Final response

The authors gratefully thank to the editor and the anonymous reviewers for the valuable comments on our manuscript which drive us to improve the manuscript greatly. We made a major revision of our manuscript, the title of the manuscript was changed to make it more fit to the content of our study as "Quantify the impacts of climate change and human agricultural activities on oasis water requirements in an arid region: A case study of the Heihe River Basin, China". And the introduction part, study area part, spatial variations of the oasis, and discussion part were rewrote to make our manuscript more clear and scientific. The figures in the manuscript have been rearranged. The comments and questions were addressed point by point as below. The text quoted from the revised manuscript is shown in red.

Response to Referee #1

We thank the anonymous reviewer for the constructive comments on the manuscript and the effort made to review the manuscript very much. Here are the point-by-point responses for the weak points.

1. I cannot see the points of comparing the simulation water requirement with the actual ET simulated by other models. Firstly, other models don't have the detailed data the authors have collected. Secondly, in an arid region, the actual ET is limited by the water available thus it can be largely different from the potential ET. Moreover, the reference data is too short to provide solid results, for example, in Figure 9, there are only three years and a few months samples.

   Response: Thank you for the comments. In this study, water requirement is defined as a theoretical value, and there are no available data to validate it directly. In most researches about water requirement, the validation part were omitted. But we wanted to validate it through an indirect way, so we used the actual ET data. Firstly, the spatial resolution of the actual ET data estimated by ETWatch showed in the original Figure 8 was also 30 m as the same with the resolution we used to calculate the water requirements. The resolution was stated in part 2.2.3, and could also be found in the part of "Validation of the oasis water requirements validation". Secondly, the study area was dominated by the irrigated farmland which used too much water from the Heihe River and caused serious ecological problems downstream. Though the irrigation could not make the soil water conditions optimum all the time, the actual ET can also serve as a reference to some extent. Moreover, we used two kinds of reference data to validate the results. The data showed in the original Figure 9 was only one kind of the data, which could be taken as the supplementary data for the other kind data showed in the original Figure 8. We wanted to use as much available ET data as possible. In the revised manuscript, we rearranged the figures, the original Figure 8 and Figure 9 were combined into one new figure named Figure 7.

2. A few questions on the water balance analysis. (1) In Table 3, what do you mean the "runoff for mainstream of the middle Heihe River"? Is it the river discharge flowing into the middle river basin (measured at Yingluo Gorge)? However, the value is not the same as you gave in the study area description. (2) In L106, you mentioned that there is more groundwater withdrawal in the basin recently. How much is the groundwater withdrawal compared to the surface water and to the water requirement? It will affect your water balance analysis in section 3.4 and Figure 10. (3) Is it possible to remove the water balance analysis since it is very close to the main topic.

Response: We appreciate the valuable comments very much.

(1) The oasis is irrigated by the mainstream of middle Heihe River and some small tributaries like Liyuan River and Shandan River which have been separated from the mainstream. "The runoff for the mainstream of the middle Heihe River" means the runoff consumed in the middle Heihe River Basin from the mainstream of the middle Heihe River. The middle Heihe River flows from Yingluo Gorge to Zhengyi Gorge, so the runoff discharge flowing into the middle river basin is the difference of the river discharge between Yingluo Gorge and Zhengyi Gorge. We have changed the "runoff" to "runoff consumed in the middle Heihe River Basin" in Table 3 and clarified this point in the part of "Water balance in the middle Heihe River Basin".

(2) We have enriched the description of groundwater withdrawal in section 2.1 as below:

"According to the groundwater withdrawal data (1990-2007) of the irrigation districts in the middle Heihe River Basin (Wu et al., 2014; Zheng, 2014), which were downloaded from the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn), only 1.13×10^8 m^3 of groundwater was pumped on average in 1990s, but the amount increased to 3.25×10^8 m^3 on average during 2000-2007."

Unfortunately, we only got the groundwater withdrawal data from 1990 to 2007, so we didn't put the groundwater withdrawal data into the original Figure 10. But we put the data into Table 3 because we only got an average value of the groundwater withdrawal in 1980s besides the groundwater withdrawal during 1990-2007. And we also revised some of the water balance analysis as below:

"Compared with the available water resources in 1980s, precipitation had remained little changed in 1990s. But with the increase of water requirement in 1990s, the runoff consumed in the middle Heihe River Basin had an obvious rise and more groundwater was pumped for irrigation (Fig. 9; Table 3). Ignoring the industrial and domestic water taken from the middle Heihe River, the surface water supply seemed to be sufficient to the water requirement in the oasis in 1980s and 1990s. While entering the 20th century, the area of arable land increased fast, and high water-requiring crops (maize and vegetable) had gradually replaced the low water-requiring crop (wheat) since 2001 (Fig. 3). Therefore, the water requirement increased a lot in 2000s. With the implementation of EWCP, the available surface water from middle Heihe River decreased in 2000s. Surface water cannot meet the water requirement any more, causing more exploiting of groundwater (Table 3). The middle Heihe River Basin is in severe water shortage of water resources. To reduce the contradiction of water supply and requirement, the land use including the crop structure in the middle Heihe River Basin should be carefully planned."

(3) Water balance analysis can help researchers make clear the status of water supply and demand. We think it's meaningful to analyze the water balance.

3. The study area is very small with a catchment area of 8600 km2. It facilitates the water requirement calculation but it cannot reveal the general situation for large

scales (i.e. basins, continents or globe), while it is the aim of journal ESD.

Response: Though the middle Heihe River Basin is not very large, but it’s a very typical basin in arid regions, where river water originated from the high mountain area through snow/glacier melting and rainfall-runoff processes, consumed mainly by agriculture and human society in oases in middle reaches, and finally discharged and dispersed in the tail lake at the lower reach. All the rivers in arid region take the same hydrologic setting. Due to human over exploitation of water resources in the middle reach, i.e. oases, large amount of arid river basins are suffering severe ecological degradation in the world, such as Aral Sea basin, Lake Chad basin, Tarim basin, etc. Because of the typicality and not too large to collect data, Heihe river basin was chosen as the target basin for a key national research programme on ecohydrology and integrated basin water management by the Natural Scientific Foundation of China in 2012. And the programme is still going on, this paper is totally supported by a key project of this national research programme. Even though Heihe river basin is not a large basin, but insight of the nexus relationship between agriculture, hydrology, and ecology is considered to be significant and able to reveal the general characteristics of the arid basins. As for the facts of Heihe River basin, it is the second largest inland river in China. More than 90 % of the population and arable land in the Heihe River Basin were concentrated in the midstream, where the most water in the whole basin was consumed. Additionally, the middle river basin is the grain base for the Northwestern China. To restore the ecological environment and mediate the competition for water between agriculture development and environmental health, the Chinese government have invested 1.49 billion Yuan in the middle Heihe River Basin. The importance and typicality of the study region make the study valuable to the research for the arid regions in the world. We have rewrote the introduction part to make clear of the significance of our study.

Response to Referee #2

The authors gratefully thank to the valuable comments on our manuscript which drives us to improve the manuscript greatly. According to the comments, we have rewrote the parts of Introduction, Study area, and Discussion. The comments and questions were addressed point by point as below:

1. Part 1, Introduction: In this part, the author failed to review the existing literature thoroughly, and thus cannot naturally leads to a judgment whether the work is novel and significant when compared with previous published reports.

   Response: We appreciate this comment very much. We have reviewed much more literature and rewrote the introduction part. We hope the revised introduction have shown the novel and significant of our work naturally. The introduction part was rewrote as below:

   "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 and snow/glacier melting in the upstream mountainous areas, and are consumed mainly by agriculture and human society in oases of the piedmont plains in the midstream, then finally are discharged and dispersed in the tail lakes in the downstream (Kang et al., 1999; Shen and Chen, 2010). The precipitation in plain areas or in major economic centers of arid basins has nearly no significant meaning for generating runoff (Shen and Chen, 2010).

   Owing to scarce water resources in arid regions, ecosystems and societies are vulnerable to hydrologic changes. With the rapid growth of population in arid regions of the world (Shen and Chen, 2010), the utilization of surface- and groundwater for irrigation increased without enough consideration for ecological conservation, which caused severe deterioration of water and ecosystems in most arid river basins. For example, the Amu Darya and the Syr Darya are two main rivers in the Central Asia, which flow towards the Aral Sea. More than 90% of the water withdrawal in the region was used for agricultural irrigation (Sorg et al., 2014). With the increase in irrigated area in the past decades, irrigation withdrawals have measurably reduced inflow to the Aral Sea since 1960s, which caused significant shrinking of the water surface of the Aral Sea and land desertification, and even the fishery in the Aral Sea has almost been destroyed because of salinization (Micklin, 1988; Sorg et al., 2014; Shen and Chen, 2010; Karimov and Matthies, 2013). Similarly, the disappearance of Lop Nor in western China, the dying of the Dead Sea in the Middle East, and the shrinking of Lake Chad in Africa are all notable examples. Ecological deterioration in arid regions caused by agricultural development has become a global issue and has become the main obstacle to the sustainable development of oasis ecosystems.

Despite human exploitation, climate change can also influence the water resources in arid regions. It is reported that the climate in arid regions has become drier in the past century (Narisma et al., 2007; Dai et al., 2004), showing increasing temperature, variability of precipitation, and reduction of glaciers and snow areas (Wang and Qin, 2017) and would be more arid in the future (Bates et al., 2008). But huge amount of studies suggested that the water and ecological degradation in arid regions was largely affected much more by irrational human exploitation than climate change (Jarsjö et al., 2008; Aus der Beek et al., 2011; Huo et al., 2008; Dong et al., 2014; Ma et al., 2014).

