Advancing Stormwater Beneficial Uses: ET Mapping in Urban Areas

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ABSTRACT

In the United States, monitoring Evapotranspiration (ET) is primarily focused in agricultural and wildland environments. With educational advancements stressing water conservation in urban areas, there is a newfound desire to apply ET data as part of wastewater reuse options for supplemental irrigation, and for more accurate modeling of rain garden and green roof controls for stormwater management. Unfortunately, most publicly available data located near urban areas is found to be substantially different from a well-watered landscape surface and required conversion for use. Likewise, adjustment factors for different landscape surfaces are, in most cases, developed for agricultural situations and their use in highly disturbed urban environments has not been well documented. One of the products of this research examined these available ET_o values and then mapped them for major urban areas. The product of mapping these locations will be used in conjunction with associated rainfall information to calculate irrigation requirements in urban areas as part of a WERF-sponsored project on the beneficial uses of stormwater.

INTRODUCTION

Water Evapotranspiration (ET) can be an important aspect to complete a water balance in a bioretention device (Pitt et al., 2008). ET represents the water loss from plant and soil surfaces. Evaporation, the first component in ET, is commonly understood in society because its effects can be measured and are in many cases visible to the eye. Transpiration is the process by which plants expel water drawn from the soil. These elements combine to form ET, which can be measured by a multitude of methods. The water, most of which is not retained in the plant, transports the essential nutrients plants need for growth. Therefore, monitoring water loss by ET, especially during a growing season, is critical in maintaining a suitable level of soil moisture. The research conducted in this report looks at the current uses of ET and its applicability to stormwater management practices. The goal is to improve the beneficial uses of stormwater in urban areas. The research is supported by the WERF.

In this report, most of the ET values are sourced from historic records collected by Remote Automated Weather Stations (RAWS). One of the products of this research

is to examine these available ET_o values and map them for major urban areas. The product of mapping these locations could be used in conjunction with associated rainfall information to calculate irrigation requirements for alternative uses for stormwater. Users will then be able to choose ET_o values from tabulated data by regional maps that best fit their location.

METHODS and MATERIALS

In the United States, monitoring Evapotranspiration (ET) is primarily focused in agricultural and wildland environments. In agriculture, the growth potential of crops is dependent on a farmer's ability to monitor soil moisture for use in irrigation. Their ability to determine irrigation requirements is based on potential ET for the crop planted. With each different crop, the estimated ET will change. An approximation of this water loss helps form an irrigation schedule for the duration of a crop's growing season. Therefore, most available data and coefficients are developed for plant species associated with agriculture. A task of this project is to provide ET data for use in disturbed urban environments such as a major metropolitan area in any state. This, of course, is vastly different than a crop field or a nearby national park. The results from these agricultural-based methods in urban environments have not been well documented.

The next major focus, wildland and rangeland areas, are common in most regions of the U.S. Most of these areas are sparsely populated, and are more vulnerable to natural disasters such as wildfires. In monitoring ET in these areas, the goal is not to recharge soil moisture as in agriculture, but instead monitor drought and land management. The difference between agricultural and wildland ET is primarily that, outside of forestry, these areas are not harvested. Wildland ET is executed by placing weather stations into rural locations that constantly monitor ambient conditions and communicate those conditions by satellite. These RAWS systems are an excellent source for ET and complete climate data for most of the United States. RAWS play a critical role in defending wildfires, especially in the western U.S. Researchers monitoring air quality and climate change also use RAWS extensively. Data collected by these stations is forwarded to many organizations that collect and store this data for later use. The data is available to the public over the internet at locations such as the RAWS Climate Archive.

Researching these two main areas can be completed in many ways. Instead of creating a new weather station, researchers may be able to use archives for a specific region. One of the areas where these archives then become a valuable resource is stormwater management practices. Some of these emerging practices include wastewater reuse options for supplemental irrigation, and more accurate modeling of rain garden and green roof controls. Bioretention devices are a broad category of emerging stormwater that are being applied in many areas of the U.S., although they are most popular along the eastern coast (Pitt et al., 2008). However, most data available publicly does not cover areas where these devices are being implemented. Researchers conducting experiments in stormwater management often use equipment

similar to RAWS for monitoring ambient conditions for an experiment. During a recent comparison of rain gardens in clay and sandy soils by the United States Geological Survey (USGS), ET was used extensively to compare infiltration rates for turf grasses to natural prairie vegetation (Selbig, 2010). The ET was calculated using an onsite weather station.

