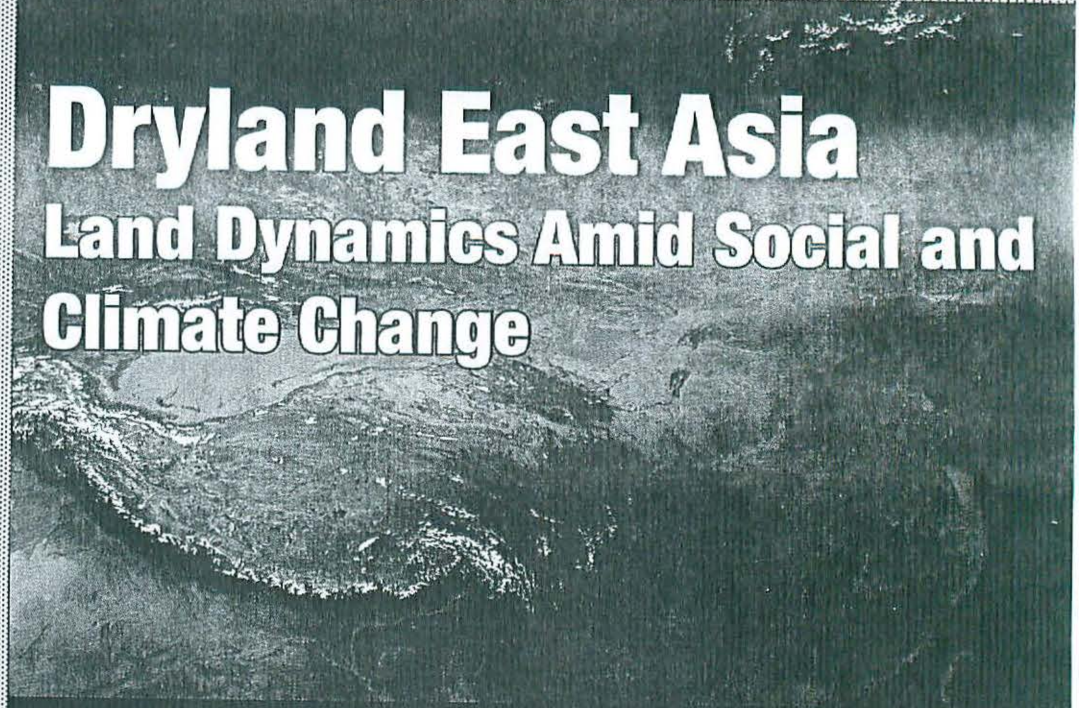
Ecosystem Science and Applications

Dryland East Asia

Land Dynamics Amid Social and Climate Change



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Chapter 8

Impacts of Global Change on Water Resources in Dryland East Asia

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Summary: The vast Dryland East Asia (DEA) area consists of several large geographic regions including the Qinghai-Tibet Plateau, Loess Plateau, and Mongolia Plateau. The region is of great importance to the functioning of the earth system under a changing climate. In the past three decades, due to the unprecedented land use/land cover change, urbanization, industrialization and climate change, water stress in many areas in DEA have reached a dangerous level that threatened the sustainability of the region. In addition to reviewing literature for the causes of the water crisis observed in the region, as case studies, we examined water balances at a basin and regional scale using multiple modeling techniques, including a remote sensing-based EC-MOD model, a watershed water balance model (WBMPlus), and an evapotranspiration model calibrated for the Loess Plateau region. Our synthesis study suggests that land use change and human water withdrawal account for most of the observed water resource declines in the study region. However, climate change will have profound impacts on areas where local water supply and ecosystem services rely on melting glaciers. The current large-scale soil conservation practices and vegetation-based ecological restoration activities such as reforestation should be comprehensively evaluated to assess their broad impacts on water resources such as groundwater recharge and water yield downstream. Much uncertainty remains to predict future water availability in DEA due to the uncertainty in predicting climate change patterns. Facing the large uncertainty of climate change and socioeconomic changes in DEA, decision-making processes and institutions must adopt a robust and adaptive framework to achieve long-term sustainability.

8.1 Introduction

Globally, about 20% of the human population live in drylands, which cover approximately 50% of the Earth's surface. Depending on local moisture and heat conditions, a variety of ecosystems with high biodiversity is found in drylands, primarily including woodlands, savannas, irrigated croplands, and deserts (e.g., John et al., 2008). Dryland East Asia (DEA) consists of several large geographic regions including the Qinghai-Tibet Plateau, Loess Plateau, and Mongolia Plateau, which are of great importance to the functioning of the earth system (Fig. 8.1) (Groisman et al., 2007, 2009; Qi et al., 2012).

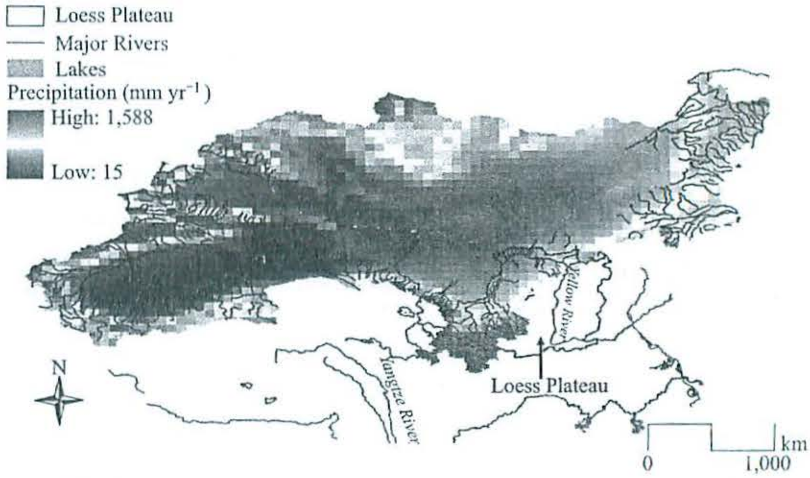

Fig. 8.1 Major river systems and precipitation regime in Dryland East Asia.

In China, about 33% of the land is in arid to semi-arid regions and about 27% of the land is considered to be susceptible to desertification. Desertification is currently expanding at a rate of 2,460 km^2 per year, resulting in serious environmental problems such as soil erosion and sandstorms (Kurosaki et al., 2011). The total DEA area (Fig. 8.1) in the Xinjiang Uygur Autonomous Region (XJ), western Gansu Province(GS), western Qinghai Province(QH), and western Inner Mongolia Autonomous Region (IM) is approximately 2.16 million km^2. The management of the area is important for combating desertification and sandstorms. The major environmental threat of the area is the lack of water resources. Sandstorms occur frequently and some oases have already deteriorated or disappeared. The Hexi corridor in GS is one of the severest desertification areas in China. The Qilian Mountains, located between GS and QH, is a major ecological conservation area for natural grasslands, forests and sources of rivers.

The DEA region is dominated by summer and winter monsoon climate systems, but influenced by land surface conditions of the massive Eurasian continent. The region contains the headwaters of many important river systems (i.e., Yellow River) that provide critical wildlife habitats and sustain stream flow for downstream water use. Dryland ecosystems and socioeconomic vitality are mainly constrained by water availability. The DEA region in China produces a significant part of the country's total production of grain (i.e., winter wheat, maize), vegetables, fruit, dairy products and meat. To produce the food, many of the Northern China croplands are irrigated (Siebert et al., 2005) and water withdrawals are in excess of sustainable water use. A global synthesis on groundwater recharge in DEA suggests that recharge rates vary from 10 to 485 mm per year, representing only 1%–25% of irrigation plus precipitation, resulting in long-term groundwater mining in groundwater-fed irrigated areas (Scanlon et al., 2006).

