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Spatial Analysis of Actual Evapotranspiration Estimates from the GAMUT Weather Stations using Geographic Information System

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Abstract

Water demand is increasing whereas the supply is diminishing in many parts of the world. Estimating the loss of water through evapotranspiration (ET) processes in arid regions like the Intermountain West is important for efficient planning and management of water resources. This study focuses on estimating the actual ET (AET) from the point estimates of reference evapotranspiration (ET_r) and analyzing it in temporal and spatial scale within selected watersheds using Geographic Information System (GIS). The ET_r map was generated using the point observations from the Gradients Along Mountain to Urban Transitions (GAMUT) meteorological stations in three watersheds (*Logan River, Red Butte creek and Provo River watersheds*) in Northern Utah. AET is estimated as the proportion of ET_r contributed by fraction of vegetation derived from Normalized Difference Vegetation Index (NDVI) in each pixel from Landsat image and presented as map for each watershed for the month of May, June, July and August.

Keywords: *Evapotranspiration, GIS, Landsat*

1. Introduction

The combined process of water loss from vegetation through transpiration and direct evaporation from the land surface is represented by Evapotranspiration (ET). It is a key component of the hydrological cycle and is therefore essential in quantifying the water budget and planning the water resources (Ray & Dadhwal, 2001; Mu et al., 2007; Sheffield et al., 2010; Baldocchi & Ryu, 2011). Large volume of water is transferred to the atmosphere by the process of ET that compels precise quantification of the consumption of water over large areas and within irrigated projects. Several studies has been conducted on estimation of ET in different spatial scale ranging from a leaf area to the basin scale (Senay et al., 2011). Estimation of ET is of prime importance for proper irrigation scheduling, water allocation, hydrological and climate modelling however it is difficult to calculate ET over land surfaces due to heteroginity soil surface , vegetation type and lack of knowledge on parameters affecting it (Mu et al., 2007; Sheffield et al., 2010; Senay et al., 2011). Precise information about temporal and spatial variations in ET is critical for better understanding of the interactions between land surfaces and the atmosphere and it is essential for study of water balance to improve water resources management (Mu et al., 2007).

Courault et al. (2005) has presented four model categories for ET estimation; (i) Direct Empirical Methods using remote sensing data, (ii) Residual methods of energy budget, (iii) Deterministic method using complex models like soil-vegetation-atmospheric transfer models and (iv) Direct empirical methods and vegetation index methods. Most of the ET measurements in the past are based on catchment scale water budget approach where evaporation is measured as residual of the water balance (Baldocchi & Ryu, 2011). The reliability of ET estimates is dependent upon presice measurement of other parameters such as precipitation and infiltration. Baldocchi & Ryu (2011) has further suggested the study of forest ET with the application of eddy covarience and upscaling the tower fluxes across complex landscapes (e.g. GAMUT watersheds) to estimate ET in regional and global scale.

Recently remote-sensing-based approach is widely used for estimating basin scale ET as it does not require information about the soil infiltration or precipitation as required in water balance approach (Ray & Dadhwal, 2001; Senay et al., 2011). In addition the ET estimation using vegetation index in arid and semiarid regions like intermountain west is more precise because ET is dominated by transpiration (Scott et al., 2008; Senay, et al., 2011). Different methods of estimating ET by using vegetation index has been proposed in which NDVI uses the difference in two adjacent bands in the red and near-infrared portion of the spectrum from the Landsat image (Groeneveld et al., 2007). Brunsell & Gillies (2003) and Groeneveld et al. (2007) used the NDVI approach using Landsat images to estimate ET in the arid regions. In both studies the raw value of NDVI is converted to scaled values (e.g. Fractional vegetation in Brunsell & Gillies 2003) assigning 0 to the bare soil and 1 for dense agricultural fields representing fully transpiring crops. As a result the NDVI values are normalized between 0 with 0 ET for bare soil to 1 with maximum ET for full vegetation cover (Senay et al., 2011). Interestingly Groeneveld et al. (2007) found that the annual ET calculated using this approach predicted the actual ET rate measured at moisture flux tower sites with a coefficient of determination (r^2) of 0.95.

This paper deals with the estimation of AET using the ET_r recordings from different meteorological stations in three watersheds in Northern Utah and the Fractional vegetation derived from the NDVI . The AET map for each watershed is plotted for four months having maximum ET_r. The main objectives of the study are to *1) to delineate the selected watershed from Digital Elevation Map, 2) to plot the values of ET to create ET map in three watersheds by applying interpolation using GIS 3) to estimate the actual ET loss from the catchments using the vegetation index from Landsat image*. This paper is composed of five sections including introduction. Section 2 states about the study area and the data applied for this project and section 3 explains the methodology and the sections 4 and 5 present results and conclusion respectively.

