Evapotranspiration of Hailiutu River Basin in Erdos Plateau Using Remote Sensing Data

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Abstract
Evapotranspiration (ET) plays an important role in the hydrological cycle and it is essential to estimate ET accurately for the evaluation of available water resources in arid regions. In this paper, the monthly change of ET in the semi-arid Hailiutu River basin in northwest China were studied. The spatial distribution of ET was assessed by using the energy balance approach SEBS (Surface Energy Balance System). Cloud free MODIS images over the Hailiutu River basin in 2008 were used in combination with SEBS to estimate ET at a spatial resolution of 1 km. This daily ET was converted to a monthly ET using daily pan evaporation values from a meteorological station in the study area. Spatial aggregation of all pixels yielded the total monthly ET for the whole study area. Subsequently, the monthly ET was summed up to annual ET values using the pan evaporation data.
Keywords: Evapotranspiration, SEBS (Surface Energy Balance System), MODIS, arid area, Hailiutu River basin

1.Introduction

Sustainable development of arid and semi-arid areas, like the arid inland basins in Northwest China, will largely depend on the availability of water resources. For the assessment of water resources in a large arid inland basin one usually needs to quantify the inflows from high mountains to the basin and the evapotranspiration (ET) loss in the basin. In an inland basin, ET is the only major loss term occurring that is relevant for the water balance. ET plays an important role in the hydrological cycle. It is site specific and varies with local meteorological conditions (radiation, wind, temperature, humidity of the air) and surface conditions (surface type, soil wetness, vegetation development stage, etc.) (Hare, 1980; Willmott et al., 1985; Mintz and Walker, 1993; Potter et al., 1993; Sun et al., 2004).

In recent years, methods for deriving surface fluxes using remote sensing data have been developed, such as SEBAL (Surface Energy Balances Algorithm for Land) (Bastiaanssen et al., 1998; Bastiaanssen, 2000; Bastiaanssen et al., 2002, 2005), SEBS (Surface Energy Balance System) (Su, 2002), TSEB (Two-Source Energy Balances) (Norman, et al., 1995) and S-SEBI (Simplified Surface Energy Balances Index) (Roerink et al., 2000). SEBAL is a robust remote sensing model that can be applied to estimate the different components of the energy balance of the earth surface including actual evapotranspiration (ET). The TSEB modeling scheme has been developed to use either microwave-derived near-surface soil moisture or radiometric surface temperature as the key remotely sensed surface boundary condition for computing spatially distributed heat fluxes. The SEBS system was developed by Su (2002) in order to estimate land surface fluxes using remotely sensed data and available meteorological observations. Being applied to many case studies in Europe and Asia (Oku et al., 2007; Ma et al., 2007; Jia et al., 2007; Su, 2002), SEBS was selected to be the method of ET estimation in this study.

The purpose of this study is to estimate the ET of the Hailiutu River basin in Northwest China and the specific objectives are: (1) to estimate the daily ET of the Hailiutu River basin using the SEBS model, (2) to extend daily ET into monthly ET, finally to annual ET.

2. Material and Methods

2.1 Study area

Located in Erdos plateau, Hailiutu River basin is an tributary of Wuding River in Shaanxi and Inner Monglia, China with an area of 2606 km^2 (Figure 1). The climate is typical inland arid to semi-arid. The precipitation is scarce with annual average varying
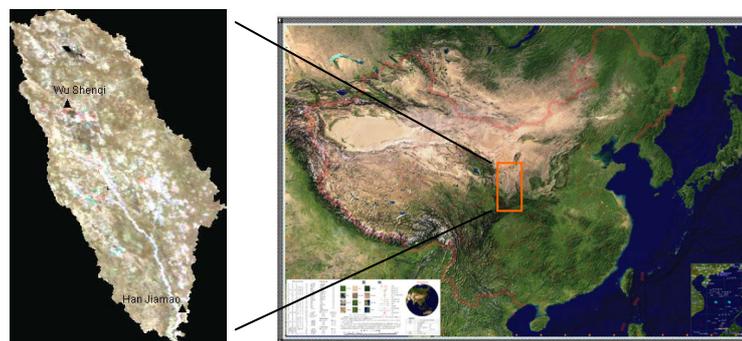

Figure 1 Satellite image of Hailiutu River basin.

from 400 mm in the south to 200 mm in the north. Potential evaporation is very high ranging from 2000 to 3500 mm/a. Because of harsh climate and fragile natural environment, desertification and soil erosion occur widely. Terrestrial ecosystem depends partially or completely on groundwater and is sensitive to climate change and groundwater levels and quality. Erdos Plateau is one of new energy bases for China and the increasing water demand has been met by exploitation of groundwater resources in recent years. Increased groundwater abstraction has caused problems such as: decrease of groundwater levels, reduction of river flows, shrinking of lakes and degradation of ecosystems.

