Potential Evapotranspiration Methods for the Assessment of River Runoff under Climate Change

河川流量の気候変動影響評価のための潜在可能蒸発散算定手法

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Abstract; Based on an overview of the main potential evapotranspiration methods, the sensitivity of four potential evapotranspiration methods to temperature in three representative river basins of different climatic and hydrological natures was analyzed. With the application of the potential evapotranspiration methods in regional hydrological models, the impact of potential evapotranspiration methods on the assessment of river runoff under climate change was studied.
KEYWORDS; Potential Evaporation Method, Climate Change, Assessment, Runoff

1. Introduction

With evidence indicating that the atmospheric concentration of greenhouse gases is increasing, there are growing concerns that these changes will have significant impacts on the hydrologic cycle in many regions of the world (Skiles *et al.*, 1990). Thus, the Committee on Earth and Environmental Sciences (CEES) in the United States identified the hydrologic cycle as the highest scientific priority for global change research (Rind *et al.*, 1992). Concurrently, hydrologists have been busy investigating the response of river basins to possible climatic variations. Usually, studies of this nature apply to a unique hydrologic model of a river catchment and then the temperature and precipitation are altered to assess the potential response of river basins (Riebsame *et al.*, 1994; Gleick, 1987). Yet it is pointed out by scientists that, different formulae of physical processes as well as different conceptualizations of hydrologic components will likely respond differently under climate change scenarios. This idea is the driving force in looking at the myriad approaches that have been and continue to be used in describing the response of river basins to hydrologic processes. In this paper, four different potential evapotranspiration (PET) methods are applied to estimate the potential evapotranspiration of typical river basins with different climatic and hydrologic characteristics, and then they are introduced into the regional hydrological models, so as to assess the impact of PET methods on the assessment of river runoff under climate change.

2. Potential Evapotranspiration (PET) Methods

A number of approaches have been applied to assess evapotranspiration and runoff changes within the context of a changed climate so far. Generally, all of these methods can be divided into three categories: hydrologic or water balance methods, analytical methods based on climate variables, and empirical methods. The water balance method is primarily a physics-based approach, and its application in climate change assessment is limited to the laboratory. The second approach, referred to as a micrometeorological method, uses the scientific understanding of the physics of evaporation and transpiration. Mathematical relationships are developed to describe these processes via two key

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climatic components: energy balance and mass transport. The third method concerns the development of empirical relationships that are often site-specific, based on local climatic conditions and often cast in regression analysis. These methods are usually "calibrated" by relating the empirical estimates to observed measurements.

Considering the availability of data required by the individual PET approach, and the applicability of each method, four different PET methods are chosen in this paper for estimating the potential evapotranspiration. Then the methods are applied to monthly water balance models, so as to assess the impacts of different PET methods on changes in river basin discharge under global warming.

2.1. Micrometeorological Method

This kind of approach considers extensively the three main driving factors (Chow, 1988) relating to evaporation: latent heat, wind and the humidity gradient in the air above the evaporation surface, and soil moisture availability.

The Penman method is regarded as a typical micrometeorological approach. The modified Penman formula (Shuttleworth, 1993) will be applied in this study:

$$E_P = \frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} \frac{f(u)D}{\lambda} \quad \text{(mm/day)} \qquad \textbf{(1)}$$

where R_n is net radiation exchange (mm/day) and *f(u)* is function of wind. Here the function put forward by the National Coordinating Group of Agricultural Climate Resources and Studies (1986) is used; D (hPa) is vapor pressure deficit; Δ (hPa/℃) is slope of the saturated vapor pressure curve; γ is psychometric constant ($C_p P K_h / (0.622 \lambda K_w)$; C_p (kJ/kg℃)is specific heat at constant pressure, K_h, K_w is diffusivity (m^2/s)); and λ is latent heat of vaporization.

Meanwhile, Priestley and Taylor (1972) found that for very large areas the second term of the modified Penman formula (1) is approximately thirty percent of the first. Thus, an approximation to the Penman equation that is less data demanding can be written as:

$$E_{rc} = \alpha \frac{\Delta}{\Delta+\gamma}(R_n - G) \qquad \text{(mm/day)} \qquad \textbf{(2)}$$

where α has been given the value of 1.26 in humid climates (relative humidity greater than 60 percent in the month with the maximum evaporation) and 1.74 for arid climates (relative humidity less than 60 percent in the month with the maximum evaporation). G (mm/day) is the heat conduction to the soil.