Alternatively, it may be viable to collect ET onsite. However, collecting time-series data onsite can be impractical for large-scale management practices. There is then a need for resources to estimate the ET portion in a water balance. The ET is used to calculate an irrigation requirement by subtracting the percent of precipitation used as soil recharge from the estimated ET.

There is no single system capable of predicting average monthly ET rates for any location in the U.S. that is available within the public sector. There are, however, several state and regionally based systems that provide rates for parts of the U.S. This leads to an overall lack of availability in approved ET rates for use by professionals in areas outside those zones. Those areas not covered include a majority of the U.S. (more specifically eastern states) and an even larger percent of urban areas. As previously stated most of the ET data available comes from states west of the Mississippi River. Some of the most established resources are listed below.

- California Irrigation Management Information System (CIMIS)
- Florida Automated Weather Network (FAWN)
- AgriMet
- Rainmaster
- Texas ET Network

Mapping in urban areas began by collecting relevant data from these sites and then matching it to data offered by the Western Regional Climate Center (WRCC). After collecting select data from the RAWS archive, several issues were noticed when comparing the data to approved rates from the sources listed above and other meteorological-based ET data. In general, the trend for the RAWS data was lower in spring and summer months and higher in the fall and winter. Most often rates differed by approximately 30 to 50 percent, but in some cases the differences could be in excess of 100 percent or higher. Several factors could contribute to the deviation from data from an expected norm, but each factor considered is not solely responsible for the deviation. Instead they are most likely interrelated, and deviations for a single factor may alter one or more compounding the resulting difference. The major factors are listed below.

- Wind speed
- Mean Temperature
- Elevation
- Humidity
- Seasonal Precipitation

A comparison of WRCC data against accepted values is required to validate the ET rates for use with bioretention devices. As seen below in Figure 1, there can be much variation between the approved rates and the data collected by the WRCC. The goal for the comparison is to determine the differences associated with WRCC values when compared to approved rates. It is expected that the trends would vary by region with climate, elevation, distance from the equator, and land use. All these factors affect the growing season of plants and trees. For example, most areas of the southeastern U.S. have near year round growing seasons, where portions of the northern U.S. are severely limited due to surface freezing. Additionally, factors such as vegetative density and plant species will also affect ET for a site. A study of the effects of site conditions on ET estimates was conducted in California to estimate ET for landscape plants. The study outlined three factors that distinctly alter the estimated ET for a site. In the next section, we will consider these factors to further refine the method of converting the WRCC wildland data into well-watered ET estimates.
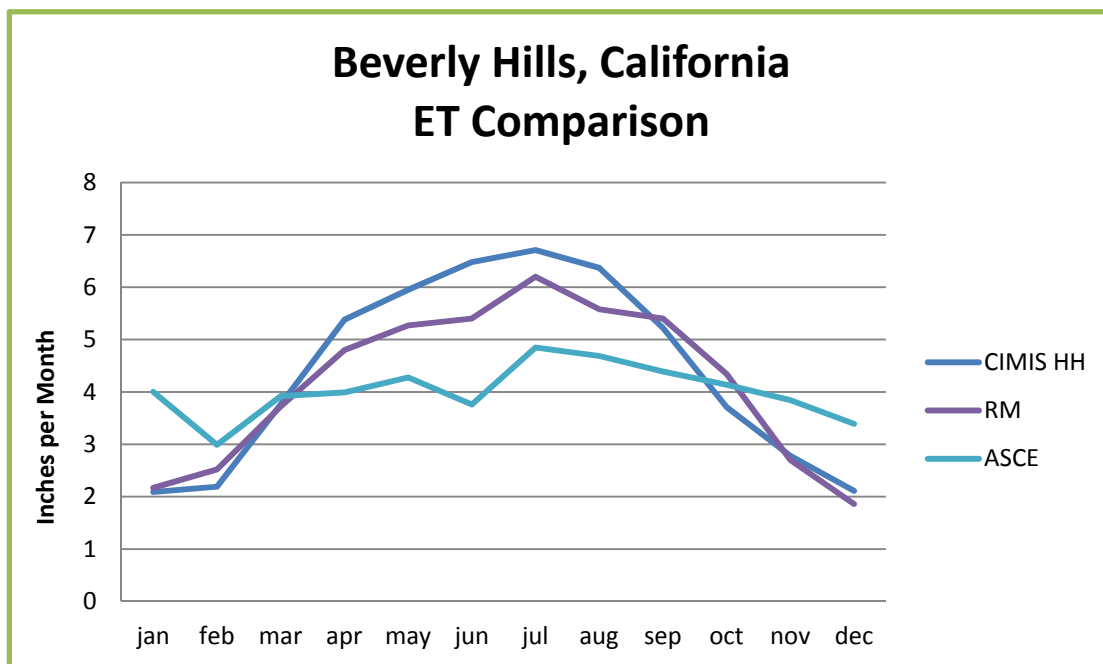
Figure 1. CIMIS, Rainmaster, and RAWS ASCE Average Monthly Data Comparison

