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Regional evapotranspiration rate of oasis and surrounding desert

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Abstract:

The surface energy balance algorithm for land method was used in this study to calculate the evapotranspiration (ET) rate for the middle reaches of the Heihe River Basin, Gansu Province, China, to analyse ET distribution within the oasis and the surrounding desert and, especially, on the edge zone of the oasis. Five profile graphs were created vertical to the river. Because of the inverse humidity phenomenon, the least amount of evapotranspiration occurred on the desert close to the oasis. The average evapotranspiration rate was roughly proportioned from the edge of the oasis to inside and outside its boundary. Two meteorological ground stations located close to the oasis edge showed a notable difference in net radiation flux that led to the difference found in ET. The primary reason for the significant differences observed in net radiation may be largely the result of differences in flux reflectivity and surface temperature. Meteorological data show that water supply also played an important role.

KEY WORDS Surface Energy Balance Algorithm for Land; evapotranspiration; edge effect of oasis

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INTRODUCTION

Reliable estimates of regional evapotranspiration (ET) are essential to improve upon the science and practice of hydrology (Morton, 1983). Establishing a reliable method to estimate the regional evapotranspiration rate from meteorological parameters that are readily and routinely obtainable from standard weather stations would prove beneficial from both the standpoint of climatology and hydrology. Moreover, methods to spatially map the evapotranspiration rate within a basin would be valuable for the practice and management of irrigation objectives (Bastiaanssen, 2000; Zhao *et al*., 2005).

Currently, no reliable method exists to collect routine direct measurements of regional ET. In spite of this, improvements in theory and measurement techniques have taken place over the past decades. Accurate methods are now available to determine the actual evapotranspiration rate at a given location. However, most of these methods can only be applied to sites in which special instrumentation has been put in place (Liu and Katoda, 1998). Remote sensing methods, such as satellite imagery, provide an excellent means to determine and map the spatial and temporal structure of ET because they can cover large areas and yield data at very high resolutions (Tateishi and Ahn, 1996; Mauser and Schadlich, 1998; Kite and Droogers, 2000; Sánchez *et al*., 2008).

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Being especially true for arid and semi-arid regions, which cover approximately one third of the world's terrestrial surface, interactions between land and the atmosphere such as evapotranspiration are important in respect of global water balance and climate change overall. Laymon *et al*. (1998) have discussed the relationship between regional evapotranspiration and geomorphology, soils, and vegetation in a semi-arid Great Basin desert in 1998. In which article, the vegetation density was taken as the primary factor of evapotranspiration. Evapotranspiration research began in the early 1990s in the Heihe River Basin. Hu and Gao (1996) summarized the results of the Heihe Basin Field Experiment (HEIFE). They showed that both the cold-island effect and the wet-island effect occur within this desert oasis microclimate and suggested that the reflectivity difference may be the dominant trigger. Hu and Gao (1996) also discovered that the inverse humidity phenomenon (water vapor transfers from atmosphere to soil) that occurs throughout the desert and, particularly, the Gobi Desert region close to the oasis is caused by microclimate cycling on the edge of the oasis. The inverse humidity phenomenon in itself may be the fundamental reason that plants can grow in the desert sand, forming an important ecological protection zone outside oases. Zhang *et al*. (2004) obtained similar conclusions by computing the evapotranspiration rate in 1991with remote sensing means. However, the inverse humidity phenomenon has not been reported on other deserts all over the world.

In this study, the Surface Energy Balance Algorithm for Land (SEBAL) method was used to compute ET rates in the middle reaches of the Heihe River Basin, Gansu Province, China, to understand ET distribution throughout the oasis and surrounding desert region, especially on the edge zone of the oasis. Meteorological data from two ground stations located close to the edge of the oasis were used to account for the edge effects observed around the desert oasis.