The drastic changes in land use and land cover (i.e., increase in irrigated croplands and urbanization), industrialization and climate warming have resulted in dramatic degradation of water quantity and quality in the arid region, as evidenced by many of the regional severe water resource problems, such as shortages for drinking water, water pollution, loss of wetlands, lakes and rivers, soil sanitization, and dust storms. Other drivers of environmental changes include woody plant extraction, overgrazing, modification of fire regimes, and urban expansion, contributing to the current ecological crisis. Land degradation, soil erosion (both wind- and water-induced), woody plant encroachment and domination by invasive species, and water shortages are the common phenomena (Wilcox et al., 2006). For example, major rivers in North China, including the mighty Yellow River, have run dry during part of the year (e.g., Yang et al., 2004; Liu and Xia, 2004) and groundwater levels in the North China Plain are dropping rapidly (Liu and Yu, 2001). Water stress in Beijing and the surrounding regions has reached a dangerous level. To alleviate the situation, a major South to North Water Diversion project is currently under construction (central and eastern routes) and in planning (western route) to divert ~45 km^3 yr^{-1} (~10% of China's surface water resources) from the Yangtze Basin to the Yellow River and North China Plain (Cheng et al., 2009). In inland river basins in Northwest China, excessive water use is leading to desertification and severe challenges for food production (e.g., Kang et al., 2008). Irrigation in northern and Western China relies, in part, on runoff from high elevations, including the Tibet-Qinghai Plateau, for a significant fraction of its sustainable irrigation water. Industrial water use in Northern China is expected to increase by >50% and domestic water demand by ~80% by 2050 (JBIC, 2004). Ecological restoration that aims at reducing soil erosion and land degradation has been challenging in DEA in large part due to the delicate relationship between water and human influences on the vegetation's consumptive water use (Sun et al., 2006; Cao, 2008; Cao et al., 2011). Recent emphasis on bioenergy production and biological carbon sequestration causes further concerns about their water impacts and promotes renewed scientific debate on the effects of vegetation on water and other ecosystem services (Jackson et al., 2005; Ellison et al., 2011).

Climate change and variability have direct impacts on water resources in DEA (IPCC, 2007). Small changes in precipitation would result in large changes in runoff. The rising air temperature is especially of concern to watersheds where streamflow is generated from snow melt. The cryosphere (snow and ice) of the Qinghai-Tibet Plateau is a major water source area for intensively developing DEA. The Qinghai-Tibet Plateau has warmed ~0.25°C per decade over 40 years while precipitation has declined 5–10 mm per decade (Yang et al., 2003). Many glaciers are found on the Qinghai-Tibet Plateau. For example, there are 15,953 glaciers in the whole Tianshan Mountains range with a total area of 15,416 km^2 and an ice volume of 1,048 km^3, supplying the majority of the river flows in XJ. However, like other glaciers in the Himalaya-Tibet Plateau, which drains to South Asia (Bagla, 2009; Barnett et al., 2009; Yang et al., 2003; Xu et al., 2009), the glaciers in XJ have been retreating rapidly in the past few decades. For example, the Tianshan glaciers retreated as much as 3 km from the 1860s to 2003 (Aizen et al., 2007). During the past 60 years, the total area of the Tianshan glaciers reduced by 14.2% due to an increase in summer air temperatures, especially since the 1970s (Aizen et al., 2007). The Qinghai-Tibet Plateau permafrost is thawing and this may be contributing to the reduced water volume and deteriorating eco-environments in the source region of major rivers in the QH region of the Qinghai-Tibet Plateau (Cheng and Wu, 2007). A recent national study on China's lakes concludes that, overall, hydrological functions (i.e., flooding mitigation) and water quality (i.e., eutrophication) are degrading. Lake water levels in arid northern and Northwestern China have dropped significantly and salinity has increased dramatically while lake water resources in the Qinghai-Tibet Plateau show large annual variability. Ecosystem functions in DEA are extremely responsive to soil moisture dynamics that are directly linked to climatic variability. For example, the remote sensing monitoring data show that vegetation evolutions are particularly sensitive to changes in air temperature and precipitation in arid and semi-arid regions in China (Cao et al., 2012).

This study focuses on drylands in Northern China. We use published literature and regional water balance, Precipitation minus Evapotranspiration modeling to answer the following questions:

- What are the key water resource issues and driving factors?
- How has land use/land cover change affected water quantity and water quality?
- How has climate change impacted the chronic water shortage in DEA?
- What are the potential options to mitigate negative impacts of climate change and to adapt to future environmental conditions with higher water stress?

Integrated watershed management practices that focus on balancing watershed services and healthy socioeconomic development could provide the best solutions to water problems and environmental sustainability for the DEA region.

8.2 Key Water Resource Challenges

Due to low precipitation (<400 mm per year, in most places) and large differences in air temperature between the growing season and non-growing season, the DEA region is dominated by grasslands and deserts that are sensitive to both natural climate variation (Cao et al., 2012) and human disturbances. The DEA region has several important river systems, notably the Yellow River and several inland rivers such as the Tarim River (Fig. 8.1). Sources of water supply include glaciers (Sorg et al., 2012) and stream flow generated from mountainous upland areas that receive relatively higher precipitation than the lowlands. Deep groundwater is another important water source that supports productive agriculture in a dry environment. Similar to other arid regions in the world, DEA is considered one of the most water-stressed regions where water supply has increasingly fallen behind water demand due to human population growth, exhaustion of groundwater resources, and climate changes. For example, the 1,321 km Tarim River, China's largest inland river that supports eight million people living in oases clustered along its banks and in an alluvial plain downstream, has been seriously impacted (Chen and Xu, 2005) and major associated lakes have been drying up for decades due to excessive water use for irrigation and random land reclamation upstream.

8.2.1 Distribution of Water Balances across DEA and Historical Changes

We use the annual water balance equation (Water Yield = Precipitation − Evapotranspiration) to examine the spatial variation of water yield. Precipitation data were derived from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis data set. MERRA makes use of observations from NASA's Earth Observing System satellites and reduces the uncertainty in precipitation and interannual variability by improving the representation of the water cycle (Rienecker et al., 2011). The MERRA data (1/2 degrees latitude × 2/3 degrees longitude) were obtained from the Global Modeling and Assimilation Office (GMAO). We calculated mean annual precipitation over the period of 2001–2010. We extracted evapotranspiration (ET) estimates for the DEA region from a global flux dataset (Jingfeng Xiao, unpublished) produced by the EC-MOD model. The EC-MOD dataset consists of gridded estimates of carbon fluxes and ET with 0.05 degree spatial resolution and eight-day time step over the period from 2000 to 2010. This dataset was developed from FLUXNET observations and MODIS data streams using a data-driven approach (Xiao et al., 2008). The MODIS land cover map (MCD12Q1) with the University of Maryland (UMD) classification scheme (Friedl et al., 2002) was used to estimate ET by land-cover type. Obtained from the NASA's Warehouse Inventory Search Tool, the land cover map was developed from various MODIS data streams using a regression tree approach. We aggregated the vegetation types of the map to the following five broad vegetation types: forests, shrublands, savannas, grasslands and croplands.