2.2 Methodology

The surface energy balance is commonly written as

$$R_n = G + H + \lambda E \tag{1}$$

where R_n is the net radiation, G_0 is the soil heat flux, H is the turbulent sensible heat flux, and λE is the turbulent latent heat flux (λ is the latent heat of vaporization and E is the actual evapotranspiration).

The equation to calculate the net radiation is given by

$$R_n = (1-\alpha) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4 \tag{2}$$

where α is the surface albedo, ε is the emissivity of the surface, R_{swd}, R_{lwd} are incoming shortwave and longwave radiation respectively, σ is the Stefan-Bolzmann constant, and T_0 is the surface temperature. α, ε and T_0 are physical parameters and can be derived from satellite data. The same estimation procedure as described by Su et al. (1999) was used in this study. R_{swd} and R_{lwd} were measured at a meteorological station.

The equation to calculate the soil heat flux is parameterized as follows

$$G_0 = R_n \cdot [\Gamma_c + (1-f_c) \cdot (\Gamma_s - \Gamma_c)] \tag{3}$$

where Γ_c and Γ_s are empirical coefficients. For most bare soil conditions a Γ_s value of 0.315 is valid (Kustas and Daughtry, 1989), and for full vegetation often Γ_s is assumed to be 0.05 (Monteith, 1973). An interpolation is then performed between these cases using the fractional canopy coverage f_c. f_c can be derived by the following equation:

$$f_c = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{4}$$

The surface energy balance computation with the SEBS algorithm is based on the determination of the relative evaporative fraction. To determine the relative evaporative fraction, the energy balance solution at limiting cases is used. At the dry-limit, the latent heat (or the evaporation) becomes zero due to the limitation of soil moisture, and the sensible heat flux is at its maximum value. It follows from Eq. (1) that

$$\lambda E_{dry} = R_n - G_0 - H_{dry} \equiv 0, \ or$$
$$H_{dry} = R_n - G_0 \tag{5}$$

At the wet-limit, where the evapotranspiration takes place at potential rate, λE_{wet} (i.e. the evapotranspiration is only limited by the available energy under the given surface and atmospheric conditions), the sensible heat flux takes its minimum value, H_{wet} i.e.

$$\lambda E_{wet} = R_n - G_0 - H_{wet}, \ or$$
$$H_{wet} = R_n - G_0 - \lambda E_{wet} \tag{6}$$

The relative evaporation then can be estimated as

$$\Lambda_r = 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}} \tag{7}$$

The evaporative fraction is finally given by:

$$\Lambda = \frac{\lambda E}{H + \lambda E} = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \cdot \lambda E_{wet}}{R_n - G} \tag{8}$$

Eqs. (1) – (8) constitute the basic formulation of SEBS. The actual sensible heat flux H in SEBS is obtained by solving a set of non-linear equations and is constrained in the range set by the sensible heat flux at the wet limit H_{wet}, and the sensible heat flux at the dry limit H_{dry}.

It is assumed that the daily evaporative fraction is approximately equal to the instantaneous value. The daily evaporation can be determined as (Su, 2002)

$$E_{daily} = 8.64 \times 10^7 \times \frac{\Lambda \cdot \overline{R_n}}{\lambda \rho_w} \tag{9}$$

where E_{daily} is the actual evaporation on a daily basis ($mm.d^{-1}$), λ is the latent heat of vaporization (JKg^{-1}), ρ_ω is the density of water (Kgm^{-3}) and $\overline{R_n}$ is the daily net radiation flux.

2.3 Dataset

Product of MOD 11 and MOD 9 of each month in 2008 are used in SEBS model in this study to estimate daily evaporation. The observed meteorological data in Wushenqi station, such as pan evaporation, precipitation, wind speed, wind direction and air temperature was interpolated in total study area by Kringing to estimate ET in SEBS.