MATERIALS AND METHODS

Study area

The study area, including the Linze and Ganzhou areas, is an oasis that lines the Heihe River (Figure 1). The area is on the middle reaches of the River Basin in northwestern China at an altitude of 1360 to 2400 m. The climate is temperate and arid, characterized by cold dry winter months and warm wet summer months. Average annual precipitation is only 117 mm and experiences great seasonal variations. However, the average annual evaporation is 2390 mm, which is 20 times as much as precipitation. The average annual temperature is 7.6 °C, with the highest average temperature of 39.1 °C and the lowest of −27.3 °C. Irrigation agriculture is the primary economy within the region, assisting with some farming industries. The Heihe River divides the region from the south to the northwest. A desert of thousand square kilometers surrounds the oasis.

Data collection

A digital elevation model (DEM) and vector map of the administrative boundary were provided by Digital Heihe (http://heihe.westgis.ac.cn). Slope and aspect images were derived from DEM using the 3D Analyst Tools module provided within the ArcGIS software package. The Landsat image used for this study was a TM5 image taken on 23 September 2007 at 10:50 h local time where weather conditions were favorable and no clouds were present. The image was treated with geometric rectification and clipped using a study area border. Root mean square (RMS) errors of each registration were maintained below 1 pixel. All raw Landsat digital number values were converted to apparent at-sensor radiance values, which were then converted to apparent at-sensor reflectance values and, finally, to surface reflectance values (Chander and Markham, 2003). The thermal band (Band 6) was converted to surface temperature (T_0) using the mono-window algorithm (Qin *et al*., 2001). Atmospheric correction procedures were carried out to ensure that the results truly indicate the earth surface rather than a fallacy because of solar illumination differences or potential differences in atmospheric conditions.

To supplement the TM image, the synchronous vegetation height and the following meteorological data from four meteorological ground stations were acquired: air temperature, wind speed, solar radiation, precipitation, and vapor pressure. Moreover, all meteorological data were measured hourly throughout the day. Two of the meteorological ground stations are close to the edge of the oasis. Measurements were taken at each one by means of automated weather instruments.

SEBAL daily evapotranspiration estimation

SEBAL is an image processing model that comprises 25 computational steps or submodels (including preprocessing

