	7.63
Saguache	7337	Saguache	7697	1948-1999	42.0	8.73
Great Sand Dunes	3541	Alamosa	8120	1950-1999	43.5	10.86
Blanca	0776	Costilla	7800	1960-1998	42.1	8.01

Figure 1
Centroid Locations

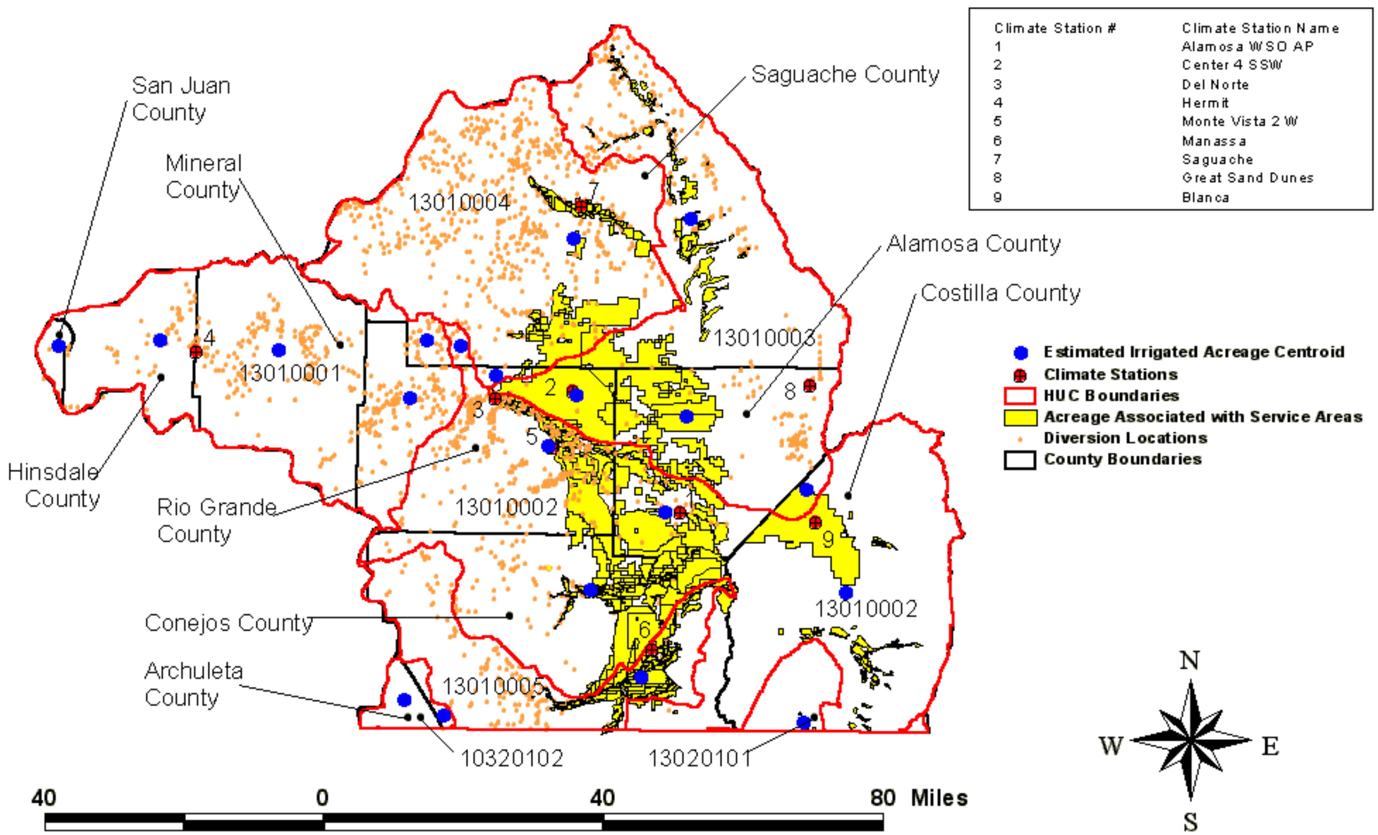

Table 2
County/HUC Irrigated Land Centroid Elevations and Distances

HUC	County	Percent of County in Basin in HUC	Elevation of Centroid of Irrigated Lands	Nearest Climate Station(s)	Distance (miles)
13010001	San Juan	100 %	12,000	Hermit	20
	Hinsdale	100 %	10,500	Hermit	5
	Mineral	100%	10,400	Hermit Del Norte	12 12
	Rio Grande	30 %	8,200	Del Norte Hermit	12 31
	Saguache	2 %	8,800	Center Del Norte Hermit	22 33 33
13010002	Saguache	1 %	8,800	Saguache Hermit	25 37
	Rio Grande	56 %	7,670	Monte Vista Center Del Norte	9 9 13
	Alamosa	32 %	7,550	Alamosa	2
	Costilla	87 %	8,000	Blanca Alamosa Manassa	11 26 28
	Conejos	56 %	7,800	Manassa Alamosa	12 17

