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A general model for estimating actual evaporation from non-saturated surfaces

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Abstract: Based on energy balance equation and mass transfer equation, a general model to estimate actual evaporation from non-saturated surfaces was derived. Making use of two concepts, "relative evaporation" and "relative drying power", a relationship was established to account for the departure from saturated conditions. Using this model, the actual evaporation (evapotranspiration) can be calculated without the need of potential evaporation estimation. Furthermore, the model requires only a few meteorological parameters that are readily and routinely obtainable at standard weather stations. Based on nearly 30 years data of 432 meteorological stations and 512 hydrological stations in China, in combined with GIS, nine typical river basins were selected. Using the data of the selected river basins, the model was tested. The results show that the actual evaporation rate can be estimated with an error of less than 10% in most areas of China, except few years in the Yellow River Basin.

QIU Xinfa1,2, ZENG Yan3, LIU Changming3 (1. Dept. of Urban & Resource Science, Nanjing University, Nanjing 210093, China; 2. Dept. of Geography, Nanjing Institute of Meteorology, Nanjing 210044, China; 3. Inst. of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) 1 Introduction Evaporation (Evapotranspiration) consumes much of the water and energy that are available on the ground of the earth and therefore influence all hydrological and most meteorological processes. It also plays an important role for the water redistribution on the earth´s surface and is a major determinant of the amounts in water cycle. With the implementing of the strategy of developing western China, the contradiction between water supply and demand becomes more pronounced. In order to rationally develop and use water resources, basic knowledge for evaporation over a range of spatial and temporal scales becomes more important. Unfortunately, it is extremely difficult to obtain sufficient reliable estimations of actual evaporation. Instruments can only measure evaporation in research context for small areas, which are subject to intensive studies (Ma Yaoming et al., 1997). Therefore, there is a strong need for reliable methods that can estimate actual evaporation (evapotranspiration) and require only a few meteorological parameters which are readily and routinely obtainable at standard weather stations. Penman (1948) suggested that when the water supply was not abundant, the actual evaporation from natural surfaces would be proportional to potential evaporation and be a function of the availability of water (Penman, 1948). Penman´s assumption has been widely applied. Up to now, most of researches to estimate actual evaporation have benn based on Penman´s assumption and are focused on seeking some functions of the availability of water (e.g., soil moisture deficit, canopy resistance, etc.). Unfortunately, it is extremely difficult to obtain sufficient reliable data of these factors (Kang et al., 1990; Wang et al., 1992; Shen et al., 1993; Sui et al., 1997; Liu et al., 1997). Furthermore, according to Penman´s assumption, the estimation of actual evaporation depends on that of potential evaporation. However, considering the current state-of-the-art, there has been some ambiguity of the concept of "potential evaporation" (Granger, 1989). Based on different assumptions, scholars such as Penman (1948), Van Bavel (1966), Priestley and Taylor et al. (1972) developed several different calculation equations for "potential evaporation". Among them, "Penman potential evaporation" has been extensively used and has been wide accepted for its solid physical foundation. Nevertheless, studies show that the estimated evaporation derived from it is distinctly larger than that of actual regime when the temperature difference between the surface and the air is relatively large (Granger, 1989). So, some scholars also use other "potential evaporation" calculation equations to estimate the actual evaporation (Liu et al., 1998; Davies et al., 1973; Mawdsley et al., 1985; Granger et al., 1989). In fact, the concept amb iguity of the potential evaporation has resulted in multiply "definitions" of it. Based on energy balance equation and mass transfer equation, a general model to estimate actual evaporation (evapotranspiration) from non-saturated surfaces was derived. Based on two concepts, "relative evaporation" and "relative drying power", a relationship was established to account for the departure from saturated conditions. Using this model, no prior estimate of the potential evaporation is required. To establish this model the meteorological and hydrological data of nine representative river basins of China were used. The results show that the actual areal evaporation can be estimated with an error of less than 10% in most areas of China. 2 Theoretical model of evaporation from non-saturated surfaces When the advection is negligible, the energy balance in the vertical direction at a horizontal surface can be written as (with the terms expressed as an equivalent depth of evaporation): Rn = E + H + B (1) where Rn is the net radiation; E is the actual evaporation; H is the sensible heat; and B is the transfer of heat by conduction in the soil. Applying the Bowen ratio: ?苗 = = (2) and the slope of saturation vapor pressure curve ?驻: ?驻 = (3) to eqn. (1) gives: Rn - B = E 1 + (4) In eqns. (2)-(4), ?苗 is Bowen ratio; ?驻 is the slope of saturation vapor pressure curve; ?酌 is psychrometric constant; Ts is evaporating surface temperature; Ta is air temperature; e and e are saturation and actual vapor pressures at the evaporating surface at temperature Ts; e and ea are saturation and actual vapor pressures of the air at temperature Ta. Actual evaporation can also be expressed by the Dalton-type bulk transfer equation: E = f (u) (e - e) (5) where f (u) is a wind speed function. Substituting eqn. (5) into eqn. (4) and rearranging terms yields: E = (Rn - B) + f (u) (e- e) = (Rn - B) + f (u) (e - e) - f (u) (e - e) (6) where f (u)(e- e) is generally referred to the "drying power" of the air. f(u)(e - e), is the evaporation rate which would occur under the same atmospheric conditions for wind and humidity, if the surface was saturated at the temperature of the surface. This term just represents the potential evaporation, EVan, given by Van Bavel (1966). The formulation of eqn. (6) requires to know the surface temperature, a parameter which is rarely observed. Introducing the concept of relative evaporation G = E/EVan, the ratio of actual to potential evaporation: G = = (7) For a wet surface, where e = e, G will be equal to unity; for a very dry surface, es approaches e, and G will approach zero. Substituting eqn. (7) to eqn. (6) and rearranging yields the general expression for evaporation from a non-saturated surface as: E = + (8) The use of eqn. (8) for estimating actual evaporation requires that a suitable expression for the relative evaporation, G, be found (Granger, 1989). According to the studies, made by Boutch (1963), Morton (1983), and Granger et al. (1989) on the "complementary relationship theory", we know that there is feedback mechanism between the surface evaporation and atmospheric parameters. For example, the effects of changes in the availability of soil water on potential evaporation can be assessed by their effects on the temperature and humidity gradients (Morton, 1983); an increase in actual evaporation can cause the vapor pressure of the overlying air to increase. The drying power, Ea, reflects to some extent the "dryness" of the surface. Furthermore, from eqn. (8), we can see that the driving power terms that affect actual evaporation including the drying power and the total available energy (net radiation subtracts soil heat). Here, introducing another parameter, D, relative drying power: D = (9) Considering the fact that for a wet surface, G will be equal to unity; for a very dry surface, G will approach zero, the G-D relationship function is set as: G = (10) where a and b are coefficients. Using eqns. (8), (10) and (9) the actual evaporation from non-saturated surface can be estimated provided that the coefficients in eqn. (10) are known. In this paper, based on water balance equation, the G-D relationship is established by hydrological and meteorological data of the selected river basins in China. 3 Data and study sites The actual average evaporation (evapotranspiration) for a closed basin can be derived from the water balance equation. Regardless of water input and output from and to adjacent river basins, the water balance equation for a closed basin can be expressed as: E = P - R ±?驻W (11) where E is actual evaporation, P is average precipitation, R is runoff, and ?驻W is the change of soil moisture storage. For long term, △W≈0, eqn. (11) can be written as: E = P - R (12) Since both the precipitation and runoff can be measured routinely, eqn. (12) provides a reliable way to estimate the long-term actual evaporation from a river basin. Considering the spatial distribution asymmetry of precipitation, the reliable estimation of long-term average actual evaporation of a river basin also needs densely distributed precipitation observations. To estimate the average precipitation of a river basin more accurately, the precipitation data from 432 meteorological stations and those from 512 hydrological stations of China are used. The researched river basins were selected according to the following criteria: 1. To assure the change of soil moisture storage △W≈0 in long term, there were no large or middle-scale water bodies built during the period of study. 2. There are sufficient meteorological and hydrological stations distributed in the river basin. 3. To represent the features of different climatic regions in China, the selected river basins should be dispersedly distributed in China, and the area of each should not be too large. With the aid of GeoStar, the GIS (Geographical Information System) designed by Wuhan University, as well as some data derived from Chinese Resources and Environmental Dataset, the river basin selection process was performed.