2. Study Area and Data

2.1 Study Area

This study is focused in three watersheds in Northern Utah; Logan River, Red Butte Creek and Provo River Watershed. All three watersheds have similar topographic feature with mountain to urban gradient as referred by GAMUT. Further description of the watersheds are presented below:

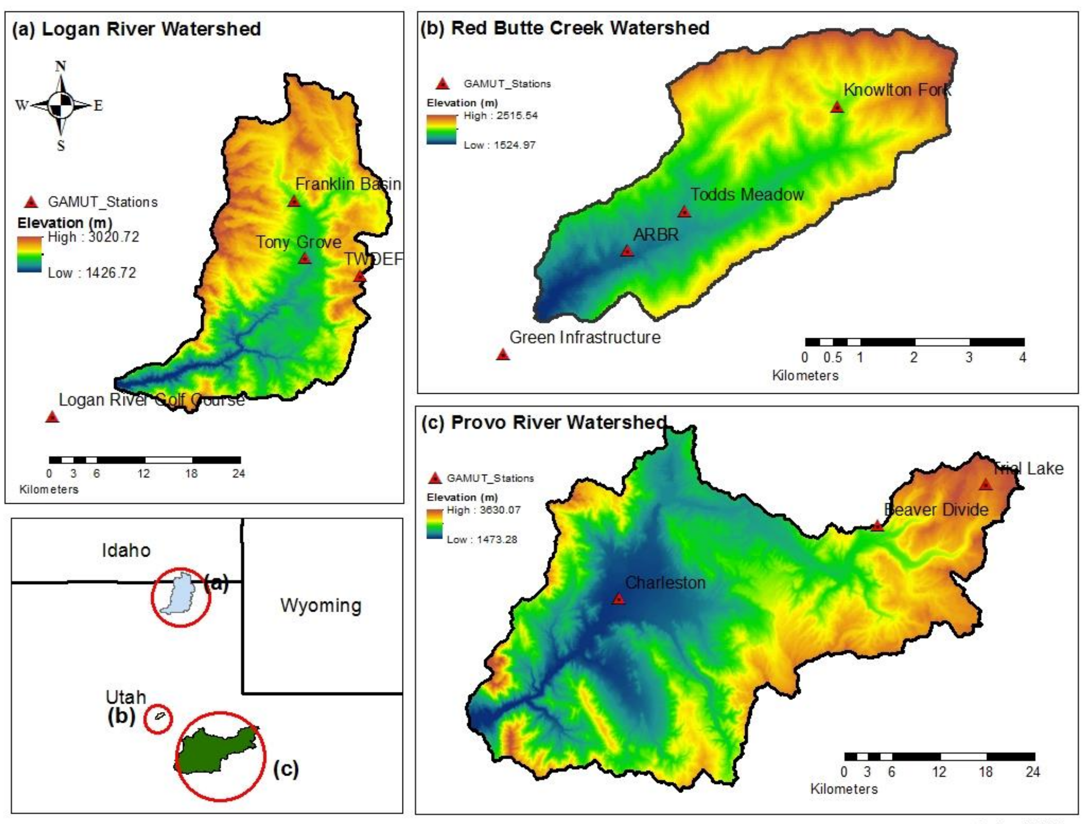


Figure 1 – Study area (a) Logan river watershed (b) Red Butte creek watershed (c) Provo river watershed and weather stations in each watershed

a) Provo River Watershed

The Provo River Watershed encompasses an area of 1700 km^2 with elevations between 1473 m and 3030 m (Figure 1-c). The Provo River originates at Trial Lake in the Uinta Mountains. It has two reservoirs created by Jordanelle Dam and Deer Creek Dam. After exiting from the high gradient it passes through urban plain of Orem and Provo and finally mixes with to Utah Lake (IUTAH 2014).

2.2 Data Collection

The data used for this project has been collected from the Innovative Urban Transitions and Arid region Hydro-sustainability (iUTAH) data repository, USGS and ESRI web services. Researchers from across the state of Utah are collaborating on an NSF-EPSCOR grant titled the iUTAH program to develop and install weather- and aquatic-stations. Participants will monitor and research water availability in the GAMUT. The weather- and aquatic-stations making up the GAMUT network measure different aspects of climate, hydrology, and water quality in three watersheds (*Logan River, Red Butte creek and Provo River watersheds*) in Northern Utah (IUTAH, 2014).The daily ETr data from eleven GAMUT meteorological stations within three watersheds in the study area has been obtained from the data repository website of iUTAH (repository.iutah-epscor.org/dataset). The locations of the weather stations is shown in Figure 1 with their coordinates and altitude in Table 1.