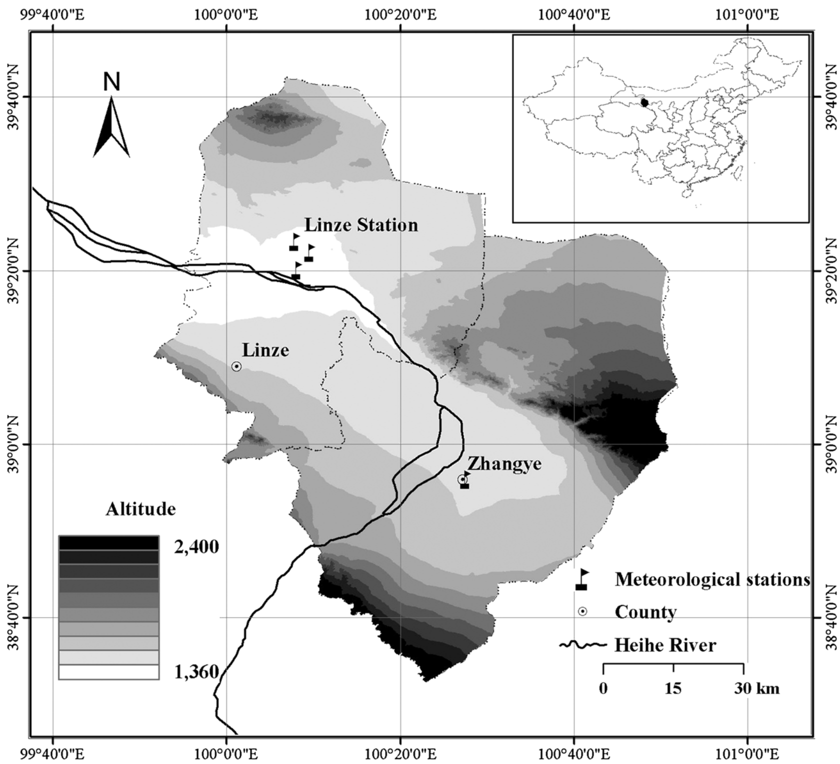

Figure 1. Location and DEM for the middle reaches of the Heihe River

of raw remote sensing image) that calculates the evapotranspiration (ET) rate and other energy exchanges that occur at the surface of the earth (Bastiaanssen *et al.*, 1998a, b; Morse *et al.*, 2000). It can use digital image data collected by any remote sensing satellites that measure visible, near infrared, and thermal infrared radiation. Certain steps require decision making by the user such as the selection of dry and wet indicator pixels, which were chosen by experience. For this study, all steps were achieved using Model Maker module within ERDAS software. Results are provided in Figure 3 where spatial resolution was set at 30 m as same as the TM image (Li and Zhao, 2010).

The results were analysed using Spatial statistics module in Arcgis environment. Five profile graphs were created perpendicular to the river to get the distribution of ET on the oasis. The edge of the oasis (Figure 2) was derived from the TM image by means of digital visual interpretation base on normalized difference vegetation index (NDVI) and land cover map, after which, a 2-km buffer zone was established to analyse the distribution of ET on the edge of the oasis.

RESULTS

Evapotranspiration rate profiles

The position and the evapotranspiration rate of the five profile graphs were shown in Figure 3. Within the profile graphs, the x-coordinate stands for the distance from the river in meters where 0 represents the river itself, a positive number represents a northern and northeastern direction (Gobi Desert), and a negative number represents a southern and southwestern direction (piedmont Rock Desert).

Extreme differences were observed in terms of evapotranspiration rate inside and outside the oasis. A high evapotranspiration rate was detected at the river in profiles 1, 2, and 3, whereas the evapotranspiration rate proved insignificant in profiles 4 and 5. The insignificance detected for profiles 4 and 5 was due to the narrowness of the river at those locations and the fact that no riparian wetlands were present. A slight increase in evapotranspiration rate was detected in the desert far from the oasis. The lowest evapotranspiration rate was detected in the desert close to the oasis. Evapotranspiration rates observed on the Gobi Desert were slightly higher than those observed on the piedmont Rock Desert.

Evapotranspiration rates on the edge of the oasis

The average evapotranspiration rate was calculated based upon the distance to the edge of the oasis in the 2-km buffer zone (Figure 4).

The evapotranspiration rate increased as measurements were taken inside, farther from the edge of the oasis, but decreased as measurements were taken away from the oasis in the opposite direction. The evapotranspiration rate changed rapidly within a range of 200 m. After 1600 m, the average evapotranspiration rate became stable. Points within the figure (Figure 4) located inside the oasis were more scattered than those located outside the oasis. Therefore, average evapotranspiration rates were more volatile inside than they were outside the oasis. The two star symbols within the figure signify the meteorological ground stations present. One is located 1.13 km inside the oasis, whereas the other is located 870 m outside it.

