Spatial Interpolation of Daily Reference Evapotranspiration in the Texas High Plains

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ABSTRACT

The Texas High Plains Evapotranspiration (ET) Network collects meteorological data from 18 grass weather stations at hourly intervals and estimates hourly and daily reference ET using the American Society of Civil Engineers (ASCE) Standardized Reference ET equation. Producers in the Texas High Plains can obtain daily reference ET for any weather station of their interest by subscribing to the fax/email service. However, one concern in using these data is to determine which reference weather station best represents climatic conditions similar to those in their irrigated fields. Availability of accurate daily reference ET maps for the Texas High Plains is expected not only to relieve producers from this concern but also to assist in attracting more producers to adopt the reference ET-based irrigation scheduling. Therefore, the main objective of this study is to evaluate two spatial interpolation methods such as inverse distance weighting (IDW) and ordinary kriging for mapping reference ET in the Texas High Plains. Daily grass reference ET maps were developed for the Texas High Plains using ordinary kriging and IDW methods for the period of 2000-2005, and assessed for mapping accuracy using Root Mean Square Error (RMSE). Comparison of RMSE values between IDW and ordinary kriging methods indicated that IDW outperforms ordinary kriging for approximately 68 % of 2179 days. However, both methods equally performed poorly during summer growing seasons when accurate grass reference ET maps are needed for irrigation scheduling.

INTRODUCTION

Daily grass/alfalfa reference evapotranspiration (ET) is widely used with crop coefficients to estimate crop water demand for irrigation scheduling purposes in irrigated regions of the world. Reference ET can be estimated using either FAO-56 (Allen et al., 1998) or the ASCE Standardized Reference ET Equation (ASCE-EWRI, 2005). Input weather parameters (solar radiation, wind speed, air temperature, and relative humidity), usually measured on a reference crop surface such as grass and alfalfa, are required for estimating reference ET. These values are used to estimate crop water demand for an individual crop by multiplying reference ET with a crop coefficient under an assumption that weather condition on the reference crop surface is similar to that in the surrounding region. In the irrigated, semi-arid Texas High Plains, the Texas High Plains ET (TXHPET) Network provides daily reference ET values via fax/email to producers and crop consultants who subscribed for this service to determine irrigation demand on individual fields. As part of the subscription, users are required to select a TXHPET weather station nearest to their irrigated croplands. One major concern with this approach is to determine which reference weather station best represents climatic conditions similar to those in their irrigated fields. Changing wind directions during the cropping season and topographic variability further complicate the solution to this problem. Erroneous selection of reference weather station and/or wrong values of reference ET rates may affect the water use efficiency and consequently producers' net profits.

Dense network of weather stations can effectively capture the spatial variability in reference ET; however, this requires great installation and operational costs. By recognizing this need, more sophisticated geostatistical techniques have been developed (Goovaerts, 2000) to perform spatial interpolation of either climatic data or daily reference ET (Kurtzman and Kadmon, 1999; Courault and Monestiez, 1999). Producers can obtain reference ET values by using geographic coordinates of their fields with interpolated reference ET maps. However, high variation in air temperature, wind speed, wind direction and other weather parameters due to both local effects such as topography (Goovaerts, 2000), land use (Li et al., 2010), elevation (Dodson and Marks, 1997), soil properties (López-Granados et al., 2005); and regional effects such as atmospheric circulation patterns (Buishand and Brandsma, 1997; Knapp, 1992) make it difficult to use one predetermined spatial interpolation technique and/or fitting model for interpolating and mapping reference ET over the region. It demands structural analysis of the dataset (Courault and Monestiez, 1999) at a daily time-step for selecting suitable interpolation technique and a model for creating accurate reference ET maps. Often different interpolation techniques available in the literature have had inherent advantages and disadvantages.

Inverse distance weighting (IDW) and ordinary kriging have been utilized widely in ecological modeling, agriculture and climate research (Kurtzman and Kadmon, 1999), mining, mineral exploration, and soil science research (Webster and Burgess, 1983). The IDW is a simple, intuitive, and non-statistical spatial interpolation method based on the principle that an observed value closer to the prediction location has more

influence on the predicted value than other observed values located farther apart (Simanton and Osborn, 1980). This method uses the nearest sampling points that are weighted by a power proportional to the inverse of their distance from the estimated point. The interpolator $\hat{z}$ for the IDW is obtained by

$$\hat{z}(x_o) = \frac{\sum_{i=1}^{n} z(x_i)\, d_{ij}^{-r}}{\sum_{i=1}^{n} d_{ij}^{-r}} \tag{1}$$

where x_o is the estimation point, x_i is a data point within a chosen neighborhood, z is the data value, r is weight, and d_{ij} is the distance between the estimation and the data point (Robinson and Metternicht, 2006).