In total nine river basins were selected . The detail information for each river basin is listed in Table 1. Monthly meteorological data are derived from Temperature Data of China, Humidity Data of China, Wind Data of China, Sunshine Data of China, respectively. Also, Surface Meteorological Monthly Bulletin is used as a reference data source. Arithmetic Average Method is used to calculate the monthly mean value of each meteorological element for each river basin. Hydrological data, including runoff, are derived from Hydrological Statistics of Main Rivers in China. 4 Estimation of actual evaporation from non-saturated surfaces 4.1 Relative evaporation simulation Rearranging eqn. (8) and simplifying gives an expression for G equal to: G = (13) The actual evaporation was calculated by eqn. (12). In the calculation, P (precipitation) and R (runoff) using 10-year-overlaping mean values, so the change of soil moisture storage approaches zero. In the calculating process of D (relative drying power), parameters related to air drying power and net radiation were determined according to The Climate Atlas of China- Water Resources. For a 10-year time scale, the ground heat flux B≈0. Based on eqns. (9), (13) and (10), the relative evaporation was simulated by the curve (Figure 1). In Figure 1, the number of data points, and the correlation coefficient square. From this figure we can see that there is a good exponential relationship between the relative drying power and the relative evaporation. The exponential function fitted to the data gives the expression: G = (14) Compared with eqn. (10), we know that a = 0.7690 and b = 4.9927. 4.2 Simulation of actual river basin evaporation Using eqns. (8) and (14), the ten-year-overlapping mean values of actual evaporation of the selected river basins were estimated (Figure 2). Figure 2 shows that the actual river basin evaporation can be estimated with an error of less than 10%, except few low actual evaporation values that belong to the Yellow River Basin. The error was caused mainly by slightly large area and complex geographical environment of the Yellow River Basin which transverses the Qinghai-Tibet Plateau and arid regions in Northwest China. It is imaginable that the model should be improved greatly if some parameters could be obtained by other means such as remote sensing techniques.

关键词： potential evaporation; actual evaporation