Table 2 Continued

HUC	County	Percent of County in Basin in HUC	Elevation of Centroid of Irrigated Lands	Nearest Climate Station(s)	Distance (miles)
13010003	Saguache	41 %	7,600	Saguache Center	15 30
	Rio Grande	12 %	7,670	Center Monte Vista Del Norte	0 8 12
	Alamosa	68 %	7,550	Alamosa Center	13 16
	Costilla	3 %	8,000	Blanca Sand Dunes Alamosa	5 15 18
13010004	Saguache	56 %	7,600	Saguache Center Del Norte	5 21 24
	Rio Grande	2 %	7,850	Del Norte Center Monte Vista	3 11 13
13010005	Conejos	42 %	7,800	Manassa Alamosa	4 24
13020101	Costilla	10 %	7,580	Manassa Blanca	24 29
13020102	Conejos	2 %	10,000	Manassa	31
	Archuleta	100 %	9,000	Manassa	36

Table 3
Recommended Climate Station Weighting

HUC	County	Climate Station Name	Weight (Percent)
13010001	San Juan	Hermit	100 %
	Hinsdale	Hermit	100 %
	Mineral	Hermit Del Norte	70 % 30 %
	Rio Grande	Del Norte Hermit	70 % 30 %
	Saguache	Center Del Norte Hermit	60 % 20 % 20 %
13010002	Saguache	Saguache Hermit	70 % 30 %
	Rio Grande	Monte Vista Center Del Norte	40 % 40 % 20 %
	Alamosa	Alamosa	100 %
	Costilla	Blanca Alamosa Manassa	50 % 25 % 25 %
	Conejos	Manassa Alamosa	50% 40%
13010003	Saguache	Saguache Center	70 % 30 %
	Rio Grande	Center Monte Vista Del Norte	80 % 15 % 5 %
	Alamosa	Alamosa Center	60 % 40 %
	Costilla	Blanca Sand Dunes Alamosa	60 % 25 % 15 %
13010004	Saguache	Saguache Center Del Norte	80 % 10 % 10 %
	Rio Grande	Del Norte Center Monte Vista	70 % 15 % 15 %
13010005	Conejos	Manassa	100 %
13020101	Costilla	Manassa Blanca	60 % 40 %
13020102	Conejos	Manassa	100 %
	Archuleta	Manassa	100 %

Table 4
Water District Default County/HUC Assignments

Water District	Default County/HUC Combination
20	Rio Grande / 13010001
21	Conejos / 13010002
22	Conejos / 13010005
24	Costilla / 13010002
25	Saguache / 13010003
26	Saguache / 13010004
27	Saguache / 13010004
35	Costilla / 13010003

Comments and Concerns

As shown in Table 1, the climate across the San Luis Valley floor is relatively consistent. Therefore, weighting a valley floor station more than another is unlikely to have a great effect the irrigation water requirement.

The following addresses County/HUC combinations that warranted further investigation:

1. Two County/HUC combinations covered extensive areas with large differences in elevations - Saguache/13010004 and Conejos/13010005. The diversion structure GIS coverage indicated diversion structures in the higher elevations on both Saguache Creek and the Conejos River. There was initial concern that these County/HUC combinations would need to be split into two areas with different climate stations and weights to accurately represent the two climate regimes.

   A closer review of the USGS County maps for both areas showed that the high elevation lands in both counties were located in the Rio Grande National Forest, and we understand that it is unlikely that much irrigation takes place within the National Forest. In addition, we reviewed information on the USGS streamflow gages located on both rivers where they flow out of the higher mountains. The remark section of the 1997 Water Supply Paper for Conejos River near Mogote indicated there are only about 500 acres of hay meadows upstream from the station. The remark section of the 1997 Water Supply Paper for Saguache Creek near Saguache did not provide an acreage estimate, but indicated there are some diversions upstream for irrigation.

   Based primarily on the fact that the upper elevations of both areas are in the National Forest, we believe the diversion structures likely provide water to irrigate lands located closer to the valley floor. The centroid for the irrigated lands was placed accordingly, and one set of climate station and corresponding weights was assigned to these County/HUCs.

2. Part of Archuleta County lies in the southwest corner of the Rio Grande Basin in HUC 13020102. A small portion of Conejos County also lies in this HUC. The runoff from these areas contributes to the Rio Chama, which flows into the Rio Grande in New Mexico. The nearest climate station is in Chama, New Mexico. We wanted to avoid using an out-of-state climate station, if possible, because we felt it would be better if Colorado did not need to update information from another State in HydroBase. There are currently no diversion structures or irrigated acreage identified on the GIS coverages in these areas. Therefore, we felt justified in assigning 100 percent of the Colorado Manassa station to these areas for use if acreage is identified in the future.