Vegetation cover, land use, hydrologic fluxes (ET, mean water yield defined as precipitation minus ET) and human settlement in the DEA region are largely controlled by surface and groundwater availability (Fig. 8.2). Precipitation varies greatly across the DEA region with a steep gradient, resulting in large spatial and temporal variability in ET rates and water yield. In this study, ET rates for areas classified as non-vegetated barren lands (Fig. 8.2 a) are not mapped (Fig. 8.2 c)

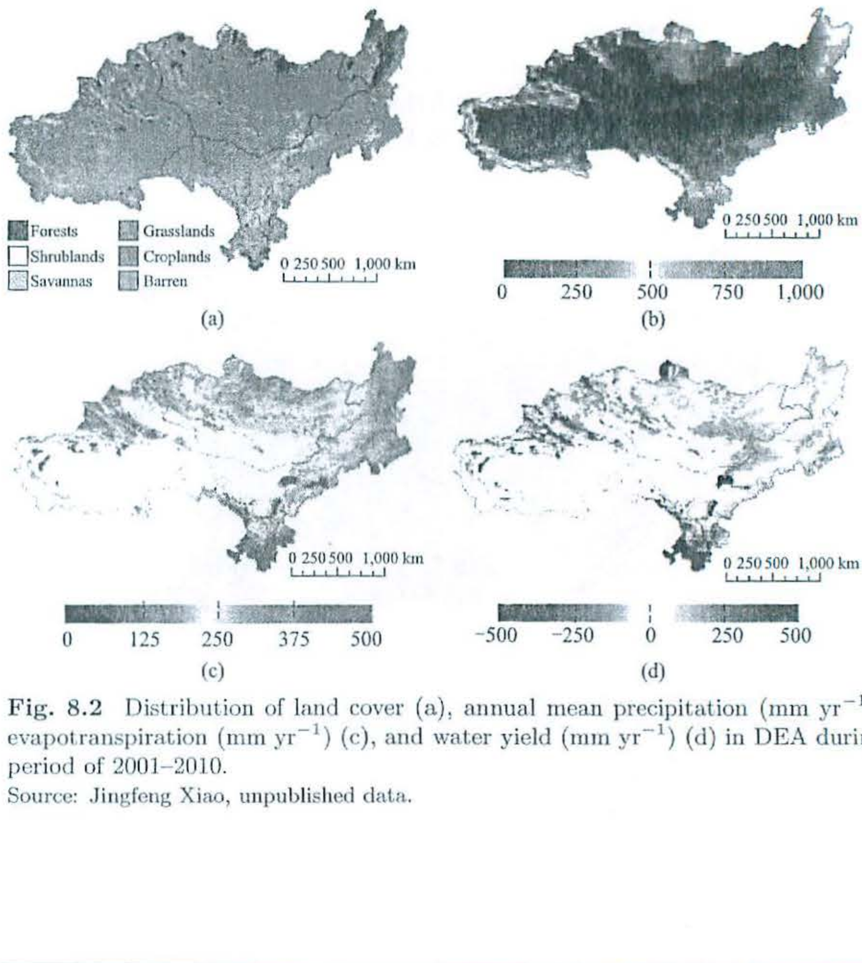

Fig. 8.2 Distribution of land cover (a), annual mean precipitation (mm yr^{-1}) (b), evapotranspiration (mm yr^{-1}) (c), and water yield (mm yr^{-1}) (d) in DEA during the period of 2001–2010.
Source: Jingfeng Xiao, unpublished data.

and are presumably similar to precipitation, which is rather low (<100 mm yr^{-1}) (Fig. 8.2b). The areas mapped with high precipitation rates (>~750 mm yr^{-1}) show high water yield, representing the source areas for local river systems (Fig. 8.2d). Large areas show negative values, indicating that local precipitation does not meet ET demands. This might be especially true for the cropland areas where irrigation is used (Liu et al., 2012). These areas are identified in northwest NX, central IM and northwest XJ (Fig. 8.2 d), where grasslands have been converted to highly productive croplands. Groundwater overuse is a major water crisis for these areas, as it is in other agriculture-dominated regions in Northern China. Because ET is estimated independently from precipitation, the negative values of water yield can be partially caused by data or modeling errors. However, the general patterns suggest that the major renewable sources of water supply in the region are concentrated in southern GS (Qilian Mountain Range), central XJ (Tianshan Mountain Range) and northern Mongolia, which are high-elevation mountainous areas with relatively high precipitation and glaciers.

Analysis of historic changes in the runoff over 2001–2010 versus 1979–2000 across Northern China and IM was made using meteorological data from the *NASA*'s MERRA (Rienecker et al., 2011) and a water balance model (WBMPlus) (Wisser et al., 2008) (Fig. 8.3). Runoff in most of the DEA region showed an upward trend except for a few wet areas. Northeastern China, the Northern China Plain, and northern Mongolia showed a decline in water availability during the past decade. Although the MERRA-driven runoff simulation had better agreement with runoff observations in Eurasia than other reanalysis products

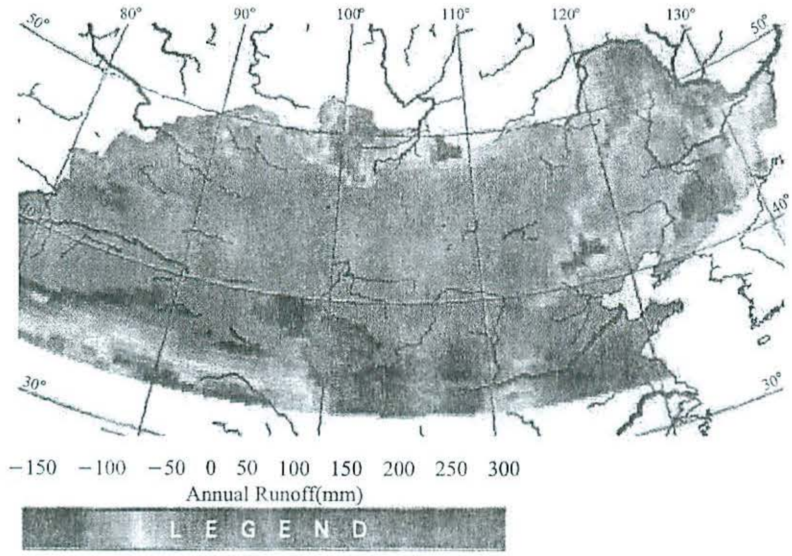

Fig. 8.3 Simulated deviation of average annual runoff during the 2001–2010 period from the mean over the 1979–2000 time period (Wisser et al., 2008).

(Shiklomanov et al., 2013), the regional modeling results showed large variability and uncertainty in predicting mean annual runoff.

8.2.2 Land Use/ Land Cover Change

In DEA, land use change is driven by several forces such as agricultural development (i.e., land conversion from forests or grasslands to croplands), intensive grazing, urbanization, and soil conservation practices. Previous global studies show that water balances in DEA can be greatly influenced by land use/land cover change (Zhang et al., 2001; Andreassian, 2004; Brown et al., 2005; Foley et al., 2005; Jackson et al., 2005; Scanlon et al., 2006). For example, deforestation generally increased river flow because of reduced total ET. Similarly, conversion of native vegetation to cropland in semi-arid regions can increase the recharge into underlying aquifers and lead to secondary impacts, such as water-table rise and salinization (Allison et al., 1990; Leduc et al., 2001; Scanlon et al., 2006), and changes from natural grasslands and shrublands to dryland (rain-fed) agriculture-altered systems from discharge (ET) to recharge in the southwest US. In Niger, the impact of land use change was much greater than that of climate variability, where replacement of savanna by crops increased groundwater recharge by about an order of magnitude even during severe droughts (Scanlon et al., 2006). A theoretical analysis on hydrologic data from Northern China suggests that annual vegetation cover dynamics affect regional water balances in the non-humid region (Yang et al., 2009).

Land use and land cover change directly alter the hydrologic processes including ET (Zhang et al., 2001; Huang et al., 2003a, 2003b; Sun et al., 2011; Yang et al., 2009; Wang, Y. et al., 2011; Wang S. et al., 2011), soil infiltration and groundwater recharge (Gates et al., 2008), and soil moisture dynamics (Lu et al., 2011). Diverting surface water or mining groundwater for cropland irrigation (Liu and Yu, 2001) are major causes of wetland losses in DEA. Land use changes may also modify land surface energy and water balances (Zhang et al., 2012) and thus alter regional climate patterns through land surface-climate feedback mechanisms (Liu et al., 2008).

