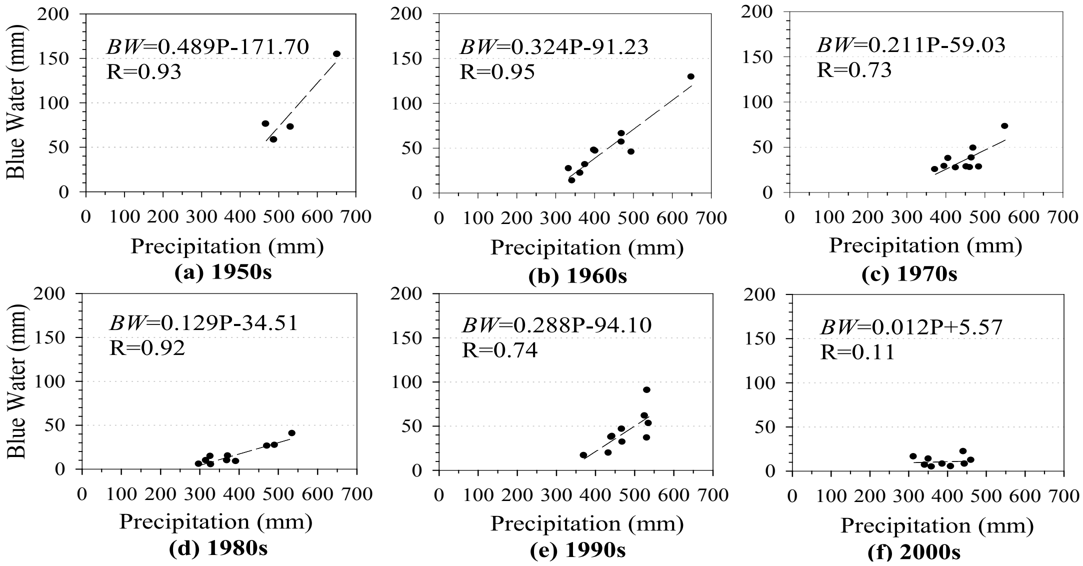

Fig. 1 Correlation between annual precipitation and runoff of the Laohahe catchment every 10 years.

negative correlation between annual precipitation and runoff over the Laohahe catchment in the 21st century.

ANALYSIS

The measured river runoff records were analysed for evidence of blue water change from the potential drivers. The business (Dooge 1986) or task (Bloeschl 2005) of hydrology is to solve the water balance equation, or the *hydrological equation*. As far as a catchment is concerned, the water balance equation on an annual or decadal scale can be expressed as $P - ET - R = \Delta W$, where P is precipitation, ET is evapotranspiration, and R is runoff. ΔW refers to the water storage change in rivers, ponds, lakes, reservoirs, soil, rock, and other media within the area of a catchment during one year or 10 years. The above formula could be written as $P = GW + BW$, where evapotranspiration corresponds to green water (*GW*) and runoff corresponds to blue water (*BW*), if ΔW only changes slightly during one year or 10 years. On annual and longer temporal scales, *BW* over a catchment is approximately equal to the difference between *P* and *GW*. Figure 2(a) and (b) indicate that, in the last 50 years, the annual *P* hardly changed, whereas *BW* tended to decrease in the Laohahe catchment. From Table 1 and Fig. 2(c), the ratio of *GW* (i.e. actual evapotranspiration) to precipitation increased in the past 50 years, i.e. *GW* has represented an increasingly greater proportion of the precipitation since the 1950s. This can be explained by dividing both sides of the water balance equation by *P* to derive $GW/P = 1 - BW/P$. The decrease of *BW/P*, or the so-called runoff coefficient, causes the increase of *GW/P* in either one year or over a longer time scale. The annual potential evaporation, Fig. 2(d), has an evident decreasing tendency during the past half-century, whereas the mean annual temperature, Fig. 2(e), shows an increasing trend since the 1950s. The above result for the Laohahe catchment provides further support to the evaporation paradox (Brutsaert and Parlange 1998, Cong, *et al.* 2009) and the complementary relationship (Yang *et al.* 2006) regarding evaporation.

In general, two types of factors, climatic change and human activities, may result in runoff change. In the Laohahe catchment, many anthropogenic factors have the potential to affect green water flow, and thereby modify blue water. These include hydraulic structures built across rivers for disaster control, water supply and power generation, LUCC, agricultural irrigation, livestock breeding for meat production, water withdrawal from streams or river channels, and abstraction from underground aquifers for increasing municipal and industrial water demands, and even for paddy rice cultivation. Our decadal study, since 1999 under the National Key Basic Research Program of the Ministry of Science and Technology, China, has shown that the increase in water withdrawal from streams and aquifers is the direct and predominant cause of blue water decrease in the Laohahe catchment. Figure 3 shows that the gross domestic product (GDP), population, agricultural products, and livestock in Chifeng, the main city within the Laohahe catchment, have increased tremendously since 1964. To meet the needs of the local economy and the livelihoods of people, more water is withdrawn and abstracted for population growth, agricultural irrigation, municipal operation, development of second and third industries, and industrial structure adjustment.

