Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management (Proceedings of Symposium HS2004 at IUGG2007, Perugia, July 2007). IAHS Publ. 313, 2007.

Analysis of water resource variability over the irrigated area along the downstream reach of the Yellow River

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Abstract Long-term changes in climate, river discharge, irrigation water and water-use efficiency were examined during a case study in the Weishan Irrigation District located to the northern side of the lower Yellow River. The relationship between actual evaporation and potential evaporation was examined on annual–regional scales. It was found that the annual precipitation fluctuated dramatically especially during the 1990s–2000s. High interannual water resource variability aggravates the water shortage, and irrigation from the Yellow River is required in order to secure agricultural production. Even though the water-use efficiency increased during the recent decade, there is a high potential for further water-saving by optimizing the irrigation schedule and irrigation methodology. In additional, a significant negative correlation between the actual and potential evaporation in the natural catchment, was found to be much weaker in the irrigated area which is located in the same region. This implies the local climate changed to some extent due to irrigation.

Key words irrigation; water-use efficiency; trend analysis; evapotranspiration; Yellow River

INTRODUCTION

The water resources of the Yellow River basin are only about 19% of the total water availability in China, however, the efficiency of water use for agricultural irrigation is very low (Kang, 1998). The Yellow River supplies the primary water source for irrigation across the whole basin. With the expansion of irrigated areas along the lower reaches, the water shortage in the Yellow River is becoming more serious and has resulted in the drying-up of the main river since 1972 (Yang *et al.*, 2004). Both water resource deficiency and waste in water use are major problems, and methods are required for improving water resources management in the future. Understanding of the variability in past water resources is helpful to increase water-use efficiency and to improve the irrigation water management.

A water budget, including precipitation, irrigation, discharge and evaporation, is normally used for analysing water resource availability within the irrigated area (Lei *et al.*, 2002; Isidoro *et al.*, 2004). A case study was carried out in the Weishan Irrigation District located along the downstream reach of Yellow River, in order to investigate the long-term variability of water resources. For this purpose, long-term changes in precipitation, air temperature, pan evaporation, river discharge, water use, and crop yield were examined. The actual and potential evaporation at annual–regional scales were examined to provide understanding of the water balance and its controlling factors.

STUDY AREA AND FIELD EXPERIMENT

The Weishan Irrigation District was selected as the study area. The area is located on the northern side of the lower Yellow River and belongs to Liaocheng City, Shandong Province. The irrigated areas are located in the region delimited by the geographical coordinates 36.14°–37.01°N and 115.43°–116.51°E (Fig. 1) with the elevation ranging 23–48 m above sea level. The average gradient is 1:7500 declining from the southwest to the northeast. The climate is temperate and semi-humid, and the annual precipitation is around 600 mm of which ~70% concentrates in the summer from June to September. The Tuhai and Majia rivers are the two principal rivers running parallel from the southwest to the northeast across the region. The major soil type is silt loam composed of the Yellow River sediments. More than 80% of area is farmland. Winter wheat and maize are the two major crops cultivated rotationally in this area. Winter wheat is sown in early October, but the growing period is from March to the middle of June. The growth season of maize is from mid June to early October.

The major irrigation infrastructures were built in 1958. However, irrigation ceased from 1962 to 1970 and was re-started from 1971. The Weishan Irrigation District is the fifth largest irrigated district in China. Three main channels and about 400 branch