The ecological degradation and water shortages have heightened the importance of water allocated to the agriculture in the oasis ecosystems. Water requirement is an important parameter for irrigation scheduling and regional water allocation. Studies on water requirements are theoretically and practically indispensable for the sustainable development of oasis ecosystems in arid regions. Scientists have obtained some research results about water requirements of oasis ecosystems, including the crop water requirements (Kawy and El-Magd, 2012; Liu et al., 2010; Siebert et al., 2007; Zhao et al., 2005; Zhao et al., 2010; De Silva et al., 2007; Kawy and Darwish, 2013), and ecological water requirements (Guo et al., 2016; Ye et al., 2010; Zhao et al., 2007; Guo et al., 2016). Studies have shown that the water requirement would increase if the climate becomes drier and warmer (Döll, 2002; Nkomozepi and Chung, 2012; Fu et al., 2014), and human activities have gradually became the predominant factor increasing the water requirement amount in the past decades (Bai et al., 2014; Coe and Foley, 2001; Zou et al., 2017). But there are few studies separately quantify the contributions of climate change and human agricultural activities to changes in water requirement amount.

Approximately one quarter of land area in China located in arid regions. As the second largest inland river in China, Heihe River Basin also suffered water conflict between agricultural development and ecological health and was chosen as the target basin for a key national research programme on ecohydrology and integrated basin water management by the Natural Scientific Foundation of China in 2012, and the programme is still going on. So the oasis in the middle Heihe River Basin where more than 90% of the arable land were concentrated was taken as the study area. The main objectives of this study are to make clear the changes in water requirements in the oasis under climate change and human agricultural activities and identify the main factor that influences the changes in water requirement amount based on the clarification on the contributions of climate and human activities, including land structure and area, to the changes in water requirement amount. The research questions addressed were: (1) How have the water requirements of the oasis changed in the past ~30 years? (2) Why the water requirement amount of the oasis have changed? We anticipate that this study would be valuable as a reference to the water resources research for the global arid regions.”

2. Line 197-203, Upon the Kc values, how did you dealing with the differences in Kc

among different crop species? In my opinion, this value could be very different even in different varieties of the same crop types, especially when considering the species evolution in history.

Response: The differences in Kc among different crop species were determined by the references Duan et al. (2004) and FAO (Allen et al., 1998). There are different Kc values for different crop species in different growth stages. These were stated in part 2.3.1 and the Kc values for different crop species were shown in Table 1. But we didn't distinguish the crop coefficients among different varieties of the same crop type.

We do agree with you that the Kc values could be very different even in different varieties of the same crop type, especially when considering the species evolution in history. But it's difficult to get the crop coefficients for every specific crop variety because there are too many varieties. Besides, the water requirement is not only related to the crop coefficient, but also related to the crop growth period. Many factors influencing the crop coefficient are also have an effect on the growth stages. Limited by the available data, the Kc values in the same growth stage for different varieties of the same crop type were the same. So we discussed this topic in the discussion part.

3. Line 162-170, the validating data you used for comparison is also a GIS-base one, which were produced by using almost the same method and the same procedure. I guess a ground-based observation dataset may be more reasonable for the validating purpose in this paper.

   Response: Thank you for your suggestion very much. When we worked on the validation part, we also thought to validate the results by using the ground-based observation dataset. But we found that the available ground-based ET datasets by eddy covariance system were not enough to validate the results, which only included the data from around June, 2012 to December, 2013 during the study period. And many daily data were incomplete. So we didn't use the ground-based observation dataset to validate the results.

4. Line 210-212, how do you treat the groundwater-dependent forest in the ecotone of

desert-oasis system and the irrigation-based forest grids in agricultural land system?

Response: The irrigation-based forest in agricultural land system is always shelter forest for farmland which usually belongs to the closed forest land in the land use dataset. The natural vegetation in the ecotone of desert-oasis system is always sparse wood or shrubs due to the lack of precipitation. Water requirement is a theoretical value which is calculated assuming that the water is always suitable. So we didn't distinguish the forest land in the ecotone of desert-oasis system from that in the agricultural land system, and just treated the forest land as closed forest land, sparse wood land and shrubs as the land use dataset showed.

5. Line 353, more details about ETMonitor model are needed here.

Response: ETMonitor model is a hybrid remotely sensed ETa estimation model developed by Hu G., and Jia, L. (2015). Please refer to the reference:

Hu G., and Jia, L.: Monitoring of evapotranspiration in a semi-arid inland river basin by combining microwave and optical remote sensing observations, Remote Sensing, 7(3), 3056-3087, 2015.

In part 2.2.3, there were introductions of the validation data which included the data estimated by ETMonitor model. We have added more information about this model in this part as below:

"The other was the daily ET datasets (2009-2011) of the Heihe River Basin at 1 km spatial resolution (Cui and Jia, 2014; Jia et al., 2013) estimated by ETMonitor, which is a hybrid remotely sensed actual ET estimation model developed by Hu and Jia (2015)."

6. Line 440-444, I believe there are more than one field station in this region and meteorological observation and flux measurements were performed regularly over there.

Response: Yes, there are some field stations in this region and meteorological observation and flux measurements that were performed regularly. But the measured ET are actual ET. We don't know whether the irrigation can make the soil water keep optimum for the crops all the time during the whole growth period. And the measurements began from around June, 2012. The available data were limited. We have enriched and made this point clear in the discussion part as below:

"Crop water requirement is the ET from disease-free, well-fertilized crops under optimum soil water conditions and achieving full production. There is no available observed crop water requirement to validate the results. Only actual ET data can be obtained. There are 18 field stations in the oasis that all located in Ganzhou district in the middle Heihe River Basin for conducting meteorological observation and flux measurements from around June, 2012. But due to the incomplete daily data and short time series, we used the ET datasets provided by Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn) to validate the results."

7. Line 450-454, You mentioned the uncertainty brought into the calculation by crop coefficient, but how much this uncertainty it could be? Is that small enough to let you get sound conclusion?

Response: Thank you for the valuable comment. We enriched the discussion part about the uncertainty of crop coefficients to make the uncertainty be clear as below: "Crop coefficient is an important parameter to estimate the water requirement, and it is related to many factors, such as the biological characters of crops, cultivation and soil conditions, etc., so the crop coefficients for different crop varieties of the same crop could be different. Some researchers (Nader et al., 2013; Mu, 2005) studied on the crop coefficients affected by different crop varieties, and found that there were differences in every growth stage between different varieties, and the differences were almost less than 0.3. But it's difficult to get the crop coefficients for every specific crop variety because there are too many varieties. Besides, the water requirement is not only related to the crop coefficient, but also related to the crop growth period. Many factors influencing the crop coefficient also have an effect on the growth stages. Like the study by Nader et al. (2013), the water requirement variation was much smaller than the variation of crop coefficients for different varieties. Therefore, though we didn't distinguish the crop coefficients among different varieties, the estimated water requirements in the study were still reliable."

Quantify the impacts of climate change and human agricultural activities on oasis water requirements in an arid region: A case study of the Heihe River Basin, China~~Water requirements of the oasis in the middle Heihe River Basin, China: Trends and causes~~

Xingran Liu[1,2], Yanjun Shen[1]

[1]Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang 050021, China;
[2]University of Chinese Academy of Sciences, Beijing 100049, China

Correspondence to: Yanjun Shen (yjshen@sjziam.ac.cn)

Abstract. Ecological deterioration in arid regions caused by agricultural development has become a global issue. Understanding water requirements of the oasis ecosystems and the influences of human agricultural activities and climate change is important for the sustainable development of oasis ecosystems and water resources management in arid regions. In this study, water requirements of the main oasis in Heihe River Basin during 1986-2013 were analyzed and the amount showed a sharp increase from 10.8×10^8 m^3 in 1986 to 19.0×10^8 m^3 in 2013. Both human agricultural activities and climate change could lead to the increase of water requirement amount. To quantify the contributions of agricultural activities and climate change to the increase in water requirements, partial derivative and slope method were used. Results showed that climate change and human agricultural activities, such as oasis expansion and changes in land cropping structure, has contributed to the increase of water requirement at rates of 6.9%, 58.3%, and 25.4%, respectively. Overall, human agricultural activities were the dominant driving forces for the increase of water requirement amount. And the contribution of oasis expanding to the increased water requirement amount was significantly greater than that of other concerned variables. This reveals that to control the oasis scale is extremely important and effective to balancing water for agriculture and ecosystems and to achieving a sustainable oasis development in arid regions.

~~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 10.8×10^8 m^3 in 1986 to 19.0×10^8 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 570.0 mm, 413.7 mm, and 728.8 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 25.4 % and 23.5 % of the water requirement variation in the oasis and cultivated land, respectively. The contribution of the climate change was relatively less, which contributed only 6.9 % and 6.7 % 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 and snow/glacier melting in the upstream mountainous areas, and are consumed mainly by agriculture and human society in ~~the oasis~~ oases ~~zone~~ of the piedmont plains in the midstream, then finally are discharged and dispersed in the tail lakes~~vanishes~~ ~~in the desert-oasis zone~~ in the downstream (Kang et al., 1999; Shen and Chen, 2010). The precipitation in plain areas or in major economic centers of arid basins has nearly no significant meaning for generating runoff (Shen and Chen, 2010).