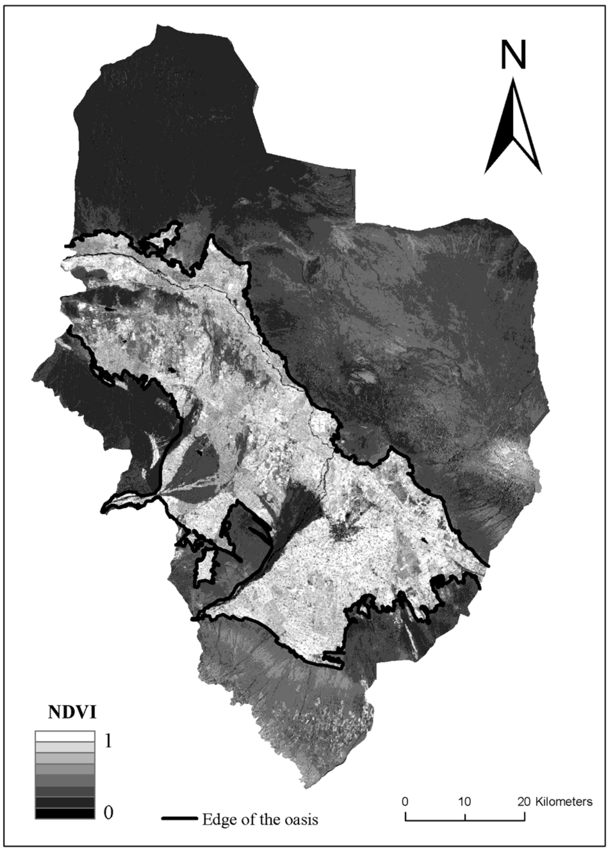

Figure 2. NDVI and the edge of the oasis

DISCUSSION AND CONCLUSION

The profile graphs show that the variation in evapotranspiration rate between the oasis and the surrounding desert is extreme. A prominent peak in values occurred close to the river in profiles 1, 2, and 3 (lower reaches), whereas the peak was insignificant in profiles 4 and 5 (upper reaches). These differences were the result of the river of the upper reaches being narrower than the lower reaches as well as no riparian wetlands being present in profiles 4 and 5.

Minimum evapotranspiration rate values were recorded in the desert region close to the oasis rather than in the surrounding desert far from the oasis. This may be due to the inverse humidity phenomenon that occurs in the desert close to the oasis that Hu and Gao discovered in 1996. There are no reports about the inverse humidity phenomenon on other deserts around the world yet. However, the inverse humidity should be a common phenomenon on the surrounding deserts of the oasis. This phenomenon may be the driver that sustains the growth of plants in the desert sand, forming an important ecological protection zone outside the oasis. The inverse humidity phenomenon was not detected within the desert region or