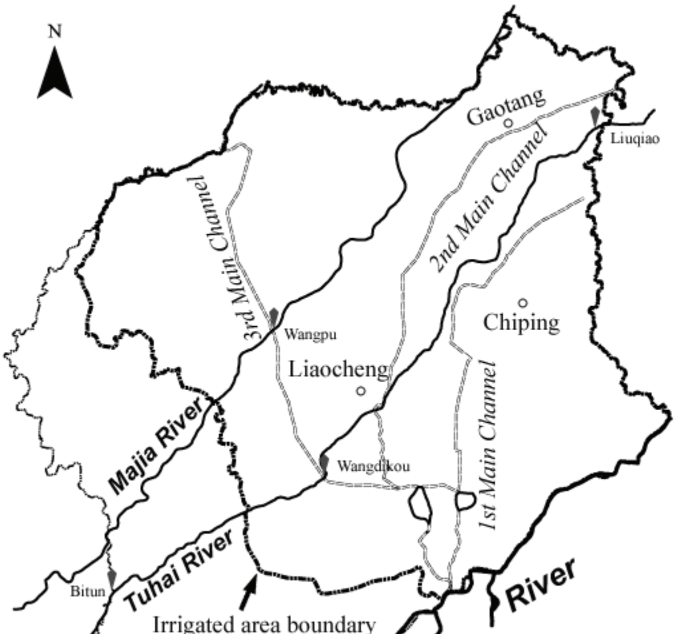

Fig. 1 Map of Liaocheng City and Weishan Irrigation District.

channels run through the whole irrigated area, and have the capacity of taking about 1.3×10^9 m^3 water per year from the Yellow River for irrigating 340 000 ha of agricultural fields. Due to the climatic conditions, spring irrigation of winter wheat constitutes about 70% of the total yearly water consumption for irrigation. Summer irrigation is usually implemented in mid or late June just before the rainy spell while autumn irrigation takes place just before the sowing of winter wheat in October.

DATA AND METHOD

Data used in the study

Meteorological data from three meteorological stations for 1961–2005 were obtained from the Liaocheng meteorological bureau. The data consist of daily precipitation, minimum, maximum and mean air temperature, wind speed, relative humidity, water vapour pressure, sunshine duration and pan evaporation. The regional average values were calculated using the arithmetic mean. Annual discharge data were obtained from the Liaocheng hydrological bureau. Data were available from one gauge on the Majia River, 1971–2005, and from two gauges on the Tuhai River, 1963–2005. Additionally, annual water intake from the Yellow River during 1958–2005 was obtained from the management office of the Weishan Irrigation District.

Analysing hydroclimatic changes

The Mann-Kendall nonparametric test (Burn & Hag Elnur, 2002) was conducted to quantify the trends in the meteorological and hydrological time series at a 5% significance level. In addition, the water-use efficiency was calculated as the ratio of annual crop yield to annual evaporation.

The regional water balance depends on hydroclimatic conditions and is affected by land surface factors. At the regional scale, the Penman equation for calculating potential evapotranspiration (Penman, 1948; Allen *et al.*, 1998) is often combined with a function of soil water availability to assess the actual evapotranspiration response to water stress. This empirical methodology is, however, questioned by the Bouchet hypothesis because it does not consider the complex surface–atmosphere interactions at the regional scale (Bouchet, 1963; Brutsaert & Stricker, 1979; Morton, 1983). The Bouchet hypothesis describes a complementary relationship between actual (E) and potential evapotranspiration (E_0), i.e. $E + E_0 = 2E_w$, where E_0 indicates the maximum possible evaporation under the prevailing climatic conditions, and varies with the wetness of the evaporating surface. The wet surface evapotranspiration (E_w) is assumed to be a constant for a given amount of available energy, and is estimated using the Priestley-Taylor formula (Priestley & Taylor, 1972) to indicate the advection-free or minimum-advection potential evaporation. The discrepancy between the Penman and Bouchet hypotheses is particularly important in non-humid regions. In this context, recent findings suggest that variations in actual evapotranspiration in non-humid regions are dominated by variations in precipitation rather than variations in potential evaporation (Yang *et al.*, 2006), and the Bouchet complementary relationship between actual and potential evaporations comes from the negative correlation between potential evaporation and precipitation. However, in humid regions, variations in actual evaporation are controlled by potential evaporation rather than precipitation, corresponding to the Penman hypothesis. This research examined the possible change of the relationship between potential and actual evaporation due to the irrigation.