Owing to scarce water resources in arid regions, ecosystems and societies are vulnerable to hydrologic changes. With the rapid growth of population in arid regions of the world (Shen and Chen, 2010), the utilization of surface- and groundwater for irrigation increased without enough consideration for ecological conservation, which caused severe deterioration of water and ecosystems in most arid river basins. For example, the Amu Darya and the Syr Darya are two main rivers in the Central Asia, which flow towards the Aral Sea. More than 90% of the water withdrawal in the region was used for agricultural irrigation (Sorg et al., 2014). With the increase in irrigated area in the past decades, irrigation withdrawals have measurably reduced inflow to the Aral Sea since 1960s, which caused significant shrinking of the water surface of the Aral Sea and land desertification, and even the fishery in the Aral Sea has almost been destroyed because of salinization (Micklin, 1988; Sorg et al., 2014; Shen and Chen, 2010; Karimov and Matthies, 2013). Similarly, the disappearance of Lop Nor in western China, the dying of the Dead Sea in the Middle East, and the shrinking of Lake Chad in Africa are all notable examples. Ecological deterioration in arid regions caused by agricultural development has become a global issue and has become the main obstacle to the sustainable development of oasis ecosystems.

Despite human exploitation, climate change can also influence the water resources in arid regions. It is reported that the climate in arid regions has become drier in the past century (Narisma et al., 2007; Dai et al., 2004), showing increasing temperature, variability of precipitation, and reduction of glaciers and snow areas (Wang and Qin, 2017) and would be more arid in the future (Bates et al., 2008). But huge amount of studies suggested that the water and ecological degradation in arid regions was largely affected much more by irrational human exploitation than climate change (Jarsjö et al., 2008; Aus der Beek et al., 2011; Huo et al., 2008; Dong et al., 2014; Ma et al., 2014).

The ecological degradation and water shortages have heightened the importance of water allocated to the agriculture in the oasis ecosystems. Water requirement is an important parameter for irrigation scheduling and regional water allocation. Studies on water requirements are theoretically and practically indispensable for the sustainable development of oasis ecosystems in arid regions. Scientists have obtained some research results about water requirements of oasis ecosystems, including the crop water requirements (Kawy and El-Magd, 2012; Liu et al., 2010; Siebert et al., 2007; Zhao et al., 2005; Zhao et al., 2010; De Silva et al., 2007; Kawy and Darwish, 2013), and ecological water requirements (Guo et al., 2016; Ye et al., 2010; Zhao et al., 2007; Guo et al., 2016). Studies have shown that the water requirement would increase if the climate becomes drier and warmer (Döll, 2002; Nkomozepi and Chung, 2012; Fu et al., 2014), and human activities have gradually became the predominant factor increasing the water requirement amount in the past decades (Bai et al., 2014; Coe and Foley, 2001; Zou et al., 2017). But there are few studies separately quantify the contributions of climate change and human agricultural activities to changes in water requirement amount.

Approximately one quarter of land area in China located in arid regions. As the second largest inland river in China, Heihe River Basin also suffered water conflict between agricultural development and ecological health and was chosen as the target basin for a key national research programme on ecohydrology and integrated basin water management by the Natural Scientific Foundation of China in 2012, and the programme is still going on. So the oasis in the middle Heihe River Basin where more than 90% of the arable land were concentrated was taken as the study area. The main objectives of this study are to make clear the changes in water requirements in the oasis under climate change and human agricultural activities and identify the main factor that influences the changes in water requirement amount based on the clarification on the contributions of climate and human activities, including land structure and area, to the changes in water requirement amount. The research questions addressed were: (1) How have the water requirements of the oasis changed in the past ~30 years? (2) Why the water requirement amount of the oasis have changed? We anticipate that this study would be valuable as a reference to the water resources research for the global arid regions.

~~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), while some concentrated on the ecological water requirement (Guo et al., 2016; Ye et al., 2010; Zhao et al., 2007). 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 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

Heihe River originates in the Qilian Mountains, and flows to the oases in the piedmont plain after reaching the mountain outlet at the Yingluo Gorge, then finally terminates at the East and West Juyan Lakes. It 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). 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), China (Fig. 1). It embraces a total area of 8.6×10^{9} m^{2}, included in Ganzhou district, Linze county and Gaotai county. More than 90 % of the population and arable land in the Heihe River Basin were concentrated in this oasis (Zhang et al., 2006).

Situated in the inner of Asia-Europe continent, the study area possesses a temperate continental arid climate with sufficient sunlight, great temperature variations and scarce precipitation. According to the observed data by Gaotai and Zhangye meteorological stations in the study region during 1953-2014, the annual average temperature is about 6.0-9.4 °C, with the lowest temperatures occurring in January and December, and highest temperatures occurring in July. The annual sunshine in the region is about 2800-3400 h. The mean annual precipitation is less than 130 mm (e.g. the mean annual precipitation is 107.86 mm and 129.10 mm at Gaotai and Zhangye meteorological stations, respectively). Over 60 % of the precipitation falls between June and August (Zhao et al., 2005). But the annual potential evaporation reaches 1400 mm (Li et al., 2016).

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. Combined with the cultivated land, forest, grass, swampland, and waters make up the oasis together. 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} during the past decades, in which the cultivated land increased about 740 km^{2} (Fig. 2). And the cropping pattern has also changed a lot in the recent ~30 years (Fig. 3). 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).

Lacking in precipitation, surface runoff has become the main surface water resources for irrigation. The middle Heihe River flows from Yingluo Gorge to Zhengyi Gorge, supplying water for oasis in the middle river basin. 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). The development of modern irrigation schemes, and the growth of population and irrigation area in the middle basin took 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;). 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 (Wang and Cheng, 1999; Chen et al., 2005). 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 around the year 2000, 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). Due to the EWCP, the discharge observed at Zhengyi Gorge has increased since 2000, which led to less available surface water for the middle Heihe River Basin, and more groundwater was taken for irrigation (Ji et al., 2006). According to the groundwater withdrawal data (1990-2007) of the irrigation districts in the middle Heihe River Basin (Wu et al., 2014; Zheng, 2014), which were downloaded from the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn), only 1.13×10^{8} m^{3} of groundwater was pumped on average in 1990s, but the amount increased to 3.25×10^{8} m^{3} on average during 2000-2007. ~~. 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. 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. 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., 2006).~~

~~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).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), which were developed by CAS, 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~~ for land cover was ~~used in~~applied to the four years' land use data. The land-use patterns in the basin have been divided into 6 types: cultivated land; forest land which includes 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~~ in the ~~percentage~~ form of percentage.~~, 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 (Fig. 3), 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 Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn). One ~~is~~ was the monthly ET datasets (2000-2013) at 30 m spatial resolution (Wu et al., 2012; Liu et al., 2011) estimated by ETWatch ~~model~~developed by Wu et al. (2008) and Xiong et al. (2010) for monitoring spatial ET for operational purposes~~at 30 m spatial resolution (Wu et al., 2012; Liu et al., 2011)~~, while this datasets only covered part of the oasis which included Ganzhou district, Linze county and small part of the Gaotai county in the middle Heihe River Basin. The other ~~is~~ was the daily ET datasets (2009-2011) of the Heihe River Basin at 1 km spatial resolution (Cui and Jia, 2014; Jia et al., 2013) estimated by ETMonitor, ~~model~~which is a hybrid remotely sensed actual ET estimation model developed by Hu and Jia (2015).~~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 comparison.

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 were considered. The water requirements ~~for~~ of 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 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 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~~different crop species in the cultivated land during the four growth stages 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 requirements for the 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 the swampland was calculated by crop coefficient approach. The K_c values of the vegetation in the swampland ~~is~~ were 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

$$\mathrm{y} = f(x_1, x_2, x_3, \dots) \tag{6}$$

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

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

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

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

$\frac{dy}{dt}$ 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. Other factors related to the water requirements were fitted into δ, combining the systemic error.

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

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

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~~ In the study, 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 and spatial variations in water requirements of the oasis in the middle Heihe River Basin

The water requirement amount of the total oasis increased from 10.8×10^8 m^3 in 1986 to 19.0×10^8 m^3 in 2013 (Fig. ~~3~~4a). According to the land use data, the area of the cultivated land accounted for ~80 % of the total area of the oasis (Fig. ~~4~~2). Therefore, the water requirement amount of the cultivated land increased from 8.4×10^8 m^3 in 1986 to 14.7×10^8 m^3 in 2013 (Fig. ~~3~~4a), 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 10.4×10^8 and 13.3×10^8 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. 4a; Fig. 2~~4~~).

The water requirement of the cultivated land per unit area increased from 519.2 mm to 624.9 mm during 1986-2013, while the water requirement of the oasis per unit area increased from 527.1 mm to 642.0 mm during 1986-2013 (Fig. ~~5~~4b). The mean annual water requirements of the cultivated land and the oasis per unit area were 544.6 mm and 557.4 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 570.0 mm, 413.7 mm, and 728.8 mm, respectively. Waters required the most water per unit area, the mean annual water requirement of which reached 1323.9 mm. The swampland covered with reeds also needed a lot of water per unit area, the mean annual water requirement of which could reach 968.6 mm. Different land surface coverages ~~of~~ for ~~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 477.5 mm, 128.9 mm, 264.0 mm, 705.1 mm, 663.6 mm, and 340.0 mm, respectively.

The oasis in the middle Heihe River Basin was scattered along the rivers. Most of the water requirement in the oasis was below 500 mm per square kilometer in 1986 considering the mixed pixel and area weight, but with the climate change and human agricultural activities, the water requirement in large area of the oasis exceed 500 mm per square kilometer in 2011 (Fig. 5). And the area of high water requirement in the oasis accorded with the location of the cultivated land (Fig. 5). Besides, the ecological vegetation in the oasis didn't show significant increase in the water requirement (Fig. 5).

The cultivated land in most area of the oasis expanded during the past ~30 years, especially in Linze county and the north of Ganzhou district (Fig. 6a). This was in accordance with the area of the water requirement increased in the cultivated land and the oasis (Fig. 6). The water requirement in the cultivated land increased above 100 mm per square kilometer in the Linze county and the north of Ganzhou district. The larger area the cultivated land expanded, the more water required for the cultivated land (Fig. 6b). Only a small part of the cultivated land shrinked in the oasis and caused the decrease of water requirement in the corresponding cultivated land (Fig. 6). As the dominant part affecting the water requirement in the oasis, the spatial distribution of the increased water requirement in the cultivated land was similar with that in the oasis (Fig. 6b, c).

