Journal of Hydrology 464–465 (2012) 352–362

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Assessing climate change induced modification of Penman potential evaporation and runoff sensitivity in a large water-limited basin

Qiang Liu [a,b,*], Tim R. McVicar [c]

[a] Key Laboratory for Water and Sediment Sciences, Ministry of Education, School of Environment, Beijing Normal University, Beijing 100875, China
[b] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China
[c] CSIRO Land and Water, GPO Box 1666, Canberra, 2601 ACT, Australia

ARTICLE INFO

Article history:
Received 23 March 2012
Received in revised form 17 July 2012
Accepted 19 July 2012
Available online 3 August 2012
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Attribution analysis
Potential evaporation
Net radiation
Ecohydrological processes
Yellow River Basin

SUMMARY

Potential evaporation (E_p) reflects the combined effects of four key meteorological variables: (i) net radiation ($\boldsymbol{R_n}$); (ii) wind speed (u); (iii) relative humidity (rh); and (iv) air temperature (T_a). Here, attribution analysis was conducted to investigate the contribution of the four key meteorological variables to changes of a physically-based E_p in a large water-limited basin, the Yellow River Basin (YRB), China. Then the influences of these changes, and precipitation (P) changes, on streamflow (Q) were explored analytically. Results show that: (i) E_p presented different temporal trends for the water yielding region (WYR) and water consuming region (WCR) with a overall changes of +0.16 mm a^{-2} and −0.66 mm a^{-2} during 1961–2010, respectively; (ii) trend analysis of E_p and the four key meteorological variables at the basin scale showed that increasing trend in T_a increased E_p during 1961–2010, while changes in $\boldsymbol{R_n}$ and u increased the 1961–1979 E_p rate and reduced it during 1980–1994 and 1995–2010; (iii) revealed by attribution analysis, E_p increased by changes in T_a and rh and reduced by changes of $\boldsymbol{R_n}$ and u in both WYR and WCR, in all, E_p rate presented positive and negative trends in the WYR and WCR, respectively; (iv) the changes of Q and actual evaporation (E) are much more sensitive to changes in P than the changes in E_p; and (v) of critical importance for water resource management of the YRB changes in Q are mainly attributed to changes in catchment-specific parameter (n) and P, while E_p reduced Q in WYR and increased Q in WCR. These results indicated that the causes of trend of E_p rates, influenced by combined effects of radiative and aerodynamic variables should be explicitly explained using fully physically based E_p formulations. Additionally, in the water-limited YRB, changes of Q are primarily controlled by the changes in catchment conditions, and secondarily by hydroclimatic factors where the available water (P) rather than energy condition (E_p) is more important. Better understanding all of these relationships and how they have varied will help water resource management in a changing climate.

1. Introduction

Decreasing trends in pan evaporation (McVicar et al., 2012; their Table 5 and the references therein) and potential evaporation (E_p) have been reported to be occurring simultaneously in many regions with increasing trends of air temperature, which has been denoted the "evaporation paradox" (Roderick and Farquhar, 2002). Possible reasons for this include: (i) complementary relationship between the actual evaporation (E) and E_p (Hobbins et al., 2004; Ramírez et al., 2005; Yang et al., 2006); (ii) reducing trends in irradiance due to increased cloudiness and aerosol concentrations (Roderick and Farquhar, 2002); and (iii) decreasing trends in wind speed (Rayner, 2007; Roderick et al., 2007; McVicar et al., 2012). E_p varies with the changes of aerodynamic and radiative variables that are influenced by both climatic changes and terrestrial conditions (e.g., Peel et al., 2010; Thanapakpawin et al., 2006; McVicar et al., 2007a; Roderick et al., 2009a, 2009b; Liang et al., 2010). E_p and precipitation (P) are regarded as available energy and water respectively, and climatologically their different amounts controls the partitioning of P into E and streamflow (Q) (e.g., Budyko, 1974; Donohue et al., 2007, 2010b; Liu and Yang, 2010; Roderick and Farquhar, 2011).

E_p can be defined as "the quantity of water evaporated per unit area, per unit time from an idealized, extensive free water surface under existing atmospheric conditions. This is a conceptual entity which measures the meteorological control on evaporation from an open water surface" (Shuttleworth, 1993, p. 4.2). This reflects the combined effects of the four key meteorological variables primarily governing they evaporative process, they are: (i) net radiation ($\boldsymbol{R_n}$); (ii) wind speed (u); (iii) relative humidity (rh); and (iv) air temperature (T_a). In order to calculate E_p many different methods, using one, or more, of these four variables have been

* Corresponding author at: Key Laboratory for Water and Sediment Sciences, Ministry of Education, School of Environment, Beijing Normal University, Beijing 100875, China. Tel.: +86 10 58802771.

E-mail address: liuqiangbnu@163.com (Q. Liu).

0022-1694/$ - see front matter © 2012 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhydrol.2012.07.032

developed according to local climatic conditions and data availability (e.g., Donohue et al., 2010a). Some formulations, such as Thornthwaite's (1948) and Priestley and Taylor (1972), just represent E_p rates via empirical relationship or only account for the vertical heat and mass fluxes (e.g., Burt and Shahgedanova, 1998). While such formulations are possibly adequate to assess monthly changes in E_p, they are inadequate when assessing the impacts of climate change on changing E_p rates as they do not consider changes to the inputs of all four meteorological variables governing the evapotranspiration processes (McVicar et al., 2012). This is because such formulations implicitly assume that some variables, especially those directly governing the aerodynamic component of evaporative process are non-trending: recently u has been shown to be trending across the global land-surface (McVicar et al., 2012, their Table 4 reports a trends of -0.014 m s^{-1} a^{-1} for 30 studies). As pointed out by Donohue et al. (2010a), such formulations should be revalidated or considered within the context of local conditions, e.g., the Priestley–Taylor method is only suited to energy-limited environments. In this context, the physically based models such as the Penman (and Penman–Monteith) equation, which incorporate both the radiative and aerodynamic components of evaporative process (Penman, 1948; Monteith, 1965), and are therefore explicitly influenced by trends in the four key meteorological variables (Liu et al., 2010b) have been shown to be the most optimal formulation to assess the climatic changes (Donohue et al., 2010a).