RESULT AND DISCUSSION

Trends in climate and discharge during the last 45 years

Figure 2(a)–(d) show the annual precipitation, annual mean air temperature, annual pan evaporation and annual discharge during the last 45 years. The annual average precipitation is only 581 mm. Two continuous dry periods were found in the late 1960s and late 1980s. Entering the 1990s, the annual precipitation fluctuated dramatically with the minimum annual precipitation reaching values as low as 266 mm in 2002. No significant trends could be identified for either annual precipitation or for the annual mean air temperature. Before 1984, the annual mean air temperature was 13.3°C. After that, a significantly increasing trend of 0.24°C per decade was observed. The annual pan evaporation shows a clear decreasing trend, –96.3 mm per decade, which is caused by a lower sunshine duration and lower wind speeds (Fig. 3).

The average annual discharge at Wangpu gauge on the Majia River was 0.65×10^8 m^3/year during 1971–1982, but decreased rapidly to 0.11×10^8 m^3/year in the period 1982–2005. On the Tuhai River, the annual discharge at Bitun and Wangdikou, which are located at the entrance of the irrigated area, shows a slightly increasing trend. However, the average inflow value is only 0.63×10^8 m^3/year. The average annual discharge entering the irrigation area through the Tuhai and Majia rivers was only 0.79×10^8 m^3/year during 1980–2005. Low discharge and high inter-annual variability of precipitation aggravate the water resource shortage, especially in the 1990s. Therefore, irrigation from the Yellow River is required in order to secure the agricultural production.

The mean annual evaporation, calculated by the water balance equation, is 898 mm during 1980–2005. And, the ratio of mean annual evaporation to the sum of precipitation and irrigation is 0.93, showing that most of the water is consumed by evaporation.

Relationship between actual and potential evaporation

Figure 4 shows the relationship between annual actual evaporation and pan (or potential) evaporation plotted against $(P + I)$. A negative correlation coefficient (–0.31) between annual E and E_{pan} was found for the irrigated area. However, it did not pass the 0.1 significance level when applying the F-test. For comparison, the Dawenhe catchment (the discharge exit control gauge is located at 35.9°N, 116.45°E), a natural catchment very close to the Weishan Irrigation District, was examined. Its actual evaporation and potential evaporation showed a significant negative correlation (–0.51). Moreover, there is a significant positive correlation between E and $(P + I)$ for both the irrigated area and the natural catchment (where $I = 0$). Similarly, a significant negative

