Development of GIS-based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming

Final Report

Project Duration: March 2010 to February 2012

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ABSTRACT

Accurate estimation of crop consumptive water use is a key component for making decisions in irrigational policy and allocations of water and administration of water rights. State water resources managers utilize crop consumptive water use data to monitor and guide farmers and make a sustainable future plan and decision. This project uses the weather station data in Wyoming and the surrounding states along with Parameter-elevation Regressions on Independent Slopes Model (PRISM) data to produce gridded historical and near real-time daily weather data that are archived in Wyoming State Engineer's Office data server. GIS-based ET calculation tools (an ArcInfo reference ET tool and an ESRI ArcGIS ET calculation tool) and a web-based analysis tool are developed to help water resources managers as well as local water users make operational decisions easier and more accurate than before. The ArcInfo reference ET tools use the daily weather data to calculate the daily reference ET at a spatial resolution of 0.01 x 0.01 degrees. The ArcGIS ET calculation tool, called Wyoming ET Calculator, can be installed on a Windows-based PC and provides a user interface to define parameters (area of interest, crop coefficients, reference ET method, effective precipitation ratios, and water stress factors) for the calculation of potential ET, consumptive irrigational requirement, and actual ET for the area of interest using spatially interpolated weather data.

1. INTRODUCTION

1.1 Overview

Accurate estimations of Evapotranspiration (ET) and Consumptive Irrigation Requirement (CIR) are essential for water resources planning and management. The Wyoming State Engineer's Office (SEO) determines monthly reference evapotranspiration (ET) with an NRCS Spreadsheet ET model (Snyder and Eching, 2003). The main purpose of this project is to replace the NRCS Spreadsheet model with a GIS-based ET calculator, Wyoming ET Calculator. This GIS-based approach uses daily weather data to calculate daily reference ET, CIR, and actual ET, and then aggregate CIR and actual ET into monthly. Among the many reference ET equations available, the ASCE Standardized Reference Evapotranspiration (ASCE, 2005) and the Hargreaves-Samani equations were selected to calculate daily reference ET. Furthermore, the FAO Blaney-Criddle equation was used to calculate monthly reference ET. Data needed for the equations (minimum and maximum temperatures, wind speed, and dew point temperature) were gathered from several sources, such as Natural Resources Conservation Service (NRCS) and the National Centers for Environmental Prediction (NCEP). High resolution (0.01 by 0.01 degree) gridded reference ET maps were produced by spatial interpolation of weather data for the state of Wyoming, including three major river basins in southern Wyoming (North Platte River, Green River, and Bear River basins). Wyoming ET Calculator, a GIS-based ET tool, was developed for

ESRI ArcGIS to calculate daily potential ET, CIR, and actual ET, using daily reference ET, crop coefficients, effective precipitation ratios, and water stress factors.

1.2 Project Objectives

The main objectives of this project are to:

- Provide an automatic script to produce spatially interpolated high-resolution (0.01 ° by 0.01 °) weather grid data from available daily weather station data using the inverse distance weighting method and bias correction for each weather variable
- Develop an ArcInfo tool for reference ET calculation to produce high-resolution reference ET maps for Wyoming using the ASCE Standardized, Hargreaves-Samani, and Blaney-Criddle equations
- Develop an ArcGIS ET calculation tool
- Develop a website to serve the data to the public

1.3 Definitions of terms

Several terms need to be defined in order to avoid confusion.

- *Potential Evapotranspiration (PET)*: The potential evapotranspiration is the maximum amount of water that would be used as evapotranspiration by crop if water supply is not limited.
- *Reference Evapotranspiration (RET)*: The potential evapotranspiration for the reference crop (either alfalfa or grass).
- *Actual Evapotranspiration (AET)*: Actual evapotranspiration from the field.
- *Effective Precipitation (P_e)*: The amount of precipitation that would be used for crop evapotranspiration. Some precipitation falling in the field could evaporate directly from the crop surface and excess precipitation would result in runoff.
- *Effective Precipitation Ratio (R_{eff})*: The fraction of precipitation that would be used for crop evapotranspiration ($R_{eff} = P_e / PRCP$), where PRCP is precipitation.
- *Consumptive Irrigation Requirement (CIR)*: The amount of water required to meet potential evapotranspiration in addition to the effective precipitation ($CIR = PET - P_e$)
- *Water stress factor (K_s)*: The fraction of water supply with respect to the consumptive irrigation requirement ($K_s = Actual\ Water\ Supply / CIR$).

1.4 Background

Evapotranspiration (ET) can be estimated from water balance, energy balance, combined energy and water balance, or measured from the field (Eddy Covariance tower or Lysimeter). Water balance and energy balance models are simpler in calculation but suffer from significant errors due to their insufficient physical descriptions of evapotranspiration processes.

Evapotranspiration is indeed a physical and biological process that is limited by both availability of energy and water as well as crop condition. Therefore, using only water or energy balance is not sufficient for reliable estimates of evapotranspiration. Field measurements can be most accurate at measurement scale, but it is not a feasible solution for measuring evapotranspiration over large area for a long period. The combined energy and water balance methods have been, therefore, widely used in estimating evapotranspiration.

The combined water and energy balance method includes FAO Blaney-Criddle (Brouwer and Heibloem, 1986), SCS TR-21 Modified Blaney-Criddle (Doorenbos and Pruitt ,1977), Hargreaves-Samani(Hargreaves and Samani, 1982), Penman (Penman, 1948), Penman-Monteith (Penman, 1953; Covey, 1959; Rijtema, 1965; and Monteith, 1965), ASCE Standardized Reference ET method (Allen et al., 2005b), and several remote sensing based methods. Satellite based methods, SEBAL (Bastiaanssen et al., 1998a; and Bastiaanssen et al., 1998b) and METRIC (Allen et al., 2005a), have drawn attentions from the community, as they can provide actual ET. However, this method requires high-quality weather data at a minimum of hourly scale and a reliable estimate of the roughness coefficients for crop types. In addition, it is necessary to have trained personnel to process imageries. Therefore, it is widely accepted procedure to use the combined water and energy balance method to estimate long-term consumptive water use in a large area. Among many methods, the Wyoming ET Calculator uses the ASCE Standardized ET, Blaney-Criddle, and Hargreaves-Samani method. The ASCE Standardized ET method is expected to provide most accurate estimates.

Several tools have been developed to make the calculation of ET easier and faster. These include NRCS Excel spreadsheet model (Snyder and Eching, 2003), Ref-ET model (Allen, 1999), the State of Colorado's Consumptive Use Model (StateCU, 2008), ArcE (España et al., 2011), and ArcET (Li et al., 2003).

Ref-ET model calculates RET using FAO and ASCE Standardized ET equations at a point where all required weather data are available. This model is also used in METRIC to calculate reference ET from the weather station. The main deficiency of this model is that it does not account for spatial variability of weather data.

The NRCS Excel Spreadsheet ET model (Snyder and Eching, 2003) uses long-term monthly average weather data at major weather stations, usually available at airports, to calculate monthly reference ET using the standardized Penman Monteith equation. These monthly values are then interpolated into daily reference ET using either linear or cubic functions. This model is therefore limited by the fact that it only uses point data from the nearest weather station to calculate reference ET, even for areas far away from the station, and uses monthly data to get daily data.

The StateCU estimates historical consumptive water use based on user inputs such as water supply condition (diversion), irrigated area, crop patterns, and climate data. It uses SCS

Blaney-Criddle method for monthly scale and the ASCE Standardized ET method for daily scale. Similar to NRCS Spreadsheet model, it also uses nearest weather station(s) to estimate weather data for the location of interest.

To overcome these temporal and spatial limitations in above models, a GIS-based approach can be used. GIS-based ET tools that have been developed for ArcGIS include ArcE (España et al., 2011) and ArcET (Li et al., 2003).

ArcE uses monthly temperature and precipitation from weather stations to calculate monthly PET using the Hargreaves equation. AET is then calculated using the Budyko model for the stations, which must be calibrated. No land use or land cover is taken into account. Similar to other non-GIS models, it only uses monthly point-scale data, and therefore, the limitations mentioned above are not addressed.

ArcET uses a database of meteorological data to interpolate weather data within ArcGIS and then calculate RET. The FAO 56 Penman-Monteith (grass RET), ASCE Standardized Penman-Monteith (short and tall RET), Hargreaves 1985, SCS modified Blaney-Criddle, and the Priestley-Taylor equations are available for reference ET calculation. A land use shape file (only polygon layer) and user-provided crop coefficients are used to get spatial grids of crop coefficients. The reference ET grids are multiplied by the crop coefficient grids to get the potential ET. The total crop PET within the user provided zones is summarized in an ET table. However, CIR and actual ET are not calculated. In addition, ArcET was developed in Visual Basic interface, which will not be supported any more by ESRI in the next version of ArcGIS.

In order to overcome these limitations in the pre-existing tools and facilitate easier and more accurate calculation of consumptive water use, we developed a GIS based ET calculator, Wyoming ET Calculator, for the State of Wyoming. The Wyoming ET calculator is a GIS extension that uses the spatially interpolated weather data from available weather stations. This project also produces same weather data for the future without additional cost, by running an automatic shell script developed for the state of Wyoming. This script collects data from several data servers and produce weather data required for ET calculation. The ArcInfo tool further calculates reference ET for the state of Wyoming. The Wyoming ET calculator was developed using C# and .NET, since ESRI will not support visual Basic interface from the next version of ArcGIS. All data and tools are stored at the SEO data server, which will provide them to the public.