2.2. Empirical Methods

Due to it's limited data demands, the empirical method has been proposed since the 1920s. Among others, the Thornthwaite method (1939) has the broadest application, which estimates E_p from the following equations:

$$E_p = 1.62 \times \left(\frac{10\overline{T_i}}{I}\right)^a \qquad \text{(mm/day)} \qquad \textbf{(3)}$$

$$I = \sum_{i}^{12} \left(\frac{\overline{T_i}}{5}\right)^{1.5} \qquad \text{(mm/day)} \qquad \textbf{(4)}$$

and

$$a = 6.7\times10^{-7}\times I^3 - 7.7\times10^{-5}\times I^2 + 1.8\times10^{-2}\times I + 0.49 \quad (5)$$

Where, $\overline{T_i}$ is monthly average temperature in month i. Furthermore, the studies in China (National Coordinating Group of Agricultural Climate Resources and Studies, 1986) indicated that the following equation is suitable for E_p estimation in most parts of that country:

$$E_p = 0.0018 * (25 + T)^2 * (100 - f)/30 \qquad \text{(mm/day)} \quad (6)$$

Where, T (℃) is the monthly air temperature; and f (%) is the monthly relative humidity. From here on, this empirical method will be referred to 'local Method'.

2.3. Calibration of Empirical Methods

A calibration procedure was used to adjust the empirical E_p estimates. It was based on the idea that the long-term water balance of a large catchment can be simply written as $R_a = P_a - Ev_a$; annual runoff equals annual precipitation minus annual evaporation (Dooge, 1992). If it is assumed that there is no over-year storage when using long-term averages, then a simple monthly runoff model for a basin can be expressed as:

$$R_i = \begin{cases} BF(\hat{E}_{p,i} \geq P_i) \\ P_i - \hat{E}_{p,i} + BF_i(\hat{E}_{p,i} < P_i) \end{cases} \qquad \text{(mm/month)} \quad (7)$$

Then, summing up the monthly runoff values and letting them equal the observed values,

$$\sum R_i = \sum R_{0,i} \quad (8)$$

it is possible to find a coefficient, β, that gives an estimation of the potential evapotranspiration value for the basin based on a given potential evapotranspiration.

$$\hat{E}_{p,i} = \beta E_{P,i} \quad (9)$$

where, $R_{0,i}$ is the observed runoff in month i; R_i is the computed runoff in month i; $\hat{E}_{pi}$ is the adjusted potential evapotranspiration estimate in month i; $E_{p,i}$ is the potential evaporation in month i by empirical methods; P_i is the precipitation in month i; β is the calibration coefficient for empirical methods; and BF_i is the baseflow in month i.

3. River basins and data

As described above, PET estimates depend largely on the climate to which they are applied. In this discussion, three basins of different scale and climatic characteristics are selected to span a range of climate variability: the Yellow River, the Yujiang River and the Lhasa River. A brief description of the climatic and hydrological natures of these basins is given in Table 1.

The data series of monthly precipitation and runoff for 1951-1970 are acquired from the "Statistics on Hydrological Characteristics of Main River Basins in China (1975)"; the monthly temperature, wind, humidity, air pressure, and sunshine hours for 1951-1980 are from "Field Climate Data of China (1983)".

Table 1 Characteristics of selected river basins

River Basin	Observation Station	Catchment area (km2)	Annual Precipitation (mm)	Annual Evaporation	Annual Discharge (m3/s)	Climate Zone
Yellow River	LanZhou	222551	327.7	1437.7	1070	Temperate, Semi-Arid
Yu Jiang River	NanNing	75520	1300.6	1693.4	1290	Subtropic, Humid
Lhasa River	Lhasa	27482	444.6	1393.5	281	Alpine, Semi-Arid

*Evaporation in Lhasa Station was observed by the E601 evaporation meter, while in other station from 20 cm ones.

Table 2 Change in E_p to temperature increase by respective estimation method

	Yellow River					Yu Jiang River					Lhasa River				
	1°C	2°C	3°C	4°C	5°C	1°C	2°C	3°C	4°C	5°C	1°C	2°C	3°C	4°C	5°C
Modified Penman	3.2	6.4	9.6	12.8	16.5	3.6	7.8	10.8	14.5	19.0	3.6	7.2	10.8	14.5	19.0
Priestly-Taylor	3.2	6.4	9.6	12.8	16.0	3.2	6.4	9.6	12.8	16.9	3.5	7.0	10.5	14.0	17.5
Thornthwaite	15.1	31.8	47.4	68.7	97.5	12.0	24.0	38.0	50.0	65.0	10.2	20.2	32.2	43.6	51.0
Local	10.1	20.2	31.4	42.3	53.2	4.0	8.0	12.0	16.0	19.0	6.4	12.8	19.3	27.4	34.5

4. Sensitivity of PET methods to temperature

Considering the fact that the river runoff responses to climate change are usually assessed by altering the base temperature and precipitation while keeping the other variables constant, the sensitivity of PET methods to temperature is analyzed. Using the averaged monthly meteorological data for 1951-1980 and the different changes in temperature, the sensitivity of different PET methods to temperature is then analyzed. Table 2 reveals that: (1) with the same change in temperature, there are notable differences in the relative changes in PET among different methods. Compared to empirical methods, mircrometeorology-based methods produce much smaller relative changes in PET, which reflects the much lower dependence of PET estimates from Penman Series formula on temperature; (2) Between the two empirical methods, the Thornthwaite method produces larger relative changes in PET, because this method relies more on temperature; and (3) the two empirical methods are much more sensitive to temperature in the Yellow River than at the other selected rivers, which reflects the temperate climate characteristics of the Yellow River.