Ordinary kriging is a widely recognized statistical method which predicts unknown values using observed data from a region where a variogram is known (Webster and Oliver, 2001). The experimental variogram for a separation distance h, which is half the average squared difference between values at $z(x_i)$ and $z(x_i + h)$, is described as

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[z(x_i) - z(x_i + h) \right]^2 \tag{2}$$

where $N(h)$ is the number of datasets within a given class of distance and direction (Robinson and Metternicht, 2006). Kriging is based on the variance structure that may exist in data. The absence or presence of such structure can be revealed from the variogram (Hajrasuliha et al., 1980). Kriging generally uses a user-selected variogram model among linear, exponential, Gaussian, or spherical models to express the spatial variation.

Numerous studies have been reported on the application of IDW and ordinary kriging methods for mapping purposes in precision agriculture. For example, the IDW and ordinary kriging methods were used for mapping soil organic matter and nitrogen concentration to manage fertilizer application in central Nebraska (Gotway et al., 1996). Results from this study suggested that IDW outperformed ordinary kriging for mapping soil organic matter and ordinary kriging performed well for soil nitrogen mapping. This is because IDW has the tendency to be less accurate with higher coefficient of variation. Thus, careful choice on interpolation method was recommended by Gotway et al. (1996). In a study conducted in Western Australia, ordinary kriging, lognormal ordinary kriging, IDW, and splines were used to interpolate soil properties such as pH, electric conductivity, and organic matter (Robinson and Metternicht, 2006). Comparison of root mean square errors (RMSE) indicated that all four methods performed equally well. However, in a Chesapeake Bay study (Murphy et al., 2010), kriging outperformed IDW method for mapping salinity, water temperature, and dissolved oxygen.

Based on the literature, it can be concluded that each interpolation technique should be thoroughly evaluated before being adopted for mapping data of interest. Furthermore, spatially interpolated reference ET maps developed for irrigation

scheduling purposes need to be highly accurate as those have a direct impact on producers' net profit. Therefore, the main objective of this study is to evaluate IDW and ordinary kriging interpolation techniques for mapping reference ET in the Texas High Plains.

MATERIALS AND METHODS

Study Area

This study covers a 39-county area of the Texas High Plains. Elevations above the mean sea level range approximately from 760 m in the eastern boundary to more than 1200 m along the northwest area of this region (Colaizzi et al., 2008; Fig. 1). Most of this region is semi-arid with extremely variable precipitation (both temporally and spatially, averaging 400–560 mm west to east, respectively). This region is also known to have high evaporative demand (approximately 2500 mm yr^{-1} Class A pan evaporation) due to high solar radiation, high vapor pressure deficit, and strong regional advection.

The grass reference ET data from eighteen reference weather stations, for the period of 2000-2005, managed by the TXHPET network (Porter et al., 2005) were considered for this study. The reference ET data were screened for continuous data availability. In the screening process, we identified 2179 days that had data from at least sixteen stations. Measured climatic data in these weather stations include soil temperature at 50- and 150-mm depths, air temperature, dew point temperature, relative humidity, saturation vapor pressure, actual vapor pressure, vapor pressure deficit, solar irradiance, wind speed, wind direction, precipitation, leaf wetness, and barometric pressure.

Spatial Interpolation Analysis

Spatial interpolation of 2179 days of data was carried out using ordinary kriging and IDW. Accuracy assessment of developed reference ET maps was conducted using leave one-out cross-validation method (Cawley, 2006). This involves removal of a measured data point for a known location and applies an interpolation technique to estimate a value for that location. The leave one-out cross-validation procedure was repeated 16 times to cover all weather stations. Performance of each interpolation method was made by comparing predicted daily reference ET values with the observed data for those sixteen stations. The RMSE was calculated and reported for accuracy assessment of interpolated reference ET maps.