Table 1 – Meteorological stations in three watersheds

Station	Latitude	Longitude	Elevation	Network
Franklin Basin	41.950	-111.581	2109.52	Logan River
Logan River Golf Course	41.706	-111.854	1364.89	Logan River
Tony Grove	41.885	-111.569	1927.86	Logan River
TWD Experimental forest	41.865	-111.507	2629.20	Logan River
Beaver Divide	40.613	-111.098	2508.00	Provo River
Trial Lake	40.678	-110.948	3040.00	Provo River
Charleston	40.485	-111.463	1659.00	Provo River
Above Red Butte reservoir	40.781	-111.807	1666.04	Red Butte Creek
Green Infrastructure	40.761	-111.830	1487.12	Red Butte Creek
Knowlton Fork	40.810	-111.767	2178.10	Red Butte Creek
Todds Meadow	40.789	-111.796	1763.00	Red Butte Creek

The ETr is calculated using the standarized equation developed by American Scociety of Civil Engineers (ASCE), Environmental and Water Resources Institute (EWRI) as shown in equation 1 (Walter et al., 2002). The equation uses different coefficients to give two equations for calculating the ETr for short crop (grass) as ET_o and another for a taller crop (alfalfa) as ET_r (Allen et al. 2000). ETr represents the maximum possible ET of a hypothetical, freely transpiring reference alfalfa crop under a given set of meteorological conditions (Senay et al., 2011).The equations were developed for ET estimation in daily, hourly or even shorter time steps. The ASCE-EWRI standardized ETr equation is based on the FAO-56 Penman- Monteith equation (Allen et al., 1998) for a hypothetical crop with typical characteristics (Walter et al., 2002).

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s^{\,o} - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (1)$$

where :

R_n = net radiation at the grass surface (MJ m^{-2} $hour^{-1}$)

G = soil heat flux density (MJ m^{-2} $hour^{-1}$)

T = mean hourly air temperature (^oC)

Δ = saturation slope vapor pressure curve at T_{hr} (kPa $^oC^{-1}$)

e^o_s = saturation vapor pressure at air temperature T_{hr} (kPa)

e_a = average hourly actual vapor pressure (kPa)

u_2 = average hourly wind speed (m s^{-1})

C_n,C_d = Coefficients that varies for tall and short crops for day and night times

γ = psychrometric constant (kPa $^oC^{-1}$)

The Landsat 8 data is acquired from the distribution website of United States Geological Survey (USGS; http://glovis.usgs.gov/). One image was downloaded for each month (image dates: 2014/5/27; 2014/6/28; 2014/7/14; 2014/8/15) for path 38 and row 31 for Logan and, row 32 for RB creek and Provo watersheds. The Landsat 8 satellite which was launched in February of 2013, is equipped with Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). It collects images of the Earth with a 16-day repeat cycle in an 8-day offset to Landsat 7 (USGS, 2014). The approximate scene size is 170 km north-south by 183 km east-west.

3. Methodology

Brief methodological overview of this project is shown in figure 2, 3. The source and process of data collection is discussed in section 2.2. The point estimates of the ET_r values were plotted in GIS and interpolated across the selected watershed delineated from the Digital elevation Map (DEM). The output is then multiplied with the vegetation coefficient to get the AET using raster calculation in ArcGIS.

