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Study on Variability of Wheat Evapotranspiration in Irrigation Farmland Areas of Northwest China

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Abstract: Evapotranspiration (ET) is the process that returns water from the earth surface to the atmosphere and therefore completes the hydrologic cycle. The collection and analysis of crop ET at different spatial and temporal scales has received much attention. Studies showed that the coefficients of variation(*CV*) for wheat ET at different growing stages is large with *CV* ranging from 30% to 50% even for "apparent" homogeneous fields of experimental farmland. During the stage of tillering-shooting, shooting-heading and heading-milk, the *CV* of accumulative ET decreased with the increasing of measurement time scales. The spatial variation analysis of ET based on the semivariance function showed that ET data obeyed a normal distribution and optimal spherical models. At the original tillering-shooting stage, the spatial structure of accumulative ET was the strongest, and then turned to sharply reduce at the shooting-heading stage. The temporal stability of ET was also important for determining the mean ET. The significant correlation of ET that estimated from different growing stages showed temporal stability. The temporal stability analysis showed that wheat ET had a higher temporal stability after the stage of tillering-shooting, which was often used to determine sample sites for the field mean ET fluxes.

1. Introduction

Evapotranspiration (ET) is the principal part of a hydrological cycle in semi-humid and arid regions, affected by both biophysical and environmental processes at the interface between soil, vegetation and atmosphere. Thus, understanding the spatial and temporal variability of ET is very important for identifying the impact of meteorology, soil water and crop factors on ET, and it is vital for hydrologic modeling and irrigation scheduling [1].

For Shiyang river basin in northwest China where average annual rainfall is below 200mm and agriculture depends largely on the irrigation water from glaciers in the mountains, there is a particular need of ET studies for increasing water using efficiency. The estimation of ET at different spatial and temporal scales is very important in hydrology. Generally, the analysis of the ET measurements is carried out for two different scales: the regional scale (large areas) and the small catchment scale (small areas).

Remote sensing provides an approach to monitor land surface ET over a large area simultaneously [2]. However, retrieving of remote sensing data often requires ground-based sampling to optimize the

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model parameters and study results. And Getting the Spatial and Temporal evapotranspiration helps solve the matching problem of the remote sensing data and ground observation data.

Up to now, methodologies used to assess the spatial and temporal variability for surface land parameters can be summarized as the followings：

- Statistical analysis, aims to define the probability density function of the estimated ET and to characterize its variability through the coefficient of variation.
- Geostatistical analysis, aims to describe the variance between the point values sampled in a spatial field as a function of their distance and to assess if the estimated ET pattern is continuous in space or erratic.
- Temporal analysis, aims to investigate if some locations within the field are representative for the mean ET value and if this representativeness is conserved during the given period.

However, the results were different according to the different study areas, and this makes their use in other climatic regions incredible. Based on the above contents, the objectives of the study are:

- to analyze the ET data collected in experimental region, in order to determine their statistical properties;
- to investigate their spatial structure in relation with the estimated ET values;
- to analyze the temporal variability of ET data, and address the issue concerning the minimum sample number to estimate mean ET in a given area within a threshold of error;
- to analyze the impact factors of ET, and investigate the relationship between ET and LAI , surface soil moisture.

2. Experiments and methods

2.1. Experiments Sites

Field experiments sites were carried out during 2010 at an experimental station for Water-Saving in Agriculture and Ecology in Gansu Province, China. The experimental station is within the typical continental arid zone between Tenggeli Desert and Badanjilin Desert of northwest China (latitude 37o51'N, longitude 102 o 50'E, altitude 1550 m). The region is deficient in water resources, with a mean annual precipitation of 164.4 mm and water surface evaporation of 2000 mm. The groundwater table depth is consistently below 25 m. The surface relief of the experimental field is rather uniform with the maximal elevation difference about 0.5 m. The spring wheat in the experimental field was irrigated four times a year, each with about 97.5 mm of water.

