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Water requirements of the oasis in the middle Heihe River Basin, China: Trends and causes

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Abstract. The middle Heihe River Basin is the main grain base of the northwestern China, where consumed the most water in the whole Heihe River basin. Increasing share of water resources in the middle Heihe River Basin has caused various issues in hydrology, ecology and environment in the Heihe River Basin, especially the downstream. To make clear how and why the water requirement has changed is significant for the water management in the study region. During the past ~30 years, the water requirement amount of the oasis increased from 10.7×10^8 m^3 in 1986 to 18.8×10^8 m^3 in 2013. And 76 %-82 % of the oasis water requirement amount was consumed by the cultivated land. Maize, spring wheat, and vegetable are the main crops in the middle Heihe River Basin. The mean annual water requirements of the maize, spring wheat, and vegetable were 562.4 mm, 408.7 mm, and 719.0 mm, respectively. By the contribution analysis, the extended planting area was the primary reason why the water requirement has increased in the past ~30 years, the contribution of which to the long-term trend in annual water requirement was 58.3 % and 60.6 % for the oasis and cultivated land, respectively. The changes in land structure were the secondary reason, which explained 25.3 % and 23.4 % of the water requirement variation in the oasis and cultivated land, respectively. The contribution of the climate change was relatively less, which contributed only 7.0 % and 6.8 % to the water requirement variation in the oasis and cultivated land, respectively.

1. Introduction

Inland river basins take up about 11.4 % of the land area in the world and most of them are distributed over arid regions (Li et al., 2013). Water resources in arid regions are scarce and critical to ecosystems and societies. For the inland river basins in arid regions, water resources mainly originate from the precipitation in the upstream mountainous areas (Shen and Chen, 2009; Kang et al., 2007), and are consumed in the oasis zone of the piedmont plain in the midstream, then finally vanishes in the desert-oasis zone in the downstream (Kang et al., 2007). The precipitation in plain areas or in major economic centers of arid basins has nearly no significant meaning for generating runoff (Shen and Chen, 2009).

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As the second largest inland river in China, Heihe River breeds an ecosystem which consists of ice-snow, frozen soil, and mountain vegetation zones at the upstream, and oasis zone and desert zone at the middle and down streams (Ersi et al., 1999; Kang et al., 2005; Zhao et al., 2007). More than 90 % of the population and arable land in the Heihe River Basin were concentrated in the oasis zone in the midstream, where the most water in the whole basin was consumed (Hu et al., 2008; Li et al., 2015; Zhang et al., 2006b). Over the past decades, the annual streamflow coming from the upstream stayed at a relative high level, while the streamflow supplied to the downstream showed a significant decrease since 1990 (Jia et al., 2011). The development of modern irrigation schemes, and the growth of population and irrigation area in the middle basin are taking up an increasing share of water resources, endangering the hydrological conditions, ecology and environment in the Heihe River Basin (Chen et al., 2005; Jia et al., 2011; Wang and Cheng, 1998). More than 30 tributaries as well as the terminal lakes have dried up, and the discharge in the downstream decreased significantly in the past 50 years (Chen et al., 2005; Wang and Cheng, 1998). Such hydrological changes have resulted in a marked degradation of the ecological environment, land salinization and desertification in the entire basin. To restore the ecosystem of the downstream, the Ecological Water Diversion Project (EWDP) was launched by the Chinese Government. Water use in the middle Heihe River Basin has been regulated since around the year 2000 to ensure the delivery of minimum amount of water to the downstream, which leads to less water for the middle Heihe River Basin.

With scarce precipitation, irrigation is essential for maintaining the productivity of oasis agriculture. To use the water resources rationally, water requirement of the oasis is necessary to be made clear as an important parameter for irrigation scheduling and regional water allocation. Scientists have obtained some research results about water requirements of oasis ecosystems. For the research method, some focused on the crop water requirement (Kawy and El-Magd, 2012; Liu et al., 2009; Siebert et al., 2007; Lian et al., 2012; Su et al., 2002), while some concentrated on the ecological water requirement (Guo et al., 2016; Ye et al., 2010; Zhao et al., 2007; Liu et al., 2010; Zhang et al., 2006a). From the perspective of research scale, some researchers studied the water requirement at site scale (Zhao et al., 2005; Zhao et al., 2010), some studies were conducted on regional scale (De Silva et al., 2007; Guo et al., 2016; Kawy and Darwish, 2013). However, little is known about the contributions of the influencing factors to the oasis water requirement in the arid regions.

To make rational use of the water resources in the midstream of Heihe River, the water requirements of the oasis including the specific land types in the middle Heihe River Basin were analyzed during 1986-2013 in this study. The primary objective of this study was to clarify the spatial-temporal distribution of the water requirement, and the determinants to the variation of the water requirement amount of the oasis in the middle Heihe River Basin during the last ~30 years. The research questions addressed were: (1) What are the water requirements of the various land use types in the oasis? (2) How do the water requirement and its amount of the oasis have changed in the past ~30 years? (3) Why the water requirement amount of the oasis have changed? (4) What is the main cause of the long-term trend of the water requirement amount of the oasis? We

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anticipate that this study would be helpful to the water management in the middle Heihe River Basin, and the method to analyze the causes might be widely applicable for the oasis in the inland river basins.

2. Material and methods

2.1 Study area

The study was conducted in the oasis in the middle Heihe River Basin (between 38° 32′ and 39° 52′ N, and 98° 57′ and 100° 51′ E), Gansu Province, China (Fig. 1). It embraces a total area of 8.6×10^9 m^2, included in Ganzhou district, Linze county and Gaotai county. The climate is continental arid temperate because the study area is situated in the inner of Asia-Europe continent, with sufficient sunlight and great temperature variations. The mean annual precipitation is scarce, which is 107.86 mm (1953-2014) at Gaotai meteorological station and 129.10 mm (1953-2014) at Zhangye meteorological station. Over 60 % of the precipitation falls between June and August (Zhao et al., 2005). There are two hydrological stations in the study area, which are located at Yingluo Gorge and Zhengyi Gorge, respectively. The middle Heihe River flows from Yingluo Gorge to the Zhengyi Gorge, breeding an oasis suitable for agriculture. Annual discharge observed at Yingluo Gorge increased from around 14.4×10^8 m^3 in the 1960s to 15.7×10^8 m^3 in the 1990s, while the discharge observed at Zhengyi Gorge decreased from around 10.5×10^8 m^3 in the 1960s to around 7.5×10^8 m^3 in the 1990s (Wang et al., 2014). But the discharge observed at Zhengyi Gorge has increased since 2000 due to the EWCP, which stipulated that water flowing from the Zhengyi Gorge to the downstream should be over 9.5×10^8 m^3 when the annual average water supplied from the Yingluo Gorge is 15.8×10^8 m^3 (Zhao et al., 2016). Affected by the EWCP, the available surface water for the middle Heihe River Basin decreased, and more groundwater was taken for irrigation (Ji et al., 2005).

