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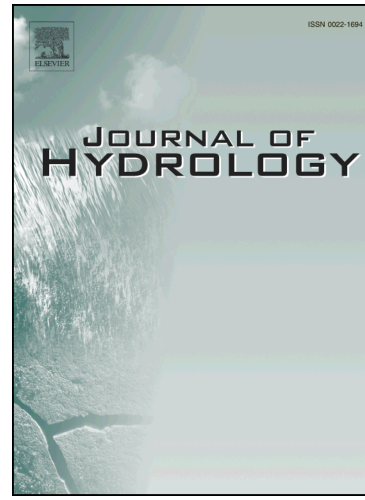

Research papers

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Potential Crop Evapotranspiration and Surface Evaporation Estimates via a Gridded Weather Forcing Dataset

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Abstract

Absent local weather stations, a gridded weather dataset can provide information useful for water management in irrigated areas including potential crop evapotranspiration calculations. In estimating crop irrigation requirements and surface evaporation in Utah, United States of America, methodology and software were developed using the ASCE Standardized Penman-Monteith Reference Evapotranspiration equation with input climate drivers from the North American Land Data Assimilation System (NLDAS) gridded weather forcing dataset and a digital elevation model. A simple procedure was devised to correct bias in NLDAS relative humidity and air temperature data based on comparison to weather data from ground stations. Potential evapotranspiration was calculated for 18 crops (including turfgrass), wetlands (large and narrow), and open water evaporation (deep and shallow) by multiplying crop coefficient curves to reference evapotranspiration with annual curve dates set by summation of Hargreaves evapotranspiration, cumulative growing degree days, or number of days. Net potential evapotranspiration was calculated by subtracting effective precipitation estimates from the Daymet gridded precipitation dataset. Analysis of the results showed that daily estimated potential crop evapotranspiration from the model compared well with estimates from electronic weather stations (1980-2014) and with independently calculated potential crop evapotranspiration in adjacent states. Designed for this study but open sourced for other applications, software entitled GridET encapsulated the GIS-based model that provided data download and management, calculation of reference and potential crop evapotranspiration, and viewing and analysis tools. Flexible features in GridET allows a user to specify grid resolution, evapotranspiration equations, cropping information, and additional datasets with the output being transferable to other GIS software.

Key Words

consumptive use; evapotranspiration; GridET; remote sensing; software

1. Introduction

Policies governing the storage, transport, and application of water resources are overridingly founded upon the amount of accessible water compared to anticipated demand. Perception of either component—whatever the accuracy—correspondingly affects controls placed on the other. For this reason, many government entities sponsor research to quantify current and historical supply, accurately measure usage, and project future supply and requirements. Within the United States, responsible parties are the states with federal oversight for interstate transactions. Over the past century, their appointed water agencies and consultancies have produced numerous reports with a trend of finer scale and greater accuracy proportionate to technological advancements. As a major addend of the earth's water balance, exchange of water at the surface has been modeled and simplified to available observations. Although increasingly automated and regulated transfers of water can be point-measured, areal fluxes have been and currently are estimated due to lack of omnipresent sensors and even then adequate computational capacities. Excluding sublimation in the upward flux of water, the evapotranspiration process has been studied for decades with reported ranges of accuracy likely in the double digit percentages for published estimates. Subsequently, intercomparison of evapotranspiration estimates may fall within the same range.

In 2015, the state of Utah updated its estimates of plant potential evapotranspiration and open water evaporation by using drivers from a longterm, gridded weather forcing dataset calibrated to local weather stations. In contrast to previous models developed to manage water rights, transfers, and allocations within the state, potential evapotranspiration was estimated for all irrigated areas including locations lacking ground-based weather parameters needed to calculate reference evapotranspiration using a Penman-Monteith method. Unique attributes of the recent model are the user-specified grid, variable period statistics, GIS data structure, and customized result toolset. Because the spatial and temporal resolution differs so radically from past estimates, this study has the ability to shape policies within intrastate and interstate basins where previously no official estimates had existed except through extrapolation. To further analyze the findings, these estimates were spatially compared to point estimates both in the state and in overlapping areas of nearby states, which satisfied the research objective of producing a statewide gridded potential evapotranspiration model with the reference evapotranspiration results comparable to those calculated from measurements at electronic weather stations situated in irrigated locations.

2. Background

Estimating potential water use is an essential function to properly manage and allocate water resources in the multiuser, interdisciplinary, and intergovernmental system that exists in the Intermountain West. Potential crop water use or evapotranspiration is defined as the amount or rate at which water would evaporate from wet soils and transpire from plants if water is not limited and the plant is not stressed. Potential crop evapotranspiration is used for irrigation system design, scheduling, and project management. Actual crop evapotranspiration is generally less than potential and includes factors that reduce water use, such as limited soil water, less than ideal soil fertility, plant diseases, plant damage from insects, climate factors, etc. Determination of potential (not actual) rates of crop evapotranspiration and surface evaporation at a high resolution is the subject of this study. Because of the diversity in topography, climate, and soils in this region, accurate tracking of water movement on, above, or beneath the land surface is difficult and has prompted research to improve measurement techniques and modeling approaches. Specific to this study are the efforts within the state of Utah to estimate potential plant consumptive use and surface evaporation. To date, five reports (Roskelley & Criddle, 1952; Criddle et al., 1962; Huber et al., 1982; Hill, 1994; and Hill et al., 2011) have been produced based on the available data, computing ability, and standard practices of the time. Initially, a calibrated reference evapotranspiration equation like the Blaney-Criddle, which relies solely on temperature, was appropriate since the bulk of weather records only consisted of daily maximum and minimum temperature and sites were not always representative of reference conditions. With the advent of electronic meteorological instrumentation and datalogging in the early 1980’s, other weather variables such as wind speed, downward solar radiation, and humidity could be measured with increasing spatial and temporal resolution and digitally handled. This dataset influenced the 1994 methodology by adjusting the Blaney-Criddle correction factors with daily output from a modified Penman equation aggregated to monthly values.

2.1. Utah Consumptive Use Estimates

Expanding upon the previous methodologies, the 2011 study by Hill et al. substituted the ASCE Standardized Penman-Monteith Reference Evapotranspiration equation (published by the American Society of Civil Engineers, further references as "ASCE equation"; Walter et al., 2000) on a daily time step in place of the monthly input-based Blaney-Criddle equation to calculate reference evapotranspiration at National Weather Service cooperative observer sites (NWS, 2015) within a one latitudinal and longitudinal degree buffer around Utah (depicted in Figure Figure). Inputs for the ASCE equation were daily maximum and minimum air temperatures at 246 NWS locations; inverse-distance interpolated monthly average wind speed, cloudiness solar radiation fractions, and dewpoint depressions from 66 agriculturally representative electronic weather stations (EWS); site aridity calibrations; and other calibrations derived from comparing hourly to daily datasets. Daily alfalfa (long) reference evapotranspiration as well as a deep water aerodynamic method were calculated from the synthesized input and when paired with daily crop coefficients produced potential evapotranspiration for 18 crops (including turfgrass), consumptive use for large and narrow wetlands, and open water evaporation for deep and shallow systems. Both potential evapotranspiration and net potential evapotranspiration (minus effective precipitation) were estimated for land covers of assumed prevalence for the NWS locations for the period 1971-2008 and for every land cover at each of the 48 suitable EWS (18 of the 66 EWS were sensor limiting) locations measuring each parameter for their period of record. Output was summed or averaged from daily to monthly values and published in the referenced report. Because the current study is a continuation of the preceding, duplicate documentation of the detailed procedures was avoided while the improvements and a greatly simplified approach are accentuated.