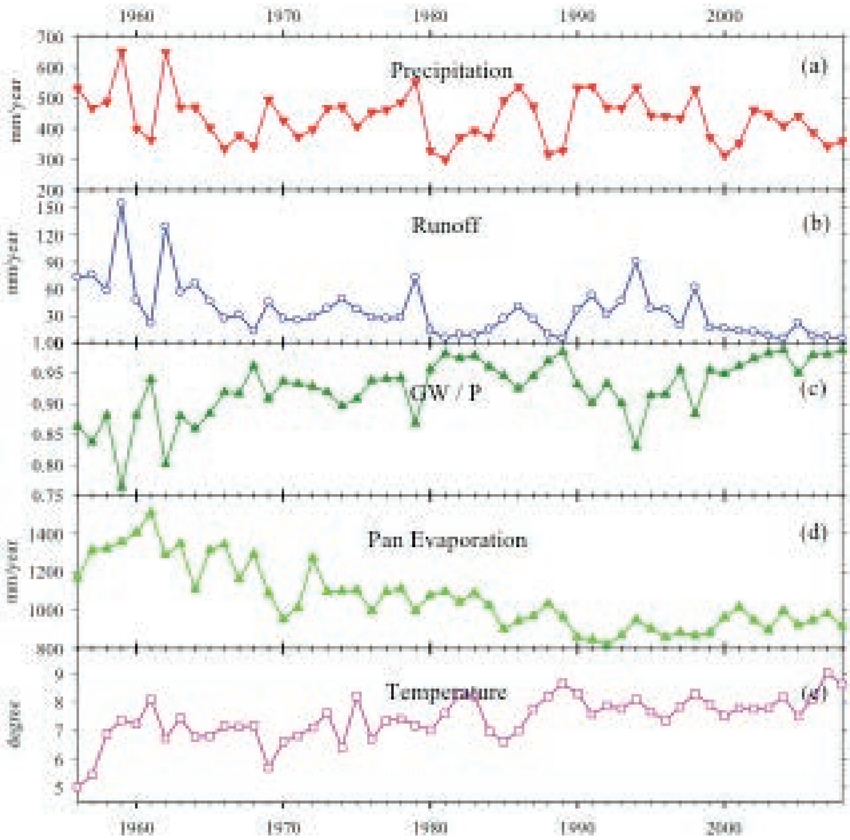

Fig. 2 Variations of annual precipitation, runoff, proportion of green water to precipitation, pan evaporation, and temperature over the Laohahe Catchment since 1956.

Table 1 Mean precipitation, runoff, pan evaporation and temperature of every decadal-year over the Laohahe catchment during the past half century.

Period	Precipitation (mm)	Runoff (mm)	Runoff coeff.	GW (mm)	GW/ Precipitation	PET (mm)	Temperature (degree)
1956–1959	535.1	90.2	0.17	444.9	0.83	1290.1	6.2
1960–1969	430.4	48.4	0.11	382.0	0.89	1285.2	7.0
1970–1979	449.4	36.1	0.08	413.3	0.92	1074.0	7.1
1980–1989	390.6	16.0	0.04	374.6	0.96	1013.8	7.6
1990–1999	475.4	43.0	0.09	432.4	0.91	874.2	7.9
2000–2008	390.2	10.5	0.03	379.7	0.97	954.2	8.0

Humans manipulate various landscape components: vegetation, soil, and water. Freshwater and ecosystem services cannot be provided without interfering with various landscape components, such as land and water pathways (Falkenmark and Rockström 2004). Evaporation from reservoirs and ponds causes the increase of green water. Population growth and livestock increase with the increase in drinking water amount, some of which becomes green water as well. Water consumed during food production evaporates and becomes green water that flows over the

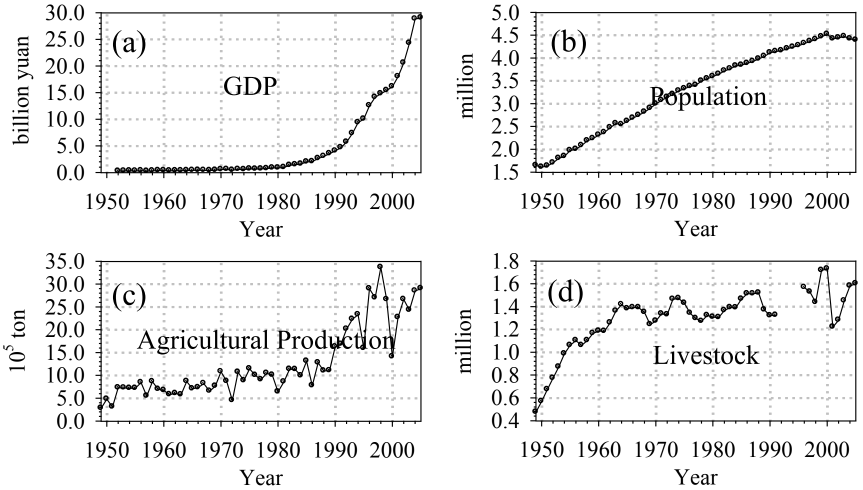

Fig. 3 Variations in GDP, population, agricultural products, and livestock in Chifeng, the main city within the Laohahe catchment, from 1949 to 2005