The effects of land use change, land management, and climatic variability on water balances have been studied across DEA in China such as the Loess Plateau and Mongolia Plateau that span a complex physiographic gradient. Techniques used include stable isotope tracers (Gates et al., 2008), weighing lysimeter (Ohte et al., 2003; Wang, X. et al., 2004), eddy-covariance flux measurement (Miao et al., 2009; Chen et al., 2009; Wilske et al., 2009), plot or small watershed vegetation manipulations (Wang, Y. et al., 2008; Zhang, et al., 2008a, 2008b; Wang, S. et al., 2008), remote sensing techniques (John et al., 2009; Cao et al., 2012), and watershed ecosystem modeling (Zhang et al., 2008).

Lu et al. (2011) found that, compared to the undisturbed grasslands, the mean ET/P ratios of croplands and grazed grasslands were significantly lower. The observed lower surface soil moisture content in the grazed and fallowed croplands was part of the reason for the measured lower ET/P. The widely planted and fast-growing poplar trees in Northern China, albeit in their early growing stages, used more water (a higher ET/P) than the undisturbed shrubland, presumably because of its ability to access groundwater by deep roots. Lu et al. (2011) concluded that ecosystem ET was mainly controlled by soil moisture in the semi-arid region unless groundwater was available and accessible. This study indicates that land cover and land use can have different sources of water for ET due to altered soil physical properties and root distributions. Water balance studies in the Tengger Desert (IM) by Wang et al. (2004) showed that re-vegetating shifting dunes used all available soil water. Similar findings were reported that planting trees in some dry areas (precipitation <400 mm per year) on the Loess Plateau can result in soil moisture desiccation and increase compaction (Chen et al., 2010; Jin et al., 2011), thus causing a decrease in infiltration, promoting overland flow and reducing groundwater recharge. Studies with stable isotope tracers also suggest that mature trees and shrub plantations can prevent deep drainage in the Loess Plateau.

Wang, Y. et al. (2008, 2011) examined how the soil erosion control measures, such as reforestation, the affected water yield at the watershed scale in the semi-arid Loess Plateau region in Northwestern China. Multi-year water balances were constructed to estimate the respective long-term mean annual ET and runoff for the forestlands and non-forestlands of 57 basins. They reported that the overall annual runoff and corresponding runoff/precipitation ratio were low, with a mean of 33 mm (7%) ranging from 10 mm (2%) to 56 mm (15%). The average of annual precipitation was 463 mm for all basins. The corresponding averages of annual ET and runoff were 447 and 16 mm for forestlands and 424 and 39 mm for non-forestlands, respectively. Although the absolute difference in the grand average of annual runoff was only 23 mm, it represents a large difference in relative terms, representing 58% of annual runoff from non-forestlands. Similar findings were reported in a synthesis study that aimed at detecting forests' roles in influencing annual water yield across Northern China (Wang, S. et al., 2011). The authors concluded that stream flow amount and runoff/precipitation ratios for watersheds on the Loess Plateau were negatively correlated to the percentage of forest covers. However, the relationships between forest cover percentage and stream flow were not as obvious and consistent in two other relatively wetter regions in northwestern (XJ/GS) and Northeastern China (Fig. 8.4). Air temperature regime, snow/glacier distribution, and forest cover types might have masked the true forest-water relationships (Wang, S et al., 2011) found in the semi-arid Loess Plateau region or other regions in the

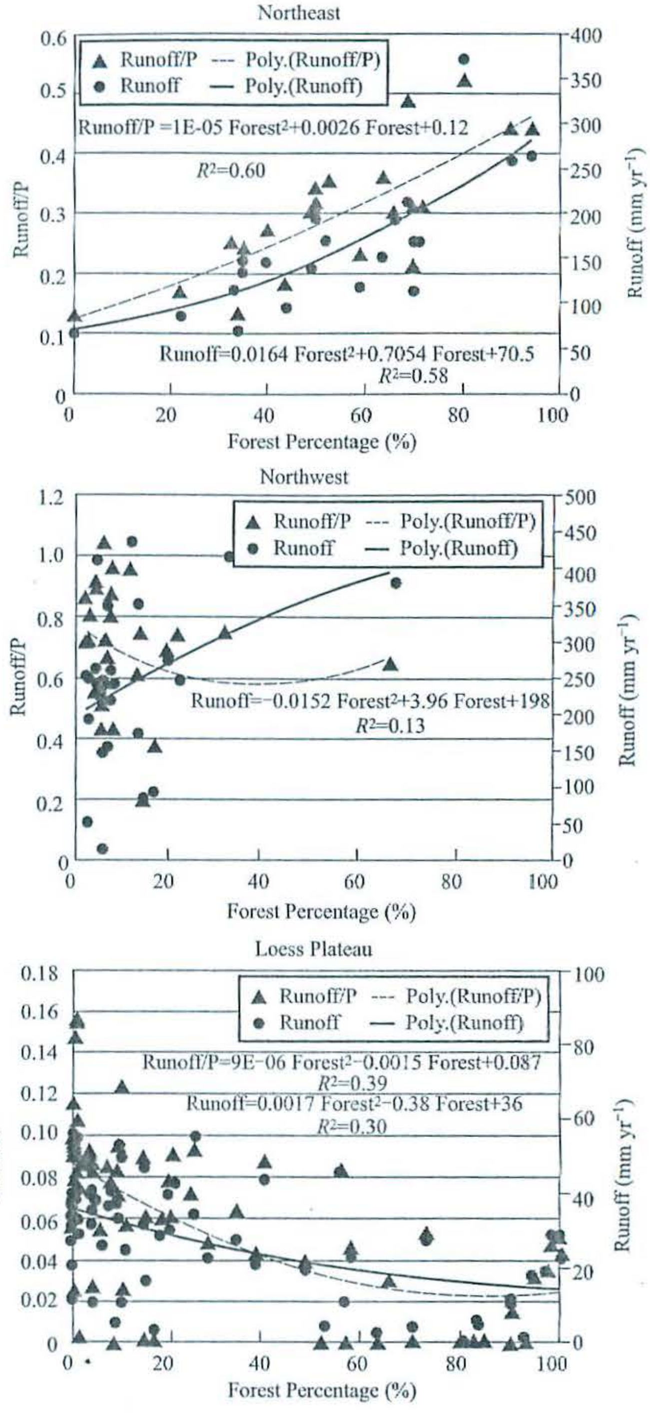

Fig. 8.4 A comparison of the complex relationships between forest cover rates and observed stream flow in three regions in Northern China (Wang et al., 2011).

world (Andreassian, 2004). These studies suggest that large-scale forestation may have serious consequences for water management and sustainable development in the dry regions because of the potential stream flow reduction, especially during low-flow periods (Brown et al., 2005). Soil conservation practices such as reservoir construction can increase or decrease base flow depending operation schemes (Huang and Zhang, 2004; Zhang et al., 2008b). It is important to quantitatively evaluate how land cover change may affect the water balances in arid environments. Soil conservation measures that include both biological (reforestation) and engineering approaches (check dams, terracing, etc.) have been implemented in arid Northern China, particularly in the Loess Plateau region, since the 1950s to reduce soil erosion and sediment loading to the Yellow River, which increases crop productivity and improves the harsh environments.

8.2.3 Agricultural Irrigation and Industrialization

It was estimated that China has 141.1 million ha cropland, about 25% of which is paddy lands and 75% dry farmlands (Liu et al., 2005). More than 30% of farmlands rely on irrigation that accounts for a large portion of all water use, especially for the dry north (Lu et al., 2012). Irrigation is essential for growing winter wheat and maize in the Northern China Plain and for producing cash crops (e.g., cotton, vegetables or fruit trees) in the DEA region. During 1990–2000, the northeast and northwest regions of China gained cropland areas by converting grasslands, wetlands, and through deforestation, while the north and southeast regions showed a loss of high-quality croplands due to urbanization. The newly created croplands in the dry regions in China most likely need irrigation to achieve profitability, causing emerging environmental concerns.