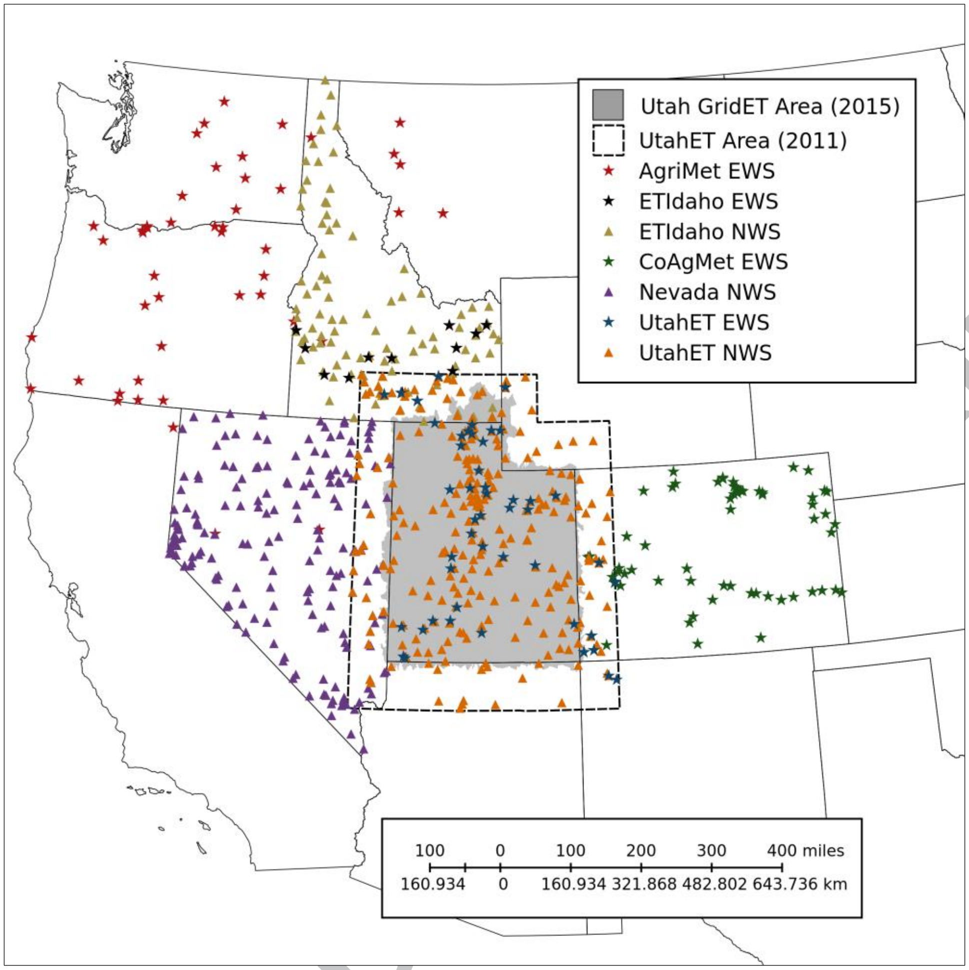


Figure 1: National Weather Service (NWS) and Electronic Weather Station (EWS) Locations from Different Networks Overlying Two Potential Evapotranspiration Study Areas in and about Utah (Some Weather Stations are used by More than One Network)

2.2. Gridded Reference Evapotranspiration in the Western United States

While the volunteer NWS cooperative effort has traditionally provided the atmospheric drivers for creation of regional evapotranspiration normals, satellite imagery datasets have been accumulating with increasing resolutions, better calibrated instrumentation, more data analysis tools, and knowledge to use these tools in scientific evaluations. As a result, the North American Regional Reanalysis (NARR; Mesinger et al., 2006) was assimilated from a combination of orbiting, airborne, and earthbound sensors at a 3-hour temporal resolution and 20 mile [32 kilometer] spatial resolution grid over North America. By interpolating and applying corrections to NARR weather drivers, the North American Land Data Assimilation System (NLDAS; Cosgrove et al., 2003;

NLDAS-2, 2015) produced weather parameters at the earth's surface at a roughly 7 mile [11 kilometer], hourly grid intended to predict drought conditions by application in various land surface energy flux models. Lewis et al. (2014) investigated whether the NLDAS (version 2A) climatic data could be used to calculate reference evapotranspiration and contrasted the hourly estimates from the ASCE equation to 704 agriculturally-zoned, hourly reporting electronic weather stations in the 17 western states of the mainland United States. Excluding the lower half of the southern states where NLDAS overestimated solar radiation, they found that incoming solar radiation and air temperature compared well, humidity and wind speed were somewhat lacking, and that overall NLDAS alfalfa reference evapotranspiration correlated respectably with EWS estimates owing to the predominance of the first two variables—albeit with a high bias. Most errors between the two datasets were concentrated in the nongrowing season (lower temperatures) and in high NLDAS nighttime temperatures (also influencing nighttime humidity) which was negligible since reference evapotranspiration is near zero at night. Congruence was hypothetically attributed to the aggregate nature of the grid with back-interpolation of weather drivers smoothing microclimate variability and hence more closely matching reference evapotranspiration conditions. Summarily, it appeared that NLDAS was suitable for modeling reference evapotranspiration at an hourly temporal resolution from the state of Washington to Oklahoma with proper removal of a high bias.

3. Materials and Methods

With the procedures for calculating irrigated potential consumptive use already outlined in the UtahET report, a switch from calculating evapotranspiration at the sparse and point-located NWS cooperative network calibrated by nearby EWS locations to the gridded and validated NLDAS dataset was now feasible. Different corrections would be required to remove any bias in the input data, and these would have to adapt to a region spanning multiple latitude degrees [fractional radians] and thousands of feet [meters] change in elevation. Even with holding reference evapotranspiration constant, other variables in calculating potential evapotranspiration would be influenced by the new climate data, in particular the determination of yearly variable phenological dates for the crop coefficient curves. With the agriculturally-positioned electronic weather stations being the standard and the 2011 report a reference point, potential deviations in date modeling would need to be checked.

3.1. Weather Parameter Calibration

Following a similar procedure to NLDAS downscaling weather parameters from the coarser NARR grid (Cosgrove et al., 2003; described in detail in the data preparation section of Lewis et al., 2014), downward solar radiation, air temperature, air pressure, u (longitudinal) and v (latitudinal) components of wind speed, and relative humidity (derived from air temperature, air pressure, and specific humidity) at or above the surface were topographically adjusted for surrounding NLDAS pixels to match the target resolution coordinates and then bilinearly interpolated for each hour. Output resolution was a finer 1/3 mile [0.54 kilometer] grid with adjustment factors of elevation, slope, and aspect being computed from the higher resolution national elevation dataset (Gesch et al., 2002). Atmospheric parameters were independently adjusted, interpolated, and in the case of wind speed combined in preparation for evapotranspiration calculations. Differences in methodology from the 2014 NLDAS-EWS validation were inclusion of modeled as opposed to estimated air pressure (a minor variable in the ASCE equation), expansion of solar radiation interpolation to incorporate slope and orientation, removal of air temperature and relative humidity bias by regression, combination of wind vectors after and not prior to interpolation, and limiting the wind speed.

Solar Radiation

By translation of the direct, reflected, and diffuse radiation components between coordinates of interest, downward shortwave radiation was estimated and then interpolated from each corner NLDAS pixel. This was accomplished through an instantaneous solar positioning algorithm which claimed to be quite exact or within an uncertainty of ±0.0003 degrees [0.0000052 radians] (Reda and Andreas, 2004) that calculated instantaneous extraterrestrial radiation from the angle of incidence, earth-sun distance, and solar constant. These instantaneous radiations were converted to hourly values by averaging 15 increments, which when combined with the modeled solar radiation and destination slope represented the atmospheric transmissivity, the direct radiation fraction, and the reflectance factor in the site-to-site interpolation method provided by Allen et al. (2006).

Air Temperature

Since NLDAS did not fully replicate the diurnal temperature extremes in arid and mountainous terrain with high biases at night and at cooler (winter or nongrowing season) temperatures, a sinusoidal least-squares regression function was employed to fit the error between electronic weather stations in Utah and the NLDAS model (defined in Equations Text, Text, and Text). Least-squares coefficients output in Table Table encompassed the variable linear offset as well as the seasonal and daily fluctuations by taking the sine and cosine of Julian day of year and hourly fractions, respectively. This modeled error was added to the air temperature after the NLDAS pixels had been adjusted for a standard lapse rate of -18.83 Fahrenheit/mile [-6.5 Celsius/kilometer] and bilinearly interpolated.

Relative Humidity

Because relative humidity is a function of air temperature (and vapor pressure), the hourly error between the model and the agriculturally-situated EWS truth behaved similarly, although inversely, throughout the daytime and season. Equations Text, Text, and Text were also applied to the hourly relative humidity with the least-squares coefficients recorded in Table Table. The calculated bias was subtracted after bilinear interpolation of the NLDAS relative humidity to the intended pixel and limited to a maximum of 100 and minimum of 7 percent.

$$Offset = C_0 + C_1 cos(F_{DoY}) + C_2 sin(F_{DoY}) + C_3 cos(F_{Hr}) + C_4 sin(F_{Hr}) + C_5 V \qquad (1)$$

$$F_{DoY} = 2\pi \frac{DoY - 1}{365} \qquad (2)$$

$$F_{Hr} = 2\pi \frac{Hr}{23} \qquad (3)$$

Where $Offset$ is the error adjustment applied to the variable (in Fahrenheit degrees for air temperature and percent for relative humidity), F_{DoY} and F_{Hr} are the seasonal and daily sinusoidal values, DoY is the Julian day of year, Hr is the beginning time of an hour (0 through 23), V is the value of the variable itself, and the constants are what was derived from the model-measurement comparison in Table Table.

Table 1. Air Temperature and Relative Humidity Error Regression Coefficients from Comparison of UtahET Electronic Weather Station Datasets to Corresponding NLDAS-Interpolated Hourly Pixel Values

V	Units	C_0	C_1	C_2	C_3	C_4	C_5
Air Temperature	Fahrenheit [Celsius]	1.58 [0.878]	0.59 [0.328]	-1.53 [-0.85]	-3.73 [-2.072]	1.4 [0.778]	0.0551 [0.0306]
Relative Humidity	Percent	-21.9	0.78	3.55	11.6	-5.05	0.274

<u>Wind Speed</u>

Orthogonal wind vectors were initially adjusted from 33 feet (10 meters) to 6.6 feet (2 meters) according to the logarithmic profile relationship in the ASCE equation before bilinear interpolation. After the resultant magnitude was found, the wind speed was capped at 5.5 mile/hour [2.46 meter/second] which corresponded to a 132 mile/day [212.4 kilometer/day] maximum effective wind speed determined and reconfirmed by Hill in his 1994 and 2011 reference evapotranspiration analyses for Utah.