2. METHODS AND DATA

The study area includes the three major basins in southern Wyoming: the North Platte River Basin, the Green River Basin, and the Bear River Basin. These basins, along with the digital elevation model (DEM), are shown in Figure 1. The 90 meter DEM was obtained from Shuttle Radar Topography Mission (SRTM) data and was upscaled to a resolution of 0.01° by 0.01° (approximately 1 km by 1 km), which is the resolution used for all weather data and

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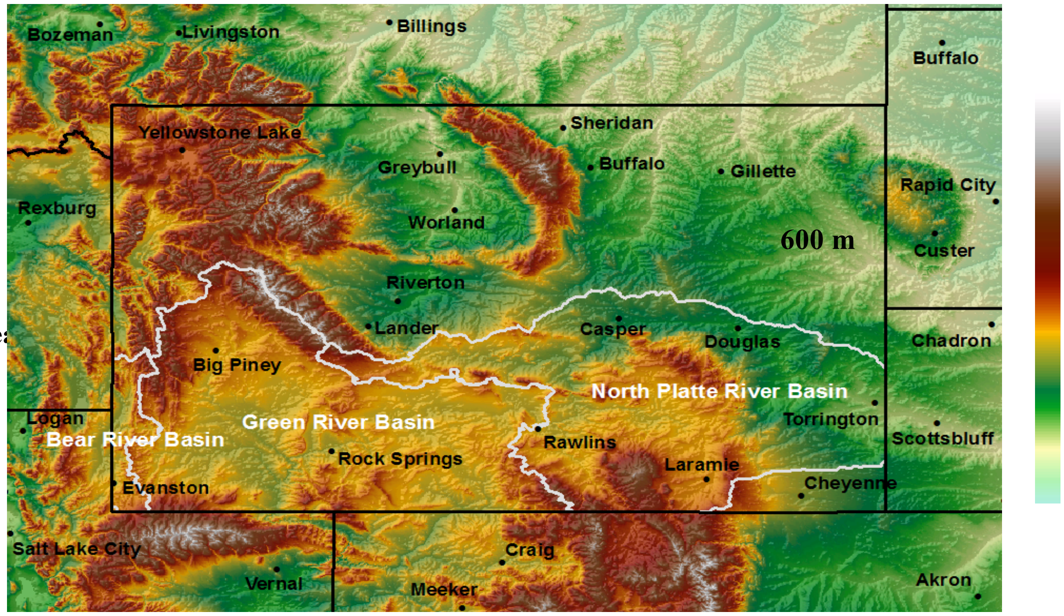
reference ET maps. Although most irrigated are located in the three major river basins, we produced high resolution weather data for the State of Wyoming for the other future uses.



ıre 1: Project are

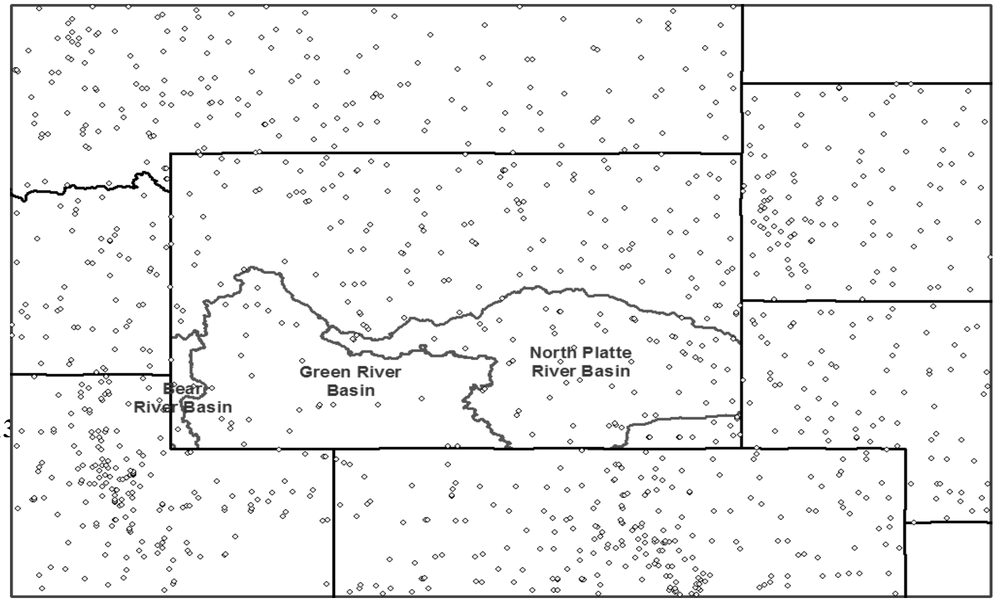
2.1 Weather Data Interpolation

The data needed for the ASCE standardized reference ET equation includes maximum and minimum temperature, wind speed, and dew point temperature at a minimum. These weather data were obtained from various sources in a daily timescale from 1960 to 2010 (a total of 18,628 days). Daily precipitation was also acquired to calculate consumptive irrigation requirement (CIR).

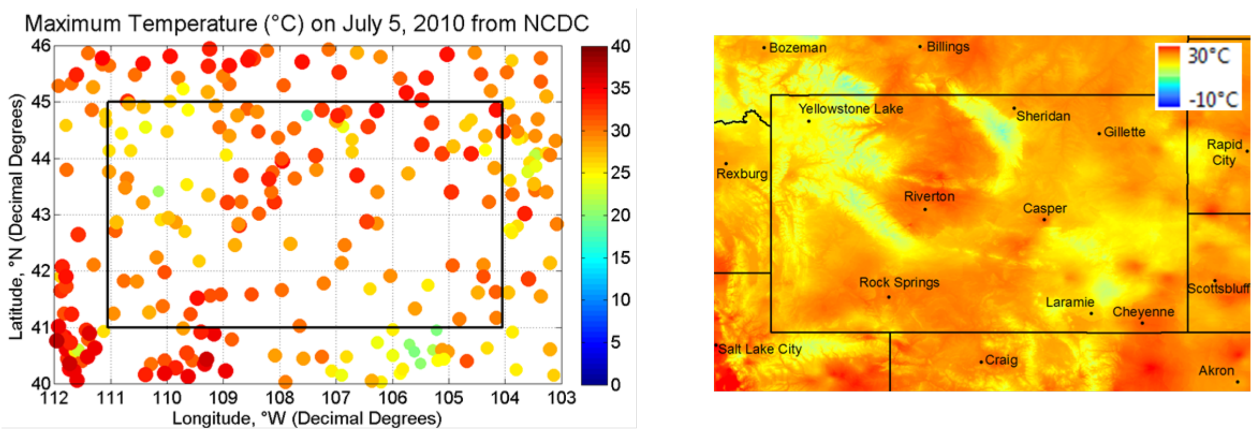
2.1.1 Maximum and Minimum Temperature

Maximum and minimum temperature (TMAX and TMIN, respectively) data were obtained from the National Climatic Data Center (NCDC) from January 1960 to December 2010. To get a better interpolation at the boundary of the state of Wyoming, weather data were not limited to Wyoming. Figure 2 shows the 1,135 weather stations in Wyoming and in parts of Colorado, Utah, Idaho, Montana, South Dakota, and Nebraska that were used for the project.

For temperature, inverse distance weighted (IDW) was used to interpolate data into a 0.01° (1 km by 1 km) grid (the same grid as the DEM), while lapsing into it according to elevation using dry adiabatic lapse rate. Examples of this interpolation are shown in Figure 3 and Figure 4.

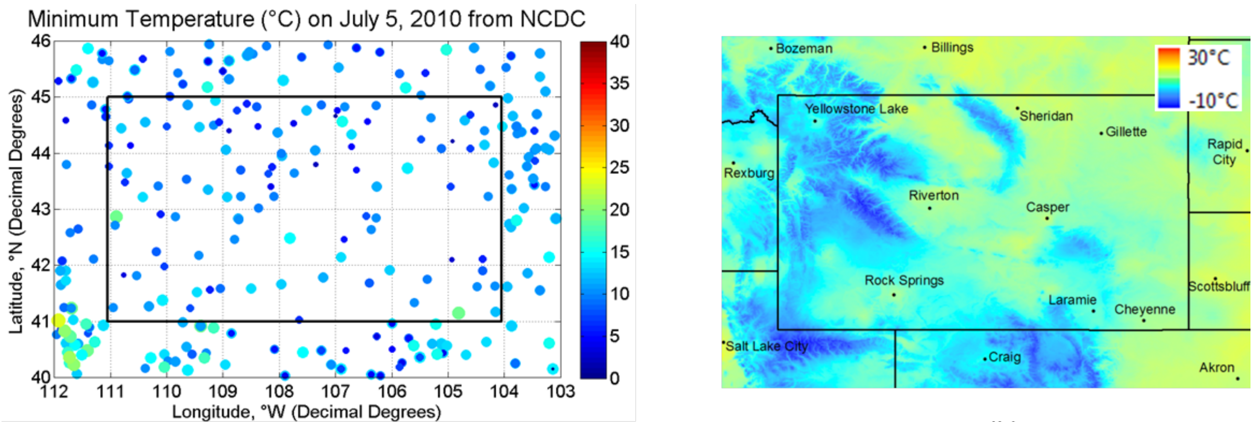


ıre 2: Location of 1,13



(a) (b)

Figure 3: An example of spatial interpolation of maximum temperature (TMAX) for July 5, 2010.