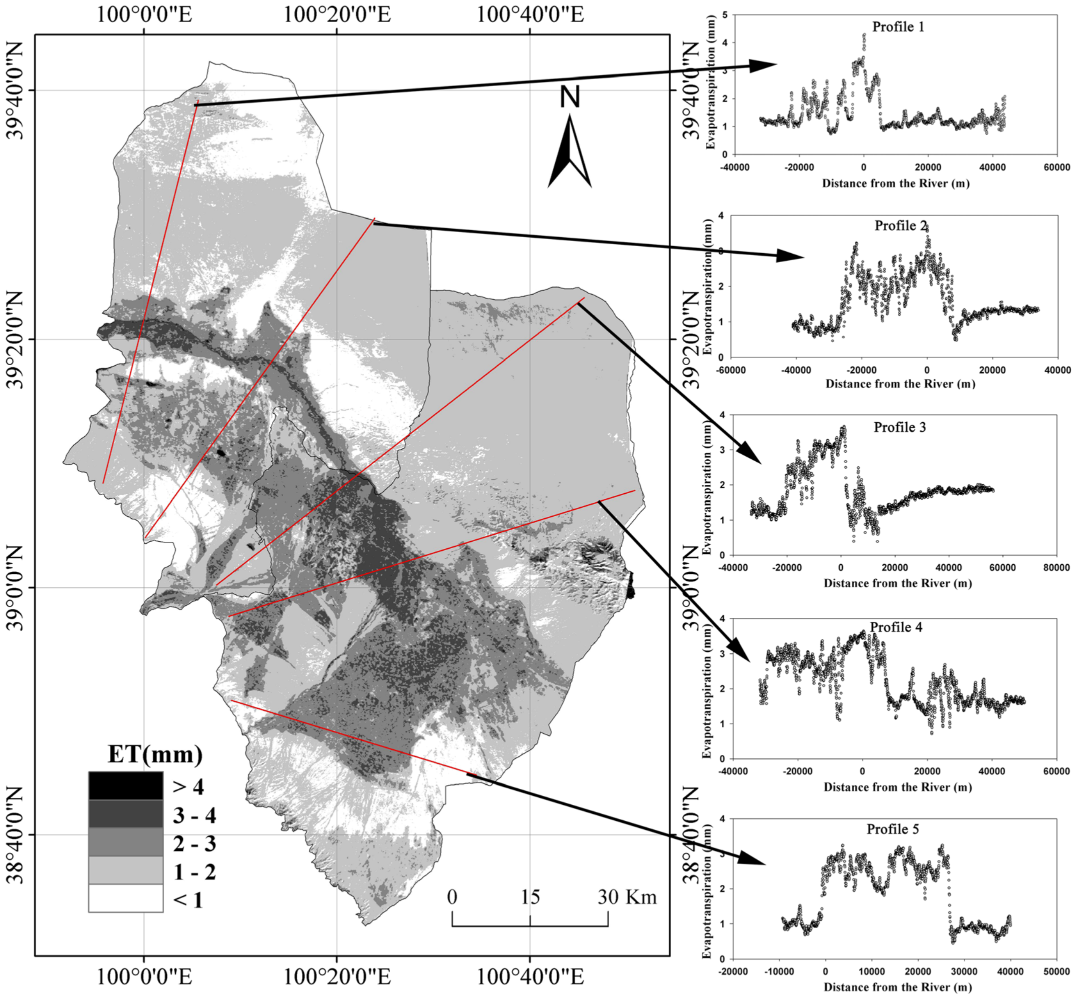

Figure 3. Daily evapotranspiration rate and profile graphs

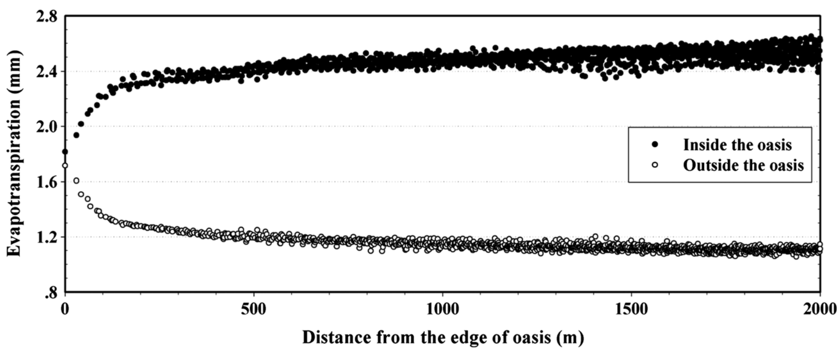

Figure 4. Average evapotranspiration rate based upon the distance to the edge of the oasis. (The two star symbols within the figure signify the meteorological ground stations present. One is located 1.13 km inside the oasis, and the other is located 870 m outside it.)

the Gobi Desert far from the oasis. Therefore, the evapotranspiration rate increased slightly within the desert region at a distance from the oasis.

Evapotranspiration rate differences observed inside the oasis and the desert region outside the oasis were primarily because of the land cover (Figure 5). The NDVI produced a value of 0.36 on average inside the oasis and 0.19 outside it. For this reason, surface reflectance outside the oasis was approximately twice as high as it was inside the oasis. Therefore, the net radiation flux (R_n) was significantly different inside and outside the oasis.

The two meteorological ground stations are situated close to the edge of the oasis. One is located inside the oasis, and the other is located outside the oasis. Although the distance between the two stations is only 4.5 km, the meteorological data acquired from the two sites are considerably different (Table I).