<u>Air Pressure</u>

Interpolation of air pressure duplicated the process by NLDAS (Cosgrove et al., 2003) by adjusting the pressure as a function of change in elevation and lapse rate-adjusted air temperature.

3.2. GridET Software

Custom software, entitled GridET and illustrated in Figure Figure, was developed as a graphical user interface for gridded consumptive use calculations and data handling for this study. Inspiration for GridET stemmed from previous projects of UtahET—which calculated consumptive use at point locations—and the NLDAS-EWS validation. In order to enable others to review, enlarge, or reuse its source code, GridET was given a permissive license and hosted by a third party distributor as an open source project (GridET 2015). Specific capabilities include a modular format that could easily envelope multiple climatic dataset inputs, automated file transfer protocol downloads of datasets, user-supplied area mask and variable pixel resolution, single file database output per variable for independent querying and distribution, multiprocessor support, scheduled calculations, documentation, and a foundation on open source geospatial libraries. Of the last, processing of vector and raster datasets was managed by the open source library GDAL/OGR (Warmerdam 2008), likewise image rendering by the open source MapServer (Lime 2008), and storage by public domain SQLite (Hipp 2013). Because GridET was written in managed .NET code, it also has the potential for cross platform application through compilation with the Mono Framework (King and Easton, 2004). In its current form, primary operations of GridET comprise download and interpolation of weather parameters, calculation of reference evapotranspiration, determination of annual crop coefficient curve dates, calculation of potential and net potential evapotranspiration, and the averaging, viewing, and extracting of output. While specific description of GridET processing routines are contained in its help file, core theories and their applications are described below.

Reference Evapotranspiration and Open Water Surface Evaporation

Upon download and completion of the bilinear interpolations, NLDAS-derived weather parameters were entered as inputs into hourly hydrologic models and subsequently converted to daily values. Consumptive use methodologies outlined by Allen and Robison (2009) in their Idaho implementation were generally adopted with several modifications, notably model calibrations to represent Utah conditions. Among these was the estimation of aerodynamic deep water surface evaporation originating from Kondo (1975) to represent deep water where the vapor bulk transfer coefficient was calibrated to a two-year evaporation study by Amayreh (1995) over northern Utah Bear Lake and found to be 0.0014 (unitless). With corresponding curve coefficient adjustments, the reference estimate for shallow open water surface evaporation was switched from the 1982 Kimberly-Penman to the ASCE equation. Alfalfa reference evapotranspiration was estimated both by the ASCE equation and the Hargreaves equation (Hargreaves and Samani, 1982), with selection of long reference numerator and denominator constants for the former and calibration of the latter to magnitudes reported in UtahET. GridET's version of Hargreaves evapotranspiration (Equation Text) was specific to the adjusted NLDAS and interpolated air temperatures, from which the maximum hourly average, minimum hourly average, and mean daily hourly average air temperatures coupled with the mean daily 15-minute instantaneous extraterrestrial solar radiation are inputs.

$$ET_H = R_A \frac{(C_1 + T_{MEAN})}{C_2} \sqrt{T_{MAX} - T_{MIN}} \quad (4)$$

Where ET_H is long reference evapotranspiration (inch/day [millimeter/day]), R_A is the daily total extraterrestrial solar radiation averaged from 15-minute instantaneous calculations (Langleys), C_1 is a temperature conversion constant equal to 0 Fahrenheit [17.78 Celsius], C_2 is a calibration constant equal to 800,000 [13,042], T_{MEAN} is the daily mean temperature (Fahrenheit [Celsius]), T_{MAX} is the daily maximum mean hourly temperature (Fahrenheit [Celsius]), and T_{MIN} is the daily minimum mean hourly temperature.

Potential and Net Potential Evapotranspiration

For the same 22 land covers as in UtahET (listed in Table Table), crop potential evapotranspiration and open water surface evaporation were estimated by multiplying the daily reference value—which was ASCE long reference evapotranspiration for all but deep water evaporation, which relied on the aerodynamic method—by the single crop coefficient approach defined in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998). Crop coefficient curves were broken into two segments (except for alfalfa which modeled variable year cuttings with additional segments) that were anchored by the vegetative initiation (e.g., planting, green up, ...), intermediate (e.g., full cover, flowering, ...), and termination (e.g., harvest, frost, …) dates. Segments could contain an arbitrary number of crop coefficient values that were interpolated between either the initiation and intermediate date or the intermediate date and the termination date as a function of percent days, number of days, or cumulative growing degree days (CGDD) defined by 32, 41, and 86-50 Fahrenheit [0, 5, 30-10 Celsius] to daily fractions that were then multiplied to the reference value to determine the potential rate. Other than for open water surface evaporation which was year-round, land cover initiation dates were modeled annually by selecting the later date of a last spring frost temperature or when a sum of Hargreaves evapotranspiration had accumulated. Likewise, termination dates were selected when either the crop curve threshold had been reached or when a killing frost temperature had occurred. Calculation of potential evapotranspiration differed from UtahET in some slight adjustments of the spring frost temperatures and summed Hargreaves evapotranspiration thresholds to accommodate NLDAS air temperatures. Additionally, whereas UtahET contained dual versions of crop curves where interpolations were based on days or CGGD, only the first option was transferred to GridET.

Net potential evapotranspiration was calculated by subtracting monthly effective precipitation from summed monthly evapotranspiration or evaporation at corresponding grid cells. Although NLDAS estimated precipitation, its low resolution with respect to the irregular patterns imposed by mountainous terrain to characterize local precipitation disparities would've required an intricately designed interpolation based on topography. However, daily gridded precipitation estimates already existed at a higher resolution (0.62 mile [1 kilometer]) in the Daymet weather dataset (Thornton et al., 2012), and the precipitation rasters were downloaded and bilinearly interpolated to the target grid. Effective precipitation was determined by either applying 100 percent of the interpolated Daymet precipitation as in the case of open water or by a fraction of the total that was based on a relationship between monthly evapotranspiration and precipitation the United States Department of Agriculture developed in 1970 (selection recorded for each land cover in Table Table; Bos et al., 2008). Finally, before effective precipitation was subtracted it was converted to horizontal equivalents as a function of the cosine of the slope.

Table 2. Crop Curve Dates Selection and Effective Precipitation Methods for Crops, Riparian Vegetation, and Water Surfaces Included in the GridET Model of Utah

No.	Land Cover	Initiation Threshold	Intermediate Threshold	Termination Threshold	Effective Precipitation
1	Alfalfa (Beef)	Hargreaves ET	CGGD/Days*	CGGD/Days*	USDA 1970
2	Alfalfa (Dairy)	Hargreaves ET	CGGD/Days*	CGGD/Days*	USDA 1970
3	Apples or Cherries	Hargreaves ET	Days	Days	USDA 1970
4	Barley	Hargreaves ET	CGDD	CGDD	USDA 1970
5	Corn (Field)	Hargreaves ET	CGDD	CGDD	USDA 1970

6	Garden	Hargreaves ET	Days	Days	USDA 1970
7	Melon	Hargreaves ET	Days	Days	USDA 1970
8	Onion	Hargreaves ET	Days	Days	USDA 1970
9	Open Water (Deep)	-	-	-	Full
10	Open Water (Shallow)	-	-	-	Full
11	Other Hay	Hargreaves ET	Days	Days	USDA 1970
12	Other Orchard	Hargreaves ET	Days	Days	USDA 1970
13	Pasture	Hargreaves ET	Days	Days	USDA 1970
14	Potato	Hargreaves ET	CGDD	CGDD	USDA 1970
15	Safflower	Hargreaves ET	Days	Days	USDA 1970
16	Small Fruit	Hargreaves ET	Days	Days	USDA 1970
17	Sorghum	Hargreaves ET	Days	Days	USDA 1970
18	Spring Grain	Hargreaves ET	CGDD	CGDD	USDA 1970
19	Turfgrass	Hargreaves ET	Days	Days	USDA 1970
20	Wetlands (Large)	Hargreaves ET	Days	Days	USDA 1970
21	Wetlands (Narrow)	Hargreaves ET	Days	Days	USDA 1970
22	Winter Wheat	Hargreaves ET	CGDD	CGDD	USDA 1970

Definitions: Hargreaves ET = Equation Text, CGGD = Cumulative Growing Degree Days, Days = Number of Days, USDA 1970 = Detailed in Bos et al. (2008), Full = 100 Percent of Reported. *For alfalfa, presented thresholds regulate the first cutting with additional thresholds to simulate cutting cycles.

Raster Operations

Because of the large number of records—over 13,000 daily images for the period of record per variable (e.g., daily average temperature, daily precipitation, daily Pasture potential evapotranspiration)—tools to effectively summarize and view the data were created. Among these was a routine for averaging any input or output variable for a user-specified monthly date range (customizable daily date periods were also applicable to the download and evapotranspiration calculations), which could then be further analyzed by an additional routine that extracted and averaged pixel values within a polygon vector file by joining on the variable or land cover name. Any of the outputs could then be viewed in the graphical interface via the MapServer plugin and visually inspected (as shown in Figure Figure).