In the Northern China Plain, groundwater is the major source for irrigation because surface water is not sufficient to meet the high ET demand from May to September under the monsoon climate, in which most precipitation occurs from June to September. In some areas in the Northern China Plain, pumping groundwater for irrigation has resulted in water table declines of 20–30 m over the past 30 years and large reductions in stream flow (Jin et al., 2009; Foster et al., 2004; Liu and Xia, 2004). A groundwater monitoring well in the Daxing District, 90 km outside of downtown Beijing, showed that the water table level of the surficial aquifer has declined at a rate of 1.4 meter per year in the last decade (Fig. 8.5). In this area, large groundwater withdrawal occurred during spring and summer seasons as a result of irrigation but water table decline recovers as a result of groundwater recharge during fall and winter seasons when water use by agriculture subsides. Similarly, rapid groundwater level declines are common in the Heilongjiang Province and surrounding regions, Northeastern

China, where agriculture accounts for 84% of water use (Liu and Xia, 2004). Observed monthly streamflow and rainfall data over a period of 35 years (1961–1966, 1973–2001) from the Chao-Bai River in Hebei Province that provides much of the water supply for Beijing show that human activities had bigger impacts on streamflow than climate (Wang et al., 2009) (Fig. 8.6). It was estimated that human activities (i.e., forest cover change, human water withdrawal, siltation dam and reservoir constructions) and precipitation decreases contributed to 70% and 30% of the observed decrease in runoff, respectively. Similar findings are

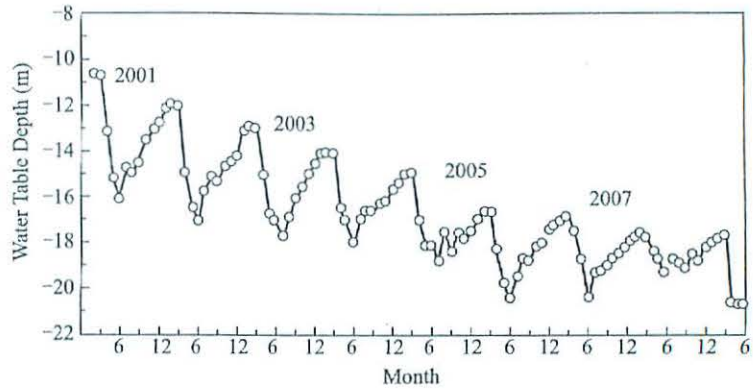

Fig. 8.5 Water table level declines during 2001–2009 measured by a well in the Daxing District, suburban Beijing (Zhang, Y. et al., 2012).

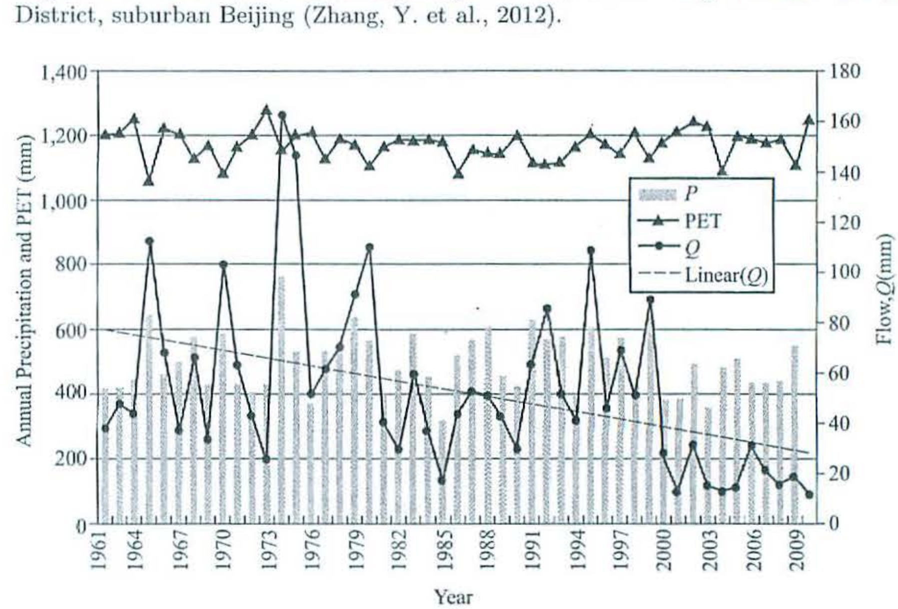

Fig. 8.6 Observed long-term (1961–2009) trend of streamflow change in the Chao-Bai River of Hebei Province, showing a sharp decline in surface water resources since the early 2000s due to human water use. Both precipitation and potential evapotranspiration variables have no significant trend.

reported by Zheng et al. (2009) to explain the observed streamflow decline in the headwaters of the Yellow River Basin. The lower reach of the Yellow River had similar water shortage crisis due to increased water consumption for irrigation. Irrigation accounts for about 90% of water consumption in the Yellow River basin (Chen et al., 2003; Xia et al., 2004). With the rapid industrialization, water demand by other economic sectors increased rapidly as well in the Yellow River Basin (Xu, 2005).

8.2.4 Climate Change

Climate change is hydrologic change, which has profound impacts on all aspects of water resources. The water-limited drylands are especially sensitive to climate change, precipitation in particular (Ma et al., 2008) because surface and groundwater resources are scarce and the hydrologic balances are dominated by precipitation variability (Zheng et al., 2009).

China's climate is warming up by 1.1°C over the past 50 years, faster than the global average of 0.74 °C (1906–2005) (IPCC, 2007) or even that of the Northern Hemisphere for the same period (Dong et al., 2009). The warming has been accelerating since the mid-1980s, particularly in Northern China. The rise of air temperature is particularly significant in winter. The air temperature in the Yellow River basin has increased 0.29 °C per decade since 1989. The largest warming is found in Northeast China, with a trend of 0.36 °C per decade, and in IM with 0.4°C per decade (Piao et al., 2010). The air temperature in XJ increased 1.01 °C during 1881–2001 (Xia et al., 2011). Precipitation is increasing in southern and some western regions and decreasing in the north and northeast (Tao et al., 2003). In the Tarim river basin, the temperature experienced a significant monotonic 1°C rise, and annual precipitation showed a significant decrease in the 1970s, and a Significant increase in the1980s and 1990s at a rate of 6.8 mm per decade. A step change occurred in both temperature and precipitation time series around 1986 due to global climate change (Chen and Xu, 2005). The climate records of IM suggested a warmer and drier trend from 1955 to 2005 (Lu et al., 2009). The annual daily mean, daily maximum and daily minimum temperature increased whereas the diurnal temperature range (DTR) decreased. The decreasing trend of annual precipitation was not statistically significant. However, the vapor pressure deficit (VPD) increased significantly. By biome region, climate in the grassland and the desert biomes had more pronounced change than in the forest biome. DTR and VPD showed the largest inter-biome gradient from the lowest rate of change in the forest biome to the highest rate of change in the desert biome, suggesting drier regions were experiencing more changes.

China experienced a series of severe extended droughts (1920–1930, 1939–1940, 1956–1958, 1960–1963, 1965–1968, 1978–1980 and 1999–2002) during the 20th century (Xiao et al., 2009). Future projections for China's climate are uncertain (Piao et al., 2010), but most studies show climate change will have serious impacts on water supply in the drylands in Northern China. Climate change will likely have a larger impact on water supply in light of projected widespread summer drying in mid-latitude regions during the 21st century (IPCC, 2007). Two major water resources issues related to climate change are summarized below.

1. Glacier retreat

There are about 46,000 glaciers covering an area of 59,000 km^2 in the Qinghai-Tibetan Plateau region, Western China (Xia et al., 2011). Glaciers play a key role in providing water for the dryland rivers and recharging local groundwater systems. There are serious concerns about the short- and long-term hydrologic impacts of glacier retreat on freshwater supply, irrigation and hydropower potential (Immerzeel et al., 2010; Sorg et al., 2012).