~~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 4.7×10^8 m^3 in 1986 to 7.8×10^8 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 557.7 mm,~~

~~539.0 mm, and 551.3 mm, respectively. For the whole oasis in the middle Heihe River Basin, Ganzhou still occupied the most water requirement which increased from 5.5×10^8 m^3 in 1986 to 9.4×10^8 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 549.9 mm, 536.6 mm, and 612.5 mm, respectively.~~

~~3.~~3. ~~3~~2 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 observed or calculated by others for the potential crop ET, so ~~we used~~ the actual ET data were adopted to validate ~~it~~ the water requirement in the oasis to see if the results were~~as~~ acceptable.

According to the yearly and monthly ET estimated by ETWatch and ETMonitor, the total ET was well correlated with the estimated water requirement amount with the determination coefficient (R^2) of 0.91 (Fig. 7), and slope of the linear regression of 1.05 (Fig. 7). ~~According to~~Compared with the ~~monthly~~ yearly 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 both 0.68. And~~ the root mean square error (RMSE) between the ET and water requirement amount for the cultivated land and the oasis were 0.71×10^8 m^3 and 0.66×10^8 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.~~,~~ W~~w~~hile 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 requirement amounts~~, and the slope of the linear regression was smaller than 1~~ (Fig. ~~8a~~7). ~~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~~7). And the RMSE for the cultivated land and the oasis were 0.35×10^8 m^3 and 0.36×10^8 m^3, respectively, which were much smaller than the yearly RMSE. Most of the monthly water requirement amounts were~~as~~ higher than the monthly ET data~~, and the slope of the linear regression was about 1.1 when set the intercept at 0~~ (Fig. ~~8b~~7)~~.~~.

Compared with the ET datasets (2009-2011) estimated by ETMonitor ~~model~~ at 1 km spatial resolution in the middle Heihe River Basin, t~~T~~he yearly and monthly water requirement amounts were all larger than the corresponding ET data~~.~~ (Fig. 7), and the RMSE for the monthly data in May, June, and July was 1.27×10^8 m^3. ~~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 estimated by ETMonitor 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 1.27×10^8 m^3. But t~~The yearly estimated water requirement amounts ~~ET data estimated by ETWatch~~ in 2009, 2000, and 2011 were smaller~~larger~~ than the ET data estimated by ETWatch ~~estimated water requirements~~ for the oasis, which was contrary to the results compared with the ET data estimated by ETMonitor, which showed that the two ET datasets deviated from each other~~.~~, ~~A~~and the estimated water requirements were acceptable.

~~3.~~3. ~~4~~ 3 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. So the surface runoff of the mainstream of the middle Heihe River consumed in the middle Heihe River Basin can be considered as the difference between Yingluo Gorge and Zhengyi Gorge. 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-~~2013~~2010) obtained from the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn) (Yang et al., 2015), the surface water including the precipitation landing on the oasis and the river discharges~~runoff data~~ ~~including~~of the 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~~8).

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~~Compared with the available water resources in 1980s~~ and~~, precipitation had remained little changed in 1990s.~~, precipitation has remained little changed, but~~ But with the increase of water requirement~~ increased~~ in 1990s~~ slowly~~, ~~and~~ the runoff consumed in the middle Heihe River Basin had an obvious rise and more groundwater was pumped for irrigation (Fig. ~~10~~8; Table 3).~~,~~ Ignoring the industrial and domestic water taken from the middle Heihe River, the ~~so the~~ surface water supply seemed to be sufficient to the water requirement in the oasis in 1980s and 1990s. While entering the 20th century~~In the 2000s~~, the area of arable land increased fast, and high water-requiring crops (maize and vegetable) had gradually replaced the low water-requiring crop (wheat) since 2001 (Fig. 3). Therefore, the water requirement increased a lot in 2000s. With the implementation of EWCP, the available surface water from middle Heihe River decreased in 2000s. Surface water cannot meet the water requirement any more, causing more exploiting of groundwater (Table 3). The middle Heihe River Basin is in severe water shortage of water resources. To reduce the contradiction of water supply and requirement, the land use including the crop structure in the middle Heihe River Basin should be carefully planned. ~~the water requirement increased much more than the water supply (Table 3), so the water resources from land surface was in short supply.~~

3.4~~5~~ Contributions to the water requirement trend

Both climate change and human agricultural activities can influence the water requirement of the oasis. In this study, the land expansion, which influences the total oasis area, and the land structure, which influences the area proportion of each land-use type in the oasis, were considered for the human agricultural activities. ~~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~~ both the contributions of the influencing factors ~~to~~ to the changes in water requirement amount ~~both~~of the oasis and of the cultivated land were analyzed. For the cultivated land, the three influencing factors considered ~~are the~~to be the climate change, ~~total area~~the expansion of the cultivated land, and the ~~area proportions of the crops~~crop structure 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~~land expansion, 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 t~~The water requirement amounts of the oasis and cultivated land increased 0.3447×10^8 m^3 and 0.2743×10^8 m^3 per year during

1986-2013, respectively (Fig. ~~11a~~9a). Considering the ~~effect~~ impact of climate change ~~to~~on the water requirement amount, the ~~total~~ land 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 amount increased slowly at the rates of 0.0238×10^8 m^3 and 0.0184×10^8 m^3 per year for the oasis and cultivated land, respectively (Fig. ~~11b~~9b), which revealed that climate change had a positive effect on the increase in water requirement. Based on ~~the~~ Eq. (9), the contributions of the climate change to the increase in water requirement amount ~~was~~ were ~~only~~ 6.9 % and 6.7 % for ~~the water requirement change in~~ the oasis and cultivated land, respectively.

Considering the ~~effect~~impact of ~~total area~~land expansion ~~to~~ on the water requirement amount, the climate and ~~the area proportions of~~ the land structure were set stable, and only the total land area ~~varied~~ changed with ~~the~~ time during 1986-2013. In this situation, the water requirement amount increased ~~fast~~ rapidly at the rates of 0.2008×10^8 m^3 and 0.1661×10^8 m^3 per year for the oasis and cultivated land, respectively (Fig. ~~11c~~9c), which were nearly 9 times faster than the increasing speed caused by climate change. ~~Then t~~The contributions of land expansion ~~the total area was~~were 58.3 % and 60.6 % to~~for~~ the increase in water requirement ~~change~~amount ~~in~~ for the oasis and cultivated land, respectively.

Considering the ~~effect~~ impact of ~~the area proportions of the~~ land structure ~~to~~ on the water requirement amount, the climate and ~~total~~ total land 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 amount increased at the rates of 0.0874×10^8 m^3 and 0.0645×10^8 m^3 per year for the oasis and cultivated land, respectively (Fig. ~~11d~~9d), which were approximately 4 times faster than the increase speed caused by climate change. ~~So t~~The contributions of ~~the area proportions of~~ the land structure were~~was~~ 25.4 % and 23.5 % ~~for~~ to the water requirement changes ~~in~~ for the oasis and cultivated land, respectively.

The three influencing factors explained approximately 91 % of the ~~reason~~ increase in~~why~~ the water requirement amounts of the oasis and cultivated land ~~changed~~ during 1986-2013. In the recent ~30 years, human agricultural activities including land expansion and changes in land structure contributed about 84% to the increase in water requirement amount, and the climate change only contributed about 7% to the increase. And land expansion was the dominant factor contributing to the increase in water requirement amount of the oasis.

~~the main 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 impact of climate change and human agricultural activities, including land expansion and changes in land structure, on 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. The results suggest that both climate change and human agricultural activities can lead to the increase in water requirement amounts and the contribution of human agricultural activities to the increase was significantly greater than the climate change. And the land expansion was the dominant factor contributing to the increase in water requirement amounts. ~~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.~~

Crop water requirement is the ET from disease-free, well-fertilized crops under optimum soil water conditions and achieving full production. There is no available observed crop water requirement to validate the results. Only actual ET data can be obtained. There are 18 field stations in the oasis that all located in Ganzhou district in the middle Heihe River Basin for conducting meteorological observation and flux measurements from around June, 2012. But due to the incomplete daily data and short time series, we used the ET datasets provided by Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn) to validate the results. Compared with other research results, the mean annual water requirement of the main crop (maize), which was 570.0 mm in this study, basically accorded with the result by Liu et al. (2010). And the mean annual water requirements of cultivated land and wheat, which were 544.6 mm and 413.7 mm, respectively in this study, was consistent with the results by Liu et al. (2017).

Crop coefficient is an important parameter to estimate the water requirement, and it is related to many factors, such as the biological characters of crops, cultivation and soil conditions, etc., so the crop coefficients for different crop varieties of the same crop could be different. Some researchers (Nader et al., 2013; Mu, 2005) studied on the crop coefficients affected by different crop varieties, and found that there were differences in every growth stage between different varieties, and the differences were almost less than 0.3. But it’s difficult to get the crop coefficients for every specific crop variety because there are too many varieties. Besides, the water requirement is not only related to the crop coefficient, but also related to the crop growth period. Many factors influencing the crop coefficient also have an effect on the growth stages. Like the study by Nader et al. (2013), the water requirement variation was much smaller than the variation of crop coefficients for different varieties. Therefore, though we didn’t distinguish the crop coefficients among different varieties, the estimated water requirements in the study were still reliable.

There are many factors influencing the water requirement. This study only analyzed the major factors which influence it (climate change and human agricultural activities). Climate change including factors for air temperatures, wind speed, relative humidity and sunshine duration, and Human agricultural activities, including the land expansion and changes in land structure totally contribute about 91% to the increase in water requirement amount of the oasis. Other influential factors, such as changes in location of different land types, are difficult to quantify and were not considered in the study.