The study area has an agricultural development history of over 2000 years owing to its flat land, adequate sunlight, and convenient water resource from Qilian Mountains. The oasis in the middle Heihe River Basin has then become an important commodity grain base in China. Mixed with the cropland, forest, grass, wetland, and rivers make up the oasis together. The cropping pattern has changed a lot in the recent 30 years (Fig. 2). The area of maize increased significantly; on the contrary, the wheat planting area decreased evidently. Besides, the planting area of vegetable also increased especially in Gaotai county during the past 30 years. The cropping pattern in the study area are turning to be simple to focus on the maize, which providing more than 40 % of maize seeds in China (Xing, 2013). The oasis area has been expanding in the recent ~30 years. According to the land use data developed by the Chinese Academy of Sciences (CAS), the oasis area increased ~ 906 km^2 in the recent ~30 years, in which the cultivated land increased about 740 km^2.

2.2 Data handling and processing

2.2.1 Meteorological data

Daily meteorological observations were collected from China Meteorological Administration (CMA), mainly including the maximum, minimum and average air temperatures, wind speed, relative humidity and sunshine duration. 10 meteorological stations, which covered the Gaotai, Zhangye stations inside the study region and Dingxin, Jinta, Jiuquan, Tuole, Yeniugou, Qilian, Shandan, Alxa youqi stations outside the study region, were selected to get the spatial distribution of meteorological elements (Fig. 1). Observations on crop growth and phenology were collected from the agricultural meteorological stations in Gansu Province, especially from the station in Zhangye. But the data on crop growth and phenology were only basically recorded completely for the maize (1993-2013) and spring wheat (1992-2013), so the growth and phenology data for other vegetation were obtained by references (Liu, 2014; Allen et al., 1998; Pu et al., 2004; Li et al., 2009; Zhou et al., 2015), combining practical investigation. The growth and phenology data for maize before 1993 were set as that in 1993, and for spring wheat before 1992 were set as that in 1992.

2.2.2 Land use data

Land use data for years 1986, 1995, 2000, 2011 at a spatial resolution of 30 m (Wang et al., 2011a, b; Wang et al., 2014) were used in this study. The land use data for years 1986, 1995, 2000 were clipped directly from the 1:100,000 scale land use database developed by the Chinese Academy of Sciences (CAS). And the land use data for 2011 were developed by the Laboratory of Remote Sensing and Geospatial Science in the Cold and Arid Regions Environmental and Engineering Research Institute, CAS. The same classifying system of land cover was used in the four years' land use data. The land-use patterns in the basin have been divided into 6 types: cultivated land; forest land which include closed forest land, sparse wood land, shrubs, and other wood land; grassland which contains high coverage grassland, moderate coverage grassland, and low coverage grassland; waters which comprise rivers, lakes, reservoirs, and beach land; construction land; and unused land which contains sand, gobi, saline-alkali land, swampland, bare land, bare rock and gravel. To get the continuous land use maps, the land use data at the spatial resolution of 30 m were transformed to the land use data at the spatial resolution of 1 km by the percentage form, i.e. every land use type was showed in the form of percentage in each grid. Then the spatial distribution of the land use data between the four discrete years could be obtained by linear interpolation.

To obtain the spatial distribution of specific crops in the cultivated land, the socio-economic statistical data were collected from the *Gansu Development Yearbook* (1984-2014) and *Gansu Rural Yearbook* (1990-2014), including various crops sown at the county level. Based on the main crops in the Statistical Yearbooks, the cultivated land was classified into 7 types: maize, spring wheat, cotton, oilseed, sugar beet, potato, and vegetable. According to the proportion of each crop in each county, the spatial distribution of the seven crops were determined.

2.2.3 Validation data

The water requirements estimated in this study were compared with two Evapotranspiration (ET) datasets provided by Science Data Center for Cold and Arid Regions (http://westdc.westgis.ac.cn). One is the monthly ET datasets (2000-2013) estimated by ETWatch model at 30 m spatial resolution (Wu et al., 2012; Liu et al., 2011), while this datasets only cover part of the oasis which include Ganzhou district, Linze county and small part of the Gaotai county in the middle Heihe River Basin. The other is the daily ET datasets (2009-2011) of the Heihe River Basin estimated by ETMonitor model at 1 km spatial resolution (Cui and Jia, 2014; Jia et al., 2013). The intersections of the ET datasets and water requirements were used for comparision.

2.3 Estimates of water requirements

In this study, we considered the water requirements of the cultivated land, forest land, high coverage grassland, moderate coverage grassland, waters except the beach land, and the swampland in the unused land. The water requirements for the low coverage grassland, beach land, construction land, and unused land except the swampland were taken as zero.

2.3.1 Water requirements for the cultivated land and grassland

Water requirements of the crops and grass in the oasis refer to the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions. This can be calculated using crop coefficient approach as following:

$$ET_c = K_c \times ET_0 \tag{1}$$

where ET_c is the crop water requirement; K_c is the crop coefficient; ET_0 is the reference evapotranspiration.

ET_0 was calculated using the modified Penman-Monteith equation recommended by United Nations Food and Agriculture Organization (FAO) (Allen et al., 1998). Reference evapotranspiration is only related to meteorological factors (Shahid, 2010). It can be used in a wide range of locations and climates, and can be calculated using the following equation:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \tag{2}$$

where ET_0 is the reference evapotranspiration (mm); R_n is the net radiation at crop surface [MJ/(m^2 d)]; G is the soil heat flux density [MJ/(m^2 d)]; u_2 is the wind speed at a height of 2 m (m/s); T is the mean daily air temperature at a height of 2 m (℃); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); Δ is the slope

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of the vapor pressure-temperature curve [kPa/℃]; and γ is the psychrometric constant [kPa/℃].

Different vegetation types have different K_c coefficients. The changing characteristics of the vegetation over the growing season also affect the K_c coefficient, so K_c for a given vegetation type will vary over the growing period, which can be divided into four distinct growth stages: initial, crop development, mid-season and late season. In the current study, K_c for the crops in the cultivated land were determined according to Duan et al. (2004) and FAO (Allen et al, 1998). And K_c for the grassland were determined according to Liu (2014). The K_c values are shown in Table 1.

