Analysis of Spatial Distribution and Temporal Trend of Potential Evapotranspiration in Hexi Corridor

Y M Wang[1,*], D F Peng[1], X Y Guo[2], H Huo[3], O Cheng[1], L L Tong[1] and D S Hu[1]

[1]Changsha Normal University, No. 9 Teli Road, Changsha, 410100, China;
[2] Northwest Institute of Ecology and Environmental Resources, Chinese Academy of Sciences, No. 320 West Dong Gang Road, Lanzhou, 730000, China;
[3] Kunming University, No. 2 Puxin Road, Kunming, 650214, China

Corresponding author and E-mail: Y M Wang, wangyamin@lzb.ac.cn

Abstract. In this paper, the FAO Penman-Monteith (FAO-56 PM)model are evaluated to estimate daily potential evapotranspiration (PET) values, at 14 meteorological stations during 1960-2011 in the Hexi Corridor in China are calculated. Using GIS spatial analysis techniques and mathematical statistical theory to analyzed temporal and spatial characteristics of potential evapotranspiration in Hexi Corridor. Their spatial distributions and temporal variations are examined and the causes for the variations are discussed. The contributions of various meteorological variables to the temporal trend detected in the PET is then determined. The results show that: (i) The annual PET showed a mixed pattern of upward and downward trend during 1960-2011 in Hexi Corridor. The trends in the seasonal changes were particularly strong in summer and spring, whereas the increase is in summer. (ii) The potential evapotranspiration was decreased from northwest to southeast in Hexi Corridor, the minimum were in the Qilian Mountains. The potential evapotranspiration mainly concentrated in the spring and summer, account for 30% and 40% in potential evapotranspiration, respectively, autumn followed and winter was minimum. (iii) The main factor effect potential evapotranspiration of Hexi Corridor was wind speed, which effect the spring potential evapotranspiration was temperature.

1. Introduction

Potential evapotranspiration (PET) is a key hydrological variable quantifying a major water loss from catchments, which can be used to calculate actual evapotranspiration (ETa), schedule irrigation and prepare input data for hydrological models. The only factors affecting PET are climatic parameters as water is abundantly available at the reference evapotranspiring surface [1]. According to the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (AR4), global mean surface temperatures have raised by 0.74 ℃ ± 0.18 ℃ over the last 100 years. Besides the obvious increases in temperature, atmospheric moisture, precipitation and atmospheric circulation also change and their changes are more uncertain (IPCC, 2007). Potential evapotranspiration is the maximum possible evaporation rate, which has been widely formulated using meteorological variables such as net radiation, wind speed, relative humidity and air temperature [2]. In recent years, decreasing trends in PET have been reported in several regions of the world in contrast of increasing air temperature; this

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has been called the "evaporation paradox" [3-4]. Researchers describe this phenomenon in several ways: complementary relationship between the actual evaporation and PET [5-6], reduction in irradiance due to increase in cloud coverage and aerosol concentrations [3], decreasing levels of wind speed [7-9], etc. In turn, changes of PET resulting from climate change can greatly influence hydrological parameters such as soil water content, actual evaporation and runoff [10-11]. Therefore, exploring the impacts of climate changes on PET will provide insights into novel water management practices.

Under the background of climate and vegetation changes on the semiarid area, it is necessary to understand the present changes and project the future changes of PET to provide useful information for the vegetation construction and water management on the semiarid area. As a semiarid area, Hexi Corridor which is lying in northwest in China was catching more attention by government in recent years. In semiarid climates where water resources are limited and seriously endangered by overexploitation, it is essential to estimate potential evapotranspiration with the greatest possible precision. This way, good management and planning of available water resources is attained. This type of study is very useful in the area where it was conducted, but also offers the possibility of extrapolating results to other geographical areas of similar climatic conditions. It permits irrigation advisory services and also allows technicians interested in the subject to know what the most precise equation is for estimating PET values. This knowledge can mean significant water savings, as well as a more efficient utilization. Potential evapotranspiration (PET) estimations require accurate measurements of meteorological variables (solar radiation, air temperature, wind speed, and relative humidity) which are available in China [12-16]. Thus, this study was carried out with the objective of studying the temporal variation of PET on annual and seasonal basis over the semiarid climate of northwest of China.