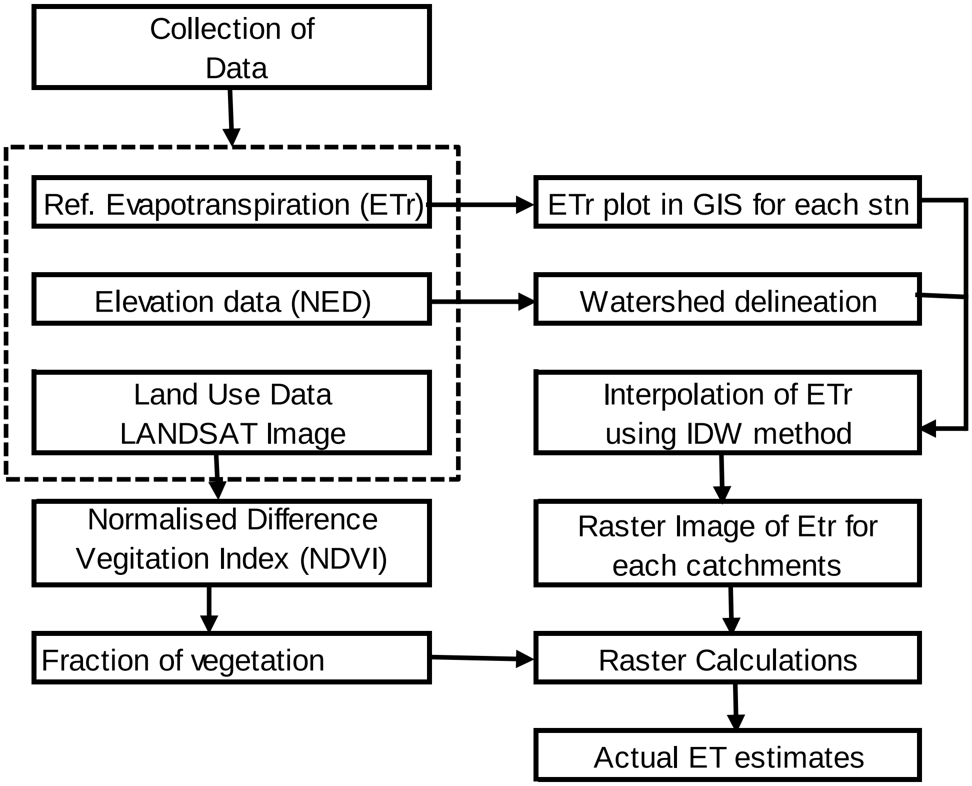


Figure 2 – Methodological chart for estimating actual evapotranspiration

Schematic view of the methodology is presented in figure 3.

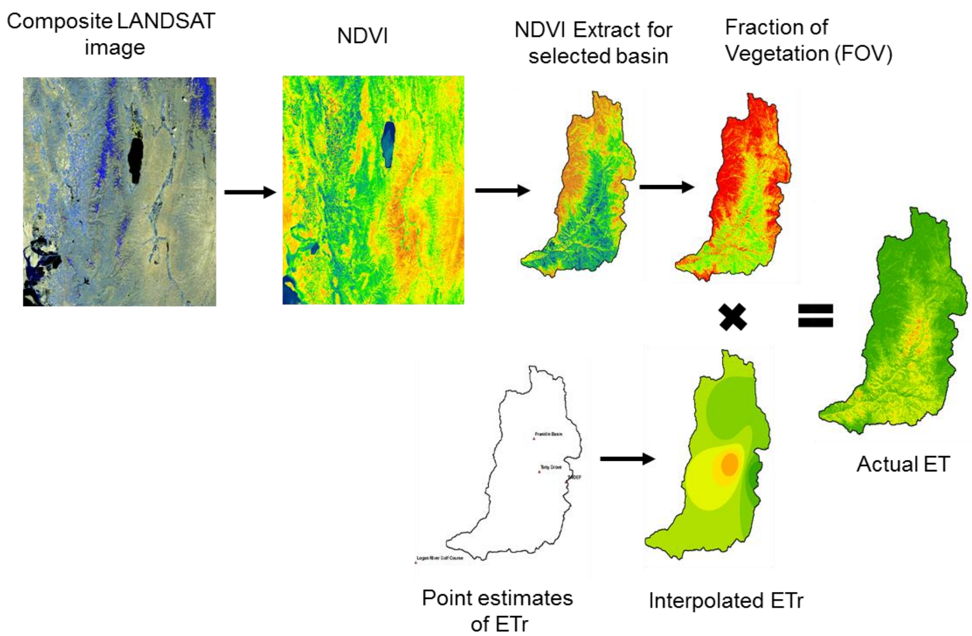


Figure 3 – Calculation of actual ET using Landsat image and point estimates of ETr

The ETr maps were generated by the interpolation of point estimates of ETr at selected stations using Inverse Distance Weightage (IDW) method. It is simple method of interpolation in which the interpolated value *u* at a given point **x** based on samples $u_i = u(x_i)$ for i = 1,2,3,….,N as shown in equation 2.

$$u(x) = \sum_{i=0}^{N} \frac{w_i(x) u_i}{\sum_{j=0}^{N} w_j(x)} \qquad (2)$$

Where, $w_i(x) = \frac{1}{d(x,x_i)^p}$ is a simple IDW weighting function (Shepard, 1968), x denotes an interpolated (arbitrary) point, x_i is an interpolating (known) point, *d* is a given distance (metric operator) from the known point x_i to the unknown point x, *N* is the total number of known points used in interpolation and *p* is a positive real number, called the power parameter.