2.3.2 Water requirement for forest land

For the forest land, the water requirements of closed forest land, sparse wood land and shrubs were estimated by phreatic evaporation. It can be calculated as below:

$$W_i = S_i \times W_{gi} \times k_p \tag{3}$$

where W_i is the ecological water demand of vegetation i; S_i is the area of vegetation type i; W_{gi} is the phreatic evaporation capacity of the vegetation type i at a certain groundwater depth; k_p is the vegetation coefficient, which is related to the groundwater depth (Table 2)(Song et al., 2000).

W_{gi} is the key to calculate vegetation ecological water demand using the phreatic evaporation method, and it is usually calculated using Averyanov's phreatic evaporation equations:

$$W_{gi} = a(1 - h_i/h_{max})^b E_0 \tag{4}$$

where a and b are empirical coefficients (0.856 and 3.674 in the study area) (Wang and Cheng, 2002); h_i is the groundwater depth of vegetation type i, which is 1.5 m, 2 m, 2.5 m for the closed forest land, sparse wood land and shrubs, respectively; h_{max} is the maximum depth of phreatic evaporation, which is 5 m (Wang and Cheng, 2002); and E_0 is the surface water evaporation.

The other wood in the study area was mainly orchard, so the water requirement of other wood land was calculated by the crop coefficient approach (Table 1).

2.3.3 Water requirements for waters and the swampland

The water requirement of waters can be taken as the evaporation from water surfaces, which can be calculated according to Shuttleworth (1993):

$$ET_w = \frac{\Delta R_n + 6.43\gamma(1 + 0.536u_2)(e_s - e_a)}{\lambda(\Delta + \gamma)} \tag{5}$$

where ET_w is the water requirement of waters (mm); λ is the latent heat of vaporization (MJ kg^{-1}).

The water requirement for swampland was calculated by crop coefficient approach. The K_c of the vegetation in the swampland is determined depending on the single crop coefficients suggested in FAO (Table 1).

2.4 Contribution assessment

According to the methods to estimate water requirements of the oasis in the middle Heihe River Basin, the value of the water requirements (y) is mainly related to the climate (x_1), total area of the oasis (x_2), and area proportions of the land structure (x_3). Mathematically, the function can be write as

$$y = f(x_1, x_2, x_3, \dots) \quad (6)$$

The variation of the dependent variable y can be expressed by a differential equation as

$$\mathrm{dy} = \frac{\partial f}{\partial x_1}dx_1 + \frac{\partial f}{\partial x_2}dx_2 + \frac{\partial f}{\partial x_3}dx_3 + \cdots \quad (7)$$

As y varies with time t, we can rewrite Eq. (7) as

$$\frac{dy}{dt} = \frac{\partial f}{\partial x_1}\frac{dx_1}{dt} + \frac{\partial f}{\partial x_2}\frac{dx_2}{dt} + \frac{\partial f}{\partial x_3}\frac{dx_3}{dt} + \delta \quad (8)$$

$\frac{dy}{dt}$ is the slope of the linear regression for y against time t; $\frac{\partial f}{\partial x_1}\frac{dx_1}{dt}$ can be taken as the slope of the linear regression for y against time t when x_2 and x_3 don't change with the time; $\frac{\partial f}{\partial x_2}\frac{dx_2}{dt}$ can be taken as the slope of the linear regression for y against time t when x_1 and x_3 don't change with the time; $\frac{\partial f}{\partial x_3}\frac{dx_3}{dt}$ can be taken as the slope of the linear regression for y against time t when x_1 and x_2 don't change with the time; Because the spatial distribution of the climate is not homogeneous, the location where a certain land-use type is located can also affect the water requirement. In this study, we didn't consider the influence of land-use location on the water requirement, so we fitted it into δ, which can be taken as the error.

The individual proportional contribution (ρ) of related factors to the long-term trend in y can be estimated as

$$\rho(x_i) = (\frac{\partial f}{\partial x_i}\frac{dx_i}{dt})/(\frac{d_y}{d_t}) \times 100\% \quad (9)$$

where x_i can be the variable x_1, x_2 and x_3.

3. Results

There are 15 specific land-use types in the oasis of the middle Heihe River Basin, which are cultivated land (maize, spring wheat, cotton, oilseed, sugar beet, potato, vegetable), grassland (high coverage grassland, moderate coverage grassland), forest land (closed forest land, sparse wood land, shrubs, the other wood), waters, and swampland. Different land-use types may require different water amounts. To understand the water requirements in the oasis, the spatial and temporal variations of the total water requirement amount and the water requirement per unit area were analyzed. Here the water requirement per unit area for each land-use type were calculated by dividing the total water requirement of each land-use type by the corresponding land area. After the validation to ensure the accuracy of the results, the water balance and determinants to the variation of the water requirement amount of the oasis in the middle Heihe River Basin were analyzed.

3.1 Temporal variations in water requirements of the oasis in the middle Heihe River Basin

The water requirement amount of the total oasis increased from 10.7×10^8 m^3 in 1986 to 18.8×10^8 m^3 in 2013 (Fig. 3). According to the land use data, the area of the cultivated land accounted for ~80 % of the total area of the oasis (Fig. 4). Therefore, the water requirement amount of the cultivated land increased from 8.3×10^8 m^3 in 1986 to 14.6×10^8 m^3 in 2013 (Fig. 3), which occupied 76 %-82 % of the total oasis water requirement amount during 1986-2013. The mean annual water requirements amount of the cultivated land and the whole oasis were 10.3×10^8 and 13.2×10^8 m^3, respectively. The water requirement amounts of the swampland and waters from 2000 to 2013 increased a lot, so was the water requirement amount of the forest land from 1986 to 1995. But the waters, swampland, forest land, and grassland needed less water amounts which were all smaller than 1.7×10^8 m^3 because the proportion of them in the oasis were all smaller than 9 % (Fig. 4).