The objectives of this study are: (1) to analyze seasonal cycle and annual variation of PET series in the Hexi Corridor from 1960–2011; (2) to quantify the trends of PET series of the Corridor and those at stations, and present spatial structure of the trends at each station; (3) to detect abrupt changes of PET series by two different methods, and give spatial distribution of abrupt changes at each station. This study will also shed light on our understanding of climate change and the accompanying effect on hydrology, as PET being not only a climatic variable but also an important hydrological process.

2. Material and methods

2.1 Study area

The Hexi Corridor, which is the study area, lies in the north-west of the Gansu Province and to the west of the Yellow River in China. It is a long corridor between the South Mountains (including Qilian Mountains and Aerjin Mountains) and the North Mountains (including Mazong Mountains, Heli Mountains and Longshou Mountains). It starts at Wushaoling Mountains in the east, and ends at Yumenguan (an important col in ancientry) in the west. It ranges from 92°21′ to 104°45′ E and from 37°15′ to 41°30′N, with a total area of 27.6×104 km^2. The distance from north to south is 40–100 km and the distance from east to west is about 1120 km. The Badain Jaran Desert and the Tengger Desert lie in its northeast (Figure 1) [17]. The Hexi Corridor lies in the transition zone between the monsoon and westerlies, and is an important location because of its ecological fragility and climatic sensitivity [18].

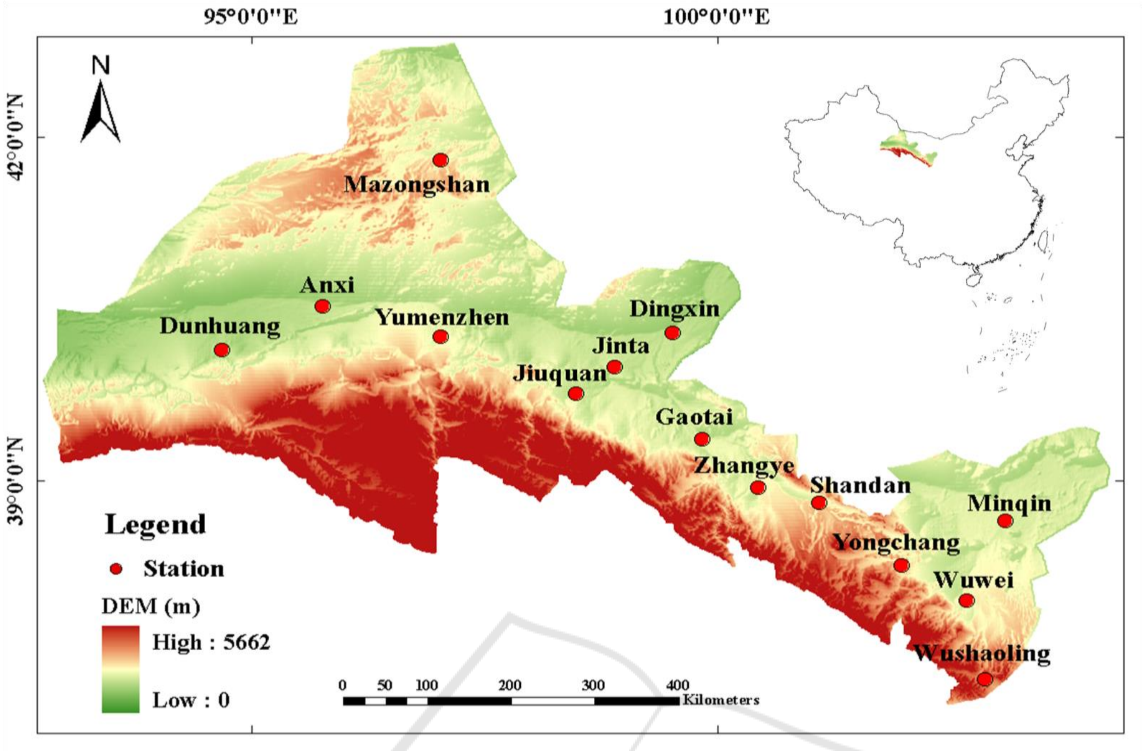

Figure 1. The spatial distribution of meteorological stations in study area.