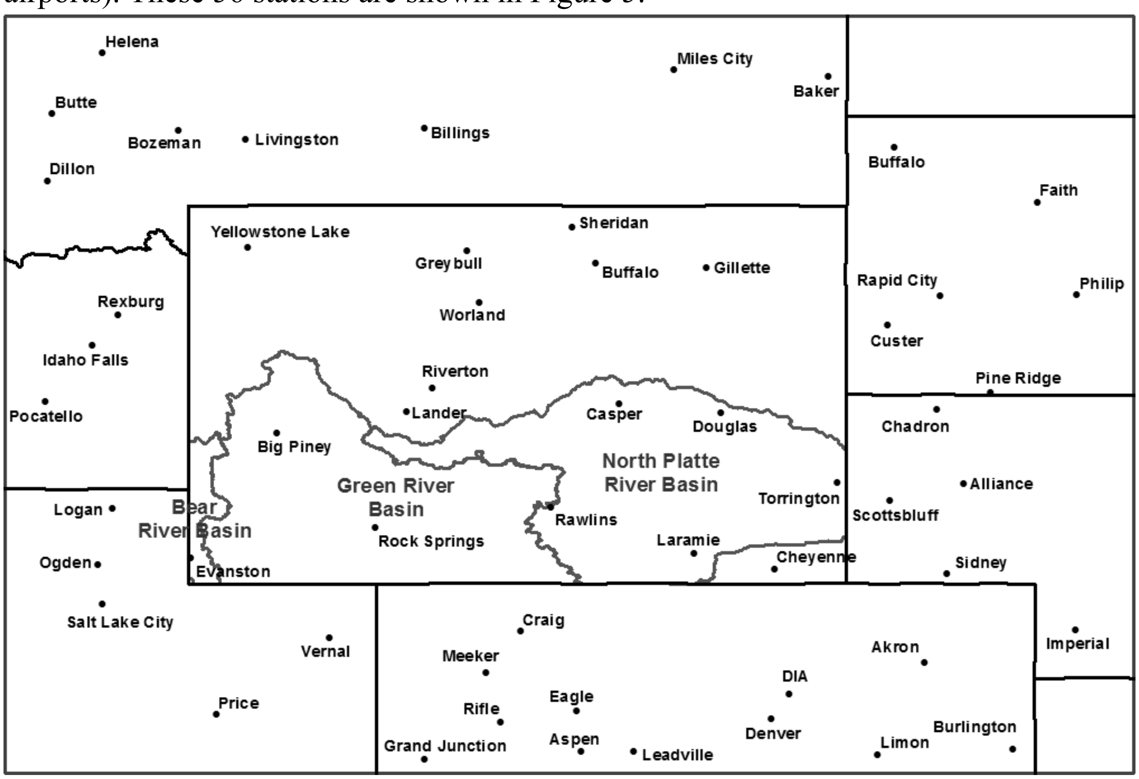
(a) (b)

Figure 4: An example of spatial interpolation of minimum temperature (TMIN) for July 5, 2010.

ıre 5: Locations of 56 WBAN stations that provide dew point temperature.

2.1.2 Dew Point Temperature

Compared to minimum and maximum temperature data, daily dew point temperature data is very scarce. Daily dew point temperature data were downloaded from Quality Controlled Local Climatological Data (QCLCD) from July 1996 to December 2010. The QCLCD only has records after July 1996 for Weather-Bureau-Army-Navy (WBAN) stations (mostly at the airports). These 56 stations are shown in Figure 5.



The daily dew point temperatures (TDEW) were subtracted from daily TMIN to get a daily TDEW adjustment at 56 stations, as shown in Figure 6.

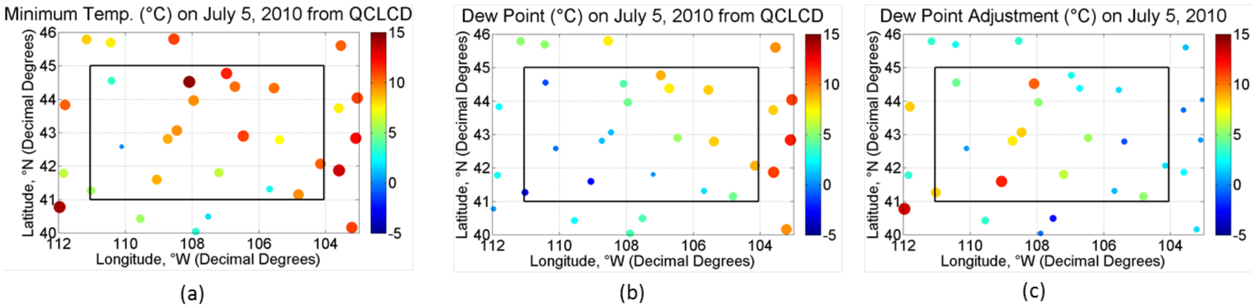


Figure 6: Bias adjustment for Dew point temperature. (a) TMIN, (b) TDEW, (c) daily TDEW adjustment (TMIN – TDEW)

The monthly average dew point adjustment was then calculated for each station, resulting in 12 monthly dew point adjustments for each station. These monthly point values were then interpolated using IDW to get monthly grids of dew point adjustment, as seen in Figure 7.

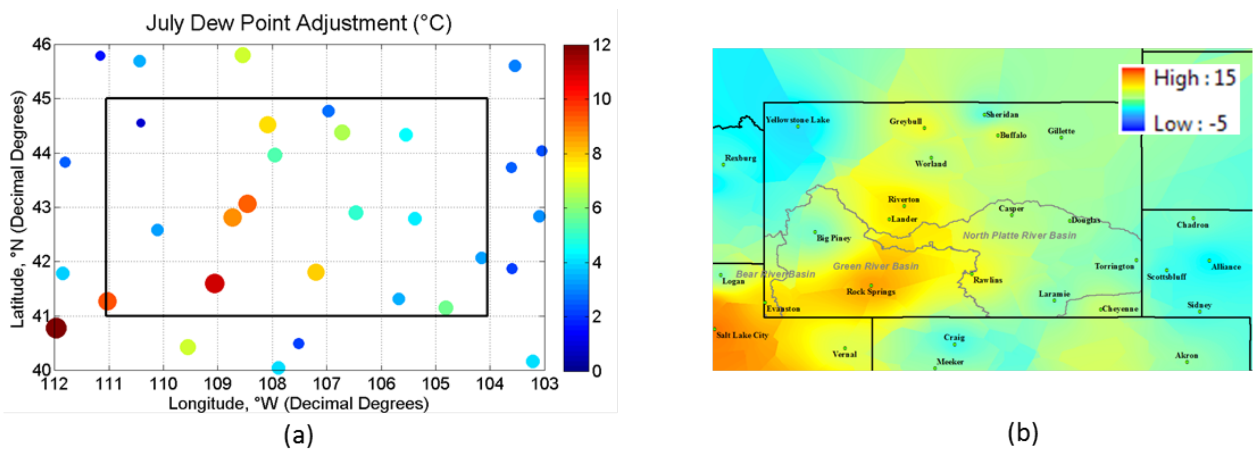


Figure 7: Spatial interpolation of dew point temperature adjustment: (a) monthly point dew point adjustment and (b) spatially interpolated monthly dew point adjustment.

The actual dew point grids were calculated by subtracting the appropriate monthly dew point adjustment grid from the daily TMIN grids, as shown in Figure 8.

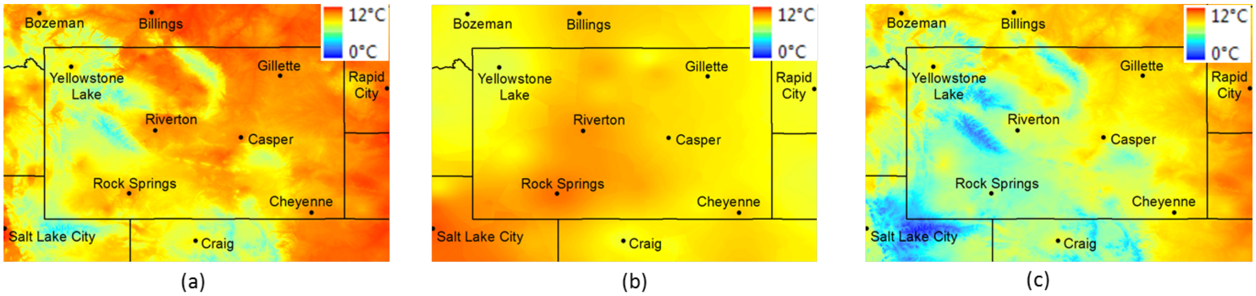


Figure 8: Daily Dew point temperature (c) is calculated by subtracting monthly bias of the dew point temperature (b) from spatially interpolated daily dew point temperature (a).

2.1.3 Wind Speed

Wind speed Reanalysis I and Reanalysis II data were obtained from National Centers for Environmental Prediction (NCEP). Since these two data sets have a spatial resolution of 2°, it was necessary to downscale them into 0.01°, as shown in Figure 9.

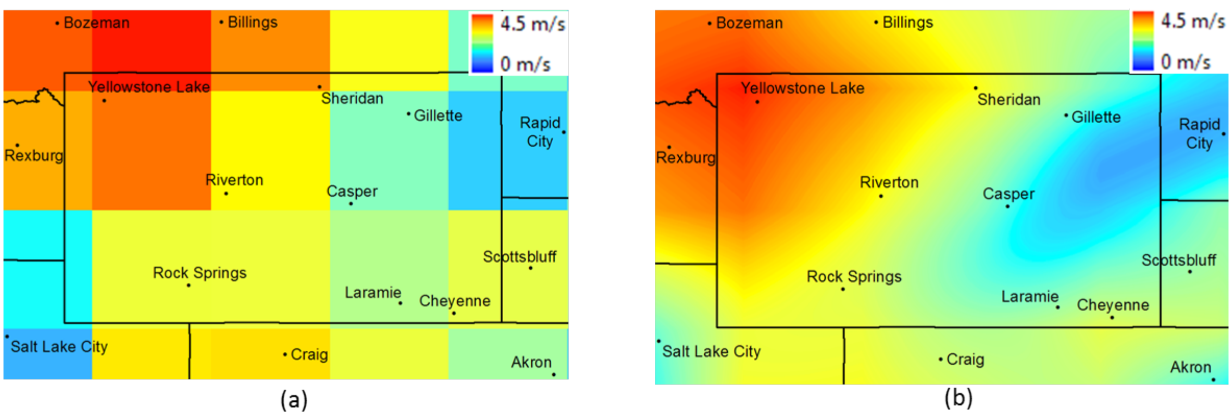


Figure 9: Downscaling of NCEP wind speed. (a) 2 degree NCEP wind speed and (b) Spatially interpolated NCEP wind speed in 0.01 degree resolution.