It was estimated that roughly 1,400 km^2 of glaciers has been lost in Western China in the past 50 years (Xia et al., 2011). Since 1985 alone, glacier storage in the dryland areas in Western China has decreased by 15%, resulting in 5%–32% increase in annual streamflow. Consequently, the Tarim River basin in central XJ saw a significant rise in the water levels of glacier lakes and an record floods down streams in the 1990s (Chen and Xu, 2005; Xia et al., 2011; Sorg et al., 2012). Piao et al. (2010) summarized observed changes in glaciers at 22 monitoring stations in Western China. They reported that the some glaciers have shrunk as high as 50% in the Tianshan Mountains over the past 30–40 years. Tianshan Mountains, known as the "water tower of Central Asia", has had shifts of seasonal runoff maxima in some rivers (Immerzeel et al., 2010; Sorg et al., 2012). The increasing trend in glacial runoff, especially in spring and early summer, may result in reduced water availability in late summer and fall and in a water shortage in the long run. Over the next 50 years, small glaciers (<1 km^2) may disappear. Overall, 5%–27% of the glacial area is projected to disappear by 2050 and 10%–67% by 2100. Glacier melt runoff may increase in the next few decades and peak around 2030–2050 and could gradually decline afterwards (Piao et al., 2010). Other studies suggested that, by 2030, the total area of glaciers in China will shrink 5.6%–8.5% and storage will decrease by 6.1%–9.3%; consequently, total river flow will increase by 9.6%–15%. Long-term exhaustion of glacial water supply will have a considerable impact on the availability of water for both agricultural and human consumption in the region.

2. Surface water and groundwater availability

An increase in air temperature and decrease in precipitation partially contribute to the general drying trend in Northern China (Xia et al., 2011). Compared to the time period of 1956–1979, total water resources decreased by about 25% during 1980–2000 in the four major rivers (Yellow River, Huaihe, Haihe, Liaohe) in Northern China. An increase in air temperature will increase water used for irrigation. A 1°C temperature rise will increase the demand for irrigation by 6%–10% (Cruz et al., 2007). In the past 30 years, stream flow of the Yellow River (recorded at Huayuankou Hydrologic Station at middle reach) has decreased by 22%. During 1972–1999, the Yellow River was found to be dried up for 22 years of the 28-year record. In 1997, the river stopped running for 226 days with over 88% of the river channel being dried up. Sediment loading has decreased from 1.4 billion tons per year in the 1950s to only less than 0.4 billion tons in the early 2000s. Climate change (decrease in precipitation and rise of air temperature), soil conservation activities, and water withdrawal upstream for irrigation all contributed to the hydrologic and sediment dynamics (Xia et al., 2011). Li et al. (2009) reported that the large climate variability during 1981–2000 influenced surface hydrology more significantly than the minor land use change in an agriculture-dominated basin in GS. Overall, climate fluctuations and massive land-use changes are the root causes of the water shortages of the Yellow River Basin (Yang et al., 2004; Xu, 2005). It appears that the disturbance magnitude and forms of land use changes determine the relative influences of climate change vs. land use change for one particular basin.

According to several Global Circulation Models (GCMs), droughts will likely continue to dominate the Northern China Plain, but precipitation in Northwestern China may increase in the next 40 years. Water stress in the Yellow River Basin will likely increase due to a rise of water demand (Wilske et al., 2009). Headwater regions of the Yellow River will see rapid soil thawing that affects wetland resources and water balances (Sato et al., 2008). There are also concerns that an increase of precipitation and intensified rain storms will cause large flooding and sediment movement events in sections of the river where the channel beds are already high due to chronic sediment deposition (Xia et al., 2011).

8.3 Water Resources under Environmental Changes: Case Studies

8.3.1 Loess Plateau

The Loess Plateau, approximately 640,000 km^2 in land area, is dominated by grasslands, dry farmlands, and shrublands in a semi-arid, continental monsoon climate in Northern China. Annual precipitation rates vary from less than 200 mm per year in the desert to more than 750 mm in the mountains. The region is well-known for its high rate of soil erosion and sediment loading to the upper and middle reaches of the Yellow River (Fu, 1989; Lal, 2003). The Loess Plateau is one of the most severely eroded areas in the world as a consequence of the loose loess soils, steep slopes, high rainfall intensity, and poor vegetation conditions as a consequence of intensive human disturbances (Li et al., 2009).

In the past three decades, large-scale soil conservation efforts that involve structural approaches (i.e., terracing, check dams) and vegetation approaches (i.e., reforestation) have been devoted to reducing soil erosion and improve the local people's well-being in this traditionally economically disadvantaged region (Fu et al., 2011). The regional ecological effects of these long-term efforts are being evaluated (Chen et al., 2010; Fu et al., 2011; Jin et al., 2011). Numerous studies are available in the literature that describe the combined impacts of climate change and land use change on water resources at different spatial scales (Huang et al., 2003a, b; Huang and Zhang, 2004; Zhang et al., 2008a, b; Rustomji et al., 2008; Li et al., 2009; Wang et al., 2011).

We conducted a case study that aimed at understanding the hydrologic effects of a recent reforestation campaign: the Grain-for-Green (GFG) project. Specific objectives were to: 1) detect the individual and combined roles of climate and land cover in affecting evapotranspiration and water yield across the Loess Plateau region, 2) understand how climate variability may enhance or mask the effects of land cover change across the Loess Plateau region, and 3) examine the spatial and temporal hydrologic responses to vegetation in the Loess Plateau region so that we can provide recommendations to land planners at the regional scale. Empirical evapotranspiration models are developed from global eddy flux measurements and local watershed hydrological monitoring data. Remote sensing data such as vegetation cover type and leaf area index (LAI) derived from MODIS products are integrated with models to extrapolate site-level hydrologic measurements to the regional scale and are used for model validations (i.e., ET validation). Research methods are illustrated in Fig. 8.7 to demonstrate the processes of model development, validation and application. Details of this study can be found in Feng et al. (2012).

The land cover change considered in the study was mostly a result of the government-funded GFG project that involved converting croplands and abandoned farmlands into forests and pasture lands. Vegetation covers in some areas have improved greatly since the project was implemented at the end of 1999. For example, total vegetation cover in northern Shaanxi Province (combined for planted forest and herbaceous vegetation, i.e., grasses, forbs, herbs) increased from 30% in 1998 to 42% in 2005 as a result of the GFG project (Cao et al., 2009). Although it is generally accepted that reforestation and soil conservation practices can result in reduced water yield and sediment (see review in McVicar

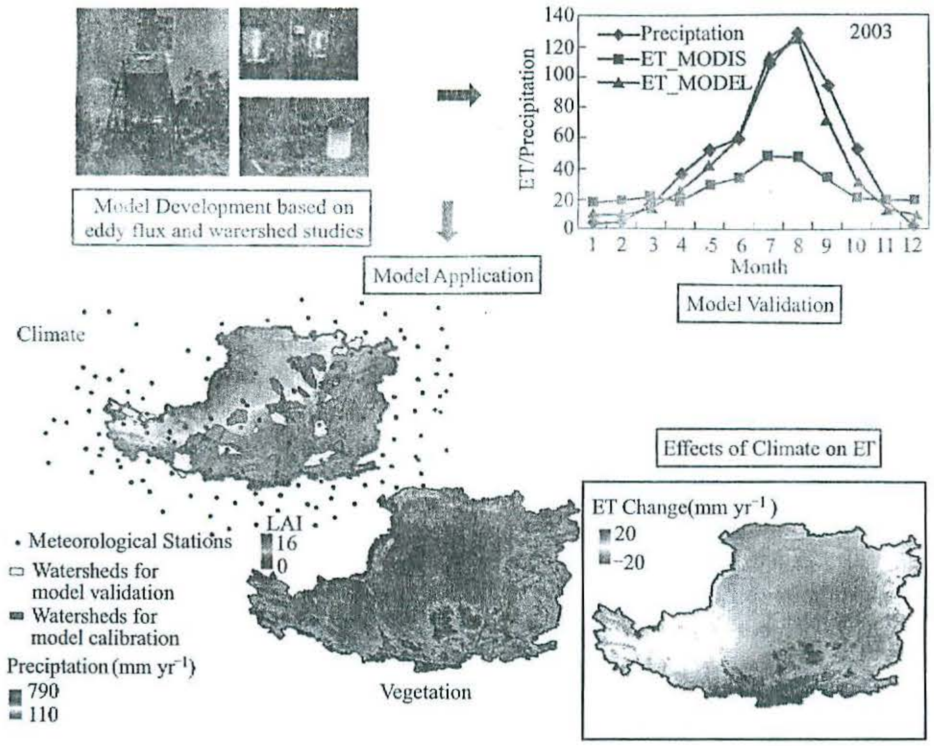

Fig. 8.7 Illustration of the method to model regional evapotranspiration and water yield across the Loess Plateau region.