SPDSS Memorandum
Final

To: Ray Alvarado and Ray Bennett

From: LRE – Bruce Rindahl, Erin Wilson, and Beorn Courtney

Subject: Task 53.3 – Assign Key Climate Information to Irrigated Acreage and Reservoirs

Date: September 1, 2005 (Revised February 1, 2006)

Introduction

This memorandum presents the general approach for the following Task 53 subtasks:

1. *Assign key climate stations to geographic areas for the SPDSS modeling efforts.*
2. *Estimate average monthly reservoir evaporation rates for geographic areas.*

Temperature and/or precipitation climate data will be used in the SPDSS in four model efforts:

- Consumptive Use (CU) Model
- Ground Water (GW) Model
- Surface Water (SW) Model
- Water Budget (WB) Model

Consumptive Use Model. Monthly temperature and precipitation climate data will be used to estimate historic crop consumptive use in the CU model throughout the South Platte, North Platte and Laramie River Basins (SPDSS study area). Key climate stations were selected and monthly data were filled under the SPDSS "Task 53.2 – Collect and Fill Missing Monthly Climate Data." By assigning key climate stations to geographic areas (irrigated lands) within the SPDSS study area, consumptive use can be estimated at any location.

Ground Water Model. Monthly precipitation data will be used to estimate recharge for the GW model. As with the CU model efforts, by assigning key climate stations to geographic areas (ground water model cells) within the GW model area, recharge from precipitation can be estimated at any location.

Surface Water Model. Average annual precipitation data will be used in the baseflow calculations in the SW model to distribute flow at gages to ungaged locations. The average annual precipitation GIS coverage, developed by the Colorado Climate Center, will be used to estimate average annual precipitation within a defined sub-basin.

Water Budget Model. Two water budgets will be developed to represent the SPDSS area; a monthly water budget representing the ground water model area, and an average annual water budget representing the entire South Platte drainage. For the monthly water budget, monthly precipitation data will be used to estimate precipitation inflow over the ground water model area. By assigning key climate stations to geographic areas within the ground water model area, precipitation inflow can be estimated at any location. For the average annual basin-wide water budget, the average annual precipitation GIS coverage, developed by the Colorado Climate Center, will be used to estimate the basin-wide average annual precipitation.

Reservoir evaporation rates and water surface areas will be used in preparing the Consumptive Use and Losses Summary, the water budget, and for the potential future surface water modeling efforts. Reservoir evaporation data exist at only a few reservoirs in the SPDSS study area and only for a short period during the 1950 through current year study period.

Approach and Results

1. Assign Key Climate Stations to Geographic Areas

Several interpolation methodologies commonly used to spatially distribute data to a subset of a given area were investigated including: Thiessen polygon weighting, linear interpolation, and kriging. The advantages and limitations of each method were investigated and are summarized below. The criteria used to evaluate the methods were as follows:

1. Data Centered Approach – The method must be able to respond to changes in the input data sets. For example, if the irrigated area associated with a structure is adjusted, the method must be able to adjust the associated climate stations and weights in a straight forward manner, preferably by just rerunning a procedure with a new input data set.

2. Applicability – The method must be applicable for the use intended. For example, the climate station weights should be applied for those portions of the models where the elevation of the respective stations is similar to the data set.

3. Engineering Judgment – The method must be able to be adjusted based on an engineering review of the results. For example, the automated procedure may develop climate station weights for a structure from six or seven climate stations while the practical limit may be to use only the highest three or four stations.

4. Compatibility with Existing Models – The method must be developed with the existing CDSS models in mind. For example, StateCU requires that each structure have a fixed number of climate stations and fixed weights throughout the study period. Variable weights by year would not be practical nor needed for SPDSS.

5. Standard Tools – The method should be developed with existing software currently in use in the CDSS. This includes the ArcView GIS software package with standard extensions.

Thiessen Polygon Weighting

A Thiessen polygon weighting procedure can be used to assign weights associated with defined point climate station locations. This procedure is straightforward in the standard GIS software packages used in the SPDSS. The method works well for regions larger than the individual Thiessen polygons. However, discontinuities can arise from this method when areas are relatively small and near the boundaries of the computed polygons. The climate station weights could differ enough to result in abrupt changes in the climate station data used to estimate consumptive use (or evaporation, recharge, etc.) across a short distance.

Linear Interpolation of Climate Station Weights

An alternate method is to use varying weights based on the distance from each station, ranging from 1.0 at the station itself to 0.0 at each adjacent station. A Triangular Irregular Network (TIN) is created by joining the location of each climate station into a series of triangles that cover the entire region of interest. The triangular network defined around each climate station can be adjusted, if necessary, to reflect engineering judgment (elevation consideration, topographic influences, extrapolation, etc.) At the selected climate station, each triangle vertex is assigned a value of one while all other vertices are assigned a value of zero.

A grid is then created for each climate station as a linear interpolation of each triangle in the TIN. This automated process is then repeated for each climate station. The final product is a spline interpolation with linear basis functions. This assures that the sum of the weights at any point equal one and that at a particular climate station, the weight for that climate station is equal to one. It also assures that all weights are greater than zero, which is not always guaranteed in the kriging method described below. By using ArcView's spatial analyst extension, the weights are stored as separate grids and can be combined easily for a point location or summarized for any polygon area. Note that weights can be automatically extended between the edge of the study area and climate stations within the study area based on user-input criteria or climate stations outside the study area (for instance climate stations in the Republican Basin).