Besides, some driving factors are not independent, and changes in one factor can cause changes in other factors, such as the climate change and changes in crop phenology. So in the contribution analysis, when the climate were set stable, the crop phenology also kept stable, and when the climate changed, the crop phenology varied according to the statistical data. ~~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~~oasis ecosystem concerns the ecological security of~~in~~ the ~~lower Heihe River~~whole ~~Basin~~basin. To promote the harmonious development among the upstream, midstream and downstream, the water amount consumed in the ~~middle Heihe River Basin~~agricultural oasis 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 amount 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~~oasis.

5. Conclusion

Affected by the climate change and human agricultural activities~~, total area of the oasis, and land structure~~, the water requirement amount of the oasis increased significantly during 1986-2013, which increased from 10.8×10^8 m^3 in 1986 to 19.0×10^8 m^3 in 2013. Cultivated land is the main part of the oasis, the water requirement amount of which increased from 8.4×10^8 m^3 in 1986 to 14.7×10^8 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 570.0 mm, 413.7 mm, and 728.8 mm, respectively, which showed the vegetable required much more water than the maize and wheat.~~ Contribution analysis identified the dominant factors influencing the water requirement amount were the human activities, the contribution of which including the land expansion and changes in land structure to the increase in water requirement amount was about 84%, and the climate change only contributed about 7% to the increase. For the human activities, land expansion contributed most to the increase in water requirement amount, which contributed 58.3 % and 60.6 % for the oasis and cultivated land, respectively. To reduce the water requirement amount and ensure the sustainable development of oasis ecosystems in arid regions dominated by agriculture, it is necessary to further rationalize the scale of the oasis and cultivated land, and optimize the crop structure. ~~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 25.4 % and 23.5 % 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 6.9 % and 6.7 % 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.

Acknowledgements.

This study was supported by the National Natural Science Foundation of China (No. 91425302). We would like to extend our thanks to Yulu Zhang from Qinghai Normal University, who helped process the wind speed data in three meteorological stations.

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: Guidelines for computing crop requirements. Irrigation and Drainage Paper No. 56, FAO, Rome, Italy, 1998.

Aus der Beek, T., Voß, F., and Flörke, M.: Modelling the impact of Global Change on the hydrological system of the Aral Sea basin, Physics and Chemistry of the Earth, 36 (13): 684-695, 2011.

Bai, J., Chen, X., Li, L., Luo, G., Yu, Q.: Quantifying the contributions of agricultural oasis expansion, management practices and climate change to net primary production and evapotranspiration in croplands in arid northwest China, Journal of Arid Environments, 100-101, 31-41, 2014.

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P.: Climate Change and Water, IPCC Technical

Paper VI, Intergovernmental Panel on Climate Change, 2008.

Chen, Y., Zhang, D., Sun, Y., Liu, X., Wang, N., and Savenije, H. H. G.: Water demand management: A case study of the Heihe River Basin in China, Physics and Chemistry of the Earth Parts A/B/C, 30, 408-419, 2005.

Coe, M. T., and Foley, J. A.: Human and natural impacts on the water resources of the Lake Chad basin, Journal of Geophysical Research, 106, 3349-3356, 2001.

Cui, Y., and Jia, L.: A modified gash model for estimating rainfall interception loss of forest using remote sensing observations at regional Sscale, Water, 6(4), 993–1012, doi:10.3390/w6040993, 2014.

Dai, A., Lamb, P. J., Trenberth, K. E., Hulme, M., Jones, P. D., and Xie, P.: The recent sahel drought is real. International Journal of Climatology, 24(11), 1323-1331, 2004.

De Silva, C. S., Weatherhead, E. K., Knox, J. W., and Rodriguez-Diaz, J. A.: Predicting the impacts of climate change—A case study of paddy irrigation water requirements in Sri Lanka, Agricultural Water Management, 93, 19-29, 2007.

Döll, P.: Impact of climate change and variability on irrigation requirements: a global perspective, Climatic Change, 54, 269–293, 2002.

Dong, W., Cui, B., Liu, Z., and Zhang, K.: Relative effects of human activities and climate change on the river runoff in an arid basin in northwest china, Hydrological Processes, 28(18), 4854-4864, 2015.

Duan, A., Sun, J., Liu, Y., Xiao, J., Liu, Q., and Qi, X.: Irrigation quota of major crops for Northern China, China Agricultual Sci & Tech Press, Beijing, pp. 197, 2004 (In Chinese).

Ersi, K., Guodong, C., Yongchao, L., and Huijun, J.: A model for simulating the response of runoff from the mountainous watersheds of inland river basins in the arid area of northwest China to climatic changes, Science in China Series D, 42, 52-63, 1999.

Fu, A., Chen, Y., and Li, W.: Impact of global warming on water requirement of main crops in oasis irrigated area in yanqi basin. Advanced Materials Research, 955-959, 3079-3087, 2014.

Guo, F., Zhang, K., Lv, Q.: Dictionary of Gansu, Gansu culture Press, 2000 (In Chinese).

Guo, H., Ling, H., Xu, H., and Guo, B.: Study of suitable oasis scales based on water resource availability in an arid region of China: a case study of Hotan River Basin, Environmental Earth Sciences, 75, 2016.

Hu G., and Jia, L.: Monitoring of evapotranspiration in a semi-arid inland river basin by combining microwave and optical remote sensing observations, Remote Sensing, 7(3), 3056-3087, 2015.

Huo, Z., Feng, S., Kang, S., Li, W., and Chen, S.: Effect of climate changes and water-related human activities on annual stream flows of the shiyang river basin in arid north-west china. Hydrological Processes, 22(16), 3155-3167, 2008.

Jarsjö, J., Asokan, S. M., Shibuo, Y., and Destouni, G.: Water scarcity in the aral sea drainage basin: contributions of agricultural irrigation anda changing climate, NATO Security through Science Series C: Environmental Security, 99-108, 2008.

Ji, X., Kang, E., Zhao, W., Chen, R., Xiao, S., and Jin, B.: Analysis of water resources supply and demand and security of water resources development in irrigation regions of the middle reaches of the Heihe river basin, Northwest China, Agricultural Sciences in China, 5(2), 130-140, 2006.

Jia, L., Hu, G., and Cui, Y.: The evapotranspiration data from 2009 to 2011 in the Heihe River Basin, Heihe Plan Science Data Center, doi:10.3972/heihe.114.2013.db, 2013.

Jia, L., Shang, H., Hu, G., and Menenti, M.: Phenological response of vegetation to upstream river flow in the Heihe Rive basin by time series analysis of MODIS data, Hydrology and Earth System Sciences, 15, 1047-1064, 2011.

Kang, E., Cheng, G., Lan, Y., and Jin, H.: A model for simulating the response of runoff from the mountainous watersheds of inland river basins in the arid area of northwest China to climatic changes, , Science in China Series D, 42, s1, 1999.

Kang, E., Cheng, G., Song, K., Jin, B., Liu, X., and Wang, J.: Simulation of energy and water balance in Soil-Vegetation- Atmosphere Transfer system in the mountain area of Heihe River Basin at Hexi Corridor of northwest China, Science in China Series D, 48, 538, 2005.

Karimov, B., and Matthies, M.: Impact of salinisation of surface waters caused by irrigation and diversion of drainage waters on fisheries in Amudarya and Syrdarya Rivers basins, Central Asia, SEFS 8 Symposium fir European Freshwater Sciences, 2013.

Kawy, W. A. A., and Darwish, K. M.: Assessment of optimum land use and water requirements for agricultural purpose in some soils South Paris Oasis, Western Desert, Egypt, Arabian Journal of Geosciences, 7, 4043-4058, 2013.

Kawy, W. A. A., and El-Magd, I. H. A.: Assessing crop water requirements on the bases of land suitability of the soils South El Farafra Oasis, Western Desert, Egypt, Arabian Journal of Geosciences, 6, 2313-2328, 2012.

Li, J., Yang, X., Cao, S., Ma, Z., Xiao, J., Chen, F., Li, Y., Qiu, J., Feng, H., and Ren, T.: Water requirement and crop coefficient of different planting patterns in Zhangye area of Gansu Province, Acta Agriculturae Jiangxi, 21(4), 17-20, 2009. (In Chinese)

Li, J., Zhu, T., Mao, X., Adeloye, A. J.: Modeling crop water consumption and water productivity in the middle reaches of Heihe River Basin, Computers and Electronics in Agriculture, 123, 242–255, 2016.

Li, X., Cheng, G., Tian, W., Zhang, Y., Zhou, J., Pan, X., Ge, Y., and Hu, X.: Hydrological cycle in the Heihe River Basin and its implication for water resource management in inland river basins (Invited), AGU Fall Meeting Abstracts, 2013.

Liu, B., Zhao, W., Chang, X., Li, S., Zhang, Z., and Du, M.: Water requirements and stability of oasis ecosystem in arid region, China, Environmental Earth Sciences, 59, 1235-1244, 2010.

Liu, J.: Study on the vegetation ecological water requirement in the Heihe River Basin based on 3S technology, North West Agriculture and Forestry University, 2014(In Chinese).

Liu, S., Xiong, J. and Wu, B.: ETWatch: a method of multi-resolution ET data fusion, Journal of Remote Sensing, 15(2), 255–269, 2011.

Liu, Y., Song, W., and Deng, X.: Spatiotemporal patterns of crop irrigation water requirements in the heihe river basin, china, Water, 9 (8), 616, 2017.

Ma, L., Wu, J., Liu, W., and Abuduwaili, J.: Distinguishing between anthropogenic and climatic impacts on lake size: a modeling approach using data from ebinur lake in arid northwest china, Journal of Limnology, 73(2), 148-155, 2014.