A good lead to determining the relationship between the WRCC data and more practical agriculturally based values comes from a landscape plants study in California. The guide is a free publication from the California Department of Water Resources, and is a combination of two significant publications: *A Guide to Estimating Irrigation Needs of Landscape Plantings in California*: The Landscape Coefficient Method and *WUCOLS II*. The research was intended to reevaluate ET rates intended for crops for use in urban settings such as a landscaped park, home, or business. In theory, this research can be used in reverse to modify the natural

conditions monitored in a wildland environment into useful rates for urban environments. There are three factors that are evaluated for a site that determine a site coefficient: Species factors, Density factors, and Microclimate factors. These factors, once evaluated, are multiplied together to form a landscape plant coefficient (K_L). The coefficient is then multiplied by the local ET value to produce a water use estimate for the site. Because RAWS sites use a known water estimate, the guidelines can be used to estimate wildland conditions, and convert the values into more typical ET estimates that exceed annual rainfall. This, in turn, will help determine the potential water deficit in a given area.

This proposed method was tested at the RAWS located in the Talladega National Forest, Oakmulgee Division in Brent, Alabama shown below in Figure 2. As previously stated, the site is erected in a small field surrounded by tall mixed timber. The ground cover surrounding the site is a low-density cool season grass species. To develop a correction factor, you must first assign the three site condition coefficients as seen in Table 1 and Table 2. The new coefficients are then applied to the growing season data (April to October) by dividing the original RAWS data by the new correction factor (K_L). The results, though initially rough (as seen in Figure 3), are raised to expected levels for a well-watered reference surface. Still, using this method requires the ability to visit a site. Without a site visit, it would be difficult to make the required assumptions to convert the data. Thus, this method could not be used for converting the RAWS data used in this report. The number of sites covered in the research and expansiveness of the travel area eliminate this method for the purposes of this project.

**Figure 2. Oakmulgee, Alabama RAWS Site Conditions**

Table 1. Landscape Coefficient Method Assessment Standards (Costello et al., 2000)

Estimated Values of Landscape Coefficient Factors				
	Very Low	Low	Moderate	High
Species Factor	<0.1	0.1 to 0.3	0.4 to 0.6	0.7 to 0.9
Density Factor	-	0.5 to 0.9	1	1.1 to 1.3
Microclimate Factor	-	0.5 to 0.9	1	1.1 to 1.4

Table 2. Landscape Coefficient Estimate from Observations at Oakmulgee RAWS site

k values	Observed Site Conditions	Assessed Category	Estimated Coefficient
Species Factor	cool season grasses	High	.9*/.95
Density Factor	Low density groundcover	Low	0.75
Microclimate	Shaded with wind	Low	0.65