et al., 2007; Wang Y. et al., 2011), few studies have been conducted to examine the relationship between observed vegetation change, climate variability, and hydrological responses at a regional scale for the Loess Plateau. Such types of studies are surely needed to explain regional change patterns in ecosystem functions such as water availability and soil erosion control (Fu et al., 2011). For example, the observed land cover change toward more productive states in the 1990s is perhaps an indication of vegetation recovery due to human intervention, but the contribution of climate variability in the region cannot be excluded (Fang et al., 2003).

This case study focuses on the time period from 1999 to 2007 in which year 1999 is designated as the "baseline" period and 2000 to 2007 as the "treatment" period that has different land cover and climatic conditions from the baseline period. Changes in ET (treatment period—baseline) at both annual and monthly scales are examined. If precipitation is assumed not to be affected by vegetation cover change, the effect of land cover on water yield is considered to be equivalent to changes in ET. A summary of findings for this regional modeling study follows.

- Water yield had large spatial and temporal variability in the study region (Fig. 8.8a).
- In general, the vegetation-based ecological restoration effort, GFG project, resulted in an increase of water loss through evapotranspiration (Fig. 8.8c). However, the actual impacts on water yield depended on the variability of precipitation. Simulation showed that increased precipitation during the project implementation period masked the water yield reduction effects; the GFG project might have aggravated water shortages in some areas that received reduced precipitation.
- Due to the large spatial variability in climate and vegetation characteristics, the magnitude of hydrologic effects of vegetation change varies across the Loess Plateau (Figs. 8.8b and c). The forested areas that received more precipitation had higher responses than the drier areas in terms of absolute water yield reduction. However, drier areas are more vulnerable to flow reduction, especially in the growing season.
- The effects of ecological restoration were strongly influenced by precipitation variability in the arid region. The current regional vegetation restoration projects have variable effects on local water resources across the region

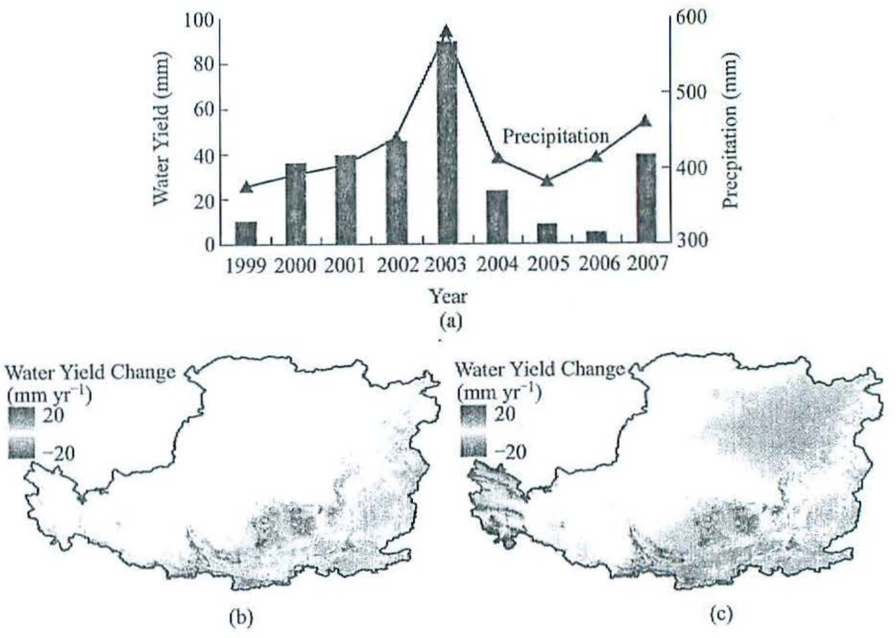

Fig. 8.8 Simulated mean annual water yield across the Loess Plateau region during 1999–2007 (a), effects of land use change only (b), and land use change + climate variability (c) over 2000–2007 when compared to year 1999. Positive values indicate an increase and otherwise a decrease in water yield (Feng et al., 2012).

that had a large precipitation gradient. The future climate change in the study region is likely to alter the water balances due to both air warming and changes in precipitation patterns. Land management planning must consider the influences of spatial climate variability and long-term climate change on water yield and ecosystem structures.

8.3.2 Impacts of Future Climate Change on Runoff across DEA

Global Circulation Models (GCMs) can more or less adequately reproduce the annual variability of air temperature and precipitation; however, they have large uncertainties in runoff simulation due to the simplified representation of land surface processes, lack of runoff routing computation and neglected local human impacts (i.e., reservoirs). To eliminate these shortcomings, we analyzed future runoff changes modeled by a modified version of the water balance model (WBMPlus) (Wisser et al., 2008; Shiklomanov et al., 2013) driven by several AO GCMs under the IPCC SRES A1B emission scenario (Table 8.1).

Table 8.1 Description of Eight IPCC AO GCMs.

GCM Models	Country	Spatial Resolution
ECHAM5/MPI-OM	Germany	$1.9° \times 1.9°$
CGCM3.1(T63)	Canada	$2.8° \times 2.8°$
UKMO-HadCM3	Great Britain	$1.25° \times 1.875°$
BCCR-BCM2	Norway	$2.8° \times 2.8°$
NCAR_CCSM3	USA	$1.4° \times 1.4°$
INM-CM3 RAS	Russia	$3.0° \times 4.0°$
GFDL-CM2.1	USA	$2.0° \times 2.5°$
MIROC3.2(medres)	Japan	$2.8° \times 2.8°$

WBM is a global-scale, gridded model that simulates both the vertical exchange of water between the ground and the atmosphere, and the horizontal transport of water through runoff and stream networks. The used version of the model also has the capability to model the impact of large reservoirs on stream flow and the role of irrigation on the vertical exchange of water. To analyze future changes in regional hydrology, we ran WBMPlus with 30×30 min spatial resolution and monthly time steps using future climate scenarios generated from eight AO GCMs (Table 8.1) (http://neespi.sr.unh.edu/maps/).