Micklin P P.: Desiccation of the aral sea: a water management disaster in the soviet union, Science, 241(4870),1170-6, 1988.

Mu, C., Ma, F., Zheng, X., Li, F., Cheng, H.: Simulation of evapotran spiration under the condition of drip irrigation with plastic film mulching in cotton field, Transactions of the Chinese Society of Agricultural Engineering, 21(4):25-29, 2005 (In Chinese).

Nader, P., Fatemeh, Z., Mojtaba, R., and Vaheedeh, A.: Derivation of crop coefficients of three rice varieties based on ET_0 estimation method in Rasht region, Cereal Research, 3(2): 95-106, 2013.

Narisma, G. T., Foley, J. A., Licker, R., and Ramankutty, N.: Abrupt changes in rainfall during the twentieth century, Geophysical Research Letters, 34, L06710, doi:10.1029/2006GL028628, 2007.

Nkomozepi, T., and Chung, S. O.: Assessing the trends and uncertainty of maize net irrigation water requirement estimated from climate change projections for Zimbabwe. Agricultural Water Management, 111, 60-67, 2012.

Pu, J., Deng, Z., Yao, X., Wang, W., Li, Q., and Zhang, H.: An analysis of ecoclimatic factors on linseed and normal region demarcation for linseed in Gansu, Chinese journal of oil crop sciences, 26(3), 37-42, 2004 (In Chinese)

Shahid, S.: Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh, Climatic Change, 105, 433-453, 2010.

Shen, Y. and Chen, Y.: Global perspective on hydrology, water balance, and water resources management in arid basins, Hydrological Processes, 24, 129-135, 2010.

Shuttleworth, W.J.: Evaporation. In: Maidment, D.R. (Ed.), Handbook of hydrology. McGraw-Hill, New York, USA, pp. 4.1–4.53, 1993.

Siebert, S., Nagieb, M., and Buerkert, A.: Climate and irrigation water use of a mountain oasis in northern Oman, Agricultural Water Management, 89, 1-14, 2007.

Song Y., Fan Z., Lei Z., and Zhang F.: The water resources and ecological problems in the Tarim River, China, Urumqi: Xinjiang people's press, 2000. (In Chinese)

Sorg, A., Mosello, B., Shalpykova, G., Allan, A., Hill Clarvis, M., and Stoffel, M.: Coping with changing water resources: The case of the Syr Darya river basin in Central Asia, Environmental Science & Policy, 43(7), 68-77, 2014.

Wang, G., and Cheng, G.: Water resource development and its influence on the environment in arid areas of China--the case of the Hei River basin, Journal of Arid Environments, 43(2):121-131, 1999.

Wang, G. and Cheng, G.: Water demand of the eco-system and estimate method in arid inland river basins, Journal of Desert Research, 24(2), 129-134, 2002 (In Chinese).

Wang, J., Gai, C., Zhao, J., and Hu, X.: Land use/ land coverage dataset in middle Heihe River Basin in 2011, Data Management Center of the Heihe River Project, doi:10.3972/heihe.100.2014.db, 2014 .

Wang, Y., and Qin, D.: Influence of climate change and human activity on water resources in arid region of Northwest China: An overview, Advances in Climate Change Research, 2017.

Wang, Y., Roderick, M.L., Shen, Y., and Sun, F.: Attribution of satellite-observed vegetation trends in a hyper-arid region of the Heihe River basin, Western China, Hydrology & Earth System Sciences, 11(2), 3499-3509, 2014.

Wang, Y., Yan, C., and Wang, J.: Land use data in Heihe River Basin, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, doi:10.3972/heihe.021.2013.db, 2011.

Wang, Y., Yan, C., and Wang, J.: Land use data in Heihe River Basin in 2000, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, doi:10.3972/heihe.020.2013.db, 2011..

Wu, B.F., Xiong, J., and Yan, N.N.: ETWatch: An Operational ET Monitoring System with Remote Sensing, ISPRS III Workshop, 2008.

Xiong, J., Wu, B., Yan, N., Zeng, Y., and Liu, S.: Estimation and validation of land surface evaporation using remote sensing and meteorological data in North China, IEEE Journal of Selected Topics in Applied Earth Observations & Remote Sensing, 3 (3), 337–344, 2010.

Wu, B., Yan, N., Xiong, J., Bastiaanssen, W.G.M., Zhu, W., and Stein, A.: Validation of ETWatch using field measurements at diverse landscapes: A case study in Hai Basin of China, Journal of Hydrology, 436-437, 67-80, 2012.

Wu, B., Zheng, Y., Tian, Y., Wu, X., Yao, Y., Han, F., Liu, J., and Zheng, C.: Systematic assessment of the uncertainty in integrated surface water-groundwater modeling based on the probabilistic collocation method, Water Resources Research, 50, 5848–5865, doi:10.1002/2014WR015366, 2014.

Wu, T., and Miao, J.: Small hydropower development and construction analysis in the rural of Linze county, Gansu Agriculture, 23, 61-64, 2015 (In Chinese).

Xing, Z.: Annexation and reorganization, integration and getting listed——Some thoughts on the reform of seed enterprises in zhangye city, China Seed Industry, 52-54, 2013 (In Chinese).

Yang, D., Wang, Y., Gao, B., Qin, Y.: Spatial interpolation of gauge precipitation using Regional Climate Model simulation in the Heihe basin (1960-2014), Cold and Arid Regions Science Data Center at Lanzhou, doi:10.3972/heihe.127.2014.db, 2015.

Yang, L., and Wang, G.: Variations of groundwater in Zhangye Basin of the middle reaches of the Heihe River in recent two decades, Journal of Glaciology and Geocryology, 27(2), 290-296, 2005 (In Chinese).

Ye, Z., Chen, Y., and Li, W.: Ecological water demand of natural vegetation in the lower Tarim River, Journal of Geographical Sciences, 20, 261-272, 2010.

Zhang, K., Song, L., Han, Y., Si, J., and Wang, R.: Analysis on supply and demand of water resources and related countermeasures in the middle reaches of Heihe River, Journal of Desert Research, 26, 842-848, 2006 (In Chinese).

Zhao, C., Nan, Z., and Cheng, G.: Methods for estimating irrigation needs of spring wheat in the middle Heihe basin, China, Agricultural Water Management, 75, 54-70, 2005.

Zhao, W., Chang, X., He, Z., and Zhang, Z.: Study on vegetation ecological water requirement in Ejina Oasis, Science in China Series D: Earth Sciences, 50, 121-129, 2007.

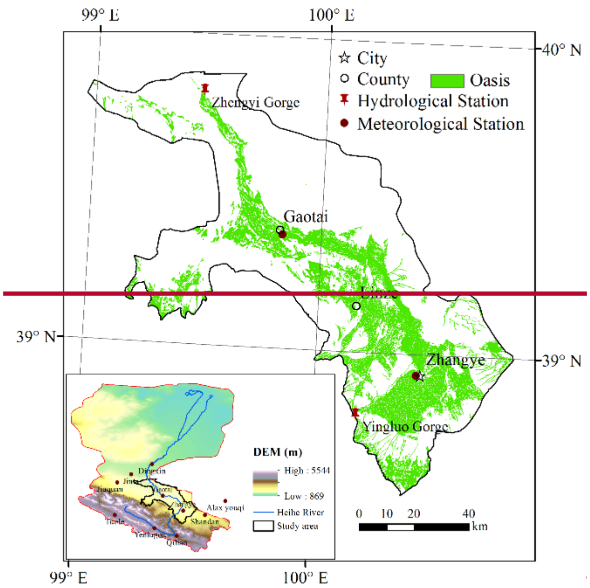
Zhao, W., Liu, B., and Zhang, Z.: Water requirements of maize in the middle Heihe River basin, China, Agricultural Water Management, 97, 215-223, 2010.

Zhao, Y., Wei, Y., Li, S., and Wu, B.: Downstream ecosystem responses to middle reach regulation of river discharge in the heihe river basin, china, Hydrology & Earth System Sciences, 20(11), 1-20, 2016.

Zheng, Y.: The simulation result of the key hydrological variables of the Zhangye Basin in Heihe River Basin, Heihe Plan Science Data Center, doi:10.3972/heihe.070.2014.db, 2014.

Zhou, L., Gao, Y., Gao, Y., and Cheng, Q.: Calculation and analysis of reed transpiration climatology based on reed growth period, Journal of Shenyang Agricultural University, 46(2), 204-212, 2015. (In Chinese)

Zou, M., Niu, J., Kang, S., Li, X., and Lu, H.: The contribution of human agricultural activities to increasing evapotranspiration is significantly greater than climate change effect over heihe agricultural region, Scientific Reports, 7(1), 2017.