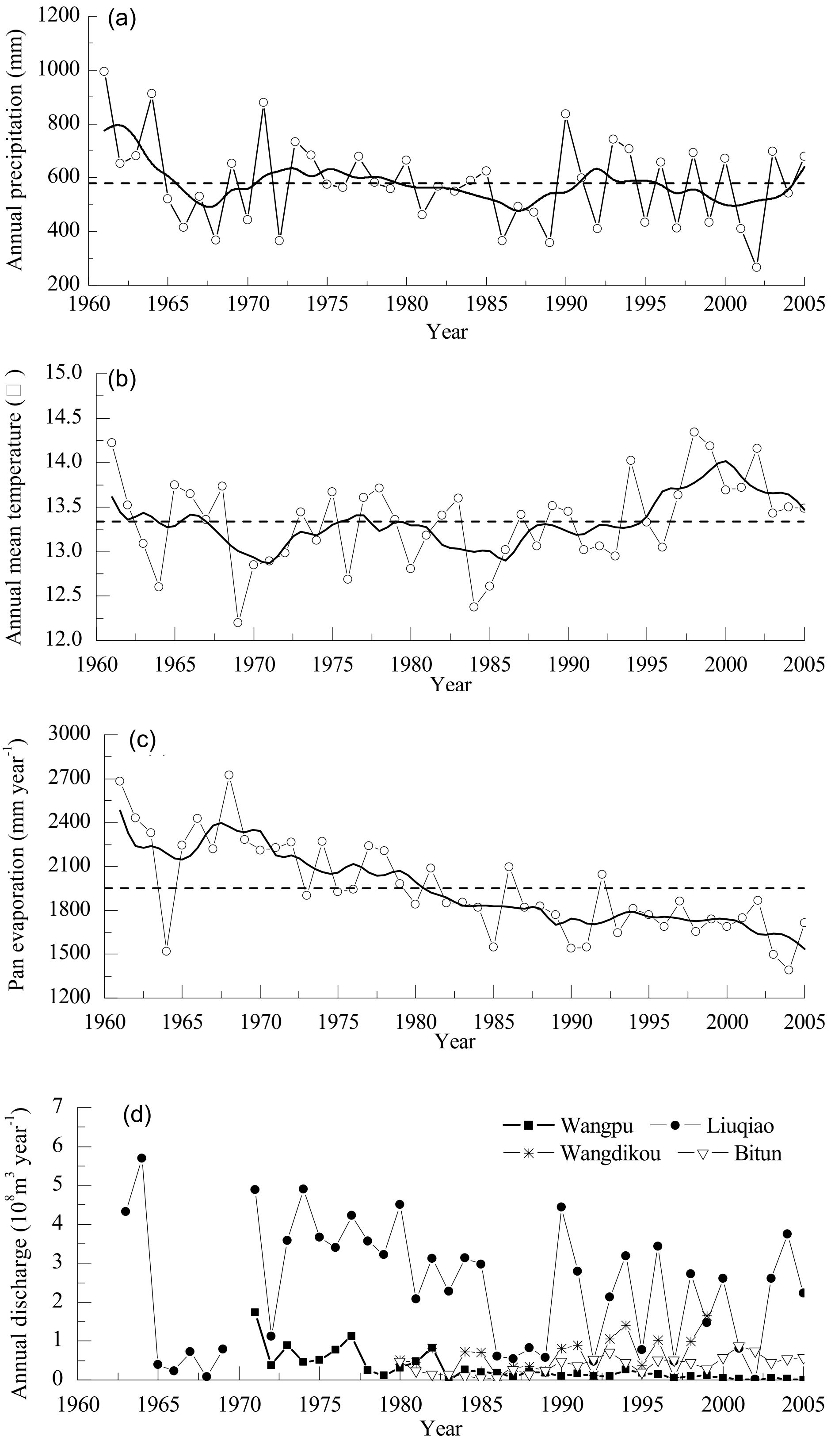

Fig. 2 Variations in: (a) annual precipitation, (b) annual mean air temperature, (c) annual pan evaporation, and (d) annual river discharge from 1960 to 2005 (the solid line denotes the 5-year average, and the dashed line denotes the annual mean).

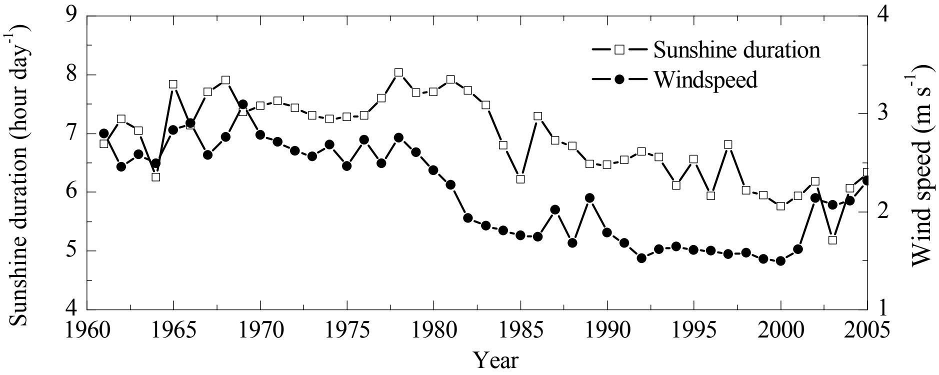

Fig. 3 The annual average daily sunshine duration and wind speed from 1960 to 2005.