Once the grids are created for each climate station, they can be used for weighting any region in the study area from large areas such as water districts to small areas including ditch structures or individual farm parcels.

Kriging

Kriging is another method for spatially interpolating point values to a continuous surface and is available in the ArcView GIS program. A major disadvantage of the kriging method in existing GIS software is that it is necessary to define the point or area at which the weights are being determined before developing the weights as opposed to the Thiessen polygon or linear interpolation method which defines a grid around each climate station. Another disadvantage is that the kriging method does not ensure that all weights are greater than zero.

<u>Results – GW Model and CU Model</u>

After reviewing the Thiessen polygon weighting, linear interpolation, and kriging methods, it was determined that the linear interpolation method was most appropriate for the SPDSS ground water and consumptive use models. This method is data centered, compatible with the existing models in the SPDSS, and provides a more continuous interpolation of the point values available for the climate station data than the Thiessen polygon method. Once the grid network is developed, it can be applied to any point location or summarized for a polygon area whereas with kriging, the locations must be determined beforehand. Note that both the linear interpolation and kriging methods may require an orographic adjustment, applied to the actual climate data, if used over areas with elevations outside the range of the climate station coverage.

The linear interpolation method was applied to develop a grid network for key climate stations east of the foothills that include the entire GW model area and the majority of irrigated acreage. For the irrigated acreage in the SPDSS, the vast majority of lands are at an elevation of less than 6,500 feet and have adequate coverage of climate stations without the need for elevation adjustment. Higher areas of the groundwater model may require an orographic precipitation adjustment to the climate station data to accurately estimate precipitation recharge. This orographic adjustment to precipitation data is described below. This network of climate station grids was then used to create a uniform coverage of climate station weights. The coverage will be used to automate the assignment of appropriate key climate stations and weights for estimating consumptive use at any point or area (parcels, groups of parcels, grid cells, etc) located in their respective study areas.

In order to extrapolate climate station weights to the limits of the study area and to those areas up to 6,500 feet, the locations of climate stations from outside the state and above 6,500 feet were utilized to create a network of grids. After this analysis, the weights from climate stations outside the state or above 6,500 feet were set to zero and the remaining weights prorated upward to assure a total value of 1.0. This maintains the requirement of insuring the sum of the climate station weights equal to one, and also avoids utilizing climate station data outside the state not currently stored in HydroBase.

In the foothills and higher elevations, climate stations were assigned to reflect climate conditions by sub-water district. **Figure 1** shows the division of water districts along the foothills with the upper and lower designations. Figure 1 was developed using digital elevations obtained from the State, originally derived from data obtained from the USGS. **Table 1** presents the upper water district climate stations that should be used in the consumptive use model.