R_n inside the oasis was approximately twice as high as it was in the surrounding desert. The primary reason for the significant differences observed in net radiation may be largely because of the differences in surface reflectance and surface temperature that depends on the land cover

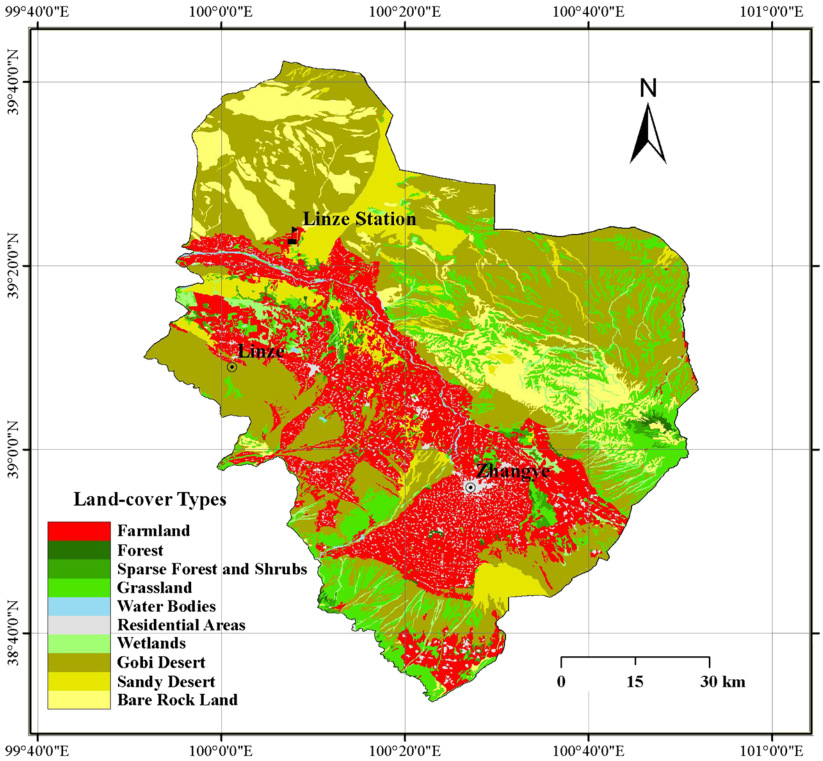

Figure 5. Land use map of the study area

Table I. Meteorological data from the two ground stations (averaged data from July, August, and September)

	R_n (W/m^2)	T (°C)	T_0 (°C)	ΔT (°C)	RH (%)	SWC (%)
Oasis	149.64	19.45	19.47	0.02	60.87	29.17
Desert	79.90	21.35	24.04	2.69	43.11	11.77

Rn: net radiation; T_0: surface temperature; T: air temperature at a height of 2 m; ΔT: T_0-T; RH: relative humidity at a height of 2 m; SWC: soil water content at a depth of 20 cm.

and soil moisture. Based upon the surface energy balance theory, R_n may in itself be the most important factor for the differences found in evapotranspiration rates. Therefore, the land cover may be the primary factor of evapotranspiration rate in a small area where the climate variation is insignificant. Meteorological data showed that the water supply also played an important role. The soil water content (SWC) of the desert was too low to supply the water required for evapotranspiration to occur, and the energy exchange between the earth and the atmosphere was dominated by sensible heat flux (as exhibited by the high ΔT in Table I). Conversely, the SWC within the oasis itself was sufficient, and R_n was expended by evapotranspiration (in which ΔT was low). This is likely the result of farmland located inside the oasis that is irrigated many times throughout the year.

The average evapotranspiration rate was roughly symmetrical from the edge of the oasis to inside and outside its boundary. Points within the figure located inside the oasis were more scattered than those located outside the oasis. This may be the result of land cover being intrinsically more complex inside the oasis. The area outside the oasis is composed of Sandy Desert, Gobi Desert, and Bare rock land, although there are a variety of vegetation types and crops inside the oasis (Li and Zhao, 2010).

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