Reanalysis I and II were compared, and it was found that both have a similar pattern, but reanalysis II generally has a higher magnitude. To help determine which data set to use, measured wind speed data were downloaded from NCDC (from January 1984 to June 1996) and from QCLCD (from July 1996 to December 2010) for the same 56 stations that had dew point data. There is no measured wind speed data before 1984. When the measured wind speeds were compared to both reanalysis sets, it was found that the measured wind speeds rarely matched the NCEP values. Therefore, to get a more accurate wind speed grid, it was decided that bias would be calculated and interpolated. Since Reanalysis I data go back to 1948 and Reanalysis II data start in 1979, Reanalysis I was chosen for the bias calculation, as shown in Figure 10.

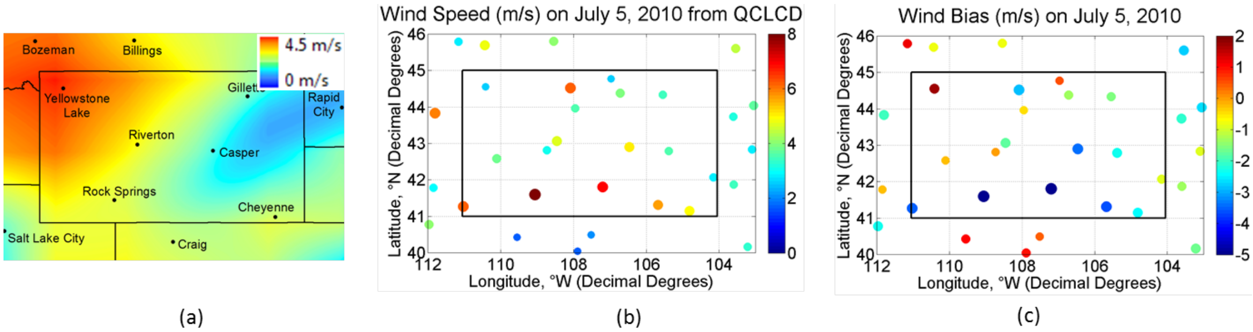


Figure 10: Wind bias calculation: (a) NCEP wind speed – (b) observed wind speed at stations = (c) wind speed bias at stations.

The daily bias point values were then interpolated using IDW to get daily bias grids, as shown in Figure 11.

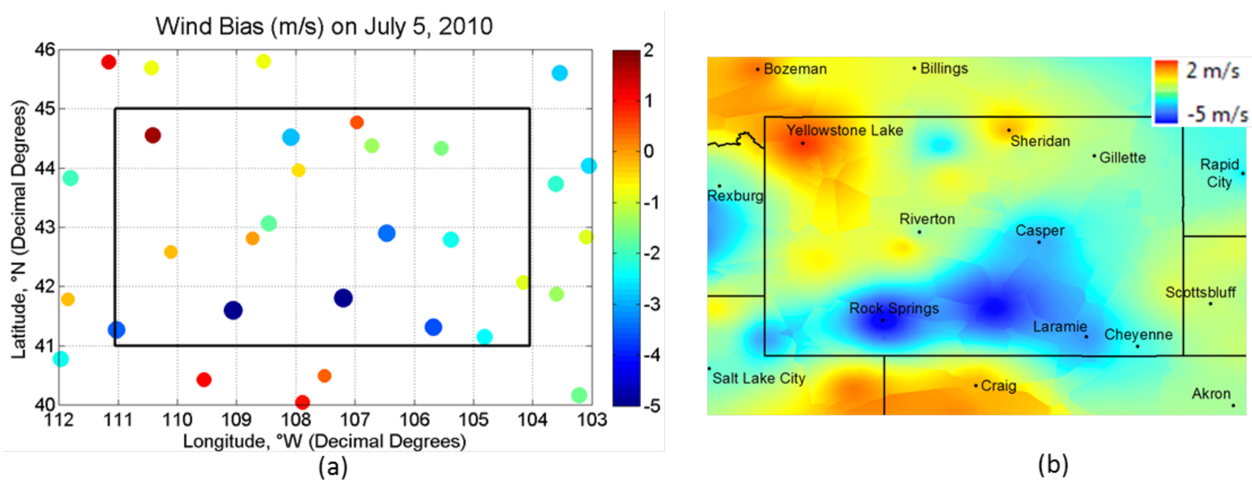


Figure 11: spatial wind bias (b) interpolated from point wind bias (a).

The final daily wind speed grids for 1984 to 2010 were calculated by subtracting the daily bias grids from the daily NCEP grids, as seen in Figure 12. Since there are no measured wind speeds before 1984, daily bias cannot be calculated. Instead, average monthly wind bias was calculated by averaging all of the daily bias grids for each month to get 12 monthly bias grids. The final wind speed grids for 1960 to 1983 were calculated by subtracting the appropriate monthly bias grids from each daily NCEP grid. All wind speeds are at a height of 10 meters. Using this procedure, some of the final wind speed grids had small negative values. Any negative wind speeds were replaced with 0.

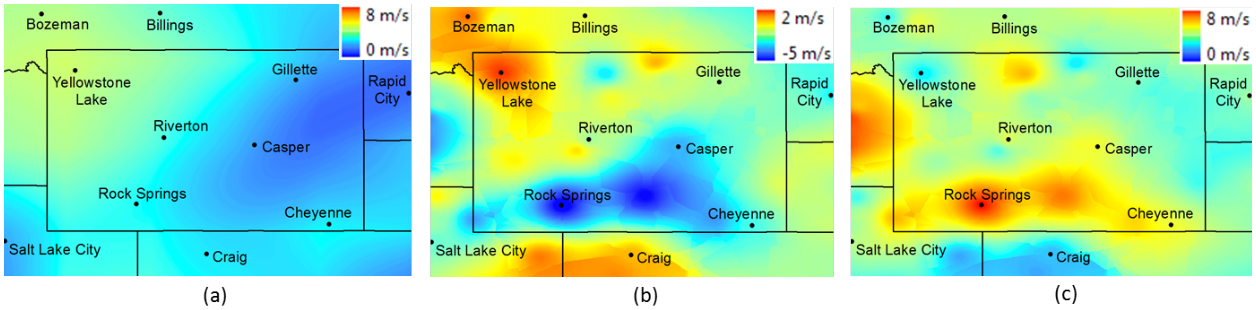


Figure 12: Final wind speed calculation: (a) NCEP - (b) wind bias = (c) final wind speed.

2.1.4 Precipitation

Precipitation (PRCP) data were downloaded from NCDC for the same 1,135 weather stations that were used for TMAX and TMIN. PRCP was interpolated the same way TMAX and TMIN were from the weather stations to a grid, except PRCP was not lapsed by elevation. An example of this interpolation is shown in Figure 13.

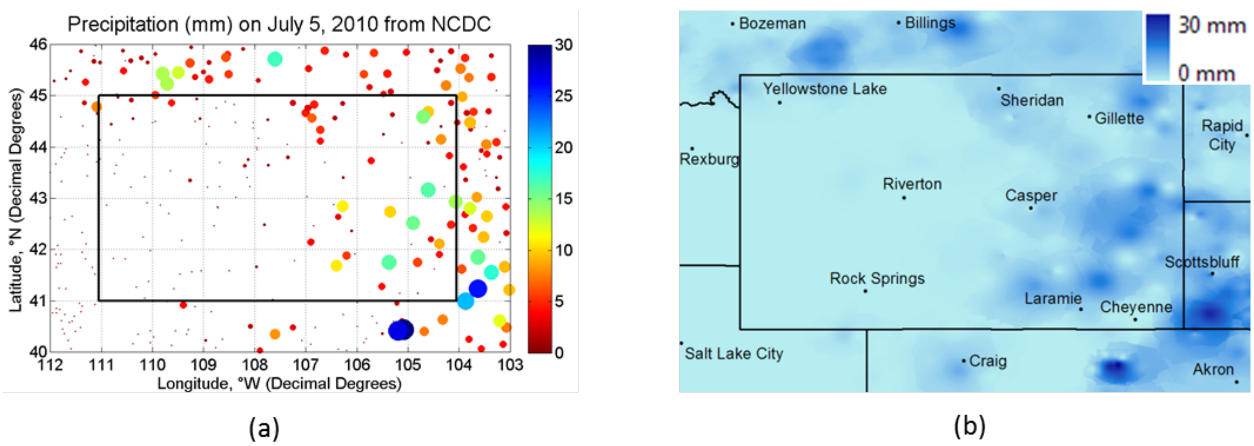


Figure 13: An example of spatial interpolation of Precipitation for July 5, 2010. (a) Observed daily precipitation at weather stations and (b) spatially interpolated precipitation.