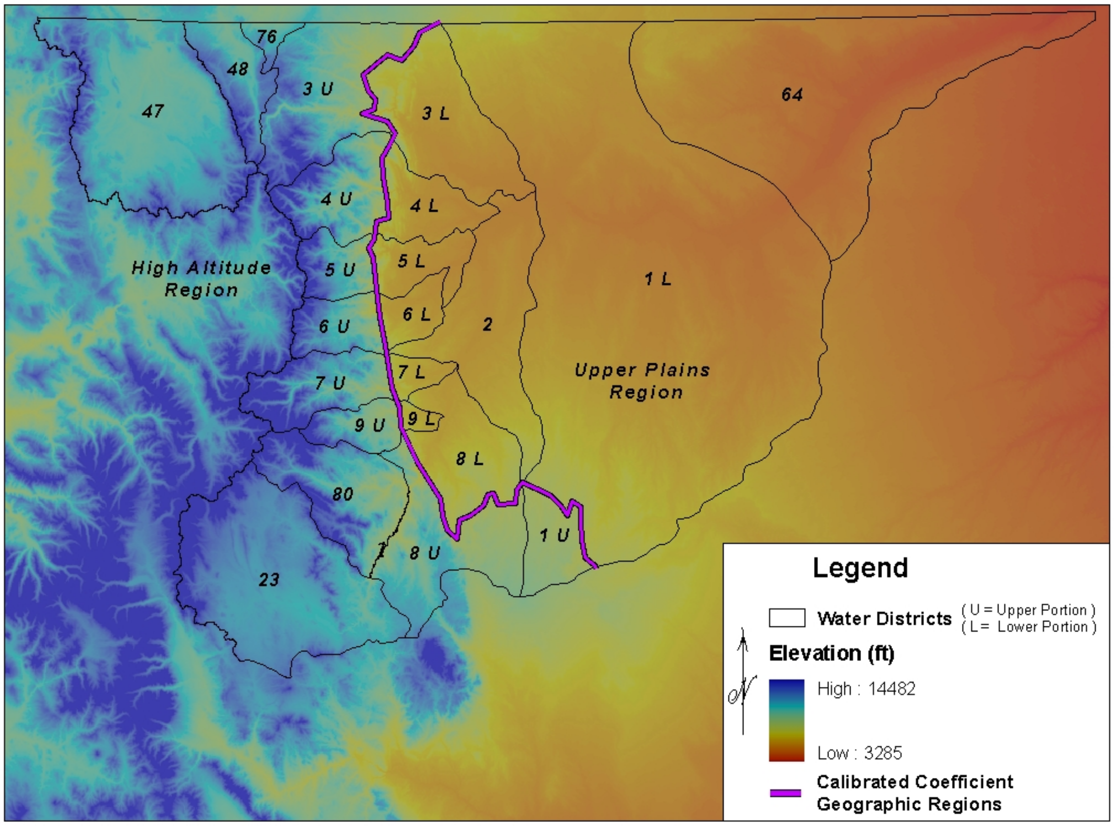

Figure 1 – Division of Water Districts along the Foothills

Table 1
Key Climate Stations Assignments for Crop Consumptive Use Estimates

Station ID	Station Names	Representative WD
0185	Allenspark 1 NW (combined)	5U
0263	Antero Reservoir	23
0454	Bailey	80
1528	Castle Rock	8U
2494	Eastonville 2 NNW	1U
2761	Estes Park 1 SSE (combined)	4U
2790	Evergreen (combined)	7U, 9U
0185	Allenspark 1 NW (combined)	6U
6921	Red Feather Lakes (combined)	3U, 48, 76
8756	Walden	47

The assignments shown in Table 1 are based on the location of climate stations compared to irrigate lands identified in the preliminary SPDSS Irrigated Acreage Assessment. Note that in the preliminary acreage assessment, no lands were identified in the upper portions of water districts 3, 5, 6, and 7; however according to the water commissioners there are minor diversions for irrigation in these water districts above 6,500 feet.

Orographic adjustment

The ground water model requires monthly precipitation estimates for recharge values. Since some areas of the proposed ground water model are at elevations not represented by nearby climate stations, an orographic adjustment will be applied to precipitation values from climate stations. This basis of the adjustments will the Colorado Average Annual Precipitation Map (1951 – 1980) published by the Colorado Climate Center. At each climate station, the average annual precipitation value will be estimated from the map. Other locations in the vicinity of each climate station will then be assigned a value equal to the estimated annual precipitation at the location of interest divided by the annual precipitation value at the nearby climate station. For example, if the average annual precipitation value at a climate station is 15 inches, then every location affected by that station with a precipitation value of 14 inches will be assigned a value of 15/14 or 0.93. This process will create a continuous grid of weights for each station. The product of the spatial grid weights and the orographic weights can then be used to automate the estimate of precipitation values throughout the groundwater model area. It is important to note that using this method, the total weights can be greater than or less than 1.0.

Results – SW Model and WB Model

As noted above, average annual precipitation data is required for the SW model and the basin-wide WB model. An automated approach will be developed within ArcGIS, as part of SPDSS Task 18, to determine the annual precipitation for a defined area using the GIS average annual precipitation coverage developed by the Colorado Climate Center. For the basin-wide average annual WB model, the defined area will be the entire basin. For the SW model, defined areas will represent drainage areas.

2. Estimate Average Monthly Reservoir Evaporation Rates for Geographic Areas

There are no continuous reservoir evaporation stations located in the SPDSS study area. The Denver Water Department and Northern Colorado Water Conservancy District (NCWCD) have developed average monthly reservoir evaporation rates for their respective models, which they provided to SPDSS for review. Denver Water also provided a memorandum documenting their evaporation rates (“Estimation of Net Evaporation Rates”, December 11, 2003). Documentation of the development of evaporation rates for NCWCD was not available and there were discrepancies between Denver Water and NCWCD evaporation rates used in near proximity. A review of the data used in these models shows that the methods used to estimate net evaporation rates (net evaporation = gross evaporation – effective precipitation) are inconsistent. For example, some of the average monthly rates were based on State Engineer’s Office data, which has applied a 70 percent factor when calculating effective precipitation (net evaporation = gross evaporation – 0.70 x total precipitation) while others were based on Denver Water Department and Bureau of Reclamation data which consider 100 percent of precipitation to be effective. In addition, Denver Water estimates winter evaporation rates at upper reservoirs to be zero, whereas our analysis shows that reservoirs in these areas can experience net winter evaporation.

The State Engineer’s Office is calculating evaporation for a different purpose than Denver Water and the Bureau of Reclamation. The State Engineer’s Office administers reservoir storage based on decreed storage rights, regardless of evaporation. However, when reservoirs are required to replace evaporation of water that was stored out of priority, for example water stored in an unlined gravel pit, then 70 percent of the total precipitation is considered effective and applied as a credit. According to the State Engineer's Office, this assumes that 70 percent of precipitation on the reservoir site was previously consumed by native vegetation, and 30 percent contributed to stream flow. (Note that this 70 percent factor should not be confused with the 0.70 pan coefficient generally applied to pan evaporation estimates to get gross evaporation estimates.)