The water requirement of the cultivated land per unit area increased from 513.9 mm to 618.3 mm during 1986-2013, while the water requirement of the oasis per unit area increased from 522.5 mm to 635.8 mm during 1986-2013 (Fig. 5). The mean annual water requirements of the cultivated land and the oasis per unit area were 537.6 mm and 550.8 mm, respectively. Maize, spring wheat, and vegetable are the main crops in the middle Heihe River Basin. The mean annual water requirements of the maize, spring wheat, and vegetable per unit area were 562.4 mm, 408.7 mm, and 719.0 mm, respectively. Waters required the most water per unit area, the mean annual water requirement of which reached 1314.6 mm. The swampland covered with reeds also needed a lot of water per unit area, the mean annual water requirement of which could reach 965.4 mm. Different land surface coverages of the grassland and forest land had different water requirements. The mean annual water requirements of the closed forest land, sparse wood land, shrubs, the other wood, high coverage grassland, and moderate coverage grassland per unit area were 470.2 mm, 127.6 mm, 261.9 mm, 696.8 mm, 654.6 mm, and 336.4 mm, respectively.

3.2 Spatial variations in water requirements of the oasis in the middle Heihe River Basin

The oasis in the middle Heihe River Basin is mainly located in Ganzhou district, Linze county and Gaotai county. The water requirements of the three regions all showed a growth trend (Fig. 6; Fig. 7). For the cultivated land, Ganzhou district required the most of water which increased from 4.6×10^8 m^3 in 1986 to 7.7×10^8 m^3 in 2013 because 54 %-

56 % of the cultivated land was concentrated here (Fig. 6a; Fig. 7). The water requirement of the cultivated land per unit area in Gaotai increased faster than the other regions due to the adjustment of the crop structure (Fig. 6b), that is to say, the largest increase of the planting proportion of vegetable happened in Gaotai (Fig. 2). The water requirement per unit area in Linze was higher than that in Ganzhou, but because of the small planting area, the total amount of water requirement in Linze was similar with that in Gaotai, and much smaller than that in Ganzhou (Fig. 6a,b). The mean annual crop water requirement per unit area in Linze, Ganzhou, and Gaotai was 551.1 mm, 530.4 mm, and 547.6 mm, respectively. For the whole oasis in the middle Heihe River Basin, Ganzhou still occupied the most water requirement which increased from 5.4×10^8 m^3 in 1986 to 9.3×10^8 m^3 in 2013 because 50 %-54 % of the oasis was concentrated here. The water requirement amount in Gaotai came second, increasing from 3.1×10^8 m^3 in 1986 to 5.4×10^8 m^3 in 2013. The water requirement amount in Linze was the least, increasing from 2.2×10^8 m^3 in 1986 to 4.1×10^8 m^3 in 2013 (Fig. 6c; Fig. 7). The emergence that the water requirement amount in Gaotai was more than that in Linze came from two aspects. One was that the oasis area in Gaotai was larger than that in Linze, the other was that the water requirement per unit area in Gaotai was the highest in the three regions (Fig. 6d). Besides the adjustment of crop structure, the swampland was mainly distributed in Gaotai, which generated the highest water requirement per unit area in Gaotai. In the beginning, the water requirement per unit area in Ganzhou was smaller than that in Linze (Fig. 6d), but it caught up with the water requirement per unit area in Linze at the end with the water area rising up in Ganzhou. The mean annual oasis water requirement per unit area in Linze, Ganzhou, and Gaotai was 543.6 mm, 528.1 mm, and 609.3 mm, respectively.

3.3 Validation of the oasis water requirements

Water requirement is defined as a theoretical value. For the crops, it can be taken as the potential crop ET. But there was no available data that were observed or calculated by others for the potential crop ET, so we used the actual ET to validate it to see if the result was acceptable.

According to the monthly ET datasets (2000-2013) estimated by ETWatch with 30m spatial resolution over part of the oasis (Wu et al., 2012; Liu et al., 2011), the evapotranspiration (ET) was well correlated with the estimated water requirement (Fig. 8a). The determination coefficients (R^2) for the cultivated land and the oasis were 0.66 and 0.67, respectively. And the root mean square error (RMSE) for the cultivated land and the oasis were 0.80×10^8 m^3 and 0.73×10^8 m^3, respectively. Because the water requirement is the potential ET, the water requirement should not be smaller than the ET. But the yearly ET included not only the ET during crop growth period, but also the ET from the bare land after harvesting the crops, while the estimated water requirement for the crops only included the water requirement during the crop growth period, so most yearly ET data were larger than the yearly water requirements, and the slope of the linear regression was smaller than 1 (Fig. 8a). Without considering the cultivated land, the ET was smaller than the water requirement of the whole rest land types. To remove the influence of the bare land, the monthly ET datasets in May, June, and July were selected to validate the water requirement because the vegetation including the crops were all in their growth period in the three months. It showed that the water requirement was highly correlated with the ET. The R^2 could reach 0.80 and 0.82 for the cultivated land and the oasis, respectively (Fig. 8b). And the RMSE for the cultivated land and the oasis were 0.34×10^8 m^3 and 0.35×10^8 m^3, respectively. Most of the monthly water requirement was higher than the monthly ET, and the slope of the linear regression was about 1.1 when set the intercept at 0 (Fig. 8b).

Compared with the ET datasets (2009-2011) estimated by ETMonitor model at 1 km spatial resolution in the middle Heihe River Basin, the estimated water requirements were strongly correlated with the ET data. The value of R^2 reached about 0.99 (Fig. 9). Because the resolution of the ET datasets was relatively low, only the results in the oasis were validated considering the problem of mixed pixels. The yearly and monthly water requirements were all larger than the corresponding ET data. The RMSE for the monthly data in May, June, and July was 1.22×10^8 m^3. But the ET data estimated by ETWatch in 2009, 2000, and 2011 were larger than the estimated water requirements for the oasis, which showed that the two ET datasets deviated from each other. And the estimated water requirements were acceptable.

3.4 Water balance in the middle Heihe River Basin

Yingluo Gorge is the divide of the upper and middle Heihe River, and Zhengyi Gorge is the divide of the middle and lower Heihe River. The two hydrologic stations recorded the inflow and outflow of the mainstream of the middle Heihe River. Besides, there are some small rivers also flow into the middle Heihe River Basin, like Shandan River and Liyuan River. The mean annual runoff of the Liyuan River and Shandan River is 2.36×10^8 m^3 (Wu and Miao, 2015) and 0.86×10^8 m^3 (Guo et al., 2000), respectively. According to the runoff data (1986-2010) of Zhengyi Gorge and Yingluo Gorge, and precipitation data (1986-2010) obtained from the Science Data Center for Cold and Arid Regions (Heihe River Basin Bureau, 2015; Yang et al., 2015), the precipitation landing on the oasis and runoff data including middle Heihe River, Shandan River and Liyuan River could meet the water requirement before the year 2004, ignoring the water conveyance loss. But with the increasing water requirement of the oasis, the water supply from the land surface could not meet the requirement any more (Fig. 10).