2.2 Data

Data from 14 National Meteorological Observatory (NMO) stations including daily observations of maximum, minimum and mean air temperature, wind speed, relative humidity, sunshine hours, absolute vapour pressure, and precipitation for the period of 1960–2011 were used in this study (Figure 1). They have been provided by the National Climatic Centre (NCC) of the China Meteorological Administration (CMA) (http://www.nmic.gov.cn/).

2.3 Methods

The Penman-Monteith equation for calculation of the daily reference evapotranspiration assumes the potential evapotranspiration (PET) as that from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, which is given by Allen et al.[1]:

$$PET = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)} \quad (1)$$

where *PET* is the potential evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (℃), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), e_s-e_a is the saturation vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve (kPa ℃$^{-1}$) and γ is the psychrometric constant (kPa ℃$^{-1}$).

In order to obtain Rn, the Ångström-Prescott formula was used to calculate the global solar radiation (R_s) [1]:

$$R_S = \left(a_s + b_s \frac{n}{N} \right) R_a \tag{2}$$

Where R_s is solar or shortwave radiation (MJ m^{-2} day^{-1}), n is actual duration of sunshine (hour), N is maximum possible duration of sunshine or daylight hours (hour), n/N is relative sunshine duration (-), R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}), a_s is regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0), $a_s + b_s$ is fraction of extraterrestrial radiation reaching the earth on clear days (n = N). According to OU et al. [19], *a* and *b* were set at 0.205 and 0.433 in the Hexi Corridor, respectively. The computation of all data required for calculating ETo followed the method and procedure given in Chapter 3 of FAO-56[1]. Annual PET was calculated by determining the total of the monthly data series of PET at individual stations.

3. Results and discussion

3.1 Trend analysis on temporal basis

The annual mean potential evapotranspiration (PET) in Hexi Corridor displayed a statistically significant decrease of 1.83 mm/a from 1960 to 2011. However, the annual PET showed a mixed pattern of upward and downward trend. The PET time series was divided into three periods: 1960-1974, 1975-1993 and 1994-2011(Figure 2). It was observed that the PET exhibited an increasing trend of 9.76 mm/a during 1960-1974. There was an acceleration of decreasing trend in 1975-1993 (12.48 mm/a, significant at the 0.05 level), but the 1994-2011 trend was a significant increase (10.52 mm/a, significant at the 0.05 level). This is coherent with the similar slow down of the decreasing trends of pan evaporation in China [13-16].

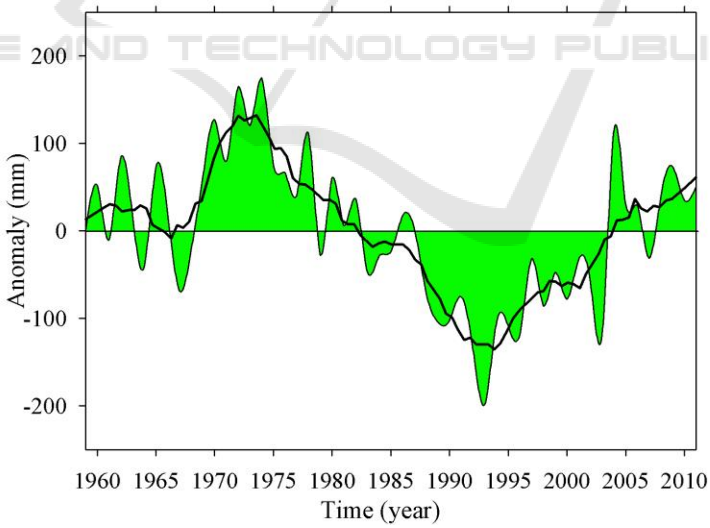

Figure 2. The change tendency curve of PET.