Denver Water and the Bureau of Reclamation, however, are calculating a mass-balance of reservoir inflows and outflows; therefore they consider the full precipitation in their net reservoir evaporation calculation. Similarly for the SPDSS Water Budget and Surface Water modeling efforts, the full precipitation should be considered in the net evaporation calculation. Due to inconsistencies noted, the reservoir evaporation rates from the Denver Water and NCWCD models were not used.

In the absence of site-specific data, the following consistent method was adopted for the entire basin, as explained in detail below:

1. Determine average annual gross evaporation based on NOAA publications
2. Determine average annual precipitation based on Colorado Climate Center publications
3. Distribute annual gross evaporation to monthly using State Engineer's Office procedure
4. Distribute annual precipitation to monthly using local climate station data
5. Estimate average net monthly evaporation rates by subtracting precipitation from gross evaporation

Steps 1 and 2: Determine average annual gross evaporation and average annual precipitation

The CDSS GIS coverage includes the following gross evaporation and precipitation shape files based on average annual estimates:

- NOAA Free Water Surface Evaporation published in June 1982, based on a 1956 through 1970 study period.
- Precipitation Isohyetal Map published by the Colorado Climate Center, based on a report titled "Analysis of Colorado Average Annual Precipitation for the 1951-1980 Period".

These files were used to develop average annual gross reservoir evaporation and total precipitation estimates for each water district or sub-district shown in Figure 1 above.

Step 3: Distribute annual gross evaporation to monthly

Average annual gross reservoir evaporation estimates developed in Step 1 above were distributed monthly with the percentages used by the State Engineer's Office (presented by Wolfe and Stenzel at a 1995 ET and Irrigation Efficiency Seminar and summarized in a paper titled "Evaporation"). There are two average monthly distributions; one for below 6,500 feet and one for above 6,500 feet above mean sea level (**Table 2**). The below 6,500 feet distribution was used for Water Districts 2, 64, and the lower portions of Water Districts 1, 3, 4, 5, 6, 7, 8, and 9. The above 6,500 feet distribution was used for the upper portions of Water Districts 1, 3, 4, 5, 6, 7, 8, 9 and Water Districts 23, 47, 48, 76, and 80. The resulting average monthly gross reservoir evaporation estimates are provided in **Table 3**.

Table 2
Average Monthly Gross Evaporation Distribution

Elevation (ft)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Below 6,500	3.0%	3.5%	5.5%	9.0%	12.0%	14.5%	15.0%	13.5%	10.0%	7.0%	4.0%	3.0%
Above 6,500	1.0%	3.0%	6.0%	9.0%	12.5%	15.5%	16.0%	13.0%	11.0%	7.5%	4.0%	1.5%

Table 3
Estimated Average Monthly Gross Reservoir Evaporation
(Inches)

Water District	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1-Upper	0.43	1.30	2.61	3.91	5.43	6.74	6.95	5.65	4.78	3.26	1.74	0.65	43.46
1-Lower	1.41	1.65	2.59	4.24	5.65	6.83	7.07	6.36	4.71	3.30	1.88	1.41	47.11
2	1.31	1.53	2.40	3.93	5.24	6.34	6.55	5.90	4.37	3.06	1.75	1.31	43.70
3-Upper	0.37	1.11	2.22	3.34	4.63	5.75	5.93	4.82	4.08	2.78	1.48	0.56	37.07
3-Lower	1.19	1.39	2.19	3.58	4.78	5.77	5.97	5.37	3.98	2.79	1.59	1.19	39.79
4-Upper	0.36	1.07	2.14	3.22	4.47	5.54	5.72	4.65	3.93	2.68	1.43	0.54	35.75
4-Lower	1.16	1.35	2.12	3.47	4.62	5.58	5.78	5.20	3.85	2.70	1.54	1.16	38.52
5-Upper	0.35	1.06	2.13	3.19	4.43	5.49	5.67	4.61	3.90	2.66	1.42	0.53	35.43
5-Lower	1.15	1.35	2.12	3.46	4.62	5.58	5.77	5.20	3.85	2.69	1.54	1.15	38.49
6-Upper	0.36	1.07	2.14	3.20	4.45	5.52	5.69	4.63	3.91	2.67	1.42	0.53	35.58
6-Lower	1.15	1.35	2.11	3.46	4.61	5.57	5.77	5.19	3.84	2.69	1.54	1.15	38.44
7-Upper	0.36	1.07	2.14	3.22	4.47	5.54	5.72	4.65	3.93	2.68	1.43	0.54	35.73
7-Lower	1.19	1.39	2.19	3.58	4.77	5.77	5.97	5.37	3.98	2.78	1.59	1.19	39.78
8-Upper	0.38	1.15	2.31	3.46	4.81	5.96	6.15	5.00	4.23	2.88	1.54	0.58	38.45
8-Lower	1.25	1.45	2.28	3.74	4.98	6.02	6.23	5.61	4.15	2.91	1.66	1.25	41.52
9-Upper	0.37	1.10	2.19	3.29	4.57	5.66	5.85	4.75	4.02	2.74	1.46	0.55	36.54
9-Lower	1.20	1.40	2.21	3.61	4.82	5.82	6.02	5.42	4.01	2.81	1.61	1.20	40.13
23	0.39	1.16	2.32	3.49	4.84	6.00	6.20	5.03	4.26	2.90	1.55	0.58	38.72
47	0.38	1.13	2.27	3.40	4.73	5.86	6.05	4.91	4.16	2.84	1.51	0.57	37.80
48	0.37	1.11	2.23	3.34	4.64	5.76	5.94	4.83	4.09	2.79	1.49	0.56	37.15
64	1.46	1.71	2.68	4.38	5.85	7.06	7.31	6.58	4.87	3.41	1.95	1.46	48.72
76	0.40	1.19	2.37	3.56	4.95	6.13	6.33	5.14	4.35	2.97	1.58	0.59	39.56
80	0.36	1.07	2.13	3.20	4.44	5.51	5.69	4.62	3.91	2.67	1.42	0.53	35.54