protection	
	.43*/.46

*Slight reduction in species factor to account for early spring growing season

Oakmulgee RAWS Average Monthly ETo
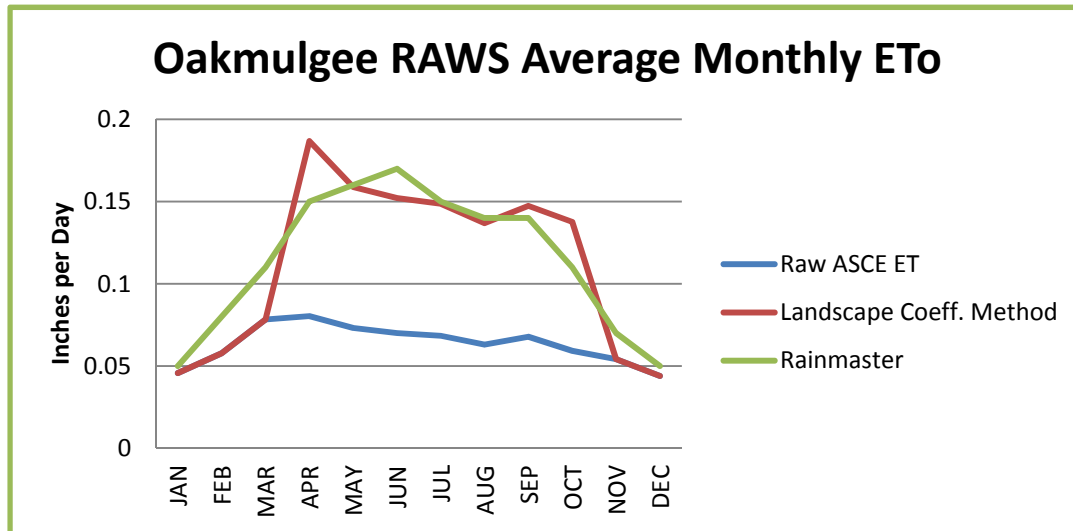
Figure 3. Landscape Coefficients Method Estimate for Oakmulgee, AL

A more practical approach is required for relating RAWS data to that of a well-watered crop. Similarly to the Landscape Method, by dividing RAWS data by approved rates, a coefficient is recovered that can be used to convert RAWS data into well-watered ET estimates. To simplify the coefficients, they are rounded to the nearest 5/1000th place. In the case that RAWS data exceeded approved values (almost always occurring in winter months), the coefficient is set to one in order show an increased potential for ET at the site. In areas where multiple ET sources are available, the highest estimates are utilized. In areas where no publicly available data can be used, the rates were compared to Rainmaster data with the nearest zip code. This method produces the best expected conditions for all data in the U.S. and could be useful in developing long-term coefficients for the sites covered in the report.

Table 2. Method for Converting RAWS Data

	Correction Factor	=RAWS/Rainmaster	RAWS ASCE(in/day)	Rainmaster (in/day)	ASCE(in/day) Converted
JAN	1	#DIV/0!	0.02	0	0.019
FEB	1	#DIV/0!	0.03	0	0.026
MAR	0.4	0.389964158	0.04	0.09	0.088
APR	0.35	0.344761905	0.05	0.14	0.137
MAY	0.275	0.287347561	0.05	0.16	0.167
JUN	0.25	0.252042484	0.04	0.17	0.171
JUL	0.225	0.243330119	0.04	0.17	0.184
AUG	0.225	0.233873874	0.04	0.15	0.156

SEP	0.225	0.243162393	0.03	0.13	0.141
OCT	0.225	0.217350158	0.02	0.1	0.096
NOV	0.225	0.319910515	0.02	0.06	0.085
DEC	0.5	0.491721854	0.02	0.04	0.039
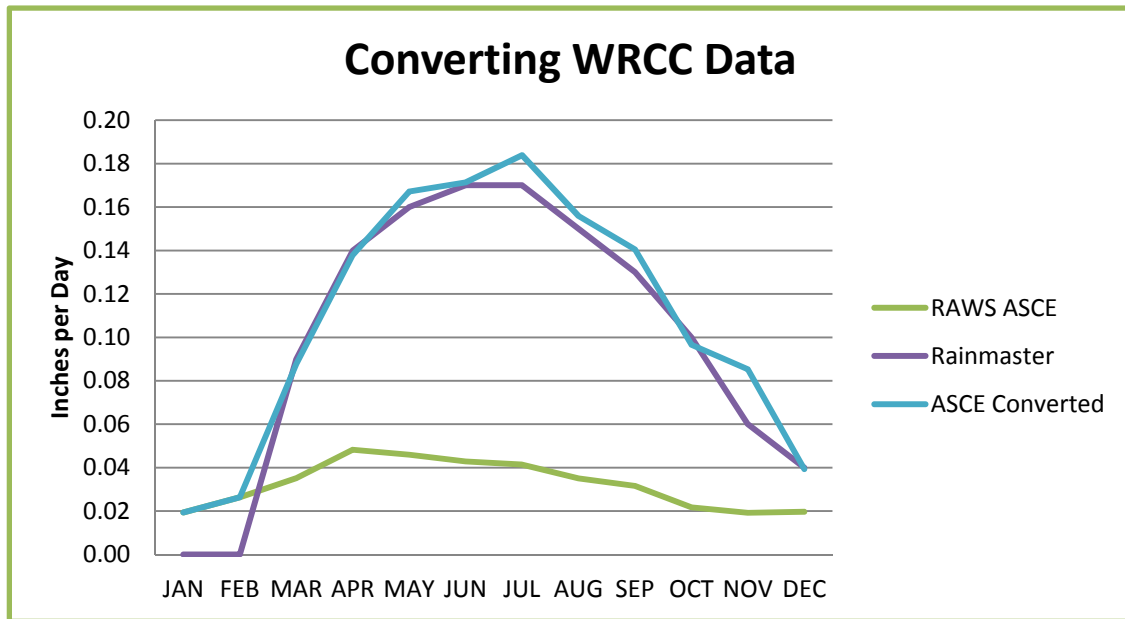
Figure 4. Averages of RAWS Data Before and After Conversion