Once the interpolation is done actual ET is calculated on the basis of fraction of vegetation derived from the NDVI as **AET = ET_r * FOV**; where, FOV is Fraction of Vegetation calculated as shown in equation 3 (Brunsell & Gillies, 2003) and ET_r is the alfalfa ETr and is about 20% more than ETo which is for short grass (Senay et al., 2011).

$$\mathrm{FOV} = \left(\frac{\mathrm{NDVI} - \mathrm{NDVI}_o}{\mathrm{NDVI}_{max} + \mathrm{NDVI}_o}\right)^2 \qquad (3)$$

$NDVI_{max}$ is the maximum NDVI in the Landsat image for watershed that represents the fully vegetated surface whereas $NDVI_o$ is for the lowest NDVI value in the watershed representing the bare soil surface. NDVI is calculated using the image processing tool in the ArcGIS.

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})} \qquad (4)$$

NDVI is calculated as shown in equation 4 where NIR and RED are spectral reflectance measurements for near infrared and red band of electromagnetic spectrum (Brunsell & Gillies 2003; Mu et al., 2007)).

Results

This section deals with the output from this project. As one of the objective the point estimates of ETr were plotted and interpolated using IDW method present in ArcGIS10.2 software. Further raster calculations were performed to estimate the AET for the selected watersheds. Time series plot of the ETr for selected meteorological stations is shown in figure 4.