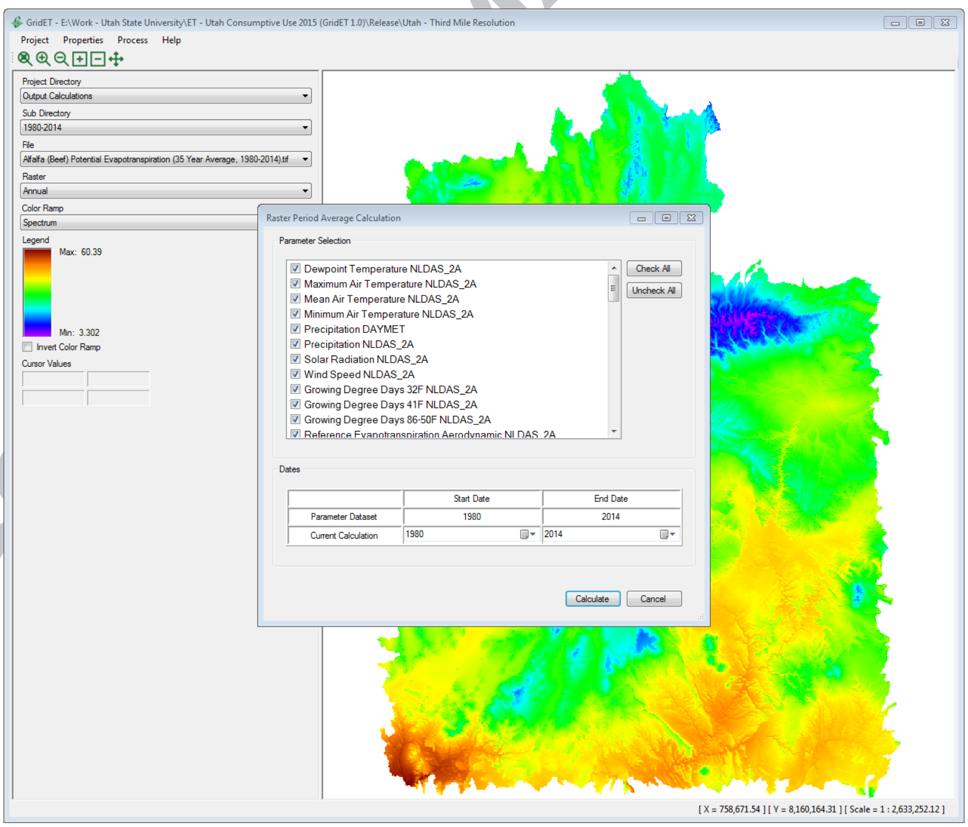
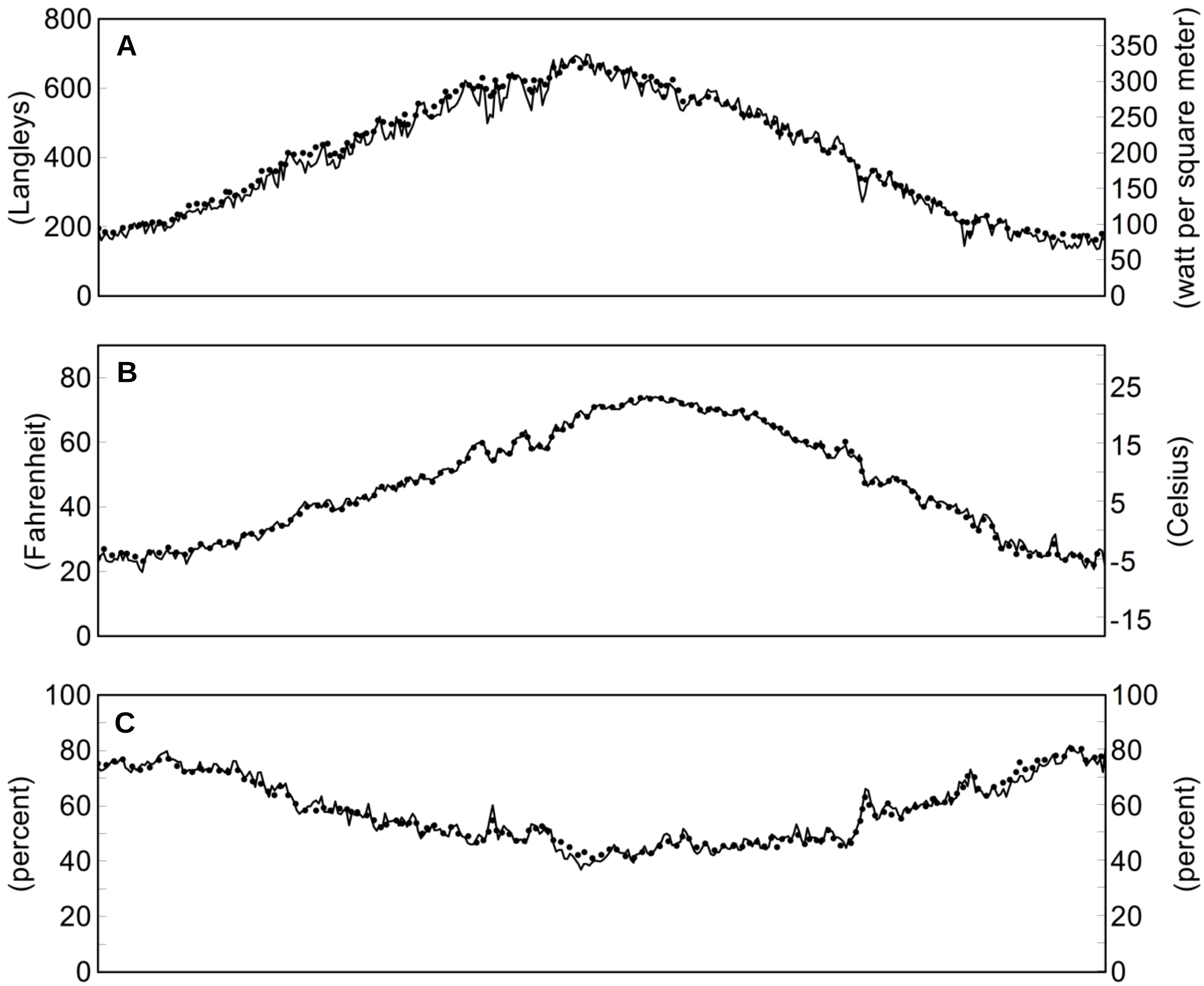


Figure 2: GridET Example Featuring Period of Record Calculations for Utah Statewide Estimates of

4. Results

Daily atmospheric parameters, long reference evapotranspiration by the ASCE and Hargreaves equations, cumulative growing degree days at their chosen base temperatures, annual curve dates, and potential evapotranspiration or open water surface evaporation for 22 land covers were computed in GridET for the 35-year overlapping histories of the NLDAS and Daymet datasets (1980-2014). By converting the effective precipitation and potential evapotranspiration to monthly values and subtracting the first, net potential evapotranspiration or evaporation was then calculated followed by period statistics. Essentially, this output duplicated UtahET for the intended extent (as shown in Figure Figure) except that the previous had 246 NWS and 48 EWS point estimates while the 1/3 mile resolution GridET model contained 863,214 pixels. Acting as the ground truth, the 37 coincident UtahET EWS (which were the intersection of the 48 from the NLDAS-EWS validation that had been used to calibrate the input data) were compared to the GridET model. While Lewis et al. (2014) spatially portrayed variance of weather drivers between the NLDAS model and multi-network EWS for each site's period of record, Figure Figure depicts the average daily bias between the UtahET EWS and corrected GridET solar radiation, air temperature, relative humidity, and wind speed. As a whole, subtraction of the error through the least squares relationship for air temperature and relative humidity proved very fitting, and solar radiation (which was only corrected topographically) also nearly matched the recorded pyranometer values. Although capped at 5.5 miles/hour [2.46 meter/second] every hour, the daily average wind speed still manifested a consistent offset higher than the measured. This was because in the 2011 report the EWS cup-based anemometers (or the majority design) were found to have an overestimated, default static friction offset of 1 mile/hour [0.45 meters/second], and the corrective action was removal of the total offset from each hour. When comparing the interpolated NLDAS data to the corrected EWS wind speed, a discrepancy of 0.5 mile/hour [0.22 meter/second] was observed year-round that reasonably characterized the average wind speed antecedent cup movement, which would indicate halving and not eliminating the static friction offset. Therefore, the vertically-scaled magnitudes from NLDAS were trusted more than the likely partial wind energy EWS measurements.

Futthermore, the EWS anemometers were positioned from 6.6-10 feet [2-3 meters] above the soil surface of actively growing reference vegetation (such as alfalfa) that would have variable canopy heights in contrast to the even 33 foot [10 meter] original height of the NLDAS estimate above the surface.