RESULTS and CONCLUSION

ET is defined as the rate at which readily available water is removed from the soil and plant surfaces expressed as the rate of latent heat transfer per unit area λET_{ref} or expressed as a depth of water evaporated and transpired from a reference crop (Jensen et al., 1990). Meaning that unless soil moisture is kept near field capacity, there will be times when ET estimates outweigh actual ET removed from the soil. Therefore, any comparison of ET methods or sources would instead follow a pragmatic approach. Calculating ET for the short reference crop does not mean that the values produced are only relevant for a small group of well-watered cool season grasses. Instead, the short grass or alfalfa is merely a baseline for numerous other plant or crop surfaces that require ET estimates during a growing season. A plant's actual ET is calculated from the product of these original equations by multiplying ET_o by approved coefficients for each plant type providing a daily estimate for the crop under well watered conditions. There are lists of approved coefficients (such as WUCOLS III) for both grass reference and alfalfa values, however these values are not interchangeable.

As previously stated, the primary difference between these two equations offered by the WRCC is their reference crop. In most cases, a short grass reference crop would be preferred in an urban setting because most landscapes are based on a

well-maintained grassy surface. Grasses are resilient plants and often recover in difficult drought conditions. However, grasses have limitations such as root depth that affect their applicability in stormwater reuse (e.g. rain gardens). Therefore, some users may believe that some plants and shrubs may be modeled better using an alfalfa reference ET. Alfalfa has a much deeper root system than a turf grass material. Hence some plants and shrubs with deeper root systems could have the ability to remove water held deeper in the soil than grass increasing the storage potential for a site as well as reducing losses from runoff. This approach could be supported in a study of prairie shrubs planted in rain gardens conducted in Wisconsin. The plants develop a root system capable of penetrating deep into the soil and may increase infiltrative capacity by creating macropores and other fissures allowing more rapid movement of water (Selbig, 2010). In reality, either of the methods could be useful for this kind of research because they offer the same information in a slightly different format. Coefficients have been developed for both grass and alfalfa references and since both rates are modeled from the same set of meteorological data there is not any significant difference between these values and the use of one over the other then becomes a matter of preference or necessity.

The eastern U.S. lacks ET data, perhaps because there is no major agriculture or wildland. With increasing interest in researching stormwater management issues, the collection of climate data in the eastern U.S. and more specifically urban areas is a necessity. Inversely, most RAWS units capable of monitoring the ambient conditions required to estimate ET using the Penman equation are most often located in the western U.S.   Since the number of available RAWS locations is lower in the east; it is important to map the locations closest to urban areas. Conversely, there is limited documentation of the applicability of rural ET for use in urban areas.

It is estimated that there are noticeable differences in ET with land use (industrial areas, residential zones, downtown cityscapes). One of the issues that could exclude these stations as an ET source is the development of boundary layers from urban micro-climates (Grimmond and Oke, 1999). The formation of boundary layers may affect performance consistency between ET measured in a city versus ET collected along the edge of the city where a RAWS stations is most likely located. It is then important to continue documentation comparing the differences between urban experiments and rural based data and methods. Such experimentation will aid in the development of methods for utilizing this type of data in an urban setting.