To account for elevation, the interpolated PRCP was adjusted using monthly total average PRCP and monthly PRISM data. The monthly total average was calculated by adding up the PRCP on every day for a particular month from 1960 to 2010 and dividing it by the number of months (51). Monthly PRISM data was obtained from the PRISM Climate Group. The rescaling factor was calculated by dividing the PRISM data by the monthly total average, as shown in Figure 14.

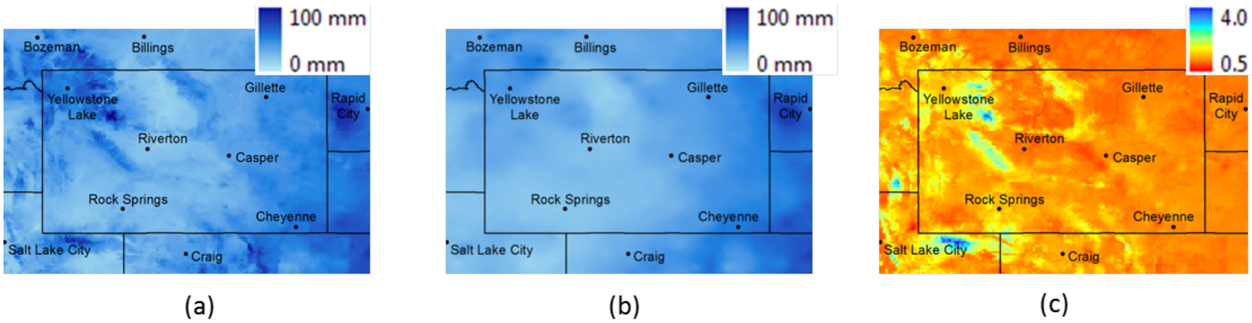


Figure 14: Precipitation rescaling factor calculation for July. Monthly Rescaling Factor (a) = Monthly PRISM (b) / Monthly Total Average (c).

The final PRCP was then calculated by multiplying the interpolated PRCP and the rescaling factor, as shown in Figure 15.

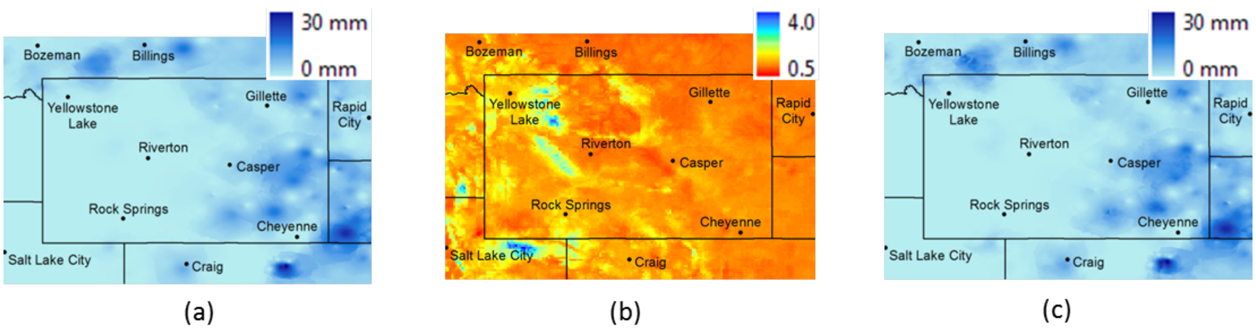


Figure 15: Final precipitation for July 5, 2010 (Interpolated PRCP x Monthly Rescaling Factor = Final PRCP).

2.2 Reference ET

Among the many reference ET equations available, the ASCE Standardized, Hargreaves-Samani, and the FAO Blaney-Criddle equations were selected for the project. Arc Macro Language (AML) scripts were developed for each equation to calculate the reference ET. For the ASCE Standardized and the Hargreaves-Samani equations, the reference ET is daily from 1960 to 2010. For the Blaney-Criddle equation, the reference ET is monthly from 1960 to 2010 because using the Blaney-Criddle for daily timescales is not recommended by ASCE (2005). Both short (grass) reference ET and tall (alfalfa) reference ET were calculated for this project.

2.2.1 ASCE Standardized

The ASCE Standardized reference ET equation is as follows:

$$ET_{ref} = \frac{0.048 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{C_n}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + C_d \cdot u_2)}$$

where

ET_{ref} = daily standardized reference ET
Δ = slope of saturation vapor pressure-temperature curve
R_n = net radiation
G = soil heat flux density
γ = psychrometric constant
C_n = numerator constant (900 for short reference, 1600 for tall reference)
T = mean temperature
u_2 = wind speed at 2 m height
e_s = saturation vapor pressure
e_a = actual vapor pressure
C_d = denominator constant (0.34 for short reference, 0.38 for tall reference)

Within the net radiation calculation, actual incoming solar radiation is required. However, solar radiation measurements were not available. Therefore, incoming radiation was estimated using the Hargreaves-Samani style of radiation prediction:

$$R_s = k_{RS} * \sqrt{T_{max} - T_{min}} * R_a$$

where

R_s = incoming solar radiation
k_{RS} = adjustment coefficient (0.16 for inland locations)
T_{max} = maximum temperature
T_{min} = minimum temperature
R_a = extraterrestrial radiation

An example of an ASCE Standardized reference ET map is shown in Figure 16.

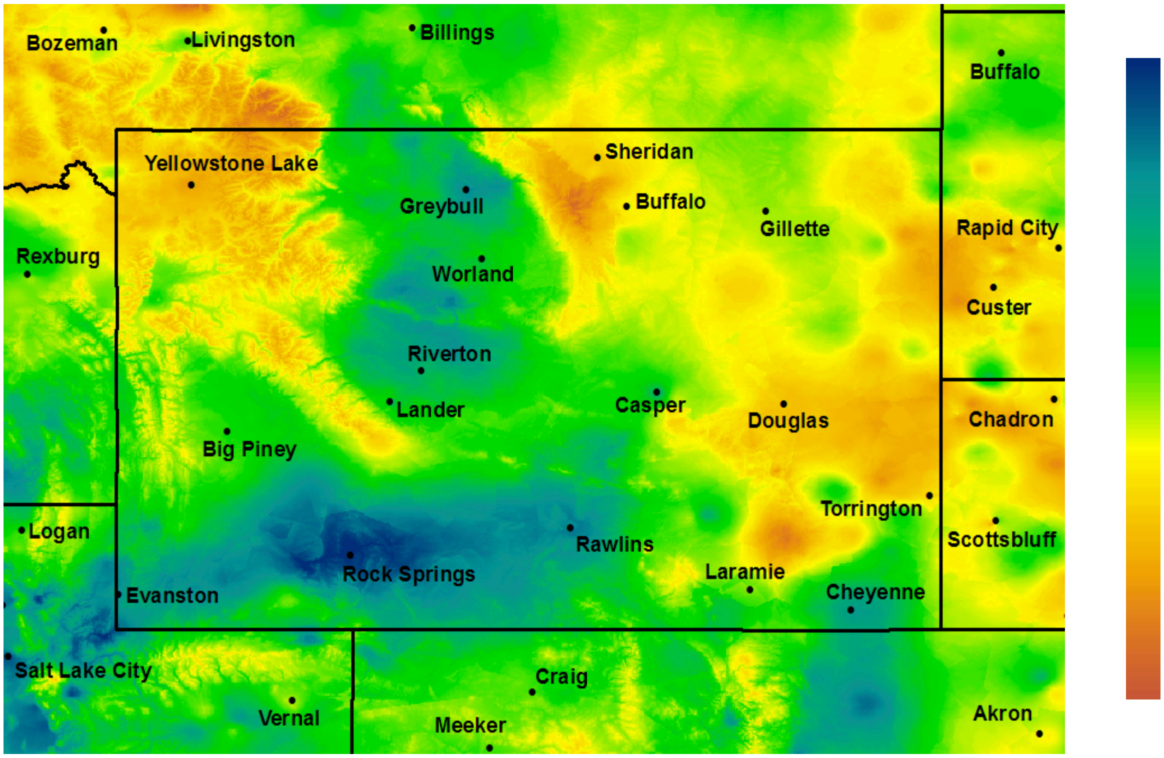


Figure 16: ASCE standardized grass reference ET (mm) for July 5, 2010.

2.2.2 Hargreaves-Samani

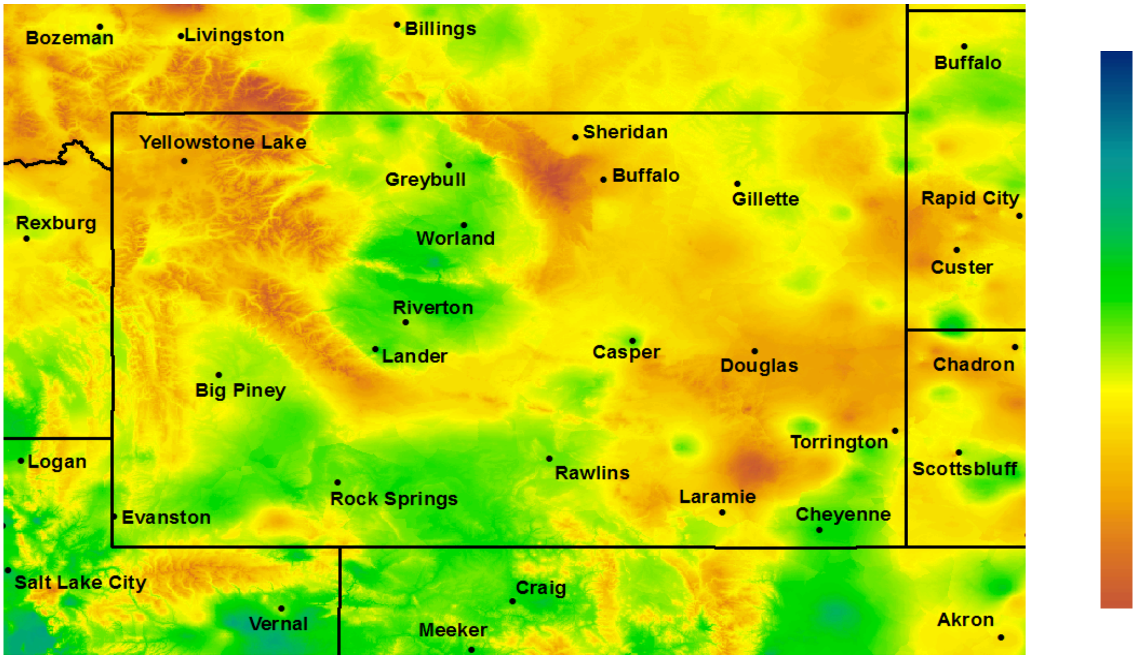
The Hargreaves-Samani reference ET equation is as follows:

$$\mathrm{RET} = \frac{0.0023 \cdot \mathrm{R_a} \cdot \sqrt{\mathrm{T_{max}} - \mathrm{T_{min}}} \cdot (\mathrm{T_{mean}} + 17.8)}{2.45}$$

where

RET = daily standardized reference ET
R_a = extraterrestrial radiation
T_{max} = maximum daily temperature
T_{min} = minimum daily temperature
T_{mean} = mean daily temperature