The vegetation in the oasis can be divided into two categories, one is agricultural vegetation which includes the crops and orchard, and the other is the ecological vegetation. The precipitation in the middle Heihe River Basin is too little to supply enough water for the ecological vegetation (Table 3). The ecological vegetation usually grows around the cultivated land, so they can absorb the water of infiltration. In addition, the shelter forest often needs irrigation, and the shrubs like tamarix chinensis and sacsaoul also need groundwater to maintain normal growth. In the 1980s and 1990s, precipitation has remained little changed, but the water requirement increased slowly, and the runoff had an obvious rise (Fig. 10; Table 3), so the water supply seemed to be sufficient to the water requirement in the oasis. In the 2000s, the water requirement

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
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Discussion started: 21 August 2017

Earth System Dynamics Discussions Open Access EGU

increased much more than the water supply (Table 3), so the water resources from land surface was in short supply.

3.5 Contributions to the water requirement trend

The water requirement of the oasis is affected by the climate, total area of the oasis, and area proportions of the land structure. Because the oasis is dominated by the cultivated land, here we analyzed the contributions of the influencing factors to both the oasis and cultivated land. For the cultivated land, the three influencing factors are the climate, total area of the cultivated land, and the area proportions of the crops in the cultivated land. The area of the oasis in 1986, 1995, 2000, and 2011 was 2048.96 km^2, 2091.13 km^2, 2216.97 km^2, and 2954.85 km^2, respectively, which showed an obvious increase in the recent ~30 years. For the specific land-use types, the area of cultivated land, waters, and swampland in 2011 showed an obvious increase, compared with the area in 1986. The area of the cultivated land was only 1614.32 km^2, and 1649.99 km^2 in 1986 and 1995, but it increased to 1835.18 km^2, and 2354.25 km^2 in 2000, and 2011, respectively. Besides the spread of oasis, the increased area of the land-use types with high water requirement like the vegetable, maize, waters, and swampland also increased the water requirement amount of the oasis.

From the equation of linear regression for the water requirement amounts of the oasis and cultivated land against time, we could see the water requirements of the oasis and cultivated land increased 0.3416×10^8 m^3 and 0.2714×10^8 m^3 per year during 1986-2013, respectively (Fig. 11a). Considering the effect of climate to the water requirement amount, the total area of the oasis and the area proportions of the land structure were set stable, which meant the area of all the specific land-use types didn't change with time, and only the climate changed as usual during 1986-2013. In the situation, the water requirement increased slowly at the rate of 0.0239×10^8 m^3 and 0.0185×10^8 m^3 per year for the oasis and cultivated land, respectively (Fig. 11b). Based on the Eq. (9), the contribution of the climate was only 7.0 % and 6.8 % for the water requirement change in the oasis and cultivated land, respectively. Considering the effect of total area to the water requirement, the climate and the area proportions of the land structure were set stable, and the total area varied with the time during 1986-2013. In this situation, the water requirement increased fast at the rate of 0.199×10^8 m^3 and 0.1644×10^8 m^3 per year for the oasis and cultivated land, respectively (Fig. 11c). Then the contribution of the total area was 58.3 % and 60.6 % for the water requirement change in the oasis and cultivated land, respectively. Considering the effect of the area proportions of the land structure to the water requirement, the climate and total area were set stable, and only the area proportions of the land structure changed as usual during 1986-2013. In this situation, the water requirement increased at the rate of 0.0864×10^8 m^3 and 0.0635×10^8 m^3 per year for the oasis and cultivated land, respectively (Fig. 11d). So the contribution of the area proportions of the land structure was 25.3 % and 23.4 % for the water requirement change in the oasis and cultivated land, respectively. The three influencing factors explained approximately 91 % of the reason why the water requirements of the oasis and cultivated land changed during 1986-2013. In the recent ~30 years, the main

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 21 August 2017

reason for the increased water requirement of the oasis was the spread of the oasis area, and the adjustment of land structure came second. The climate had the least influence on the water requirement change during 1986-2013.

4. Discussion

Based on the land use and meteorological data, the water requirements of the oasis and the cultivated land which is the main part of the oasis in the middle Heihe River Basin were calculated and analyzed. We found out how and why the water requirements in the oasis changed in the past ~30 years, which is significant to the water management, and can provide scientific basis for the adjustment of planting structure in the study region. But there are still some uncertainties in the study because of limited available data and technical constrains.

There is no observed potential ET to validate the calculated theoretical crop water requirement, field studies will be set to observe the potential ET for the main crops in the study region in the future. The ecological water requirements for the forest land, sparse wood land, and shrubs were calculated by empirical formulas which would bring uncertainties to the results. Besides, some data were difficult to achieve, such as the growth and phenology data and land use data in each year. So the growth and phenology data for the vegetation except the maize and wheat were obtained by references combining practical investigation, and the land use data in each year were achieved by interpolation. This was also one of the reasons why there were some uncertainties in the results. Additionally, the crop coefficient is related to many factors, such as the biological characters of the crop, cultivation and soil conditions, etc., so the crop coefficients should be changing during the study period. The same crop can have different varieties, and different varieties have different crop coefficients. The crop coefficients are usually determined by experiments. So additional efforts need to be made to refine on the crop coefficients.

As an oasis located at ecologically vulnerable areas and dominated by agriculture, the development of agriculture should match up with the climate and ecological capacity. The water amount consumed in the middle Heihe River Basin concerns the ecological security in the lower Heihe River Basin. To promote the harmonious development among the upstream, midstream and downstream, the water amount consumed in the middle Heihe River Basin must be controlled and a series of water-saving measures should be carry on. Because the oasis area and the land structure are the main reason why the water requirement of the oasis increased so fast, additional efforts will be made to determine the appropriate oasis area and crop structure in the middle Heihe River Basin.

5. Conclusion

Affected by the climate, total area of the oasis, and land structure, the water requirement amount of the oasis increased significantly during 1986-2013, which increased from 10.7×10^8 m^3 in 1986 to 18.8×10^8 m^3 in 2013. Cultivated land is the main part of the oasis, the water requirement amount of which increased from 8.3×10^8 m^3 in 1986 to 14.6×10^8 m^3 in 2013. In the study region, Ganzhou district required the largest amount of water because more than 50 % of the oasis was concentrated there. For the main crops (maize, spring wheat, and vegetable) in the middle Heihe River Basin, the mean annual water requirements per unit area were 562.4 mm, 408.7 mm, and 719.0 mm, respectively, which showed the vegetable required much more water than the maize and wheat.