The temporal changes of seasonal PET are the same change as the annual PET, except for winter with the non-significant trend, whereas the trends were higher in other seasons (Figure 3). The results showed that: (i) During 1960-1974, positive values for PET were recorded in spring, summer and autumn with a trend of 2.48 mm/a, 3.73 mm/a and 3.40 mm/a, respectively. (ii) During 1975-1993, negative values for PET were recorded in spring, summer and autumn with a trend of -3.84 mm/a, -5.46 mm/a and -2.23 mm/a, respectively. (iii) During 1993-2011, positive values for PET were recorded in spring, summer and autumn with a trend of 3.50 mm/a, 5.704 mm/a and 1.29 mm/a, respectively. (iv) The trends in the seasonal changes (mm/a) during 1960-2011 were -0.27 (spring), -0.91 (summer), -0.60 (autumn) and -0.32 (winter). The weakening of decreasing was particularly strong in summer and spring, whereas the increase is in summer.

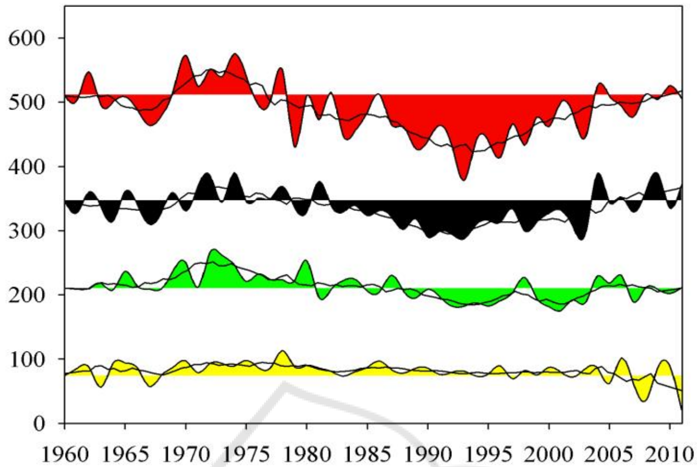

Figure 3. Temporal variation of PET in different season.

3.2 Spatial distribution of seasonal and annual PET

These spatial distribution maps provide valuable information in water resources planning and management in the Hexi Corridor, since spatial distribution of annual and seasonal values of PET is an important driving force in the hydrological cycle. Combining the spatial distribution maps of PET with the spatial distribution of meteorological variables will provide an important background and physical interpolation for climate change studies in the region.

Using GIS spatial analysis techniques and mathematical statistical theory to analyzed temporal and spatial characteristics of potential evaporation in Hexi Corridor. The spatial distributions of annual PET during 1960-2011 are plotted in Figure 4. It shows large spatial variability at places. The maximum and minimum were 1632.87 mm at Yumenzhen in the northwest of region and 655.58 mm at Wushaoling in the southeast of region, respectively. PET is the largest (on average >1000 mm) to the north of region, the area that is primarily covered by Gobi desert. On the boundary of the southeast Qilian mountain region PET is smaller than the Gobi desert. This may imply a topographic effect. The annual distribution has a rich spatial structure with a relatively low area in the central part of the catchment and high areas in south- west and southeast.

It can also be seen that the seasonal and annual variations of the PET in different regions (see Figure 5). The stations that is located in northwest of Hexi Corridor displayed a decreasing trend of annual mean PET during 1960-2011, and the maxima trends were observed at Anxi station with an average slope of 7.03 mm/a. The stations that is locate in mountains displayed a increasing trend, and the maxima trends were observed at Jinta station with an average slope of 17.90 mm/a. The other stations with non-significant trends were mainly at lower altitudes. Increasing trends were observed at Jinta and Mazongshan in spring. Jiuquan displayed an increasing trend in summer. However, decreasing trends were observed at Anxi and Yumenzhen in spring, summer and autumn. No statistically significant trend in seasonal PET was observed at eight stations (Dunhuang, Dingxin, Gaotai, Zhangye, Shandan, Yongchang, Wuwei, Minqin). The PET mainly concentrated in the spring and summer, account for30% and 40% in potential evapotranspiration, respectively, autumn followed and winter was minimum. Stations with the highest significant trends were on the Gobi desert, whereas stations with non-significant trends were in the southeast of Hexi Corridor.