An example of a Hargreaves-Samani reference ET map is shown in Figure 17.



2.2.3 FAO Blaney-Criddle

The FAO Blaney-Criddle reference ET equation is as follows:

$$\mathrm{RET} = \mathrm{p} \cdot (0.46 \cdot \mathrm{T_{mean}} + 8)$$

where

RET = monthly standardized reference ET
p = mean daily percentage of annual daytime hours
T_{mean} = mean monthly temperature

The value of p depends on the latitude and month, as shown in Table 1. The values of p were interpolated for each degree. An example of a FAO Blaney-Criddle grass reference ET map is shown in Figure 18.

Table 1: Mean daily percentage of annual daytime hours for different latitudes.

Latitude (Deg. North)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
50	0.19	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.20	0.18
45	0.20	0.23	0.27	0.30	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.20
40	0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
35	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.25	0.23	0.22

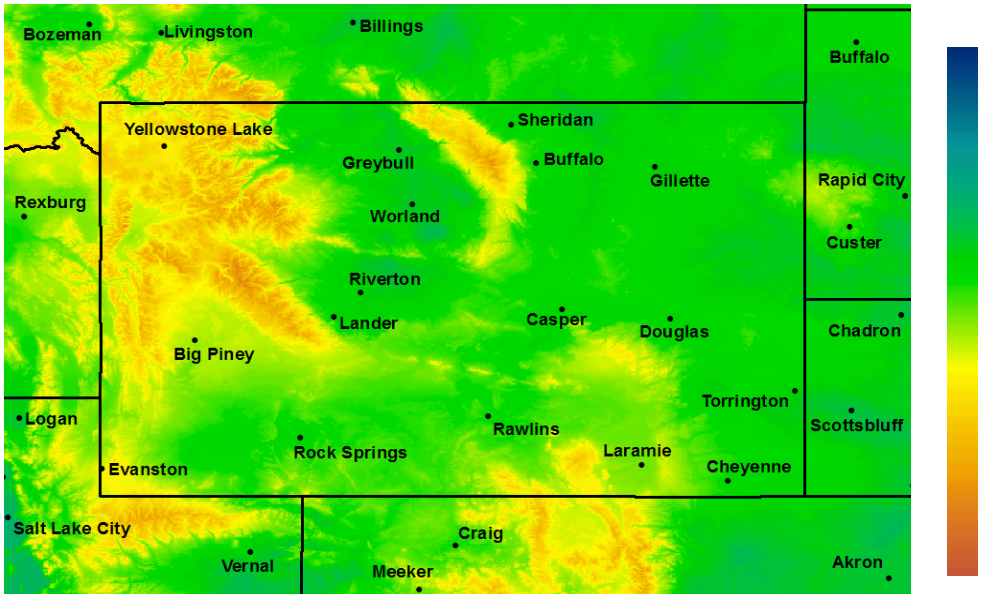


Figure 18: FAO Blaney-Criddle grass reference ET (mm) for July 2010.

2.3 Crop Coefficients and Land Use

2.3.1 Group Map

Pochop et al. (1992) classified 67 stations in Wyoming into 5 groups, as shown in Figure 19. These groups are based on elevation and growing season length. In order to obtain default growing season for each crop in Wyoming, the group numbers at stations were interpolated using the Thiessen polygon method within each basin for this project. The resulting Thiessen polygons are shown in Figure 20, and the group map is shown in Figure 21.

Group #1 4/1-10/15		Group #2 4/15-10/15	Group #3 4/15-9/30	Group #4 4/15-9/15	Group #5 5/1-9/15
Albin	Lusk	Double 4 Rch	Centennial	Afton	Big Piney
Arvada	Midwest	Ft Washakie	Encampment	Alta	L Yellowston
Basin	Morrisey	Green River	Evanston	Bedford	Moran
BoysenDam	Newcastle	Laramie	MedicineBow	Border	Pinedale
Buffalo	Pathfinder	Moorcroft	Rawlins	Dubois	South Pass
Casper	Pine Bluffs	Muddy Gap	Saratoga	Farson	
Cheyenne	Powell	Riverton	Seminoe Dam	Jackson	
Chugwater	Redbird	Rock Springs	Wamsutter	Kemmerer	
Cody	Sheridan	Sundance		Sage	
Douglas	Ten Sleep	Sunshine		Tower Falls	
Gillette	Thermopolis				
Glenrock	Torrington				
Kaycee	Upton				
LaGrange	Weston				
Midwest	Whalen Dam				
Lander	Wheatland				
Lovell	Worland				

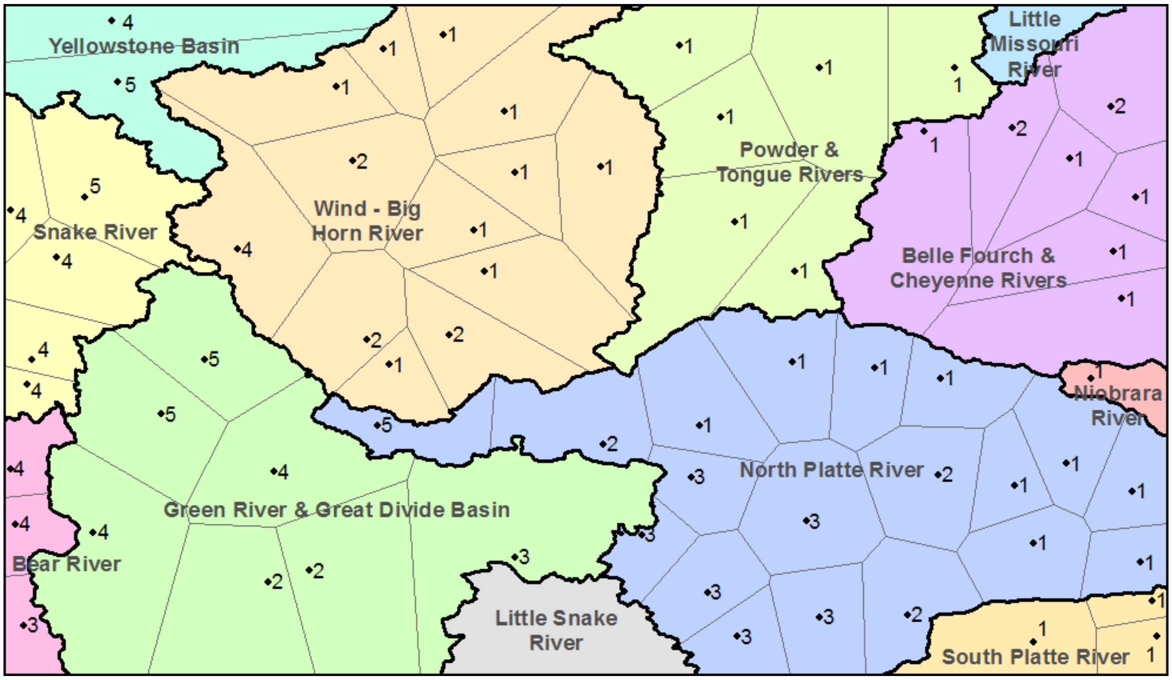


Figure 20: Thiessen polygons of group numbers.