For the influencing factors to the water requirement, the planting area was the primary factor influencing the water requirement, which contributed 58.3 % and 60.6 % to the water requirement change in the oasis and cultivated land, respectively. And then was the land structure, which contributed 25.3 % and 23.4 % to the water requirement change in the oasis and cultivated land, respectively. Climate did not have much effect on the water requirement, for the contribution of the climate was only 7.0 % and 6.8 % for the water requirement change in the oasis and cultivated land, respectively.

6. Data availability

The meteorological data are available at http://data.cma.cn/. The land use data can be obtained from http://westdc.westgis.ac.cn; http://www.resdc.cn. Other data like the validation data, runoff data, and precipitation data used in this study are available at http://westdc.westgis.ac.cn.

Competing interests. The authors declare that they have no conflict of interest.

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Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 21 August 2017

Earth System Dynamics Discussions
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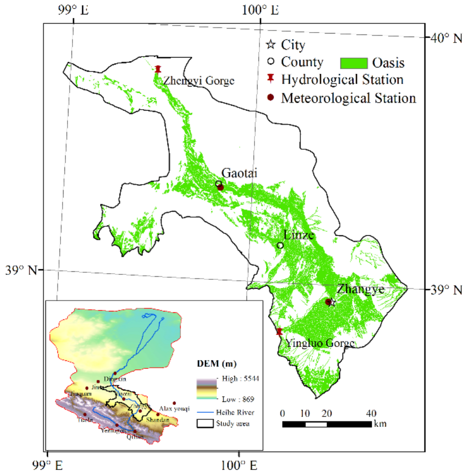

Figure 1. The location of the oasis in the middle Heihe River Basin, embedding the hydrological and meteorological stations, cities, and counties. The distribution of the oasis is based on the land use in 2000.

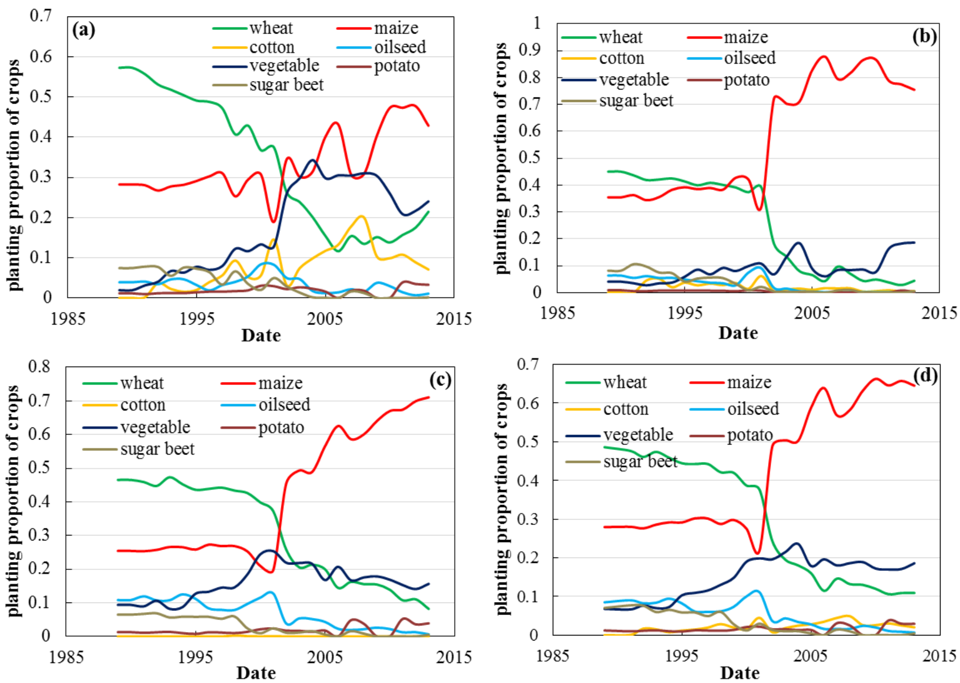

Figure 2. The planting proportion of the crops in (a) Gaotai county, (b) Linze county, (c) Ganzhou

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 21 August 2017

Earth System Dynamics
Discussions
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district, (d) the region including Gaotai, Linze counties and Ganzhou district.

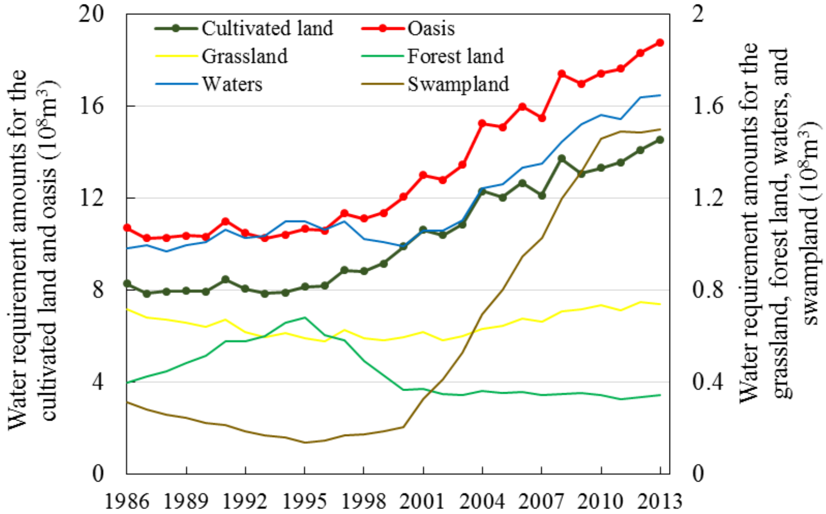

Figure 3. The water requirement amounts for different land-use types in the oasis from 1986 to 2013.

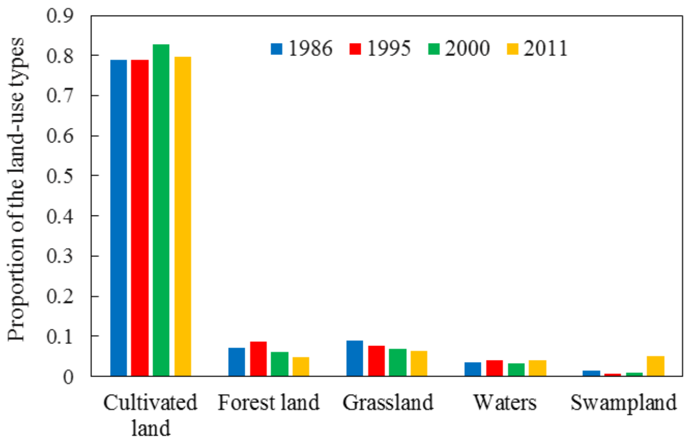

Figure 4. The proportions of the land-use types in the oasis in 1986, 1995, 2000, and 2011.