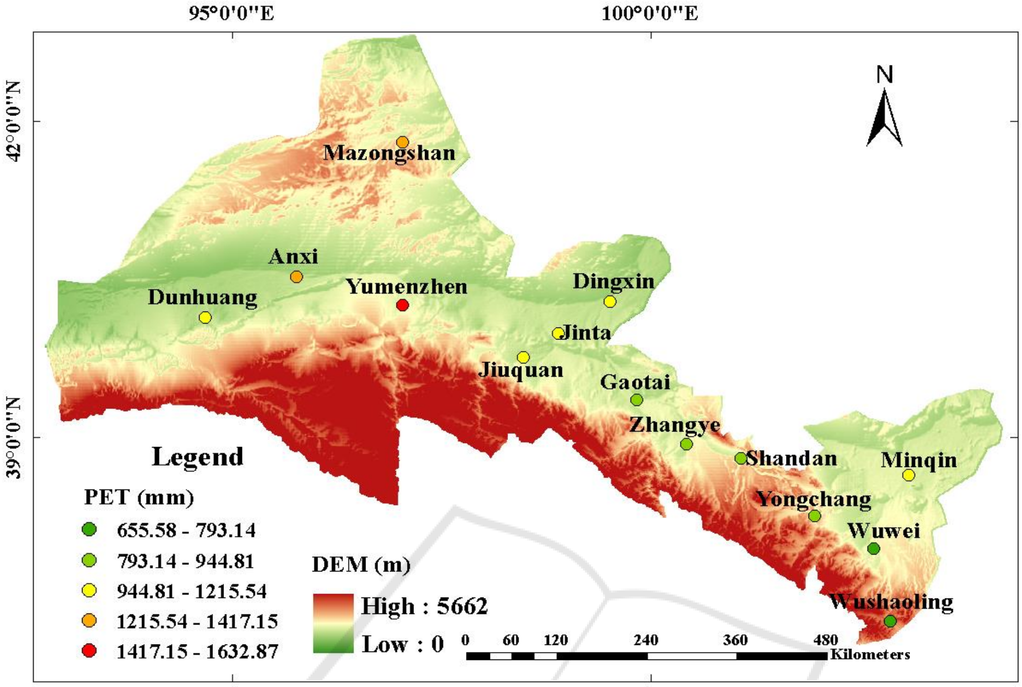

Figure 4. Spatial distribution of the PET.