Results indicate a tendency toward decreases in river runoff across DEA, although the projected changes are not spatially uniform. Figure 8.9 shows changes in annual river runoff across DEA by 2040–2060 from the long-term

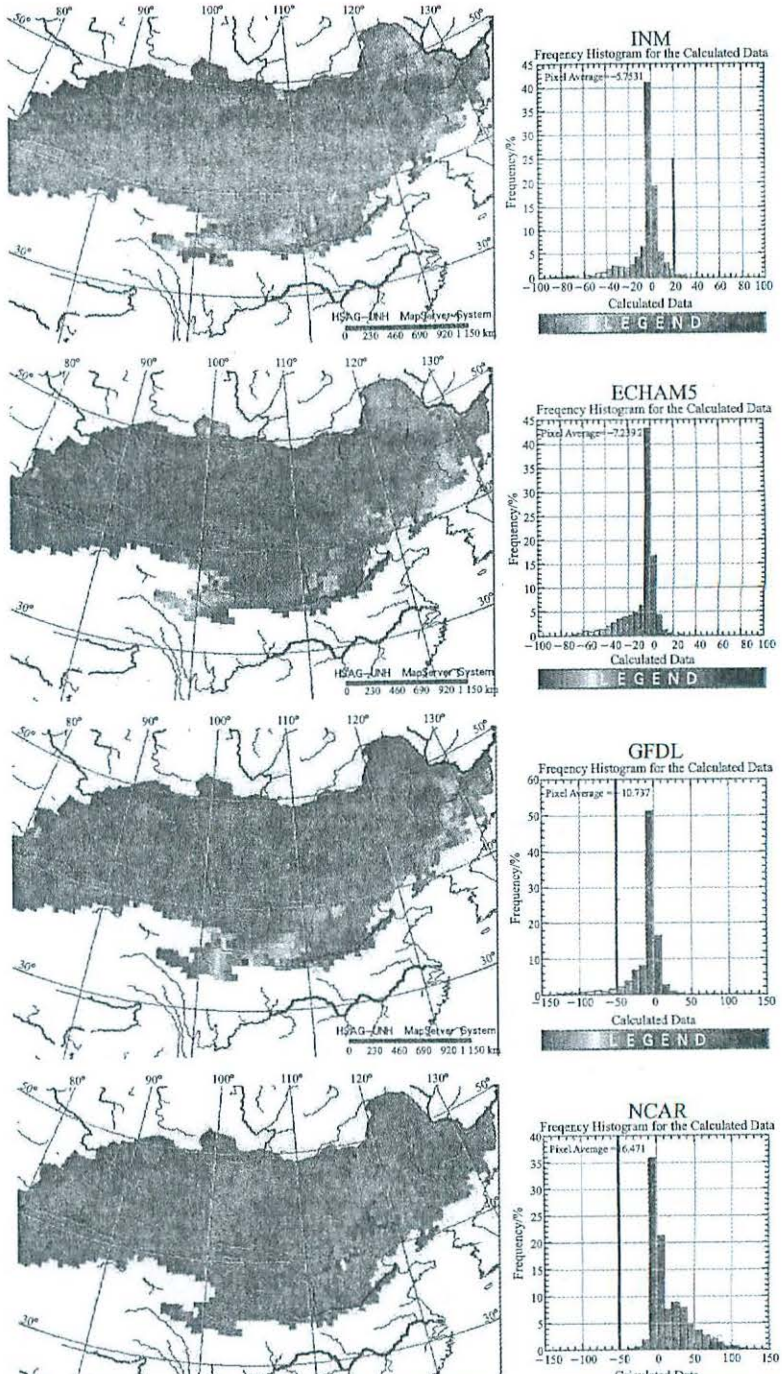

Fig. 8.9 The deviations of mean annual projected runoff for 2040–2060 from mean contemporary runoff over 1959–1999 under 20c3m scenario simulated with WBMplus using different AO GCMs (IPCC, 2007; Shiklomanov et al., 2013).

average (1959–1999) for GFDL-CM2.1, INM-CM3 RAS, MPI ECHAM5 and NCAR CCSM3 AO GCMs. The DEA region, in the future, will be drier with a decline in annual river runoff aggregated for the entire domain in the range from −5 mm to −11 mm (Fig. 8.9). However, NCAR CCSM3, with the best spatial resolution and the most sophisticated representation of land surface processes, projects completely different future climates with higher annual precipitation and thus increased annual runoff by 16 mm by 2040–2060 (Fig. 8.9). Thus, there is a great uncertainty in future runoff projections because of a great uncertainty of future climate among different IPCC AO GCMs.

There is also a large uncertainty in the projection of changes in monthly and annual river discharge for the large regional rivers, such as the Yellow River. Simulations for the same location are presented in Figures 8.10 and 8.11. Large discrepancies among models were found for the fall season. According to the most AO GCM (except NCAR), increases in river discharge are projected during winter and spring months and decreases during summer-fall when water use by ecosystems and humans is highest.

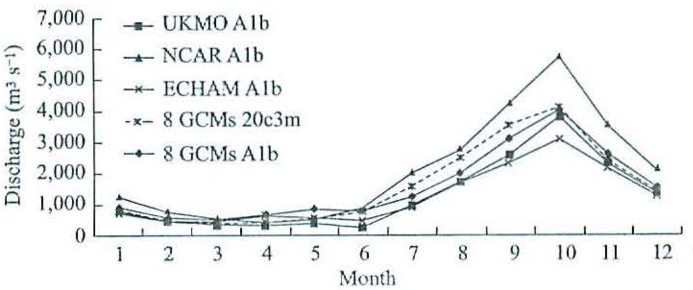

Fig. 8.10 Mean monthly discharge simulated with the WBMplus model for the Yellow River for 2040–2060 (IPCC A1B emission scenario) and 1959–1999 (for 20th century IPCC AR4 20c3m scenario) from different GCMs.

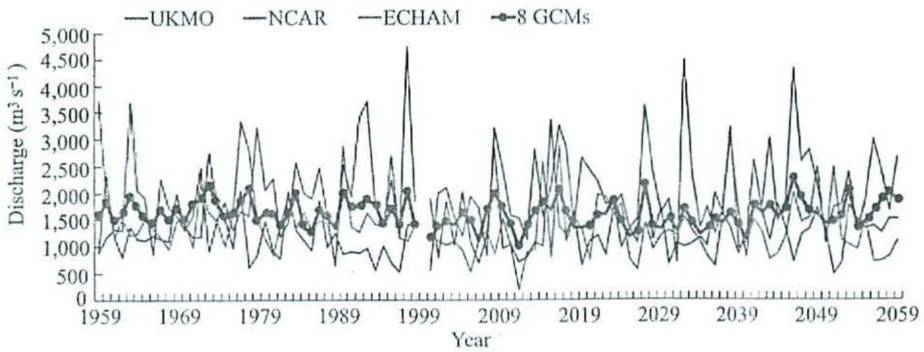

Fig. 8.11 Mean annual discharge variability for the Yellow River simulated with the WBMplus model for different GCMs using the 20c3m scenario until 1999 and SRES A1B since 2001.

8.4 Conclusions

This review found that both climate change (e.g., glacier melting due to global warming) and land use change (e.g., conservation, irrigation) have severely impacted stream flow in many areas in DEA. The region is facing an unprecedented water shortage that has caused serious concerns for the sustainability of the region as a whole. Dramatic land use changes driven by population growth, urbanization, industrialization, and poorly guided ecological restoration are the root causes for this water crisis. Global climate warming has altered the normal local hydrologic cycles and ecosystem functions in some key regions by melting glaciers, thawing frozen soils, and elevating water demand for agricultural irrigation and human use. Continued climate change will have profound impacts on DEA and will likely aggravate the current water problems characterized as diminishing surface water, groundwater depletion, increased water pollution and expansion of soil erosion/desertification.

Solving the water resource issues in DEA cannot be achieved by looking at the water sector alone. In fact, single-handed soil and water conservation practices such as reforestation in Northern China have resulted in unintended environmental consequences. An ecosystem approach is needed to manage the trade-offs between all ecosystem services (i.e., soil erosion control, water supply, groundwater recharge, carbon sequestration, and climate moderation). Integrated watershed management that considers all watershed service needs by humans and natural ecosystems should be promoted. Water conservation practices that promote increasing water use efficiency and implementing demand-based water allocation management in agricultural irrigation and industry water use may have immediate effects in the face of rapid economic transformation in Northern China. Facing the large uncertainty of climate change and socioeconomic changes in DEA, decision-making processes and institutions must adopt a robust and adaptive framework to achieve long-term sustainability in DEA (Lu et al., 2012).

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