As interactions and feedbacks between climate and hydrological processes vary in both space and time, increased knowledge of the causes of changes of E_p increases our understanding of hydrological processes in different regions (Berry et al., 2005; Rodriguez-Iturbe and Porporato, 2005). This is especially important for long-term irrigation management, water allocation and re-vegetation activities across the different hydroclimatic conditions in large basins (e.g., Ozdogan and Salvucci, 2004; McVicar et al., 2007b, 2010; Lei and Yang, 2010; Liang et al., 2010). Given this, the objectives of this research, conducted in a large water-limited basin, the Yellow River Basin (YRB), China are: (i) to investigate changes of E_p and four key meteorological variables governing the evaporative process; (ii) to quantify the contributions of the four key meteorological variables to E_p; (iii) to investigate the sensitivity of Q to the climatic change; and (iv) attribute the changes of Q due to changes in P, E_p, and watershed characteristics for different hydroclimatic conditions. These four objectives are sub-headings in our subsequent Methods, Results and Discussions sections, (Sections 3–5, respectively).

2. Materials

2.1. Study site

The Yellow River is about 5400 km long draining 795,000 km^2, originating from the Tibetan Plateau, flowing through the Loess Plateau and the North China Plain, and finally reaching the Bohai Sea. According to naturalized Q (calculated by removing anthropogenic impacts, e.g., reservoir regulation and consumptive water use, from historic flow records, estimated by the Yellow River Commission; Fu et al., 2007), the region upstream of Lanzhou (accounting for 28% of the YRB area) is the main source of water resources generating ∼60% of YRB Q. Between Lanzhou to Huayuankou, as the river flows through the arid and semi-arid Loess Plateau, only ∼40% of YRB Q originates in this 69% of land area. Downstream from Huayuankou the Yellow River is suspended above the surrounding North China Plain (due to extensive levee construction over the last 2000 years; McVicar et al., 2002) so negligible Q is produced downstream of Huayuankou (this only constitutes 3% of the YRB area). Below Lanzhou increasing water consumption for agricultural and industrial uses, combined with P decreases, have led to Q decreases in the YRB so the river is more frequently not reaching the Bohai Sea (Liu and Cheng, 2000; McVicar et al., 2002; Jia et al., 2006; Liu et al., 2008; Nakayama, 2011). Given this, we defined the area upstream to Lanzhou as the water yielding region (WYR) and that downstream of Lanzhou as the water consuming region (WCR) (Fig. 1).

2.2. Data processing

Monthly time series of sunshine hours, u, rh, T_a and P at 89 meteorological stations from 1961 to 2010 were provided by the National Climatic Centre of the China Meteorological Administration.

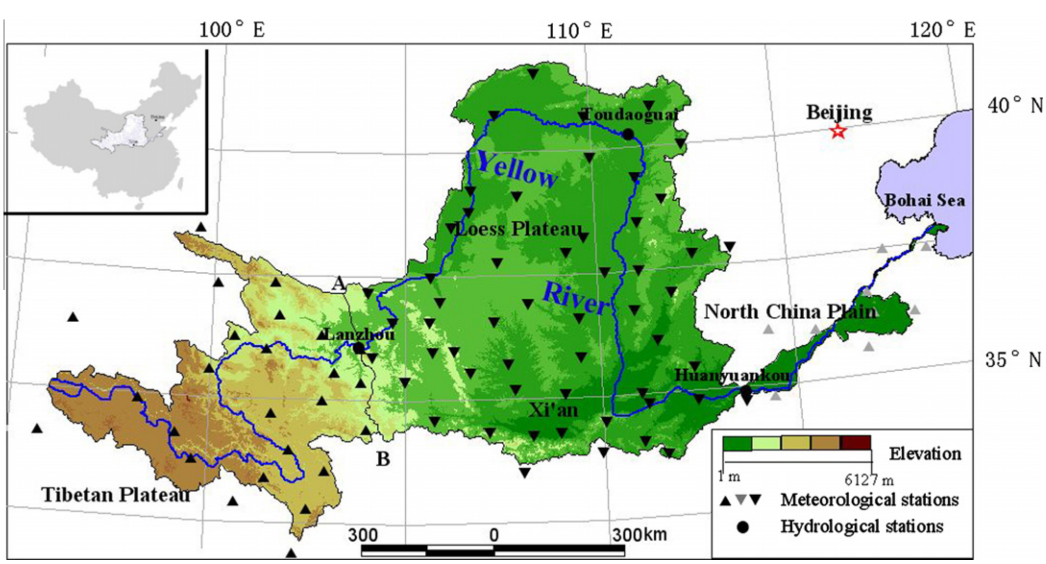

Fig. 1. The meteorological stations used in this study and location of the YRB, China. Meteorological station in the region upstream from Lanzhou station (▲), the region from Lanzhou to Huayuankou (▼), and the region downstream Huayuankou (▲) are indicated by different symbols in the figure, respectively. The blue line is the Yellow River. The demarcation line (A and B) was used to divide regions upstream of Huayuankou into WYR and WCR. Point A is located at 37.20°N, 103.38°E and point B is positioned at 34.80°N, 104.33°E. The location of the YRB in all China is shown on the inset map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)