Adding to the issue, since RAWS are located in natural environments, no supplemental irrigation is added to monitored zones creating an extremely reduced ET estimate for each site. The development of coefficients that modify the existing data to compare against approved rates could serve as a preliminary relation between the ambient differences for each site. As more data is recovered, a follow-up should be conducted to see if the coefficients are once again able to relate the natural conditions to those of a well-watered grass reference. Additionally, research should be conducted to determine if the elevated rates during winter months are a true perception for these sites. Otherwise additional time should be invested at

determining the reason for the overestimation and developing a second relation to adjust the higher rates for winter months.

A product of the research is a series of maps and tables that describe the physical location for each weather station and the average monthly ET rates for the site. The map key is used to determine the appropriate station to use for a site. Once the nearest station or stations is chosen from the map, the number can be cross-referenced with the Map ID from the table. An example map is shown in Figure 5 below.
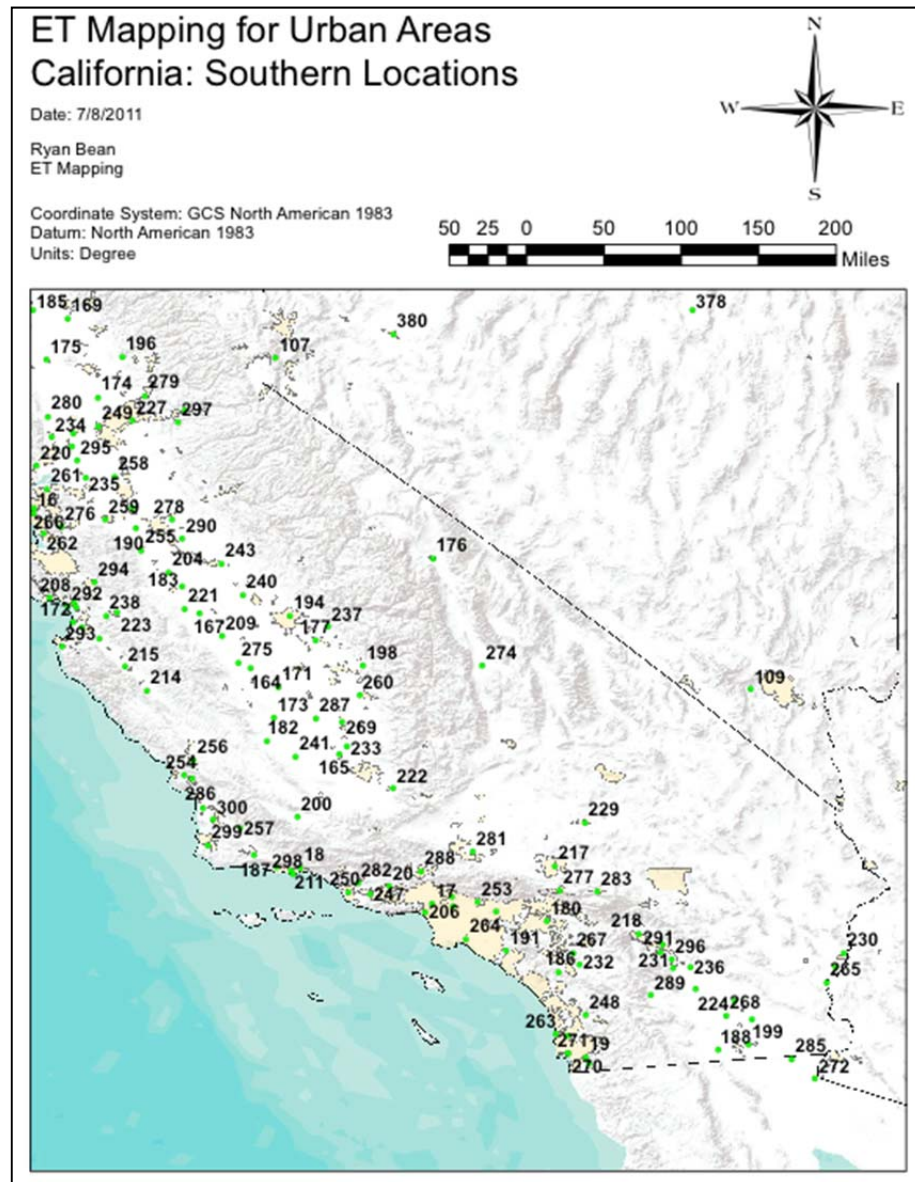

Figure 5. Collected Locations for Southern California

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