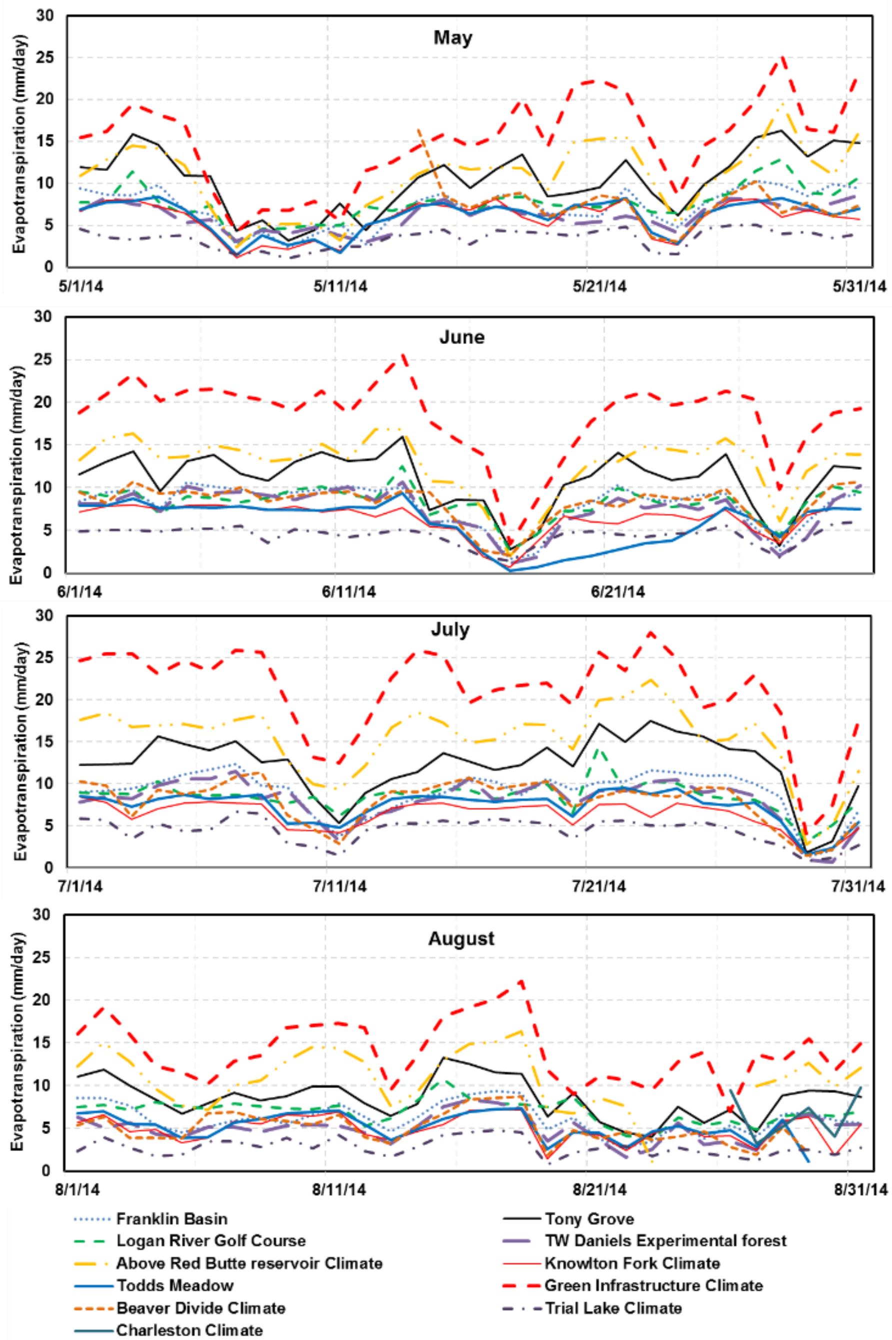
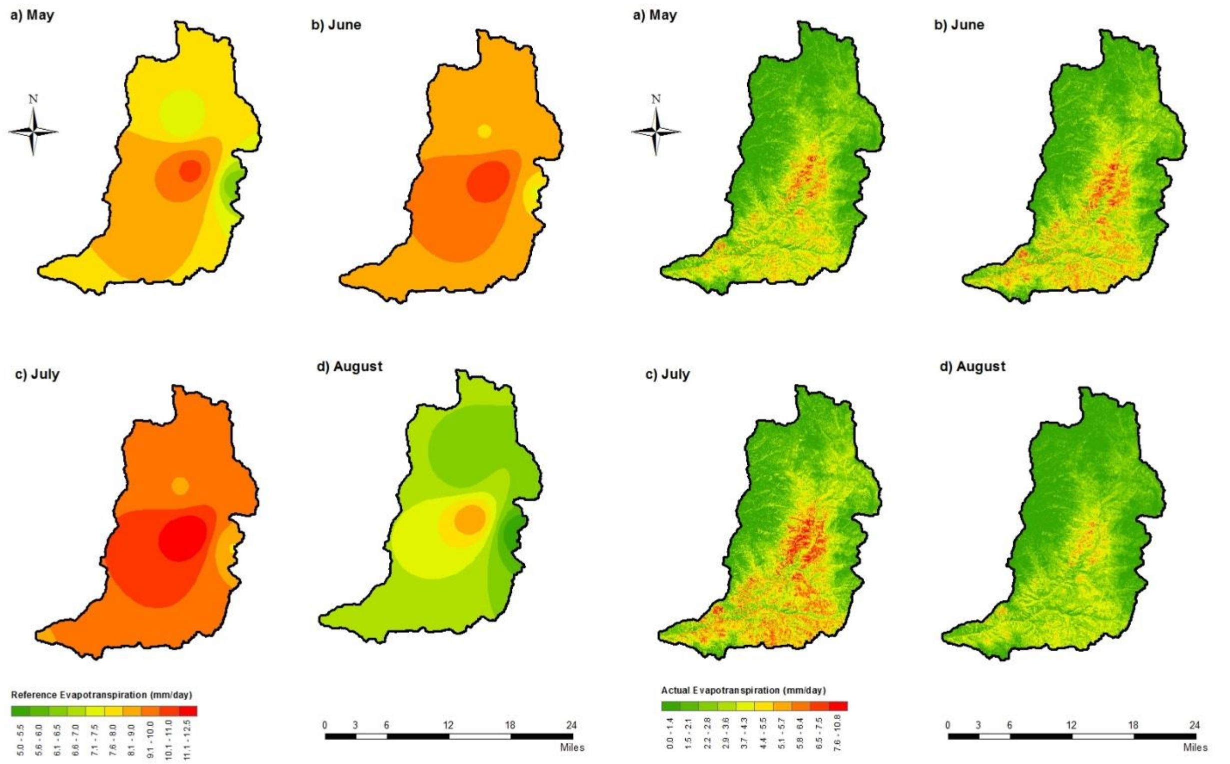


Figure 4 - Daily ETr for different stations in three watersheds for month of May, June, July and August

The daily values of ETr from each stations are plotted in figure 4 for four months (May, June, July, August) showing comparatively higher ET rates as compared to other months. The ET estimated for the stations Green Infrastructure, ARBR in the RB creek watershed and Tony grove in the Logan river watershed is relatively higher than others in each month. For the four months, the spatial interpolation of the ETr and calculated AET are shown in figure 5, 6, 7.