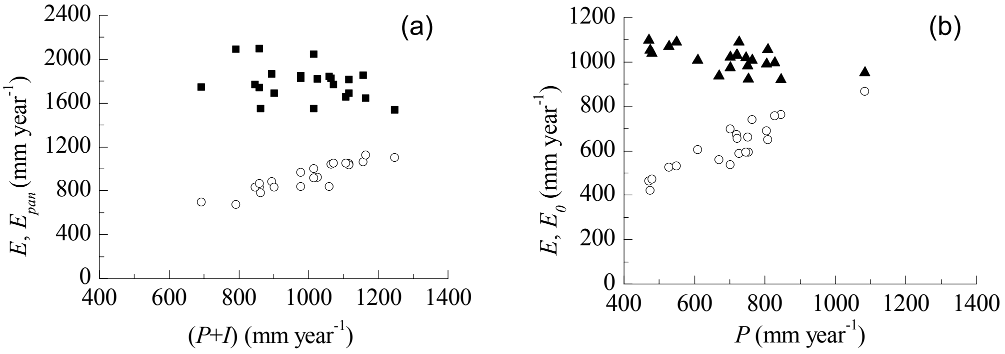

Fig. 4 The relationship between annual actual evaporation and pan (or potential) evaporation for: (a) the Weishan Irrigation District, and (b) the Dawenhe basin (the solid square denotes the pan evaporation, the solid triangle denotes the potential evaporation, and the open circle denotes the actual evaporation).

correlation between potential evaporation and $(P + I)$ was also found. However, the correlation coefficient for the irrigated area is lower than that for the natural catchment. This supports the idea that the Bouchet complementary relationship between actual and potential evaporation comes from the negative correlation between potential evaporation and precipitation. And, this also implies that water availability (i.e. the irrigation and precipitation) is the main control of the actual evapotranspiration in this region, and that irrigation greatly increases the evapotranspiration.

Trends in crop yield and irrigation

Figure 5(a) shows the annual variations of crop yield in the irrigated area and for the whole of Liaocheng City from 1968 to 1999. With the rapid increase of population, the size of the agricultural land area has increased significantly. The crop yield has the same increasing trend because of the increasing fertilizer application and the progress in agricultural modernization. It is clear that the crop yield in the irrigated area was much higher than that in the whole Liaocheng City, which indicates that irrigation has a significant positive effect on the crop yield.