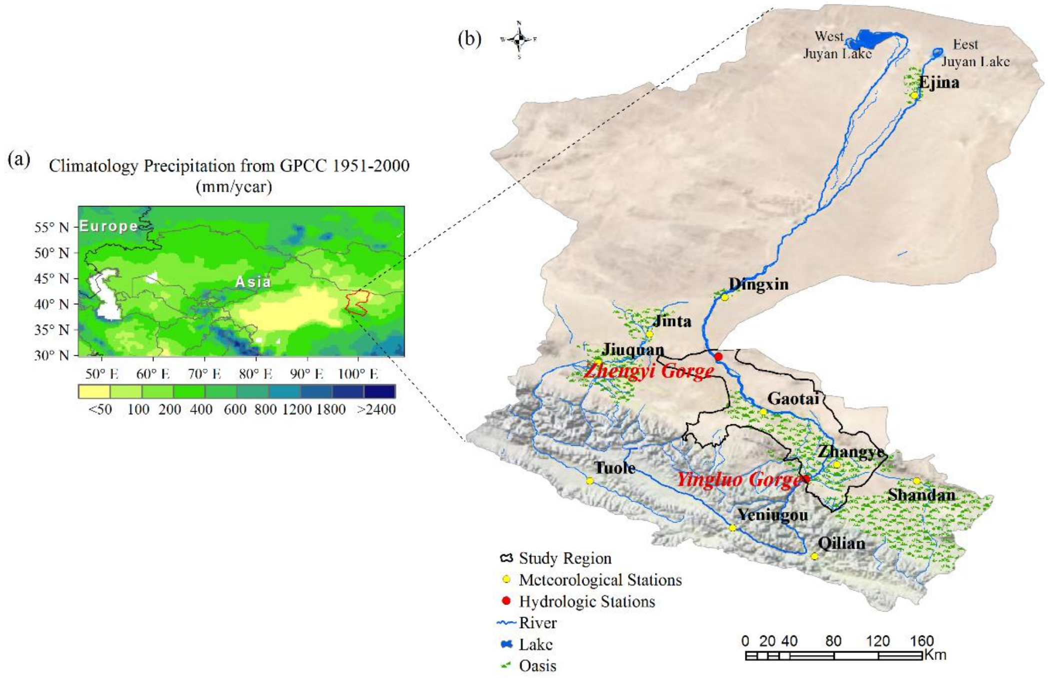


Figure 1. ~~The location of the oasis in the middle Heihe River Basin, embedding the hydrological and meteorological stations, cities, and counties. The distribution of the oasis is based on the land use in 2000.~~Details of the study area. (a) The location of Heihe River Basin and the mean annual precipitation (1951-2000). (b) Regional setting and the landscape of Heihe River Basin with location of meteorological and hydrologic stations.

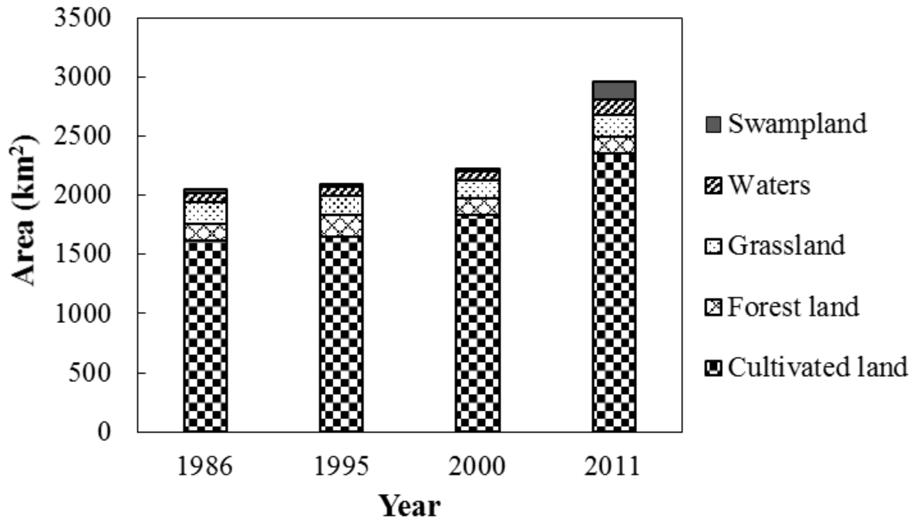
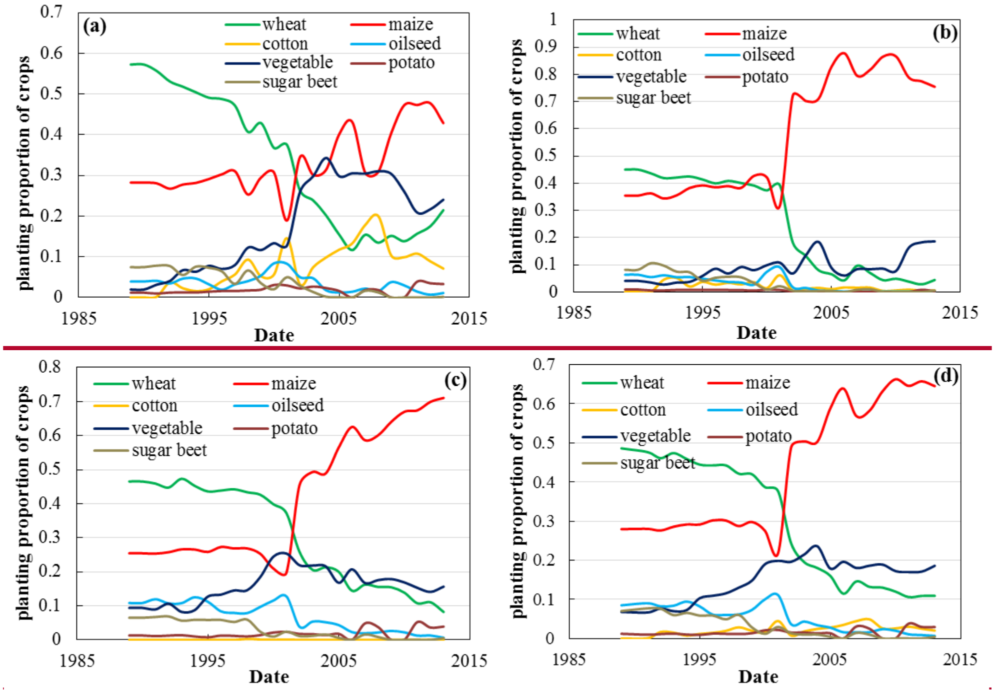


Figure 2. The areas of different land-use types in the oasis in the middle Heihe River Basin.



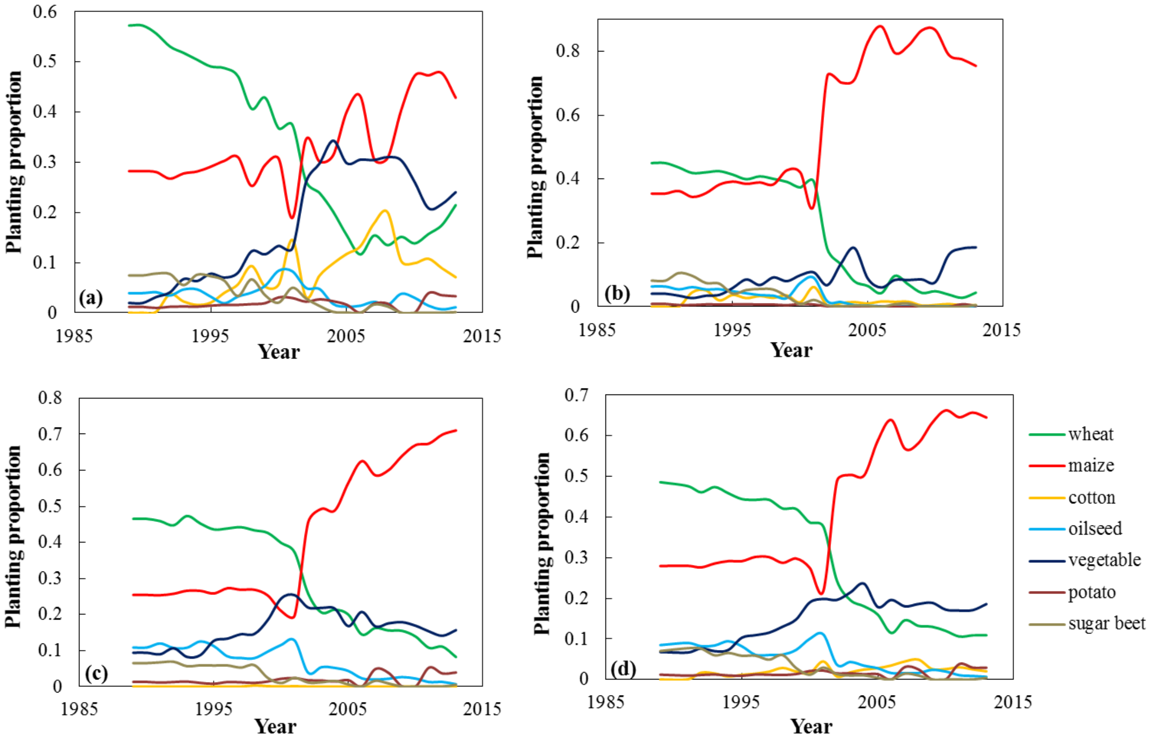


Figure ~~2~~3. The planting proportion of the crops in (a) Gaotai county, (b) Linze county, (c) Ganzhou district, (d) the region including Gaotai, Linze counties and Ganzhou district in the middle Heihe River Basin.