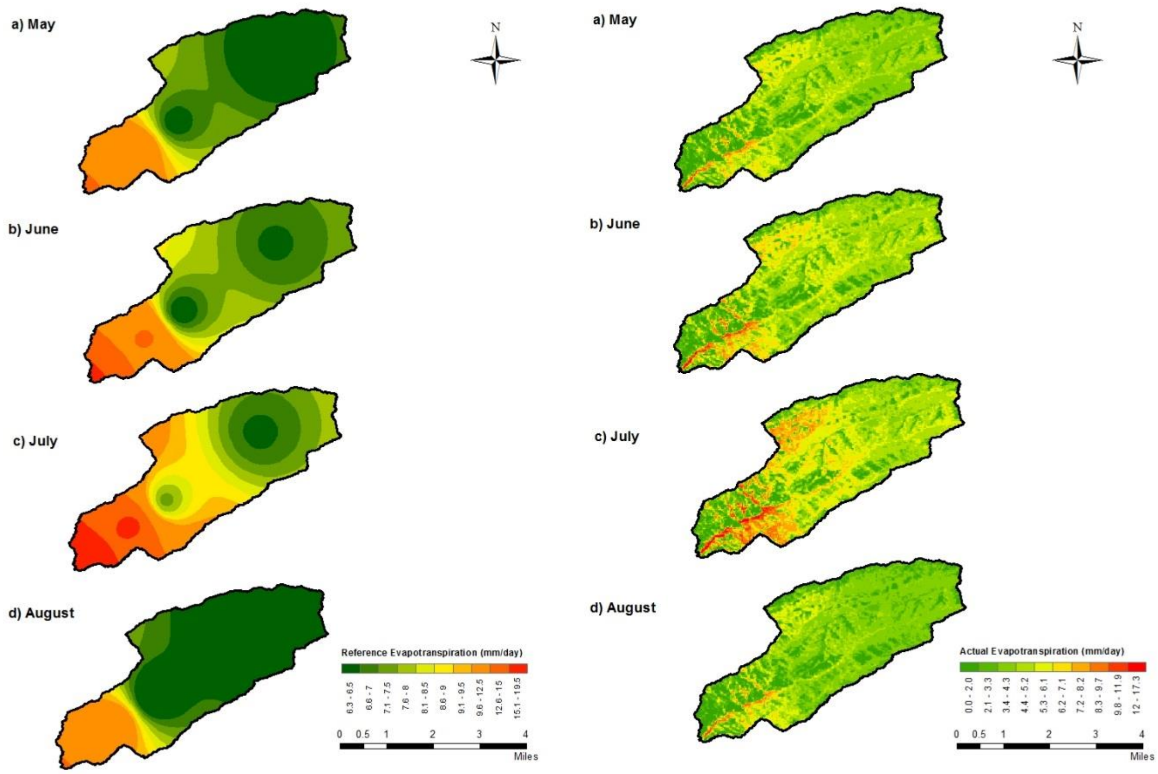


(i) *(ii)*

Figure 5 – Monthly average of daily (i) ETr and (ii) actual ET for Logan river basin for different months

The ETr has values in Logan river watershed is ranging from 5 mm/day to 12.5 mm/day (Figure 5-i). If we consider the month of June and July whole watershed loses more than 10 mm water through ET however for the month of August only the central part of basin shows high ET about 8 mm/day and most of the part is lower than 6 mm/day. The higher values at central part suggests the influence of the upper ET estimates from Tony Grove station. The AET estimated in figure 5-ii however gives more realistic estimates for ET showing the value ranging from 0 to 11 mm/day. Most of the parts in the watershed has lower values that suggests underestimation of AET as it has considered only the water loss through the vegetation cover neglecting the evaporation from the bare lands. The central and lower west part that has more vegetated surface shows more AET.

The interpolation of the ETr in the RB creek watershed are influenced by higher ET in the lower part due to the estimates from Green Infrastructure and ARBR and lower values from Knowlton Fork (Figure 6-i). The upstream lower values in the upstream and higher in the downstream of the watershed suggests the decrease in ET rate with increase of elevation. However the drastic spatial variation in ET values in smaller watersheds like RB creek requires further studies. In figure 6-i, it is shown that the lower part of the watershed has higher ETr of 19 mm/day whereas the upper part has the values as low as 6 mm/day during July. On the other hand the AET values range from 0 mm/day in the pixels with no vegetation to the highest of 17 mm/day lower part of the watershed during the month of July (figure 6-ii).