5. Impact of PET methods on river runoff assessment under climate change

To analyze the impact of PET methods on river runoff under climate change, the above PET methods are applied to monthly water balance models for the four selected basins. The monthly water balance models for arid, semi-arid regions and for humid, semi-humid regions (Hydrological Information Center, Hydrological Ministry of China, 1996) are applied to model the runoff of the Lhasa River, Yellow River and Yu Jiang River respectively. During the runoff modeling, there is only temperature change within the different PET models, while other variables and parameters hold constant.

5.1. Parameter fitting and validation

Table 2 shows the standard errors of parameter fitting and validation by the respective PET method for the respective river basin. The standard error (*S.E.*) is defined as:

$$S.E. = \left[\frac{1}{n}\sum(R_{oi} - R_i)^2\right]^{1/2} \qquad (10)$$

Where, n is the number of the total months for modeling. R_{oi} (mm/month) is the observed runoff in month i, and R_i is the modeled runoff in month i. For the Lhasa River, 7-years data (1956-1962) were used for parameter fitting and the next 8-years data (1963-1970) were used for validation, while for the other three rivers, 10-years data (1951-1960) were used for fitting and the next 10-years data (1961-1970) for validation.

Table 3 Standard errors of parameter fitting and validation (mm/month)

	Modified Penman		Priestly-Taylor		Thornthwaite		Local	
	Fitting	Validation	Fitting	Validation	Fitting	Validation	Fitting	Validation
Yellow River	43.04	40.15	51.33	49.57	42.36	41.25	42.26	41.21
Yu Jiang River	45.82	46.91	60.91	70.57	35.21	35.94	34.02	34.77
Lasha River	55.56	56.52	57.41	61.69	51.64	52.64	51.80	52.90
Average	44.97		52.91		49.96		40.75	

It is revealed from Table 3 that, in the three studied basins, the local method gives much less standard error both in the fitting and validation periods, in spite of its less data demands, while the Priestly-Taylor method results in the largest standard error. In case long-term historic records of climatic and hydrological variables are available, the local method, which takes humidity into account as well, should be a good option for river runoff estimate.

5.2. Application of E_p methods to the river runoff models

With the parameters fitted in 4.1, and the other variables constant, the elasticity for each E_p method can be calculated by altering temperature and precipitation within the models. Elasticity can be used as an indicator of the impact of E_p methods on river basin discharge. It is defined as:

$$\Phi = \Delta Q / \Delta E_p \tag{11}$$

Where, ΔE_p and ΔQ are the respective relative changes in annual potential evapotranspiration and annual runoff under certain climate scenarios. The results are shown in Table 4, which reveals that, for the Yellow River, which is located in the semi-arid region of China, elasticity has the maximum absolute value (around 1). Thus, runoff from the Yellow River is perhaps most sensitive to the potential evapotranspiration estimates.

6. Conclusions

Though it is difficult to draw definitive conclusions regarding the empirical and physical methods because different climatic regions show different trends, the present study revealed:

(1) For all of the selected rivers, under the same changes in temperature, the modified Penman method gives the smallest relative change in potential evapotranspiration, while the Thornthwaite method (temperature based) maximum gives the maximum changes; E_p estimates from Thornthwaite method are least sensitive to temperature in the Lhasa River;

Table 4 Elasticity in Different Basins for $\Delta 3$°C and $\Delta 5$°C (without precipitation change)

	Modified Penman		Priestly-Taylor		Thornthwaite		Local	
	Δ3℃	Δ5℃	Δ3℃	Δ5℃	Δ3℃	Δ5℃	Δ3℃	Δ5℃
Yellow River	−1.32	−1.24	−1.36	−1.30	−1.03	−0.80	−1.15	−0.97
Yu Jiang River	−0.47	−0.41	−0.54	−0.43	−0.62	−0.53	−0.23	−0.14
Lasha River	−1.28	−0.84	−0.94	−0.98	−0.48	−0.42	−0.87	−0.65

(2) Due to the large elasticity in the Yellow River, which is located in the semi-arid region of China, it is important to choose the appropriate E_p method in assessing the impact of climate change on river basin discharge;

(3) Empirical methods, mainly temperature-based, give significantly different marginal changes to temperature fluctuations when compared with the micrometeorologically-based methods. Drastically different results are found under the same climate scenarios for a given basin.

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