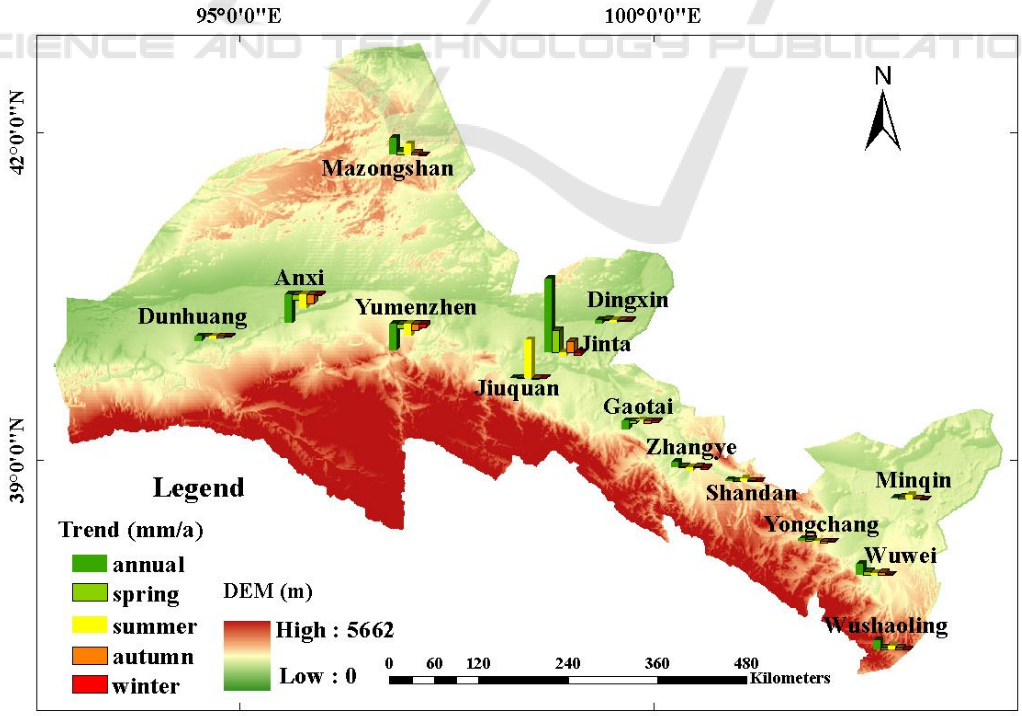

Figure 5. Spatial distribution of the PET trends.

3.3 Attribution analysis of PET

The data obtained from attribution analysis of PET are shown in Table 1. Attribution analyses reveal the contribution of different factors to the trends of PET observed over time. The attribution of meteorological variables to PET can be obtained from partial derivatives and the annual average trend of each variable [12]. The results are summarized below: (i) The annual average value of the attribution coefficients for relative humidity (RH), wind speed (W) and precipitation (P) were -0.46, 0.58 and -0.33, respectively. This indicated that the PET is most contribution to relative humidity, followed by wind speed and precipitation. (ii) Air temperature (T), precipitation (P) and wind speed (W) are more contribution of the spring PET. The attribution coefficient was 0.61, -0.47 and 0.48, respectively. The spring PET is most contribution to air temperature. (iii) The less sensitive to summer PET was air temperature (T), while the most contribution to summer PET were sun hours (S), net radiation (N) and wind speed (W). (iv) The attribution coefficients for autumn PET were sun hours (S), air temperature (T), precipitation (P) and wind speed (W), with the most attribution coefficient was sun hours. (v) The winter PET was only contribution to precipitation (P), the attribution coefficient was -0.47.

Table 1. Attribution coefficients between meteorological variables and the PET of annual and season.

	RH	S	T	R	P	W
annual	-0.46**	0.24	0.15	-0.07	-0.33*	0.58**
Spring	-0.21	0.26	0.61**	0.23	-0.47**	0.48**
Summer	-0.14	0.46**	0.35*	0.61**	-0.05	-0.57**
Autumn	-0.27	0.54**	0.41**	0.21	-0.43**	0.31*
Winter	-0.15	0.04	0.25	-0.09	-0.47**	0.12

** Denote statistically significant at the 1% level of significance;
* Denote statistically significant at the 5% level of significance.

4. Conclusions

This study addressed the changes of PET in Hexi Corridor during 1960-2011 and the attribution of different meteorological variables to the changes of PET. The present and future spatiotemporal characteristics of potential evapotranspiration (PET) are examined in this paper to understand the present and future changes in hydrology. After generating present PET by the Penman–Monteith method with historical weather data and future PET through Hurst parameter, the spatial distribution and temporal trend in PET is interpreted by Inverse Distance Weighted Interpolation. Some of the key findings are:

The annual PET showed a mixed pattern of upward and downward trend during 1960-2011 in Hexi Corridor. The trends in the seasonal changes during 1960-2011 were particularly strong in summer and spring, whereas the increase is in summer. The PET mainly concentrated in the spring and summer, account for30% and 40% in potential evapotranspiration, respectively, autumn followed and winter was minimum.

The spatial distributions of annual PET is the largest (on average >1000 mm) to the north of region, the area that is primarily covered by Gobi desert. On the boundary of the southeast Qilian mountain region PET is smaller than the Gobi desert. This may imply a topographic effect. Stations with the highest significant trends were on the Gobi desert, whereas stations with non-significant trends were in the southeast of Hexi Corridor.

The results obtained show that changes of PET were determined by a combined contribution of the different variables including net radiation, sun hours, wind speed, relative humidity, precipitation and air temperature. The annual PET is most sensitive to relative humidity, followed by wind speed and precipitation.

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