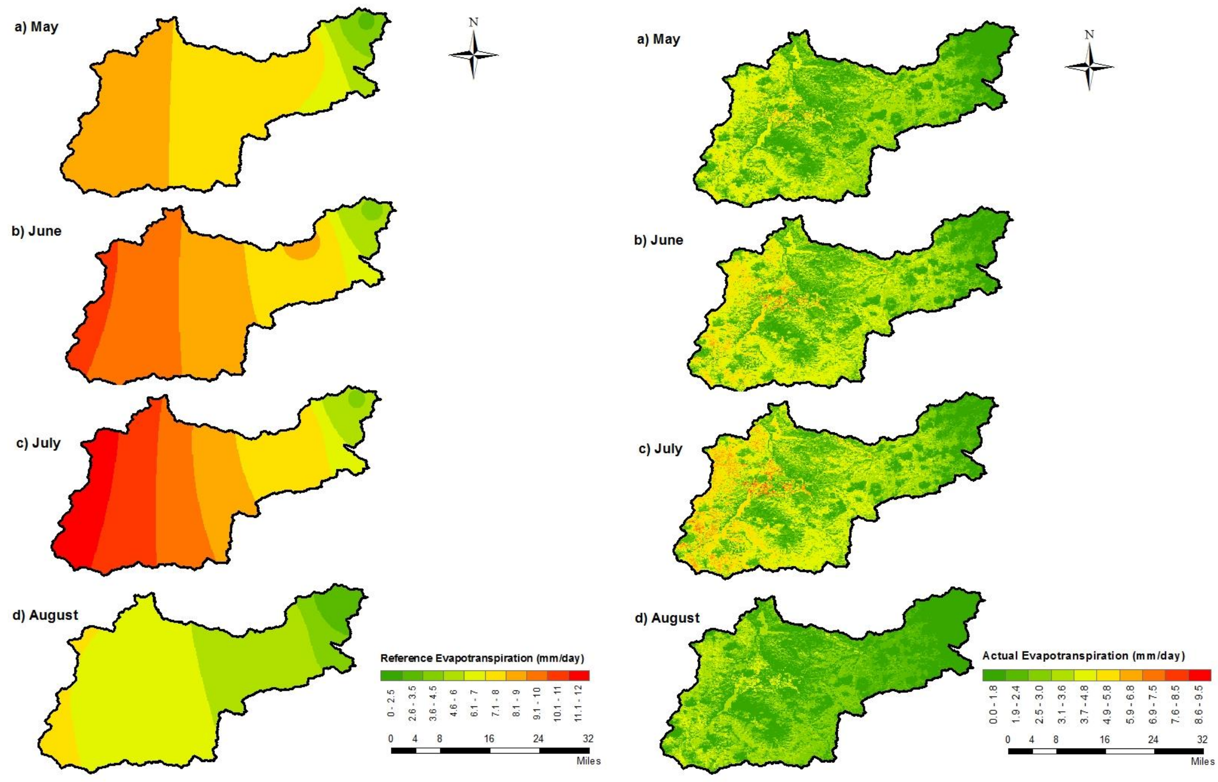


(i) *(ii)*

Figure 6 - Monthly average of daily (i) ETr and (ii) actual ET for Red Butte creek watershed for different months

Provo river watershed being a larger watershed in this study has less number of weather stations providing the estimates of ETr. Interpolation shows the large values of ETr, more than 9 mm/day for most of the lower part from Beaver Divide (Figure 7-i). While comparing the output from all the watersheds the lower elevation seem to have reduced ET as compared to the higher elevation. The values of AET in the lower part of the watershed shows the higher values of around 5-6 mm/day in most of the parts for the month of June and July (Figure 7-ii). Relatively higher ET is estimated around the area of the Jordanelle reservoir in Charlston.

On comparing the AET of three watersheds the common observance is reduction in ETr and ET along the increase in altitude. Further analysis and comparison with other variables will be performed in future.



(i) *(ii)*

Figure 7 - Monthly average of daily (i) ETr and (ii) actual ET for Provo river basin for different months

Conclusion

Direct ground observations of ET are not common. Estimating the parameters required for calculation of ET in each location of interest is challenging hence interpolation or upscaling of the ET values from measured stations the can be a better option to estimate the ET in larger spatial scale. At larger scales (watershed scale or regional) it aids in evaluation of spatial and temporal variability of ET. This would help is tracking the change in the hydrologic cycle, by supporting hydrologic and climate modelling thus enhancing the effective planning of water use.

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