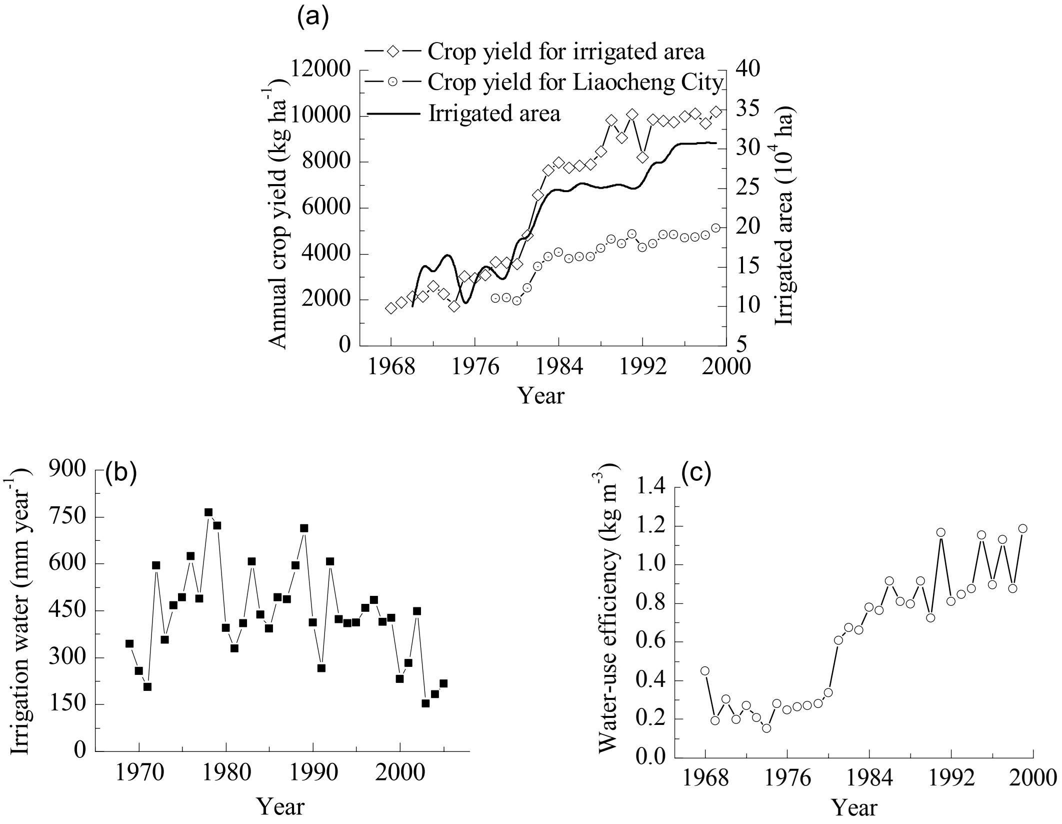

Fig. 5 Variations in: (a) crop yield and irrigated area, (b) amount of irrigation water, and (c) water-use efficiency, from 1968 to 1999.

The irrigation water from the Yellow River is the main water supply in this region. Figure 5(b) shows the annual amount of irrigation water during 1970–2005. Generally, the average annual precipitation and irrigation water were 567 and 435 mm from 1970 to 2005. The annual use of water for irrigation corresponds to 76.8% of the annual precipitation. The amount of irrigation water used was commonly high before 1990, and then it started to decrease and varied with the precipitation as a result of improved water resources management. Although the annual precipitation is low and has high interannual variability, the water supply for crop is adequate and stable due to the irrigation from the Yellow River.

On the other hand, as shown in Fig. 5(c), the water-use efficiency also increased, which implies that the irrigation water is used more efficiently. However, this value was especially low before 1980s due to both a high amount of irrigation water use and low crop yields. There was a high increase in water-use efficiency from the 1980s as a result of increasing crop yields and reduced use of water for irrigation. The average water-use efficiency was 0.84 kg/m^3 and 1.03 kg/m^3 in the 1980s and 1990s. Even though the water-use efficiency has increased considerably, there is still great potential for further improvement by optimizing the irrigation schedule and improving the irrigation method (Kang, 1998).

CONCLUSION

It was found that the annual precipitation showed a non-significant trend. The annual mean air temperature had a significant increasing trend of 0.24°C per decade since the 1980s with the strongest increase during the 1990s. The pan evaporation had a significant decreasing trend of –96.3 mm per decade, which was due to the decrease of sunshine duration and wind speed. The net river discharges were very low. In addition, a negative correlation between the actual evaporation and potential evaporation was found for both the irrigated area and a natural catchment in the same region; however, this negative correlation is much weaker in the irrigated area.

During the last 35 years, the average annual irrigation was at a very high level (435 mm). The annual amount of irrigation in this area decreased continuously from 488 mm in the 1970s to 256 mm since the year 2000. The water-use efficiency was relatively low even though it had an increasing trend during the recent 20 years. Even though the water-use efficiency was greatly increasing to the value of 1.03 kg/m^3 in the 1990s, great potential still remains to improve it by optimizing the irrigation schedule and improving the irrigation method.

Acknowledgements This research was supported by the National Natural Science Foundation of China (50679029) and the Japan Science and Technology Agency (JST).

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