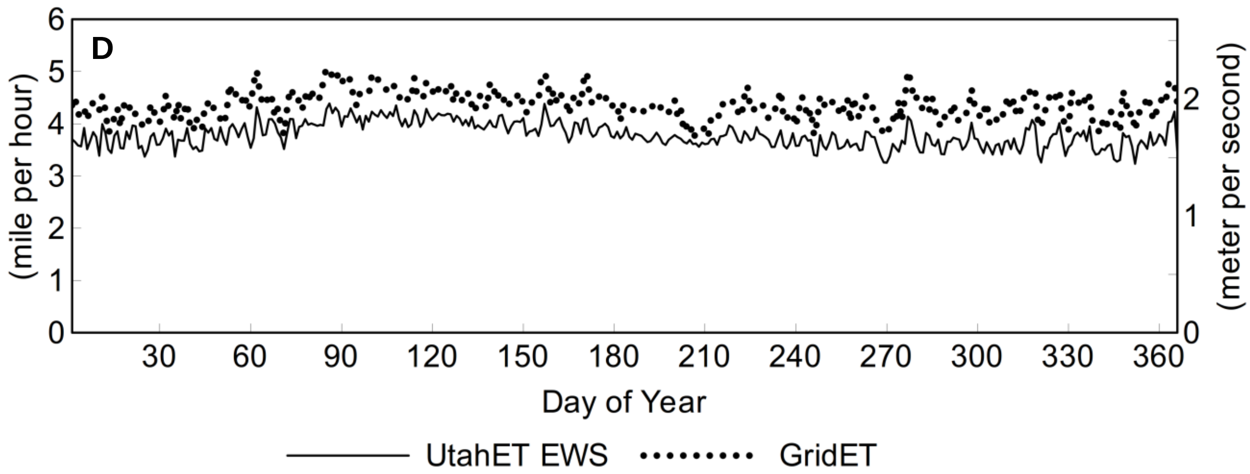


Figure 3: Mean Daily Weather Variable Input of Aggregate UtahET Electronic Weather Station (EWS) Locations and GridET Model Comparison ([A] Solar Radiation, [B] Air Temperature, [C] Relative Humidity, [D] Wind Speed)

4.1. Reference Evapotranspiration

GridET estimated reference evapotranspiration, or the basis for the land cover-specific potential evapotranspiration, was compared against both UtahET EWS and NWS locations as well as results from parallel studies in surrounding states. Agricultural weather station networks or consumptive use studies providing monthly reference and potential crop evapotranspiration for similar conditions around Utah and included in Figure Figure were CoAgMet (Colorado; Andales et al., 2009), ETIdaho (Idaho; Allen and Robison, 2009), AgriMet (Pacific Northwest; Dokter 1996), and Nevada (Huntington and Allen, 2010). Both ETIdaho and Nevada consumptive use studies each contained stations within the study area that could be correlated against GridET and were derived from the same datasets and methodology as UtahET. AgriMet and CoAgMet did not overlap but were included for their long records, regional standings, and adjacent intermountain conditions. Monthly reference evapotranspiration from the coincident UtahET EWS, UtahET NWS, ETIdaho NWS, and Nevada NWS locations were plotted against GridET and are shown in Figure Figure. Given the relatively few and straightforward adjustments to the NLDAS climatic drivers, GridET estimated long reference evapotranspiration compared closely with R-Squares at or above 0.94 and low biases. By comparing UtahET EWS, UtahET NWS, and GridET, it is apparent that the current study outperforms the 2011 NWS results in both accuracy and resolution. Further inspection reveals that ETIdaho better prepared their NWS datasets than

UtahET, although at a lower magnitude than what GridET estimated. At 2.5 inches [64 millimeters] annually on average, the error is within 5 percent of the total. Nevada NWS stations also correlated well but intrinsically contained a high bias due to it being calculated as a short reference in the ASCE equation.

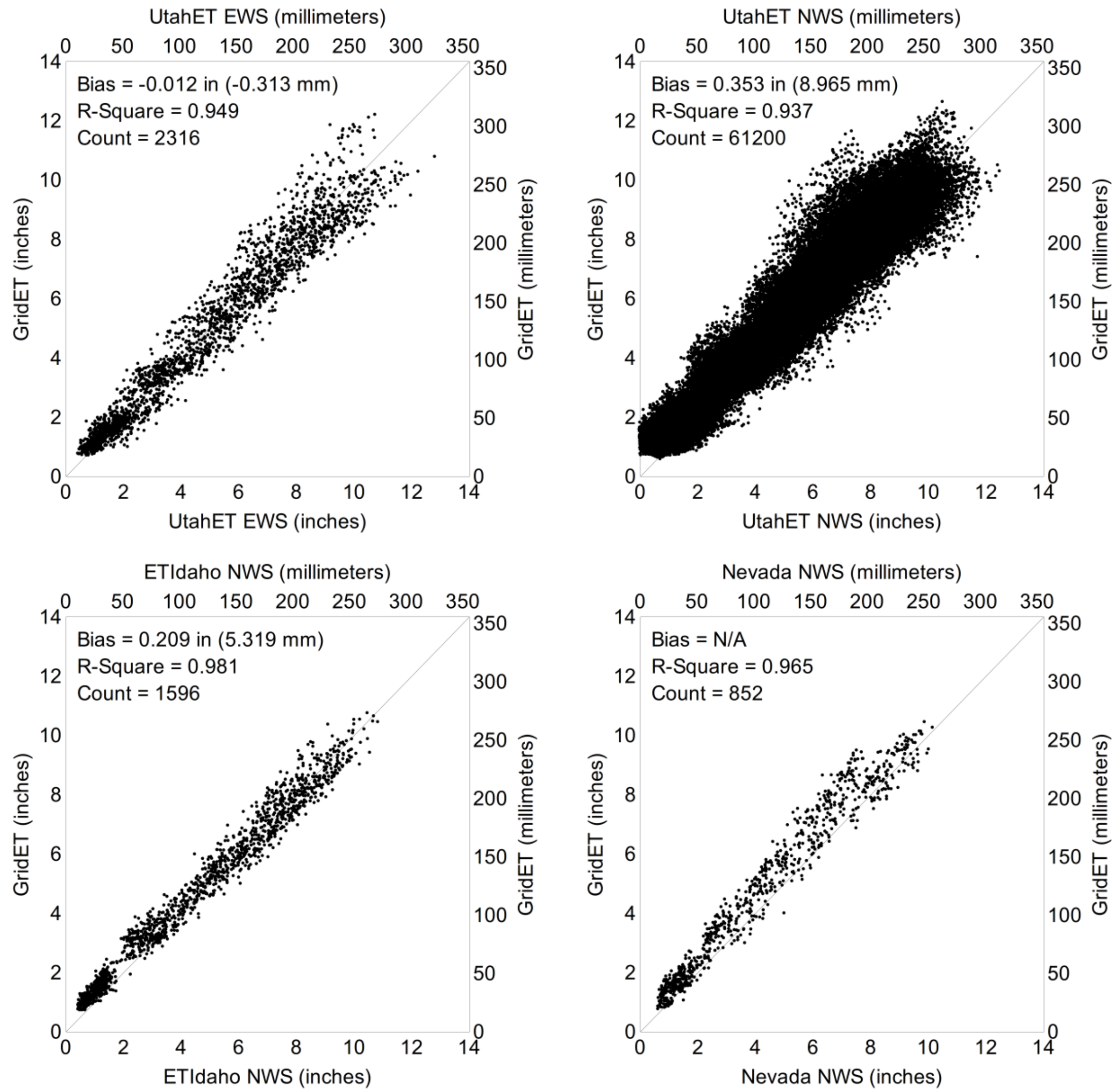


Figure 4: Comparison of GridET Monthly Long Reference (Nevada Short Reference) Evapotranspiration Pixels to Overlapping Monthly Periods and Corresponding UtahET National Weather Service (NWS), UtahET Electronic Weather Station (EWS), ETIdaho NWS, and Nevada NWS Locations within the Utah GridET Study Area

Next, the corresponding monthly reference evapotranspiration estimates were averaged and linearly graphed in

Figure Figure. As predicted, GridET imitated the UtahET EWS calibration dataset but also illuminated an underestimation of UtahET NWS in all but the latter part of the growing season. ETIdaho, as noted previously, contained lower estimates, yet these were confined to the less critical months of November-March. Hence GridET results as compared to UtahET EWS and ETIdaho NWS (with no reason to assume different behavior for the truer ETIdaho EWS) were corroborated between the months of April and October. As a southerly subset of the AgriMet network, ETIdaho EWS averages were higher but were nearly equal between the months of November-March, which when also referenced against the GridET comparison may indicate an underestimation of reference evapotranspiration during the wintertime by ETIdaho. CoAgMet was the anomaly with its monthly pattern possibly upset by the presence of EWS on the Great Plains.