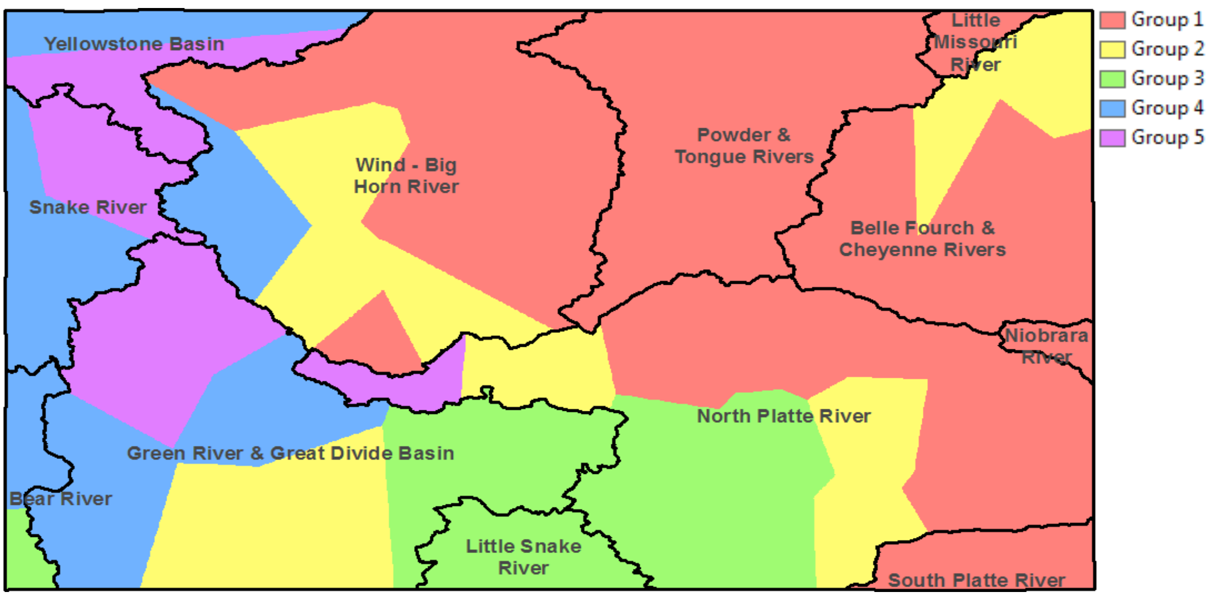


Figure 21: Group map for Wyoming.

2.3.2 Land Use Map

The 1992 National Land Cover Data (NLCD) map, seen in Figure 22, was chosen as the default crop type map. However, the users can use their own crop type map, if they desire.

Figure 22: National Land Cover Data (NLCD) map for Wyoming.

2.3.3 Crop Coefficients

A database of default crop coefficients (K_c) to use in the ArcGIS ET calculation tool was developed. The database contains both actual crops, such as corn and beans, and the land types from the NLCD map, such as evergreen forest and scrublands. For actual crops, K_c values are obtained from Pochop et al. (1992). For many of Pochop's crops, there are different K_c values for each group. Therefore, the entire database is split into 5 groups. Some of the K_c values for crops also come from FAO's Water Development and Management Unit. This database also contains growing season dates.

The K_c values for the NLCD land types were much harder to obtain. The values for July are based on a METRIC ET map of July 2009. The values for the other months are found by depreciating the July value a reasonable amount. For these land types, we recommend the user employ their own K_c values. A small portion of default K_c database is shown in Figure 23.

GROUP	PROGCROPID	CROP_NAME	PROGLANDID	GS_S_DATE	GS_E_DATE	KC_JAN	KC_FEB	KC_MAR	KC_APR	KC_MAY	KC_JUN	KC_JUL	KC_
1	0	Void	100	NONE	NONE								
1	1	Grass	101	LOCATION	LOCATION				0.87	1.03	1.04	1.03	0.
1	2	Alfalfa/Grass Mix	102	LOCATION	LOCATION				0.90	1.06	1.07	1.06	0.
1	3	Alfalfa	103	LOCATION	LOCATION				0.92	1.08	1.09	1.08	0.
1	4	Small Grains	104	LOCATION	LOCATION			0.40	0.55	0.80	1.00	1.15	0.
1	5	Corn/Grain Sorghum	105	5/15	9/20					0.48	0.60	1.00	1.
1	6	Dry Beans	106	6/1	9/15						0.44	1.04	0.
1	7	Sugar Beets	107	4/24	10/15				0.43	0.48	0.82	1.10	1.
1	8	Sterile Sorghum/Sudan/Sudex/etc.	108	LOCATION	LOCATION			0.40	0.55	0.80	1.00	1.15	0.
1	9	Potatoes	109	5/20	10/1					0.45	0.61	1.06	1.
1	10	Grapes	110	5/1	9/15					0.48	0.70	0.83	0.
1	11	Open Water	111	NONE	NONE	0.60	0.60	0.62	0.62	0.62	0.65	0.65	0.
1	12	Perennial Ice/Snow	112	NONE	NONE	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.
1	21	Low Intensity Residential	121	NONE	NONE	0.25	0.25	0.30	0.45	0.70	0.75	0.80	0.
1	22	High Intensity Residential	122	NONE	NONE	0.22	0.22	0.27	0.40	0.65	0.70	0.75	0.
1	23	Commercial/Industrial/Transportation	123	NONE	NONE	0.20	0.20	0.22	0.30	0.58	0.65	0.65	0.
1	31	Bare Ground/Rock/Sand/Clay	131	NONE	NONE	0.18	0.18	0.20	0.22	0.22	0.25	0.25	0.
1	32	Quarries/Strip Mines/Gravel Pits	132	NONE	NONE	0.18	0.18	0.20	0.25	0.25	0.30	0.30	0.
1	33	Transitional	133	NONE	NONE	0.35	0.35	0.45	0.55	0.65	0.70	0.80	0.
1	41	Forest (Deciduous)	141	NONE	NONE	0.30	0.30	0.40	0.70	0.90	1.00	1.12	1.
1	42	Forest (Evergreen)	142	NONE	NONE	0.70	0.70	0.80	0.85	0.95	1.00	1.12	1.
1	43	Forest (Mixed)	143	NONE	NONE	0.50	0.50	0.60	0.78	0.92	1.00	1.12	1.

Figure 23: Default Kc database table.

3. TOOLS DEVELOPED

The tools developed for this project include a GIS calculator and a website.

3.1 ArcInfo reference ET script

ArcInfo reference model for each equation was written in ArcInfo macro language (AML). The scripts calculate both short and tall reference ET.

3.2 Wyoming ET Calculator

The GIS tool developed for this project, shown in Figure 24, is Wyoming ET Calculator. It is an add-in to ESRI ArcMap and was developed in .NET and C# using Microsoft Visual Studio. The inputs include the gridded reference ET and precipitation maps described above, an area of interest, a timeframe, crop coefficients, effective precipitation ratios, and water stress factors. The main outputs include daily potential ET, CIR, and actual ET. Monthly total and growing season total CIR and ET can also be calculated. See Wyoming ET Calculator's user manual for more information about the interface.

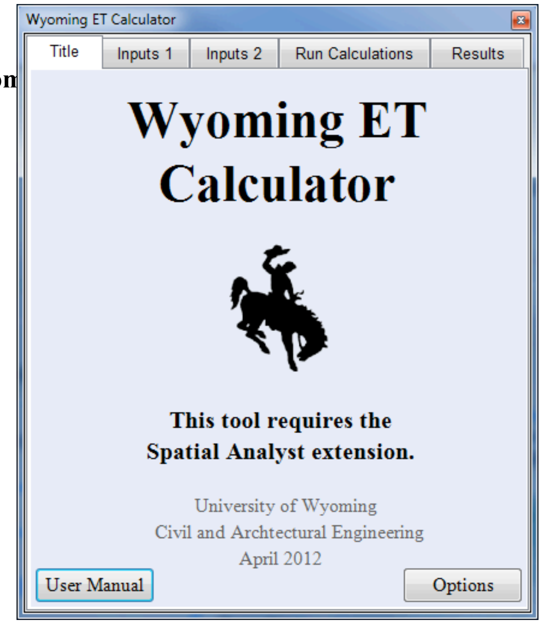


Figure 24: Wyon

3.2.1 Model Description

The model preforms several calculations on a cell-by-cell basis. These calculations include potential ET (also called crop ET), effective precipitation, CIR, and actual ET (also called consumptive use). Potential ET is the amount of ET that is possible with ample water (the ET demand due to the environment and land type). The calculation is:

$$\mathrm{PET} = \mathrm{K_c} \cdot \mathrm{RET}$$

where

PET = potential ET
K_c = monthly crop coefficient
RET = reference ET

Because not all precipitation that falls will be available to meet ET demand (for example, precipitation can become runoff or infiltrate into the ground), the effective precipitation is needed. The calculation is:

$$P_{eff} = PRCP \cdot R_{eff}$$

where

P_{eff} = effective precipitation
PRCP = precipitation
R_{eff} = effective precipitation ratio

CIR is the amount of water a crop needs to meet the ET demand. The calculation is:

$$CIR = PET - P_{eff}$$

where

CIR = consumptive irrigation requirement
PET = potential ET
P_{eff} = effective precipitation

If effective precipitation is greater than potential ET (meaning CIR is negative), CIR is set to zero. Actual ET includes a factor to account for water stress. The calculation is:

$$AET = P_{eff} + CIR \cdot K_s$$

where

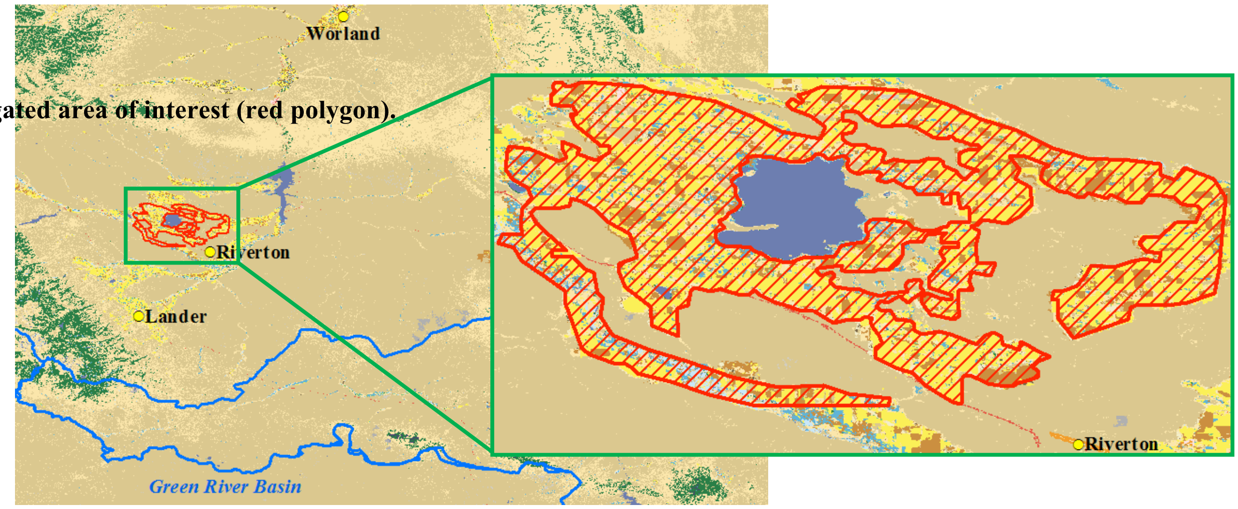
AET = actual ET
P_{eff} = effective precipitation
CIR = consumptive irrigation requirement
K_s = water stress factor

3.3 Website

A website is currently hosted at the University of Wyoming, but will be transferred to the State Engineers' Office. Total of 650 GB of weather data are available to the public, but data download is limited to 2 GB at a time. Users can download monthly data through the ftp server or define a smaller area to subset the data for the area of interest. The website provides spatially interpolated weather data, reference ET, Wyoming ET calculator, and user manual with an example.