Step 4: Distribute annual precipitation to monthly

Monthly precipitation data for key climate stations were collected and filled under Task 53.2. Average annual precipitation (100% effective) estimates developed in Step 2 above were distributed monthly based on data from designated key climate stations. The key climate stations selected to represent each water district or portion of a water district are shown in **Table 4**. These representative key climate stations were selected based on existing reservoir locations. The resulting average monthly total precipitation estimates are provided in **Table 5**.

Table 4
Key Climate Stations Assignments for Net Reservoir Evaporation Estimates

Station ID	Station Name	Representative WD
0185	Allenspark 1 NW (combined)	5U
0263	Antero Reservoir	23
0454	Bailey	80
0848	Boulder	6L
0945	Briggsdale	1L
1401	Castle Rock	8L
1528	Cheesman	8U
2494	Eastonville 2 NNW	1U
2761	Estes Park 1 SSE (combined)	4U
2790	Evergreen (combined)	9U
3261	Georgetown	6U, 7U
3553	Greeley UNC (combined)	2, 3L
4762	Lakewood (combined)	7L, 9L
5116	Longmont 2 ESE	4L, 5L
6921	Red Feather Lakes (combined)	3U, 48, 76
7950	Sterling	64
8756	Walden	47

Table 5
Estimated Average Monthly Total Precipitation
(Inches)

Water District	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1-Upper	0.36	0.37	1.08	1.66	2.26	1.92	2.49	2.54	1.19	0.86	0.65	0.40	15.79
1-Lower	0.23	0.18	0.73	1.12	2.09	2.10	2.31	1.82	1.23	0.69	0.38	0.24	13.15
2	0.41	0.34	0.97	1.56	2.44	1.76	1.43	1.17	1.14	0.87	0.68	0.37	13.14
3-Upper	0.68	0.81	1.78	2.33	2.68	2.06	2.58	2.13	1.64	1.12	1.12	0.66	19.61
3-Lower	0.44	0.36	1.03	1.66	2.60	1.88	1.52	1.25	1.22	0.92	0.73	0.40	14.01
4-Upper	0.55	0.75	1.51	2.13	3.17	2.53	3.33	2.98	1.90	1.22	0.97	0.69	21.73
4-Lower	0.43	0.42	1.22	1.84	2.62	1.76	1.17	1.35	1.35	0.90	0.75	0.49	14.30
5-Upper	1.32	1.25	2.38	2.85	3.18	2.21	2.70	2.62	1.94	1.35	1.60	1.24	24.63
5-Lower	0.44	0.43	1.25	1.88	2.68	1.79	1.19	1.38	1.38	0.92	0.77	0.50	14.60
6-Upper	0.90	0.96	1.98	2.55	2.74	2.12	3.16	3.51	2.02	1.42	1.27	1.12	23.74
6-Lower	0.55	0.67	1.52	2.07	2.67	1.73	1.54	1.41	1.41	1.06	1.04	0.59	16.27
7-Upper	0.83	0.89	1.83	2.37	2.54	1.97	2.93	3.25	1.87	1.31	1.18	1.04	22.02
7-Lower	0.49	0.55	1.33	1.87	2.58	1.89	1.71	1.59	1.32	0.95	0.92	0.51	15.72
8-Upper	0.41	0.58	1.28	1.56	1.94	1.61	2.44	2.51	1.17	1.00	0.76	0.54	15.81
8-Lower	0.50	0.60	1.35	1.59	2.24	1.75	2.07	1.88	1.13	0.94	0.79	0.55	15.40
9-Upper	0.59	0.91	1.85	2.40	3.04	2.32	2.52	2.56	1.62	1.34	1.07	0.75	20.97
9-Lower	0.49	0.55	1.34	1.89	2.60	1.91	1.73	1.60	1.33	0.96	0.93	0.51	15.86
23	0.28	0.39	0.78	1.02	1.52	1.67	2.98	3.36	1.46	1.01	0.51	0.42	15.39
47	1.02	0.96	1.21	1.60	2.32	1.91	2.35	2.25	2.03	1.46	1.30	1.03	19.45
48	0.78	0.93	2.06	2.69	3.10	2.38	2.98	2.46	1.89	1.30	1.30	0.76	22.64
64	0.30	0.28	0.80	1.22	2.70	2.57	2.49	1.71	1.08	0.87	0.48	0.29	14.79
76	0.64	0.76	1.67	2.19	2.52	1.94	2.42	2.00	1.54	1.06	1.06	0.62	18.41
80	0.45	0.65	1.46	2.09	2.45	1.90	3.03	2.99	1.56	1.29	0.87	0.62	19.35