3 Result
3.1 Spatial distribution of daily ET

The spatial distribution patterns of daily ET as estimated using SEBS over the Hailiutu River basin can be observed in Figure 2. Figure 2 shows the spatial distribution of daily ET from January to December 2008. In general, ET of north areas is larger than that of south area in the Hailiutu River basin. The monthly ET is relatively high from May to October and it is small in winter season.
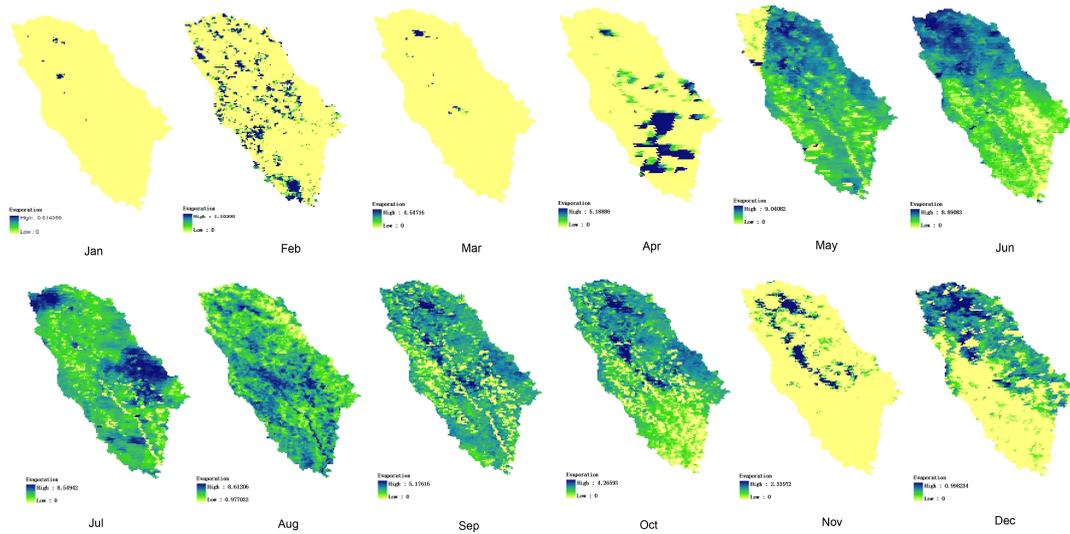
Figure 2 Spatial distribution of ET in 2008.

3.2 Annual ET estimation

The daily ET values of the SEBS results were averaged for all pixels of the study area and this mean value was considered to be the daily ET of the whole Hailiutu River basin. There are in total 2604 pixels in the study area. Due to cloud cover, there are only very few satellite images available in one month and the daily ET for each day could not be obtained. The extension of daily ET to monthly ET, and further to annual ET is very important. In this study, the monthly ET was estimated by combination of the SEBS results and the daily data of meteorological stations. Take September as example. The SEBS result of mean daily ET was 1.59 mm on 19 September, and the pan evaporation value from the meteorological station was 5.9 mm for the same day. The daily ET of other days in September can be obtained by Equation (10) and the summation is the monthly ET of September.

$$ET_s = \frac{ET_{S.d}}{ET_{M.d}} \times ET_M \qquad (10)$$

where i is the number of days from 1 to 30 in September; ET_S is the predicted SEBS monthly ET in September after calculation; $ET_{S.d}$ is the mean daily ET from the SEBS result and this value was 1.59 mm on 19 September; $ET_{M.d}$ is the observed pan evaporation of the meteorological station in the same day, and it was 5.9 mm; ET_M is the observed monthly pan evaporation of the meteorological station in September.

Based on the observed daily pan evaporation at the Wushenqi meteorological station, the monthly evaporation of year 2008 was calculated and annual ET of 2008 is 277.8 mm after summed up the monthly ET. The predicted monthly ET from the SEBS result is shown in Figure 3.
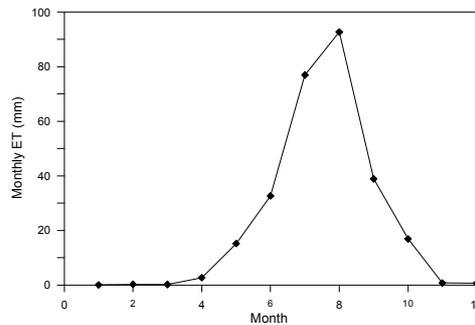

Figure 3 Monthly ET from January to December in 2008.

The result indicated that the maximum ET of 77mm and 92.7 mm is in July and August because the better vegetation growth and the high precipitation in these two months. On the contrary, the ET is relatively low in December, January, February and March due to low temperature and worse vegetation growth and the monthly ET in these four months is smaller than 1 mm.

4. Conclusions

As a key component in the water and energy budget, the change of ET in the semi-arid Hailiutu River basin in China were analyzed in this paper. The following conclusions can be drawn based on the results obtained.

1) The daily ET was estimated based on the SEBS algorithm (Surface Energy Balance System) and the monthly ET can be extended by combination of observed pan evaporation and SEBS result;

2) The annual ET of the Hailiutu River basin is 277.8 mm in 2008. The maximum monthly ET is in August and the minimum value is in January, February and December.

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