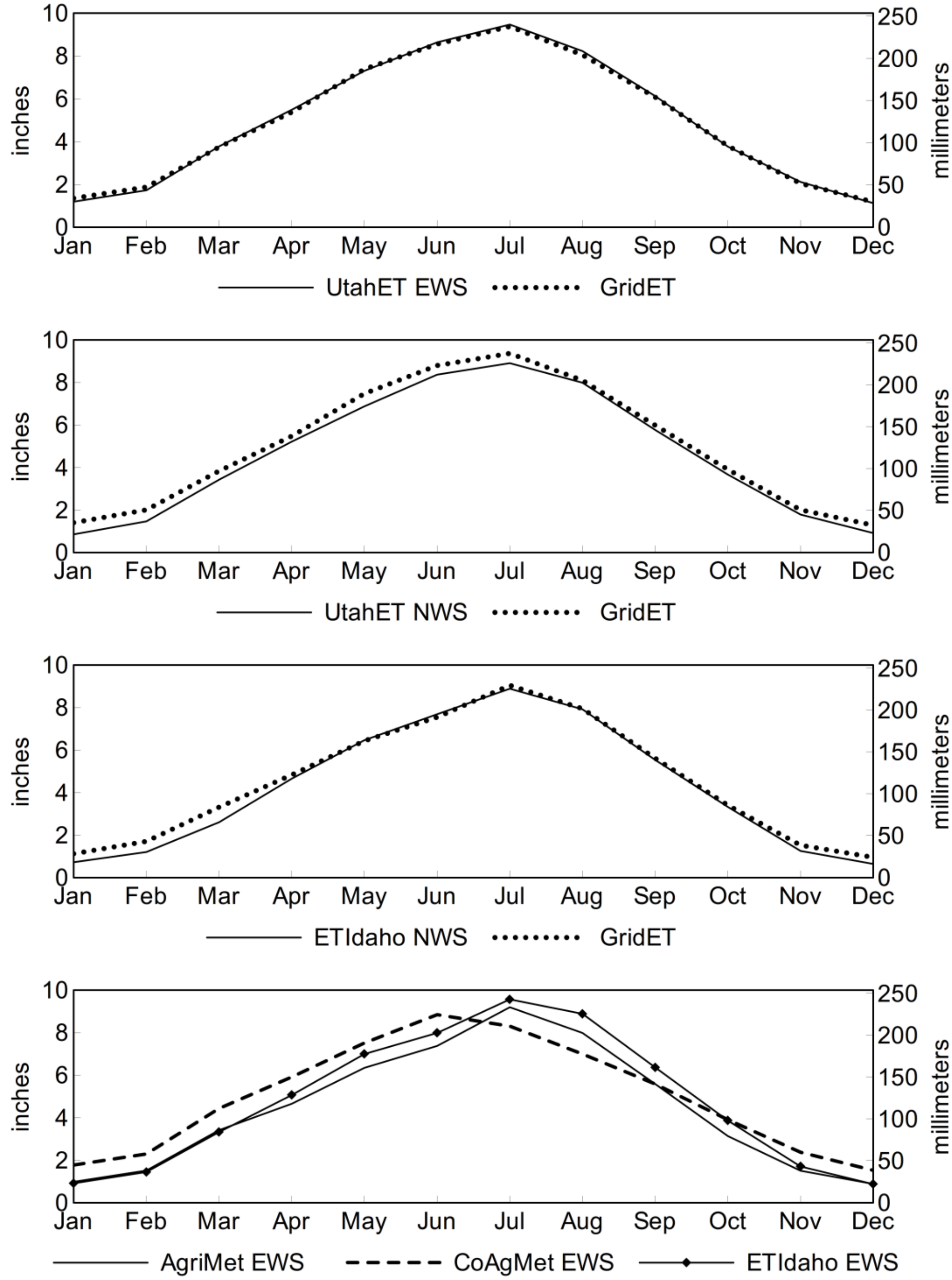


Figure 5: Comparison of Mean Period Monthly GridET Long Reference Evapotranspiration to Corresponding UtahET National Weather Service (NWS), UtahET Electronic Weather Station (EWS), and ETIdaho NWS Locations within the Utah GridET Study Area along with Network Averages of AgriMet, CoAgMet, and ETIdaho EWS

4.2. Transpiration and Surface Evaporation

GridET potential vegetative evapotranspiration and open water surface evaporation were compared with the rates of equivalent land covers from the other consumptive use studies (listed in Table Table) and referenced against the reported estimates from the agricultural weather station networks (listed in Table Table) on a totaled annual basis. As the emphasis of the comparison was change in potential evapotranspiration, presentation of net potential evapotranspiration (which subtracted the effective precipitation) was omitted as the Daymet precipitation was independent of the evapotranspiration calculations and moreover could be applied to each study if needed. Even as the main study objective, the potential evapotranspiration rates mark the maximum scenario with unlimited supplies of water and nutrients where disease, soils, drought, depth, surface temperature, or other factors contribute to a reduction defining the actually-occurring evapotranspiration or evaporation. All reported potential estimates were converted from daily to annual sums, and in the case of CoAgMet the end of season had to be selected. This was because the web interface allowed user-defined date ranges for the crop coefficient curves, for which the default start dates were kept and realistic end dates manually entered. Of note, Colorado has not maintained a published consumptive use dataset, but instead has instituted a software and database system for parametrized calculations on demand (CDSS; Malers et al., 2000).

Analysis of the 100 plus estimates of the 22 land covers in the two annual potential evapotranspiration tables (Table and Table) showed trends of GridET following UtahET EWS with a fractionally low bias, ETIdaho NWS being either higher or lower than the GridET estimates, and at times very similar or dissimilar land cover totals depending on the land cover. Obviously, open water deep and shallow had different definitions among studies—most likely relative to a simulated depth or calibration to a water body—as ETIdaho figures were lower and Nevada greater. Because UtahET NWS locations underestimated reference evapotranspiration, their potential evapotranspiration was likewise low in contrast to UtahET EWS locations which were closer to the surrounding state's studies. Given change in elevation and latitude, most estimates were within 5-10 percent except for a few crops like melons which could be biased by a difference in variety or projected management. While the general direction of consensus is evident among the studies per land cover, there exists sufficient dissimilarities to raise questions regarding the divergence of methodologies and specific land cover definitions for a shared coordinate. For example, potential crop evapotranspiration could be based on different crop stage growth dates or crop curves making the base reference evapotranspiration a better comparison. In short, the detail in the produced tables hardly begins to portray the potential probabilistic conditions caused by natural and anthropogenic influences while ignoring any suboptimal factors.

To manage this interannual variability, at least pertaining to the climatic factors, period averages are often calculated as a basis for long-term administration and planning. For this purpose, 35-year averages (1980-2014) of potential and net potential evapotranspiration were computed for the 22 land covers in the UtahET study area and are displayed in Figures Figure and Figure, respectively. Although potential evapotranspiration estimates exist for every crop at each pixel, it is not intended to infer feasibility but rather to simplify calculation procedures. In reality, a numeric threshold could be determined for each crop that would model the extent to which it could thrive, including year-to-year. Predetermined potential evapotranspiration for different land covers is also useful when comparing consumption rates for future planning, crop rotation, or water rights handling. To represent actual ground conditions, a tool was created in GridET to coalesce the various statewide potential and net potential evapotranspiration by supplying a land use vector dataset to output estimates at a high resolution.

Table 3. Annual Potential Evapotranspiration Comparison of the Utah GridET Output and Overlapping Published Estimates for Various Land Covers

Land Cover	Comparison Dataset	Year Count	GridET Annual Potential Evapotranspiration (Inches [Millimeters])	Average Annual Bias (Inches [Millimeters])	Monthly R-Square
Alfalfa (Beef)	ETIdaho NWS	133	31.71 [805.5]	0.51 [13]	0.848
	Nevada NWS	71	35.68 [906.3]	-1.68 [-42.8]	0.844
	UtahET EWS	193	37.08 [941.7]	2.39 [60.8]	0.920
	UtahET NWS	5100	37.5 [952.4]	6.49 [164.9]	0.850
Alfalfa (Dairy)	ETIdaho NWS	133	23.5 [597]	-7.7 [-195.6]	0.566
	UtahET EWS	193	32.01 [813]	-0.56 [-14.3]	0.784
	UtahET NWS	5100	27.25 [692.1]	-1.96 [-49.8]	0.529
Apples or Cherries	ETIdaho NWS	80	38.2 [970.3]	3.99 [101.4]	0.937
	Nevada NWS	52	36.11 [917.3]	-0.27 [-7]	0.896
	UtahET EWS	193	39.16 [994.6]	0.08 [2.1]	0.948
	UtahET NWS	1470	42.14 [1070.3]	5.42 [137.6]	0.908
Barley	UtahET EWS	193	21.4 [543.6]	1.96 [49.8]	0.944
	UtahET NWS	3720	21.33 [541.8]	1.05 [26.7]	0.835
Corn	ETIdaho NWS	54	19.98 [507.4]	0.27 [6.9]	0.889