In the experiment, the plot area was 20475m2 (represented in figure. 1) and divided into 91 units, each with an area of 15*15 m^2. In order to obtain a correct spatial structure of ET, the crossing densification samples with 7.5m spacing interval were also set at in the direction of both east-west and south-north. The Time Domain Reflectometer (TDR, Dinviner2000 Sentek Pty Ltd， Australia) instrument was used to measure the profile (0-100cm) soil moisture at the center of each unit. The surface soil moisture with TDR is susceptible with low accuracyfor external factors, so Portable hydrosense instrument (CS620, Campbell Scientific Inc., USA) was used to measure the surface (0–20 cm) soil moisture at the center of each unit.

The whole measurement time began with 17 April (Day of Year = 107) in 2010 and ended with 2 July (Day of Year = 183) in 2010. There are 12 times measurements, including 4 times for tillering-shooting stage (DOY=125~135, DOY=Day Of Year), 3 times for shooting-heading stage (DOY=145~155) and 5 times for heading-milk stage(DOY=173~183).

In the paper, methods of classical statistical, geostatistical analysis and temporal stability analysis were used to discuss the spatial and temporal variability of ET. The methods introduction please refer to the relevant literature [3] [4] [5].

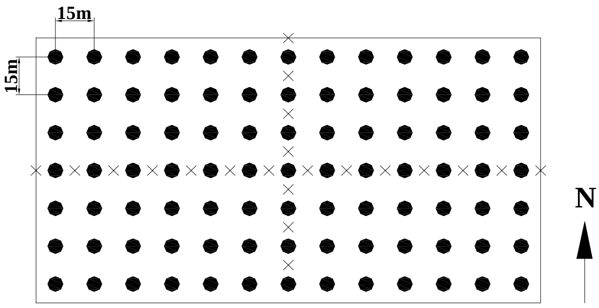

Figure 1. Sample locations (● for grid samples, × for high density samples)

2.2. Method

2.2 1.Geostatistical analysis Method

In geostatistics, the spatial variability and correlations of ET are considered. Therefore, geostatistics provides an optimal way to analyze the spatial characteristic. The spatial dependence between observations is expressed by the semivariance [5]

$$\gamma(h) = \frac{1}{2N_h}\sum_{i=1}^{N_h}\left[Z(x_i + h) - Z(x_i)\right]^2 \quad (1)$$

Where x_i represents the *it*h sampling location, $\gamma(h)$ is thesemivariance at the lag distance h, Z the sample value of soil moistureand N_h the number of pairs (xi, xi + h).

Semivariance models have three important parameters, i.e. nugget, sill and range. Nugget is the jumping variance between short sample distances, leading by the sample error and variance for short distance. Range is very important, when the distance between samples is larger than the range value, and it means the samples are independent totally. When the range reached a flat value, that is named sill. The general semivariance function is divided into spherical model, exponential model, Gauss model, nugget model and power model.

2.2.2.Temporal Stability analysis Method

Some paper introduced the time stability method to characterize the time-invariant association between spatial location and statistical parametric values of soil properties [4]. Before determining the stability sample points, the existence of stable samplings should be proven using the Spearman Rank coefficients r_s:

$$r_s = 1 - \frac{6\sum_{i=1}^{m}\left(\theta_{i,t} - \theta_{i,t'}\right)^2}{m\left(m^2 - 1\right)} \quad (2)$$

$$\overline{\theta_t} = \frac{1}{m}\sum_{i=1}^{m}\theta_{i,t} \quad (3)$$

m is the total sampling number, $\theta_{i,t}$（or $\theta_{i,t'}$）, the rank of soil moisture at the i location and the t（or t'）time. The more stability between t and t', the nearer 1 r_s. Time-stable point assessment uses the volumetric soil moisture content ($\theta_{i,t}$) at location i at time t, to calculate the mean soil moisture as $\overline{\theta_t}$.