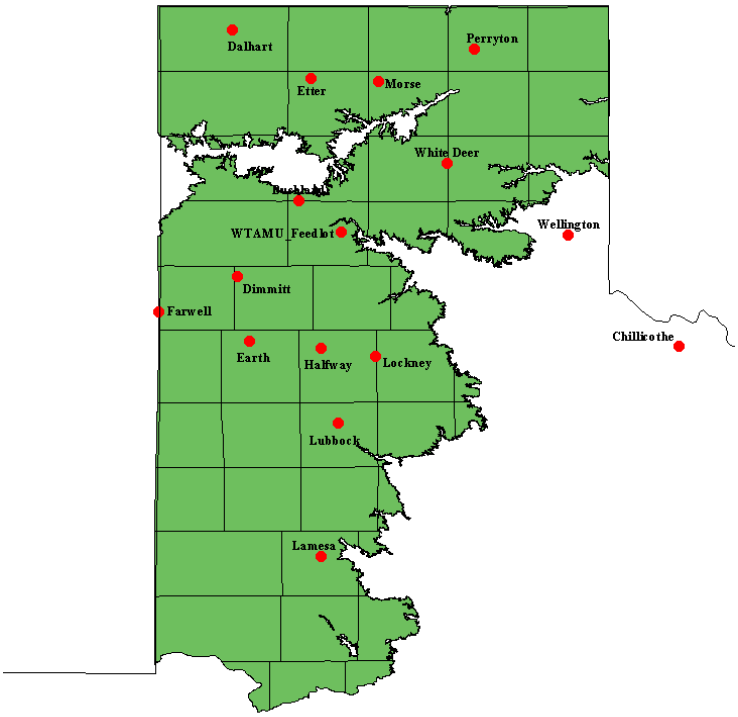

Figure 1. Locations of 16 weather stations in the Texas High Plains; a boundary line filled with the green color indicates the Ogallala Aquifer.

Method 1. Ordinary kriging

Ordinary kriging method was implemented using the 'automap' package in *R*[1] (The *R* project for statistical computing; www.r-project.org). The different variogram models were tested including spherical, exponential, Gaussian, A model of the Matern family, and Matern, M. Stein's parameterization during the experiment. The best-fit variogram model was selected automatically for each day according to Hiemstra et al. (2009).

Method 2. Inverse distance weighting (IDW)

Geostatistical routines were used from the 'gstat' package in *R*[1]. The optimal power for the IDW model was obtained by grid search method where values of the power varied from 0.1 to 10 with an increment of 0.2. The optimization criteria for the grid search were to minimize the RMSE.

RESULTS AND DISCUSSION

Daily grass reference ET maps were developed for the Texas High Plains using ordinary kriging and IDW methods for the period of 2000-2005, and assessed for mapping accuracy. Figures 2 and 3 show RMSE for the period between January 1, 2000 and December 20, 2005 (2179 days) with ordinary kriging and IDW,

[1]Mention of trade names or commercial products in this article is solely for the purpose of providing information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

respectively. With both methods, the RMSE values for summer cropping seasons were relatively and consistently greater than those for the non-summer cropping seasons. About 96 % of RMSE values with ordinary kriging were less than 1.5 mm day^{-1} (Fig. 2). A similar pattern was also observed with IDW where the RMSE values were less than 1.5 mm day^{-1} in 99% of the days (Fig. 3). Specifically, for more than 50 % of the days, the RMSE values varied within the range of 0.5-1.0 mm d^{-1} (53 % for ordinary kriging and 57 % for IDW). The numbers of days that have RMSE greater than 1.5 mm day^{-1} were 84 and 18 for ordinary kriging and IDW, respectively. Therefore, the variation in RMSE with IDW appeared to be less than that with ordinary kriging. One to one comparison of RMSE between ordinary kriging and IDW indicated that IDW performed better than ordinary kriging in 1492 of 2179 (68 %) days (Fig. 4).

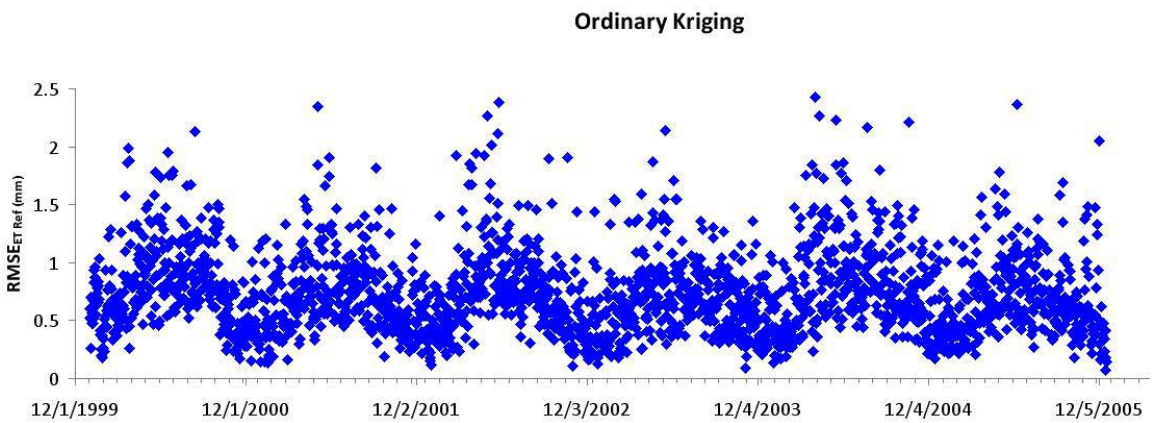

Figure 2. Temporal distribution of RMSE of reference ET in mm using ordinary kriging method.