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 21 August 2017

Earth System Dynamics
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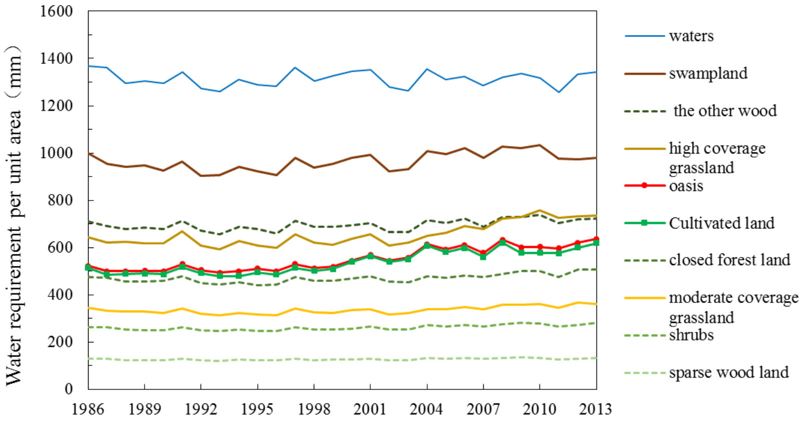


Figure 5. The water requirement per unit area for different land-use types in the oasis from 1986 to 2013.

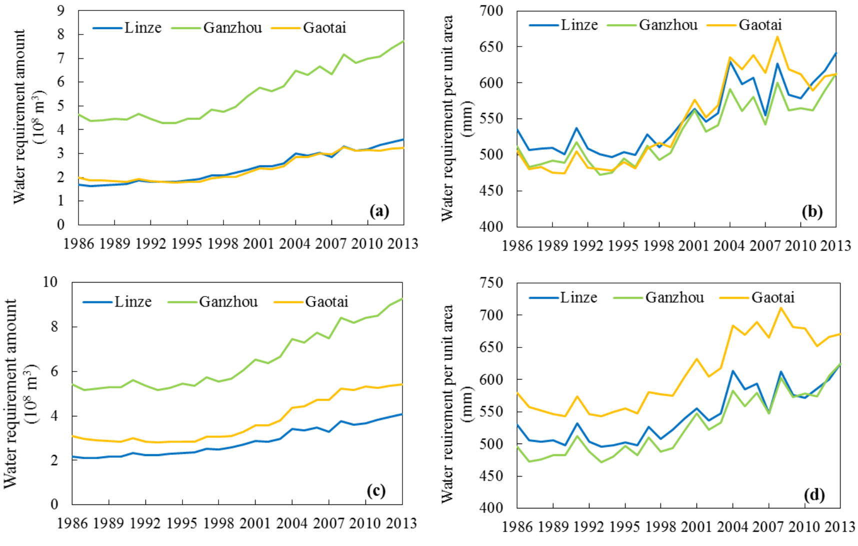


Figure 6. The water requirements of the cultivated land (a, b) and oasis (c, d) in Linze county, Gaotai county, and Ganzhou district.

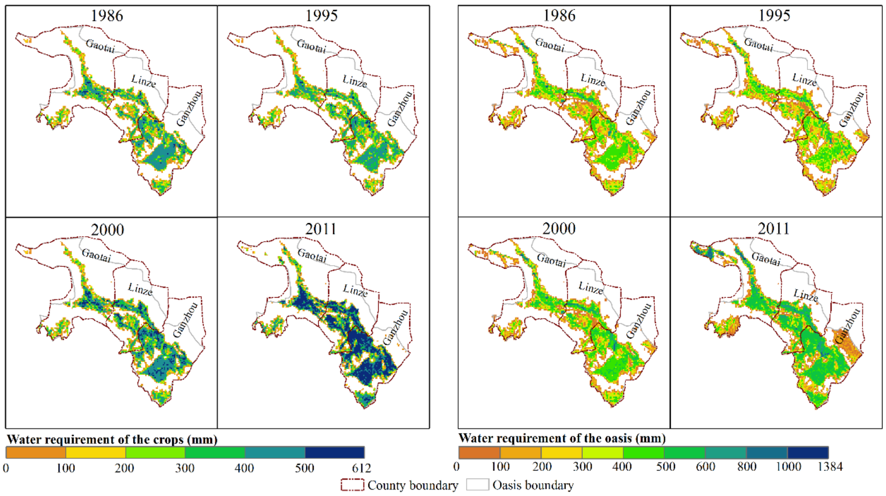


Figure 7. The spatial distribution of the water requirement per unit area in the cultivated land and oasis in the middle Heihe River Basin in 1986, 1995, 2000, 2011.

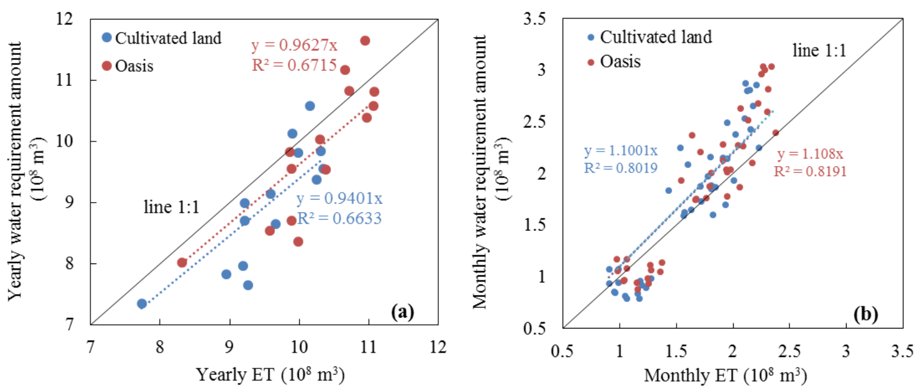


Figure 8. The comparison between the yearly water requirement amount and ET from 2000 to 2013 (a); monthly water requirement amount and ET in May, June, and July from 2000 to 2013 (b) for the cultivated land and the oasis.