Step 5: Estimate average net monthly evaporation rates

Average monthly net reservoir evaporation was calculated as the difference between gross reservoir evaporation and total precipitation (**Table 6**). Total precipitation can exceed gross reservoir evaporation, resulting in a negative net reservoir evaporation (a net addition to the reservoir). When this occurs under water rights applications, the net evaporation is estimated to be zero (a credit is not given for negative net evaporation). However, because these estimates are being used in the SPDSS to represent physical conditions for modeling purposes, negative net evaporation values are used.

Table 6
Estimated Average Monthly Net Reservoir Evaporation
(Inches)

Water District	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1-Upper	0.07	0.93	1.52	2.25	3.17	4.81	4.46	3.11	3.59	2.40	1.09	0.26	27.67
1-Lower	1.18	1.47	1.86	3.12	3.56	4.73	4.75	4.54	3.48	2.61	1.50	1.17	33.96
2	0.90	1.19	1.44	2.37	2.81	4.57	5.12	4.73	3.23	2.19	1.07	0.94	30.55
3-Upper	-0.31	0.30	0.44	1.00	1.95	3.68	3.35	2.69	2.44	1.65	0.36	-0.10	17.46
3-Lower	0.75	1.04	1.16	1.92	2.18	3.89	4.44	4.12	2.76	1.86	0.87	0.79	25.78
4-Upper	-0.19	0.33	0.64	1.09	1.30	3.01	2.38	1.66	2.03	1.46	0.46	-0.15	14.02
4-Lower	0.73	0.93	0.90	1.62	2.00	3.83	4.61	3.85	2.50	1.80	0.79	0.66	24.22
5-Upper	-0.96	-0.18	-0.25	0.34	1.25	3.28	2.97	1.99	1.95	1.31	-0.18	-0.70	10.79
5-Lower	0.72	0.92	0.87	1.58	1.94	3.79	4.58	3.82	2.47	1.78	0.77	0.65	23.89
6-Upper	-0.54	0.11	0.16	0.65	1.71	3.39	2.54	1.12	1.89	1.25	0.16	-0.59	11.85
6-Lower	0.60	0.68	0.59	1.39	1.94	3.85	4.22	3.77	2.44	1.63	0.50	0.56	22.17
7-Upper	-0.48	0.18	0.31	0.85	1.92	3.57	2.79	1.39	2.06	1.37	0.25	-0.50	13.72
7-Lower	0.70	0.84	0.86	1.71	2.20	3.88	4.25	3.78	2.66	1.83	0.67	0.68	24.06
8-Upper	-0.02	0.57	1.03	1.90	2.87	4.35	3.71	2.49	3.06	1.88	0.78	0.03	22.63
8-Lower	0.75	0.86	0.93	2.14	2.75	4.28	4.15	3.73	3.02	1.96	0.87	0.69	26.13
9-Upper	-0.23	0.19	0.35	0.89	1.52	3.35	3.33	2.19	2.40	1.40	0.39	-0.20	15.57
9-Lower	0.71	0.85	0.86	1.72	2.21	3.91	4.29	3.82	2.68	1.85	0.68	0.69	24.27
23	0.11	0.77	1.55	2.46	3.32	4.33	3.22	1.67	2.80	1.90	1.04	0.16	23.33
47	-0.64	0.17	1.06	1.80	2.41	3.95	3.69	2.67	2.13	1.37	0.21	-0.47	18.35
48	-0.41	0.18	0.17	0.65	1.54	3.38	2.97	2.37	2.19	1.49	0.19	-0.20	14.51
64	1.16	1.43	1.88	3.17	3.14	4.50	4.82	4.87	3.79	2.54	1.47	1.17	33.93
76	-0.24	0.43	0.70	1.37	2.42	4.19	3.91	3.14	2.81	1.91	0.53	-0.02	21.15
80	-0.09	0.42	0.68	1.11	1.99	3.61	2.66	1.63	2.35	1.37	0.55	-0.09	16.19

Comments and Concerns

Recommended average monthly evaporation rates vary from the rates used by Denver Water and NCWCD in their surface water modeling efforts. A comparison between SPDSS recommended average monthly evaporation rates and Denver Water rates for the same regions show they vary between 1 percent and 35 percent. The largest variations are for upper reservoirs where Denver Water sets winter evaporation rates to zero, whereas our analysis shows that reservoirs in these areas should experience winter evaporation.