The corresponding mean relative error $\overline{\delta_i}$ and variance error $\sigma(\delta)_i^2$ is

$$\overline{\delta_i} = \frac{1}{n_t}\sum_{t=1}^{n_t}\frac{\theta_{i,t} - \overline{\theta_t}}{\overline{\theta_t}} \quad (4)$$

$$\sigma(\delta)_i^2 = \frac{1}{n_t - 1}\sum_{t=1}^{n_t}\left(\frac{\theta_{i,t} - \overline{\theta_t}}{\overline{\theta_t}} - \overline{\delta_i}\right)^2 \tag{5}$$

$\overline{\delta_i}$ indicates the dry-wet degree of soil moisture relative to mean value while $\sigma(\delta)_i^2$ could well reflect the precision. In order to decrease the standard error and obtain the sampling mean, the root mean standard error should be used as

$$RMSE_i = (\overline{\delta}_i^2 + \sigma(\delta)_i^2)^{1/2} \tag{6}$$

So the ranks of each location and the corresponding mean relative error could be plotted in the same figure. And the temporal stable locations could be determined from the figure.

3. Results and Discussion

3.1. Classical Statistical Analysis

The trend relationship for ET and corresponding *CV* at different time scale was shown in figure.2. The daily ET was 2.27, 3.62 and 5.52mm respectively at stage of tillering-jointing, shooting-heading and heading-milk, showing an increasing trend with the wheat growth. The Actual ET was influenced by the atmospheric evaporation, growth stages and root zone soil moisture content. Based on the observed data, daily mean atmospheric evaporation of the above three growth stages were 6.3, 10 and 11.7mm, also increased gradually. figure 2b showed that *CV* was reducing reduced with the increase of observation time period. In the paper, the range of *CV* varied from 0.33 to 0.49, smaller than other discussions.

The observed ET variability within our experimental field is therefore not very surprising but reinforces the fact that ET is a highly spatially variable process even for 'apparent' homogeneous fields of small size. The high observed ET variability also suggests implicitly that the sampling frequency has to be quite intensive in space to obtain ideal area mean ET estimates.

3.2. Geostatistical Analysis

The spatial variability analysis of cumulative ET estimated for 10 days (ET10) at four growth stages was obtained. Figure 3 was the semi-variogram results of accumulative ET, including the stage of seeding-tillering (DOY=107~117, DOY=Day Of Year), tillering-shooting (DOY=125~135), shooting-heading (DOY=145~155) and heading-milk (DOY=173~183). The parameters of semivariance were shown in table 1.

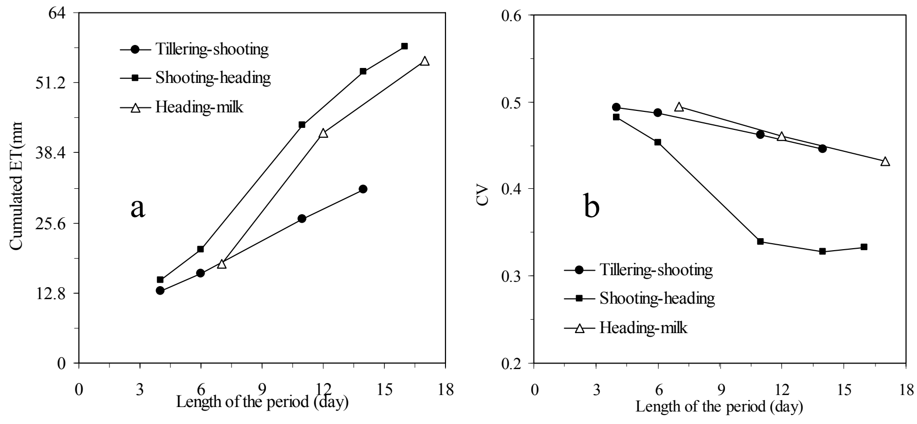

Figure 2. Mean and *CV* of ET for different time scales: (a) Mean (b) *CV*

From the table 1, the ET10 data for different stages obeyed the normal distribution, and was fitted the spherical model. At the seeding-tillering stage, the obtained ET10 was with the minimal mean value (only 3.27mm), and it also had the minimal nugget and sill value, the maximum correlation distance. After the first irrigation (May 1, DOY=121), the spring wheat came into the nutrition growth and began to induce the significant individual variation.