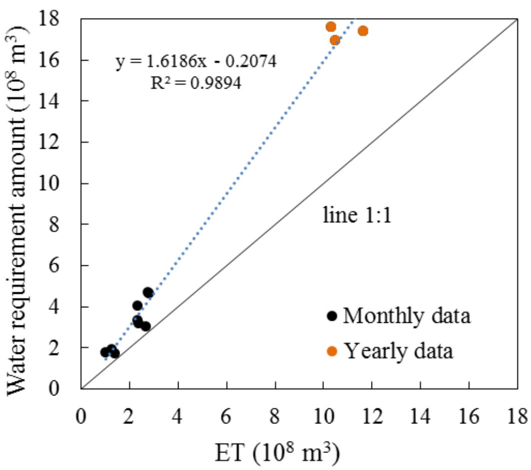
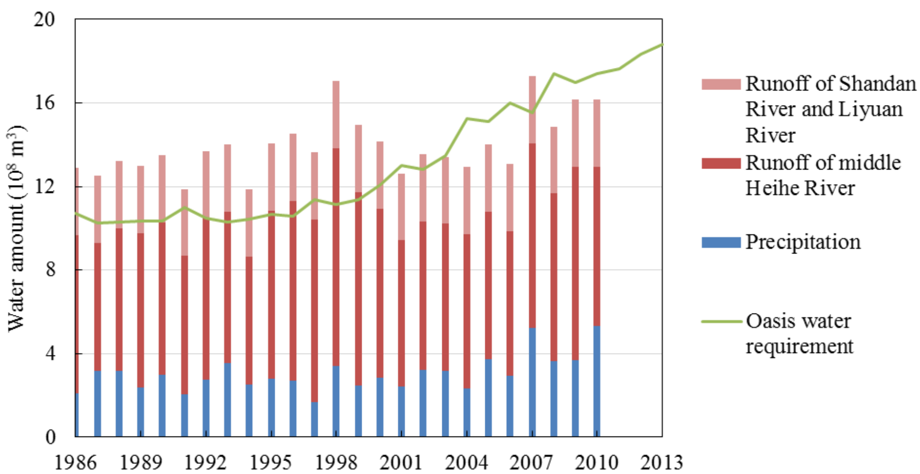


Figure 9. The comparison between the water requirements and ET of the oasis, including the yearly data from 2009 to 2011 and the monthly data in May, June and July.



618 **Figure 10.** The precipitation, runoff, and oasis water requirement in the middle Heihe River Basin.

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 21 August 2017

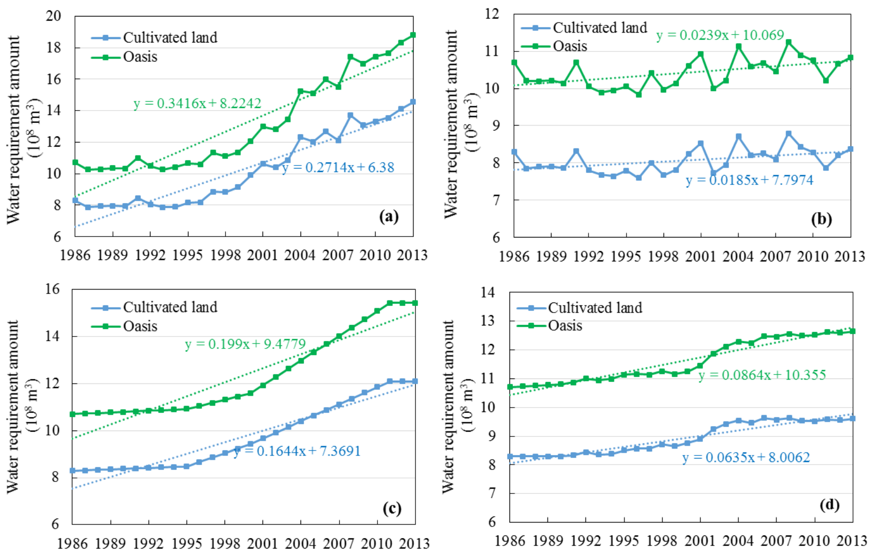


Figure 11. The long-term trend of the water requirement for the cultivated land and oasis during 1986-2013 when the climate, total area of the oasis (cultivated land), and area proportions of the land structure were changing(a); the climate was changing, but the total area of the oasis (cultivated land) and area proportions of the land structure were stable (b); the total area of the oasis (cultivated land) was changing, but the climate and area proportions of the land structure were stable (c); area proportions of the land structure was changing, but the climate and the total area of the oasis (cultivated land) were stable (d).

Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-75
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 21 August 2017

Earth System Dynamics
Open Access
Discussions
EGU

Table 1. Crop coefficients of the different crops in different growth stages in the oasis of the middle Heihe River Basin.

Crop	Development stage			
	Initial	Developing	Middle	Late
Maize	0.23	0.23-1.20	1.20	1.20-0.35
Spring wheat	0.23	0.23-1.16	1.16	1.16-0.40
Cotton	0.27	0.27-1.20	1.20	1.20-0.70
Oilseed	0.29	0.29-1.10	1.10	1.10-0.25
Sugar beet	0.34	0.34-1.21	1.21	1.21-0.70
Potato	0.27	0.27-1.15	1.15	1.15-0.75
Vegetable	0.60	0.60-1.10	1.10	1.10-0.90
Orchard	0.33	0.33-0.95	0.95	0.95-0.71
Swampland	1.00	1.00-1.20	1.20	1.20-1.00
High coverage grassland	0.20	0.20-1.04	1.04	1.04-0.44
Moderate coverage grassland	0.35	0.35-0.47	0.47	0.47-0.32

Table 2. Vegetation coefficient in different depths of groundwater level.

Groundwater depth	1	1.5	2	2.5	3	3.5	4
Vegetation coefficient	1.98	1.63	1.56	1.45	1.38	1.29	1.00

Table 3. Water balance items in the middle Heihe River Basin during 1986-2013.

Average value (Unit: 10^8 m^3)		1986-1990	1991-2000	2001-2013
Water requirement	Agricultural vegetation	8.23	8.89	12.64
	Ecological vegetation	2.16	2.04	3.33
Runoff	Mainstream of the middle Heihe River	7.05	8.08	7.62
	Shandan and Liyuan Rivers	3.22	3.22	3.22
Precipitation	Landing on the agricultural vegetation	2.22	2.21	2.92
	Landing on the ecological vegetation	0.54	0.47	0.69