4. COMPARISON TO METRIC ET

To evaluate Wyoming ET Calculator, total monthly AET over an irrigated area was compared to total monthly ET found using METRIC for June through September 2009. The area is irrigated lands surrounding the Ocean Lake near Riverton, WY, as shown in Figure 25.



e 25: Irrigated area of interest (red polygon).

To calculate AET with Wyoming ET Calculator, the model processed daily RET (assuming the entire NLCD crop areas were alfalfa, an effective precipitation ratio of 0.90, and a water stress factor of 1) to get daily AET. This daily AET was then summed to get the monthly AET.

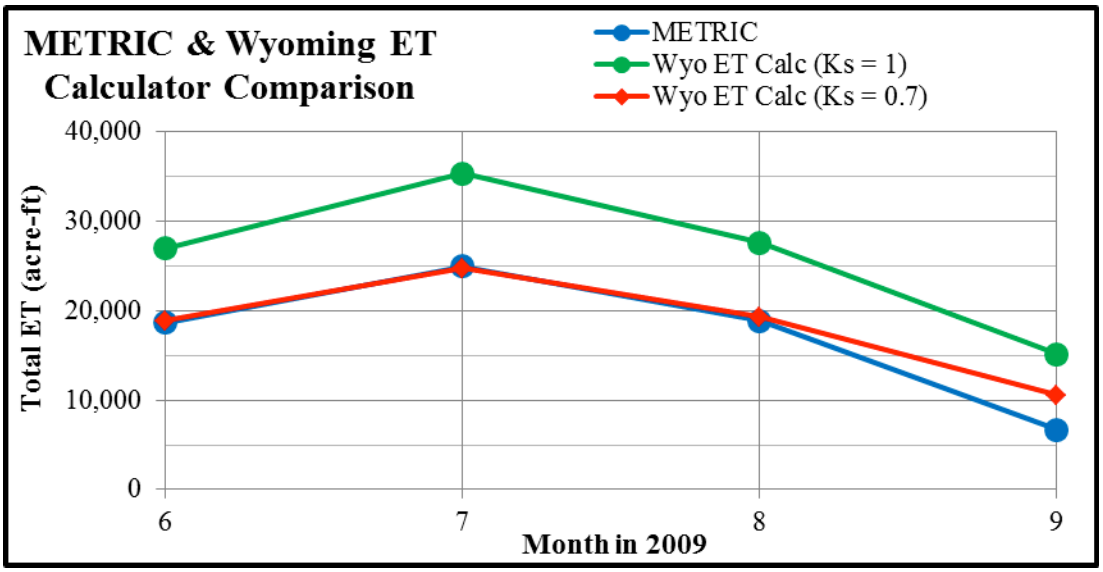
The total monthly ET for METRIC was calculated by linearly interpolating ETrF (ratio of AET to RET) between the days that had satellite imagery to get an ETrf grid for every day. The daily ETrf grids were multiplied by daily ET measured from a station (a point) to get daily grids of ET. Finally, the daily ET grids were summed to get monthly ET grids.

The results, after converting each map from depth to a volume and summing all the cells in the area of interest, are shown in the 2nd and third columns of Table 2. These results are shown graphically by the blue and green lines in Figure 26. The fourth column in Table 2 is the METRIC result divided by the Wyoming ET Calculator result. Because the water stress was assumed to be 1 in Wyoming ET Calculator, this represents an actual water stress factor. For June, July, and August, this factor remains very close to a reasonable value of 0.70. The red line in Figure 26 represents the result had a water stress factor of 0.70 been used in Wyoming ET Calculator. The spatial distribution of the volume of ET for July 2009 for both METRIC and Wyoming ET Calculator is shown in Figure 27. Figure 27 shows that ET volume is much more uniform for Wyoming ET Calculator, because there are only a few land types in the NLCD map over the area of interest, and Wyoming ET calculator uses the same crop coefficient for the same type of crop cover within the same land group.

Table 2: Results of the Wyoming ET Calculator and METRIC comparison.

	METRIC (acre-ft)	Wyoming ET Calculator (acre-ft)	Water Stress Factor (K_s)
June	18,646	26,961	0.692
July	24,976	35,334	0.707
August	18,849	27,635	0.682
September	6,683	15,141	0.441

re 26: Graph of the Wyoming ET Calculator and METRIC comparison



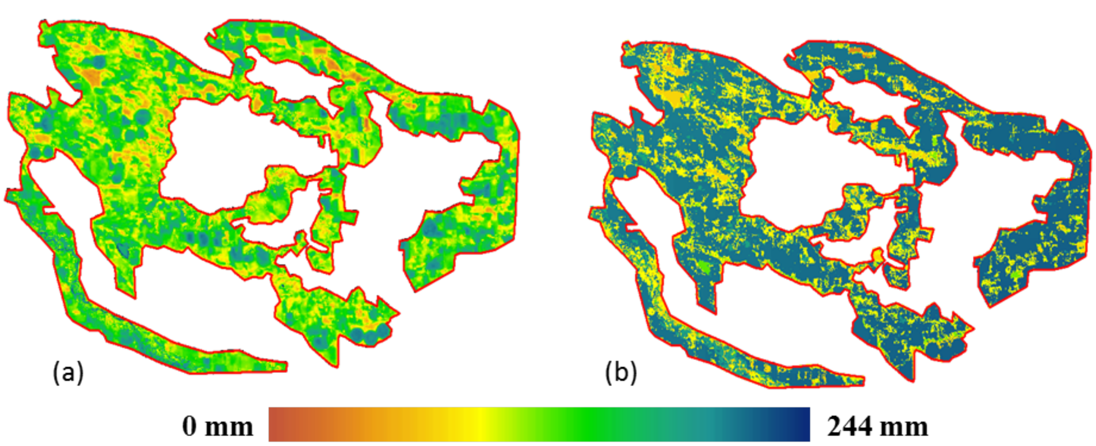


Figure 27: Spatial distribution of July 2009 ET (METRIC on the left and Wyoming ET Calculator on the right).

5. PRINCIPAL FINDINGS AND SIGNIFICANCES

- High spatial (0.01 x 0.01 degree) and temporal (daily) weather data for a long-term period (1960-2010) are produced for the state of Wyoming, and they can serve as key information for many hydrological studies.
- More accurate monthly weather data are produced from the daily data.
- Two climate normal data (1971-2000 or 1981-2010) are also produced.
- Reference ET data also are produced for a period from 1960 to 2010.
- Weather data are archived at the SEO's data server, and will serve to the public.
- The Wyoming ET Calculator is installed at SEO's PC, and it will be used as a key tool in estimating consumptive use with user specified scenarios for any given year or for climate normal.
- A webserver hosted at the SEO will serve data and tools to the public and other agencies to facilitate more accurate estimation of consumptive use in the state of Wyoming.
- The Wyoming ET Calculator provides a reliable estimation of ET, compared to METRIC.
- The automatic scripts will continuously produce same quality weather data for the future period without extra cost.

6. PROJECT PUBLICATIONS

Ryan Rasmussen and Gi-Hyeon Park, Estimation of Growing Season ET using Wyoming ET Calculator – AGU meeting December 5-9, 2011 San Francisco, California

Nancy Thoman and Gi-Hyeon Park, Satellite-based Growing Season ET Estimation using a Statistical Transformation – AGU meeting December 5-9, 2011 San Francisco, California

Gi-Hyeon Park, Nancy Thoman, and Ryan Rasmussen, Application of a Statistical Transformation to enhance Satellite-based ET Estimation – 47th AWRA Annual Water Resources Conference, November 7-10, 2011 Albuquerque, New Mexico

Ryan Rasmussen and Gi-Hyeon Park, High-resolution mapping of reference ET for the state of Wyoming – AGU meeting December 13-17, 2010, San Francisco, California

7. STUDENT SUPPORT AND TRAINING

Ryan Rasmussen, a M.S. graduate student in Civil and Architectural Engineering at the University of Wyoming was responsible for most of the work included in this project, including data processing, tool development, and web development. He will receive MS degree in Civil Engineering in summer of 2012 and will work for HDR.

Nancy Thoman, a MS student in Civil and Architectural Engineering, was partially supported during the summer of 2011 for processing several LANSAT imageries to estimate ET near Ocean Lake. She was trained for METRIC image processing.

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