Therefore, the sill value was increasing fast and the correlation distance decreased after the first irrigation. With the growth of spring wheat, the spatial organization of accumulative ET was strongest in the original stage, and then became weak until the final stage. The results showed that the spatial organization of the shooting-heading stage was the weakest.

Table 1. Data distribution and semivariogram of ET at different spring wheat stages

Growing stage	distribution	Model	Nugget(mm)2	Sill(mm)2	Range(m)	R^2	ET_{10} (mm)	σ(mm)
Seeding-tillering	Normal	Spherical	1.99	2.8	110	0.72	3.27	1.65
Tillering-shooting	Normal	Spherical	82	160	75	0.75	26.5	12.25
Shooting-heading	Normal	Spherical	70	230	55	0.83	36.8	14.87
Heading-milk	Normal	Spherical	70	210	65	0.85	37.0	14.40

3.3.Temporal Stability Analysis

The temporal variation of ET was also an important variation parameter, which was often used to determine sample sites for the field mean ET fluxes [6]. Therefore, the first step is to investigate if such temporally stable locations exist within the field with matrix of the Spearman rank correlation coefficient calculated. Table 2 showed the matrix of cumulated ET for the four growth periods. All the values presented in table 2 were highly significant (for n=111; the critical Rs-value is 0.22 at the 0.01 probability level [7] confirming therefore that time stability in the ranks of the locations in terms of cumulated ET fluxes could be assumed.

Meanwhile, the rank correlation coefficients between the seeding-tillering and other growth stages presented in table 2 were much smaller. Although some of these correlation coefficients were smaller, they indicated a quite well pronounced temporal stability.

Table 2. Spearman rank coefficient of ET at different stage of Plot

Growing stage (DOY)	Seeding-tillering (107~117)	Tillering-shooting (125~135)	Shooting-heading (145~155)	Heading-milk (173~183)
Seeding-tillering(107~117)	1			
Tillering-shooting(125~135)	0.345	1		
Shooting-heading(145~155)	0.464	0.658	1	
Heading-milk(173~183)	0.317	0.515	0.64	1

In our case, we chose rather to present extremes instead of standard deviations as the number of replicates was quite low, i.e. 4, and as the statistical distributions were in general very different from a normal distribution. Figure.3 (a) presents results obtained for cumulated ET of all observation stages. It showed that the mean relative errors obtained from 72 locations were smaller than 30%. Some sampling locations were obviously less stable (e.g, number 111) with the 100% high relative error. Figure.3 (b) was the rank distribution map of the mean relative error for ET calculated without the seeding-tillering stage. Comparing with Figure.3 (a), Figure.3 (b) showed that there was a much more temporal stability for less relative error range. The number of locations decreased 20% where the extreme difference was larger than 0.3.