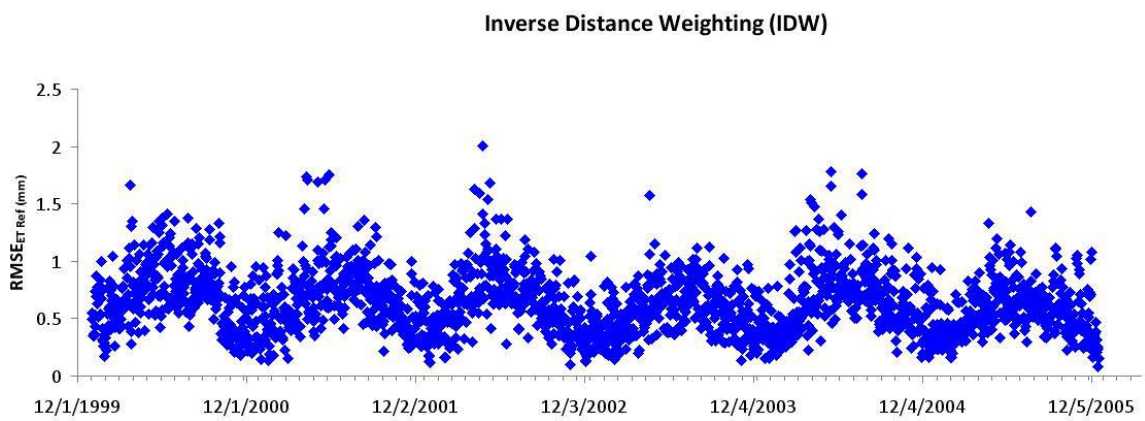

Figure 3. Temporal distribution of RMSE of reference ET in mm using IDW method.

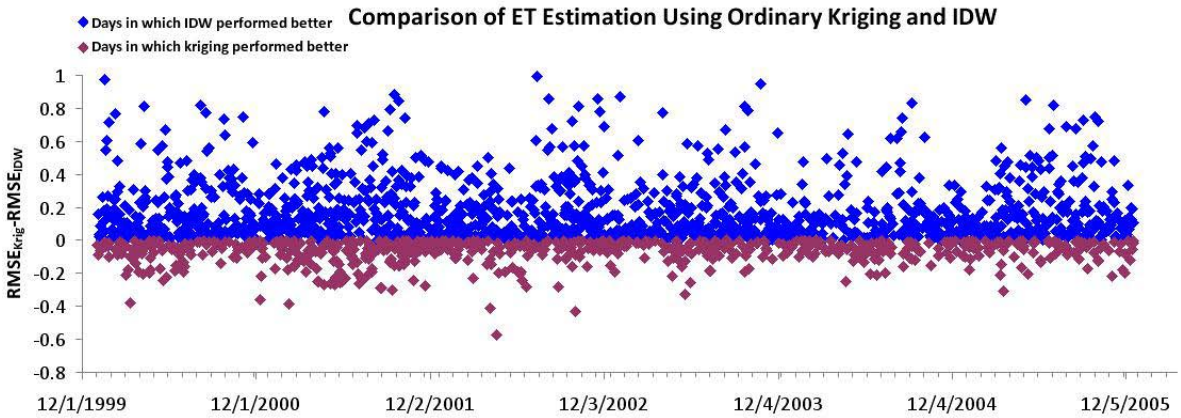

Figure 4. RMSE differences between ordinary kriging and IDW methods along the duration of experiment.

The comparison of the overall accuracy between ordinary kriging and IDW methods indicated that we cannot rely on any single method for mapping daily reference ET for the Texas High Plains. Further, with the analysis of the daily reference ET and RMSE from interpolation techniques alone, we found it difficult to understand why and when one particular method performs better over another method. We speculate that changes in the land use pattern and wind direction may have an important role in selecting a suitable interpolation technique. For example, atmospheric circulation patterns affect spatial distribution of ET over large areas (Buishand and Brandsma, 1997; Knapp, 1992). Therefore, wind direction data should be included in analyzing accuracy of various interpolation techniques, by cropping and non-cropping seasons, for mapping reference ET in the Texas High Plains.

SUMMARY

The potential of utilizing ordinary kriging and IDW to develop daily ET maps was investigated in this study. Computer programs were written in *R* environment to automate spatial interpolation of daily grass reference ET in the Texas High Plains. Results indicated that IDW performed slightly better than ordinary kriging. However, for unknown reasons, both methods equally performed poorly during the summer growing season when accurate grass reference ET maps are needed for irrigation scheduling. Further investigation of the mapping errors by summer growing season is needed to better understand the capability of IDW and ordinary kriging methods. In addition, other variations of kriging technique, for example, co-kriging with wind direction as an additional input, must be evaluated to identify a spatial interpolation technique for mapping reference ET with an acceptable accuracy for the Texas High Plains.

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