	Nevada NWS	26	22.25 [565.2]	-7.75 [-196.9]	0.918
	UtahET EWS	193	23.43 [595.2]	2.04 [51.8]	0.926
	UtahET NWS	2880	24.01 [609.8]	2.67 [67.8]	0.890
Garden	ETIdaho NWS	133	17.82 [452.7]	-4.11 [-104.4]	0.872
	Nevada NWS	26	18.74 [475.9]	-7.46 [-189.5]	0.852
	UtahET EWS	193	19.89 [505.2]	0.7 [17.7]	0.946
	UtahET NWS	5100	20.11 [510.8]	3.95 [100.5]	0.832
Melon	UtahET EWS	193	20.1 [510.5]	0.94 [23.9]	0.939
	UtahET NWS	990	21.27 [540.3]	2.64 [67.1]	0.944
Onion	Nevada NWS	18	27.92 [709.2]	-0.89 [-22.6]	0.921
	UtahET EWS	193	29.07 [738.4]	1.3 [33.1]	0.947
	UtahET NWS	480	31.92 [810.6]	2.61 [66.2]	0.943
Open Water (Deep)	ETIdaho NWS	95	26.49 [672.7]	12.54 [318.5]	0.900
	UtahET EWS	193	30.04 [763.1]	-1.2 [-30.5]	0.743
	UtahET NWS	5100	30.47 [774]	3.11 [78.9]	0.765
Open Water (Shallow)	ETIdaho NWS	132	42.76 [1086.1]	12.22 [310.3]	0.981
	Nevada NWS	71	46.51 [1181.3]	-7.2 [-182.9]	0.965
	UtahET EWS	193	47.08 [1195.9]	5.76 [146.3]	0.973
	UtahET NWS	5100	47.63 [1209.8]	8.73 [221.6]	0.964
Other Hay	ETIdaho NWS	133	23.9 [607.2]	-2.37 [-60.3]	0.644
	Nevada NWS	71	25.56 [649.2]	-4.07 [-103.4]	0.590
	UtahET EWS	193	25.63 [650.9]	-0.39 [-9.8]	0.950
	UtahET NWS	5100	25.83 [656]	0.92 [23.4]	0.859
Other Orchard	UtahET EWS	193	37.33 [948.2]	1.06 [27]	0.939
	UtahET NWS	1590	40.25 [1022.4]	5.39 [136.9]	0.891
Pasture	ETIdaho NWS	133	27.07 [687.6]	-4.25 [-108]	0.919
	Nevada NWS	71	29.94 [760.4]	-6.93 [-176.1]	0.867
	UtahET EWS	193	31.19 [792.2]	1.5 [38.2]	0.943
	UtahET NWS	5100	31.69 [805]	5.27 [133.8]	0.897
Potato	ETIdaho NWS	95	19.84 [503.9]	-2.51 [-63.7]	0.842
	Nevada NWS	26	19.53 [496]	-4.23 [-107.4]	0.819
	UtahET EWS	193	20.42 [518.6]	1.64 [41.7]	0.937
	UtahET NWS	1350	21.01 [533.6]	2.32 [58.9]	0.876
Safflower	ETIdaho NWS	133	29.19 [741.5]	7.11 [180.6]	0.891
	UtahET EWS	193	33.2 [843.3]	0.7 [17.7]	0.960
	UtahET NWS	990	32.95 [836.8]	4.34 [110.2]	0.930
Small Fruit	UtahET EWS	193	26.75 [679.4]	1.36 [34.6]	0.944
	UtahET NWS	810	26.95 [684.6]	3.16 [80.2]	0.941
Sorghum	UtahET EWS	193	23.99 [609.3]	0.46 [11.7]	0.960
	UtahET NWS	2310	24.61 [625]	2.23 [56.6]	0.902
Spring Grain	ETIdaho NWS	133	22.9 [581.7]	-3.36 [-85.4]	0.878
	Nevada NWS	26	22.23 [564.6]	-2.32 [-58.8]	0.883
	UtahET EWS	193	22.84 [580.3]	2.29 [58.2]	0.940
	UtahET NWS	4890	22.93 [582.4]	1.74 [44.1]	0.795
Turfgrass	ETIdaho NWS	133	26.32 [668.4]	-3.74 [-94.9]	0.899
	Nevada NWS	71	29.04 [737.7]	-4.93 [-125.3]	0.851
	UtahET EWS	193	30.26 [768.7]	1.29 [32.7]	0.941
	UtahET NWS	5100	30.74 [780.7]	4.9 [124.4]	0.900
Wetlands (Large)	ETIdaho NWS	133	26.33 [668.8]	3.45 [87.7]	0.878
	UtahET EWS	193	33.15 [842]	1.8 [45.8]	0.933
	UtahET NWS	5100	33.41 [848.7]	7.29 [185.1]	0.878
Wetlands (Narrow)	ETIdaho NWS	133	37.2 [944.8]	5.46 [138.7]	0.879
	UtahET EWS	193	46.92 [1191.7]	2.58 [65.5]	0.933
	UtahET NWS	5100	47.29 [1201.2]	10.41 [264.5]	0.876
Winter Wheat	ETIdaho NWS	133	28.08 [713.2]	-4.03 [-102.4]	0.873
	Nevada NWS	26	26.94 [684.4]	-3 [-76.2]	0.728
	UtahET EWS	193	27.07 [687.6]	7.89 [200.4]	0.866

	UtahET NWS	2010	26.55 [674.4]	6.95 [176.5]	0.75

Table 4. Mean Annual Potential Evapotranspiration Reported by AgriMet, CoAgMet, and ETIdaho for Various Land Covers

Land Cover	Comparison Dataset	Year Count	Annual Potential Evapotranspiration (Inches [Millimeters])
Alfalfa (Beef)	AgriMet EWS	695	35.85 [910.6]
	CoAgMet EWS	701	38.91 [988.3]
	ETIdaho EWS	312	36.3 [922]
Alfalfa (Dairy)	ETIdaho EWS	312	36.2 [919.5]
Apples or Cherries	AgriMet EWS	274	34.14 [867.2]
	ETIdaho EWS	235	36.5 [927.1]
Corn	AgriMet EWS	326	26.81 [681]
	CoAgMet EWS	700	24.07 [611.4]
	ETIdaho EWS	213	27.1 [688.3]
Garden	ETIdaho EWS	290	27.01 [686.1]
Melon	AgriMet EWS	46	16.99 [431.5]
	ETIdaho EWS	116	28 [711.2]
Onion	AgriMet EWS	162	26.7 [678.2]
	CoAgMet EWS	702	27.04 [686.8]
	ETIdaho EWS	116	31.86 [809.2]
Open Water (Deep)	ETIdaho EWS	290	23.29 [591.6]
Open Water (Shallow)	ETIdaho EWS	312	34.23 [869.4]
Other Hay	AgriMet EWS	99	28.39 [721.1]
	ETIdaho EWS	312	29.93 [760.2]
Other Orchard	AgriMet EWS	11	45.83 [1164.1]
Pasture	AgriMet EWS	719	38.23 [971]
	ETIdaho EWS	312	36.26 [921]
Potato	AgriMet EWS	450	25.42 [645.7]
	CoAgMet EWS	696	21.31 [541.3]
	ETIdaho EWS	250	22.53 [572.3]
Safflower	AgriMet EWS	8	26.09 [662.7]
	ETIdaho EWS	290	23.61 [599.7]
Small Fruit	AgriMet EWS	105	25.23 [640.8]
Spring Grain	AgriMet EWS	578	23.43 [595.1]
	CoAgMet EWS	702	20.66 [524.8]
	ETIdaho EWS	312	26.27 [667.3]
Turfgrass	AgriMet EWS	719	34.2 [868.7]
	CoAgMet EWS	702	30.47 [773.9]
	ETIdaho EWS	312	35.71 [907]
Wetlands (Large)	ETIdaho EWS	312	29.31 [744.5]
Wetlands (Narrow)	ETIdaho EWS	312	41.08 [1043.4]
Winter Wheat	AgriMet EWS	530	23.72 [602.5]
	CoAgMet EWS	702	20.62 [523.7]
	ETIdaho EWS	312	30.47 [773.9]