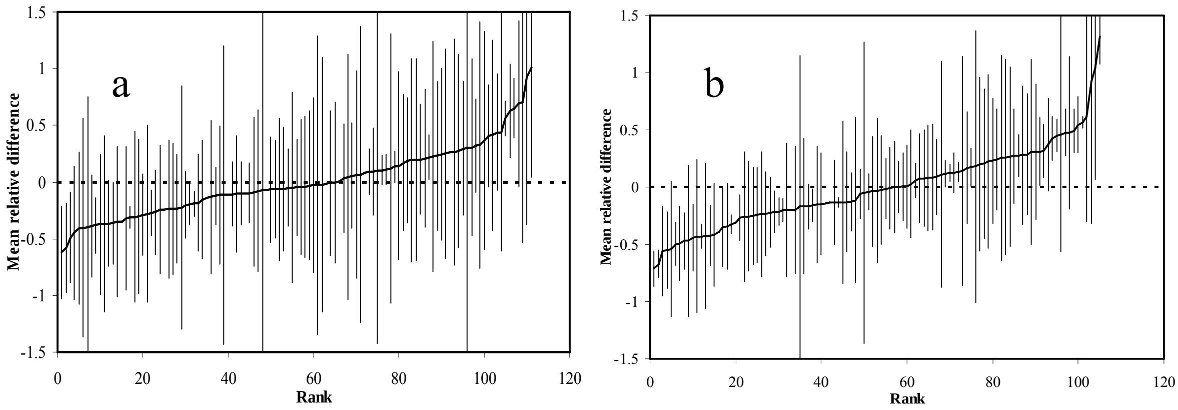

Figure 3. Rank distribution of relative error for ET: (a) in all stage (b) in stage except first irrigation

The above analysis indicated a quite well temporal stability of accumulated ET flux. But noted that the stability of locations varied with the different time and different environment, and the stable locations can be determined by consuming much time of sampling and verifying.

3.4.Regression Analysis

With the statistical analysis and geostatistical analysis methods, the sample number and corresponding locations of ET could be determined. But the ground-based sampling of ET is a long and hard work, we would better apply another auxiliary parameter easily observed to improve the precision of ET. The Actual ET was influenced by the atmospheric evaporation, crop growth and soil moisture [8]. In the study, parameters of LAI and surface soil moisture change were selected to analysis.

LAI is the best indicator of crop growth conditions, which has a direct close contact with the crop transpiration. Table 3 is the results of the relationship between cumulative ET and corresponding LAI observations for different growth stages.

Table 3. Relationship analysis between ET and LAI for different growing season

Growing stage（DOY）	Regression equation	Correlation coefficient	Associated probability
Tillering-shooting(125～135)	ET=16.6×LAI+18.3	0.47	0.000**
Shooting-heading(145～155)	ET=6.75×LAI+43.2	0.38	0.000**
Heading-milk(173～183)	ET=1.8×LAI+7.7	0.32	0.006**

** Indicate significant at the probability level of 0.05

In addition to LAI, the impact of soil moisture should be considered. Surface soil is a concentrated zone of root water uptake and rainfall. According to the analysis of the simultaneous observation of the surface soil moisture change and cumulative ET (without rainfall in the period) at different growth stages of spring wheat, there is a significant linear relationship between cumulative ET and surface soil moisture change.

Altogether, the surface soil moisture change was the most affected factor. Compared with ET ground observation, the cost of getting the surface soil moisture information is relatively small, so it is a more economical and useful method for using the soil moisture change data as auxiliary variable (named as coordination method in the paper) to improve the precision of ET.

4. Summary

The ET data set collected in experimental area of Northwest of China was investigated from a statistical, geostatistical and temporal stable point of view and in relation to soil and crop attributes.

(1) The coefficients of variation (*CV*) for wheat ET at different growing stages is large with *CV* ranging from 30% to 50%. During the stage of tillering-shooting, shooting-heading and heading-milk, the *CV* of accumulative ET decreased with the increasing of measurement time scales.

(2) At the original tillering-shooting stage, the spatial structure of accumulative ET was the strongest, and then turned to sharply reduce at the shooting-heading stage.

(3) The temporal stability analysis showed wheat ET had a higher temporal stability after the stage of tillering-shooting, which was often used to determine sample sites for the field mean ET.

The author hopes that the above results can supply information to determine the sample numbers and sample locations of ET. Meanwhile, it was an effective solution to apply auxiliary parameter such as surface soil moisture change easily observed to improve the precision of ET.

5. Acknowledgements

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