Laohahe catchment. More water also becomes green water when cropland (Yong *et al.* 2010) is irrigated by water abstracted from streams and wells. During two catchment surveys, in 2006 and 2008, we found that underground water taken from wells was used for irrigation, even for paddy rice fields (see Fig. 4), in such a semi-arid catchment. In fact, more green water flow occurs in the paddy field than from grassland and forest land. These findings contribute to the increase of *GW*. Drilling wells and pumping groundwater for paddy land and other purposes will certainly lower the groundwater table, increase infiltration, and thereby reduce blue water. Water for agriculture occupied 76.3% of the total water usage in 2008, according to the local statistics yearbook. To produce more food, water was withdrawn from streams and river channels, and pumped from wells for agricultural irrigation. Hence, more green water is released into the atmosphere over the catchment. Blue water, which should be generated in the downstream of the river, is converted into green water which remains and evaporates over the sloping farmland and plough-land surfaces in the upper and middle reaches of the catchment owing to human activities. The redirection of blue water into green water occurs in the Laohahe catchment.

Fig. 4 Photos of paddy rice fields taken *in situ* during the investigation in August 2006 and 2008.

To investigate the inter-decadal change of blue water flow from the 1970s to the 21st century, a semi-distributed hydrological model coupled with a two-source potential evapotranspiration model for simulating catchment daily runoff was developed (Liu *et al.* 2009). The comparison of land-use data for 1980 with those in 1996 showed that forest land and cropland increased, whereas grassland and water body area decreased. This change led to an increase in the evaporation of canopy-intercepted water and vegetation transpiration, whereas evaporation from bare soil tended to decrease. The result of numerical experiments showed that LUCC could cause green water or ET to increase by 0.95%, whereas blue water decreased by 8.71% in the Laohahe catchment (Liu *et al.* 2009). The computed value of the mean annual runoff depth (Liu *et al.* 2009) is 14.59 mm from 2000 to 2005, and the observed one (Liu *et al.* 2009) is 9.78 mm per year. The difference is 4.81 mm per year (49.2% of the observed). The flow direction of the blue water, amounting to 4.81 mm per annum in the 21st century, is still unknown. If 4.81 mm is multiplied by the area of the Laohahe catchment, 18 112 km^2, we obtain $8.712 \times 10^7 m^3$ per annum. This value is equivalent to the amount of water stored in a certain scale of reservoir, and is very significant and helpful to local humans and nature. Man and nature influence precipitation partitioning into green and blue water from individual plants to river basins. An extreme illustration is that of Cherrapunji in India (Falkenmark and Rockström 2004), where local people suffer severe water scarcity. Deforestation and exposure of bare soil to intensive rainfall dramatically change the first partitioning point from a high proportion of soil infiltration to a dominance of storm surface-runoff flow. This flow has been completely redirected in favour of flash floods in streams. Perhaps the present blue water flow is not dissimilar to the volumes in past humid tropical landscapes with annual rainfall of over 10 000 mm. However, the flow duration has decreased from months to days. In the semi-arid region of northern China, the situation is slightly different from the above-mentioned case in India. River flows are generally decreasing, most of them as a result of water withdrawal from streams and endless abstraction from underground aquifers. The redirection of the blue water flow branch depends on the influence of human activities against a background of climatic change, including LUCC, increased livestock numbers for meat production, urbanization for the national economy and livelihood of people, and water management for increasing municipal and industrial water demands, especially due to irrigation for more food and agricultural products.

DISCUSSION

The case study over the Laohahe catchment provides a representative example of incompatible water usage in northern China. This leads to serious conflict between human interest and biomass production upstream in a catchment. The conflict will be particularly severe in this catchment with rapid population growth and escalating food needs. The redirection between green and blue water flows impels us to perform further research on water balance alterations linked to land-use change. The current study also confirms that a land-use decision is a decision about water usage (Falkenmark and Rockström 2004).

The influence of human activities on blue water is very complex in both the spatial and temporal scales. As land cover forms the boundary between the atmosphere and the terrestrial sphere, land-cover changes may have significant implications for water availability. By altering runoff pathways in catchments, the volume, timing, and quality of water flow can be affected. Human activities and hydrological processes are, therefore, linked through LUCC. But, the effects of human activity on hydrological regimes are not easy to predict quantitatively because they influence hydrology through the interactions among various hydrological processes, climatic elements, vegetation characteristics, site-specific circumstances, and management factors (Conway 2001). However, water withdrawal could be partly calculated, such as water transfer from reservoirs or canals. However, quantifying the effects of such human activities is still very difficult, because water usage increases due to land-use change, soil conservation, and socio-economic structure modification. A methodology is needed to separate the influences of anthropogenic activities on water resources from the influences of climatic change on hydrological regimes. Although some progress have been made in this aspect (Yang *et al.* 2004, Jiang *et al.* 2011), a better modelling framework to effectively integrate climatic, hydrological, and agricultural models with social and economic analyses is still needed. Climate change should be closely related to land-use change.

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