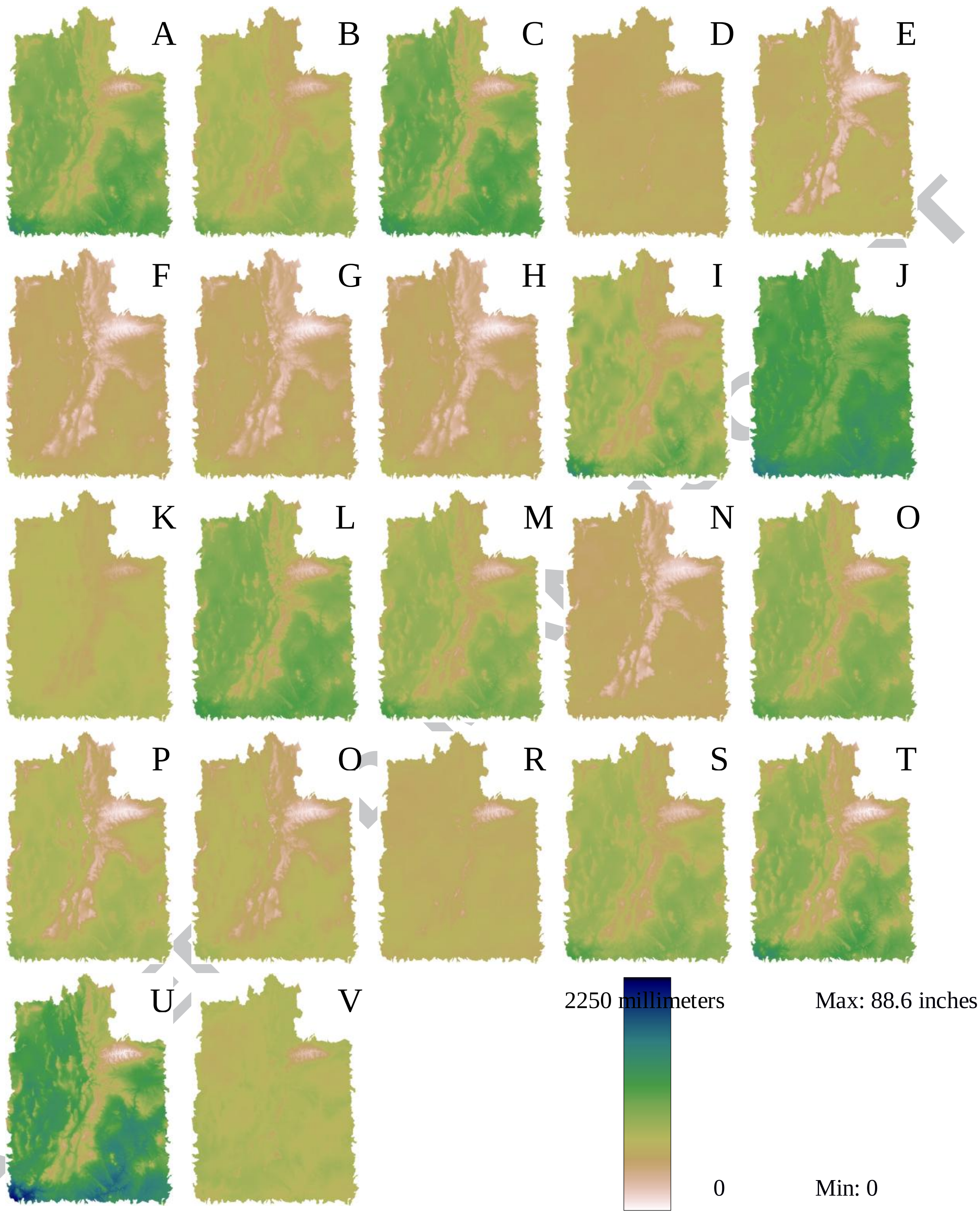


Figure 6: Average Annual Potential Evapotranspiration for Utah (1980-2014; [A] Alfalfa (Beef), [B] Alfalfa (Dairy), [C] Apples or Cherries, [D] Barley, [E] Corn, [F] Garden, [G] Melon, [H] Onion, [I] Open Water Deep, [J] Open Water Shallow, [K] Other Hay, [L] Other Orchard, [M] Pasture, [N] Potato, [O] Safflower, [P] Small Fruit, [Q] Sorghum, [R] Spring Grain, [S] Turfgrass, [T] Wetlands Large, [U] Wetlands Narrow, [V] Winter Wheat)

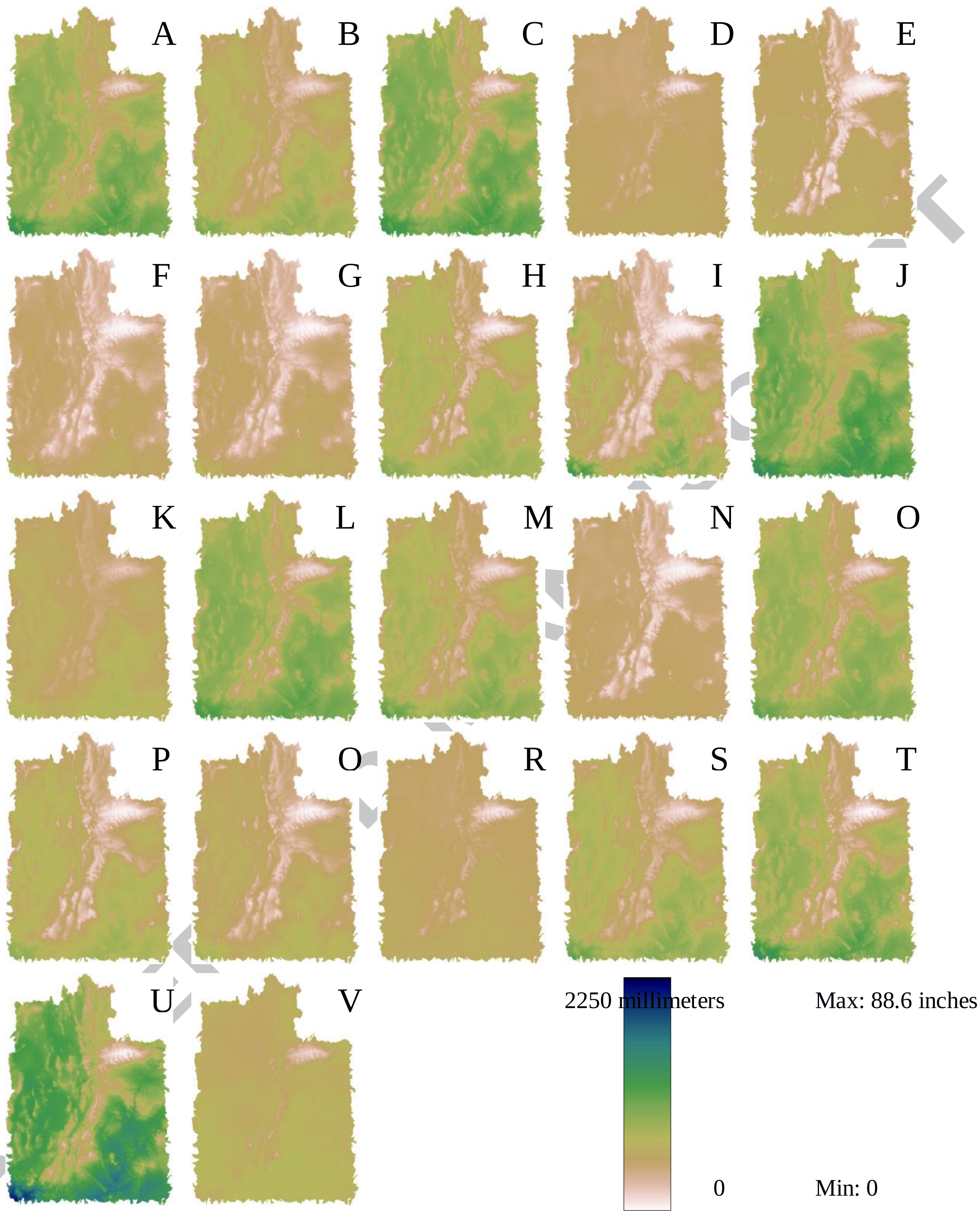


Figure 7: Average Annual Net Potential Evapotranspiration for Utah (1980-2014; [A] Alfalfa (Beef), [B] Alfalfa (Dairy), [C] Apples or Cherries, [D] Barley, [E] Corn, [F] Garden, [G] Melon, [H] Onion, [I] Open Water Deep, [J] Open Water Shallow, [K] Other Hay, [L] Other Orchard, [M] Pasture, [N] Potato, [O] Safflower, [P] Small Fruit, [Q] Sorghum, [R] Spring Grain, [S] Turfgrass, [T] Wetlands Large, [U] Wetlands Narrow, [V] Winter Wheat)

5. Discussion

From the corrections of the NLDAS model to represent reference evapotranspiration or well irrigated conditions in semiarid Utah to the compilation of the GridET software to the verification of potential evapotranspiration using standard practices, this study has tested and determined that when properly handled potential evapotranspiration can be modeled at a high resolution with acceptable accuracy in the heterogeneous climate of the American West. In addition, having a long-term record applicable in many other western states extending from 1979 (NLDAS epoch) to near-realtime allows both historical and current water year analyses or possible adaptation to other weather models including forecasting. Combined with satellite imagery, the hourly time step can be extrapolated in between overpass times to increase the temporal resolution of an energy balance model. Currently, there are researchers intent on historically estimating actual evapotranspiration for large areas in the West that would benefit from this methodology (Geli et al., 2014). Remarkably, the simple procedures to calibrate the weather drivers as opposed to the complexity of processing and adjusting individual site measurements affords an automated solution. Furthermore, without the use of zones, monthly fractions, offsets, or otherwise synthesized data, required inputs for the ASCE equation were modeled straightforwardly.

Results from GridET can be updated and expanded by federal and state agencies or whomever given its open source license. Limited only by processing, storage, and the maximum size of a Sqlite database (currently 128 terabytes per variable), study areas and image resolutions can be altered, additional land covers defined, and other climate datasets incorporated. Higher order modeling such as annual water balances could be calculated from the daily potential evapotranspiration estimates or from actual evapotranspiration based on the reference evapotranspiration estimates. With access to higher resolutions, Utah and other states that have previously created water governing policies from a smattering of point estimates not always representative of the adjacent mountain valley or from inconsistently applied correction factors (often derived from 'judgment') now possess the ability to more accurately assess the potential amount of evapotranspiration for at least the 22 land covers occurring in each watershed at fine level. GridET's standard approach also maintains a benchmark for the frequently divided estimates of competing agencies and could realistically obviate the need for the other methodologies.

6. Conclusions

Results from the GridET model in Utah showed agreement with the reference and potential evapotranspiration of the earlier UtahET EWS and exceeded the quality of the UtahET NWS locations. This was achieved by correcting the more arid NLDAS drivers to represent irrigated conditions by removing the air temperature and relative humidity error through a sinusoidal seasonal and hourly least-squares regression with the UtahET EWS and by capping the effective wind speed. Comparison of the 1980-2014 period of record to other studies, especially to ETIdaho NWS, confirmed congruency. Consequently, the high resolution, hourly method for determining reference evapotranspiration is recommended for future use in both potential and actual evapotranspiration applications. Acknowledging the open source license of the GridET software, the opportunity is reinforced.

7. Acknowledgements

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Highlights

• Gridded potential evapotranspiration for 22 land covers across the state of Utah

• Developed open source application GridET to automate calculations

• Comparison of results to studies in adjacent states