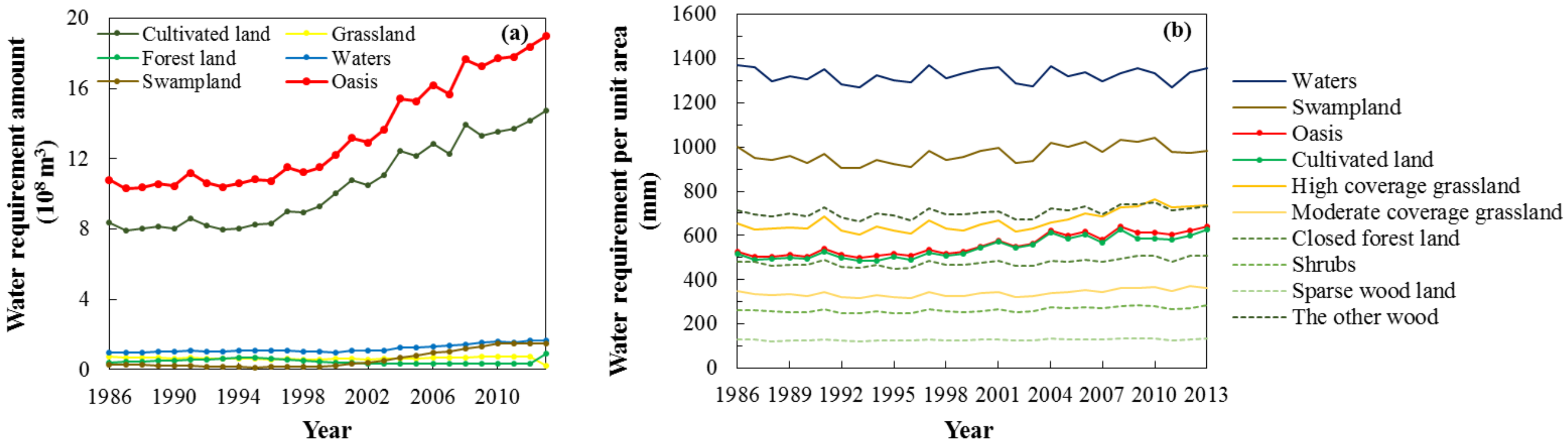
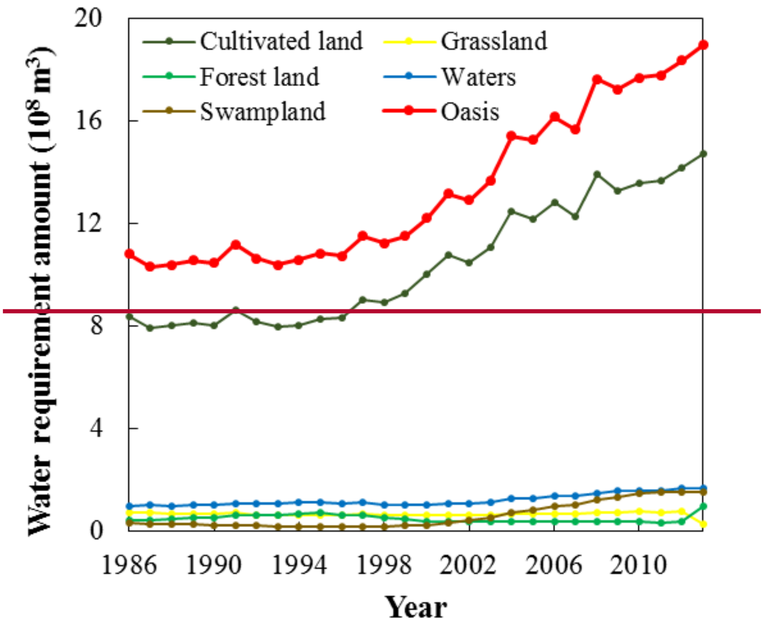
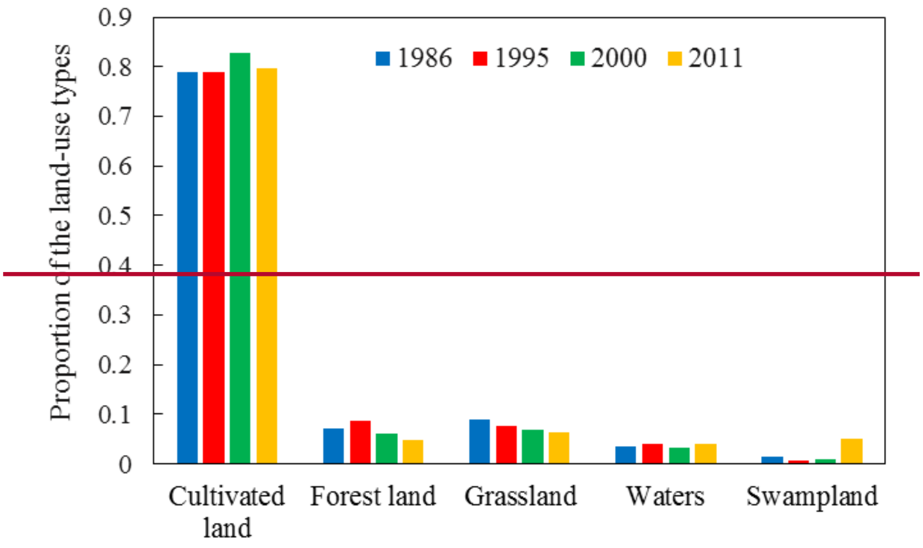


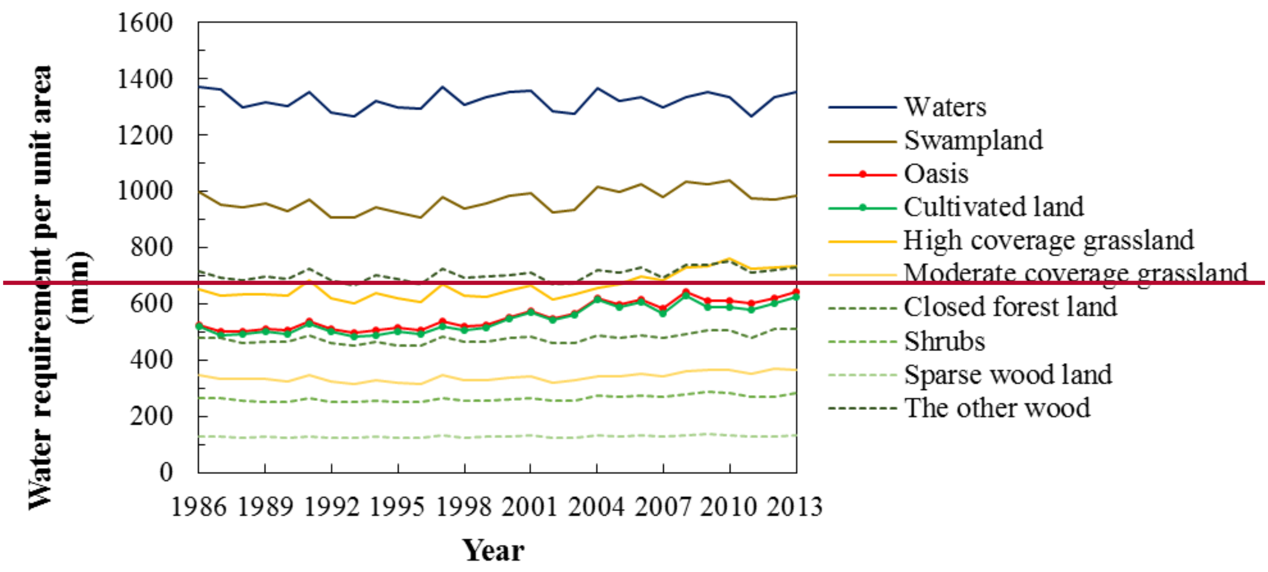
Figure 4. The water requirement amounts (a) and water requirement per unit area (b) for different land-use types in the oasis of the middle Heihe River Basin from 1986 to 2013.



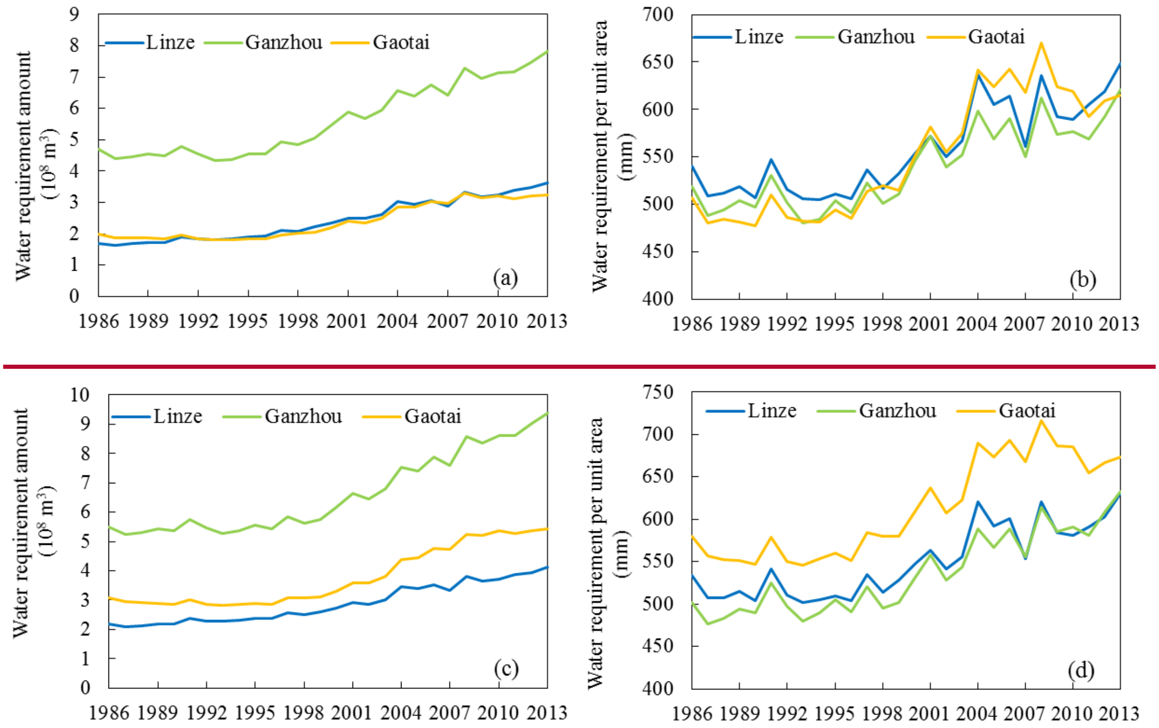
~~**Figure 3.** The water requirement amounts for different land-use types in the oasis from 1986 to 2013.~~



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



~~**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.~~

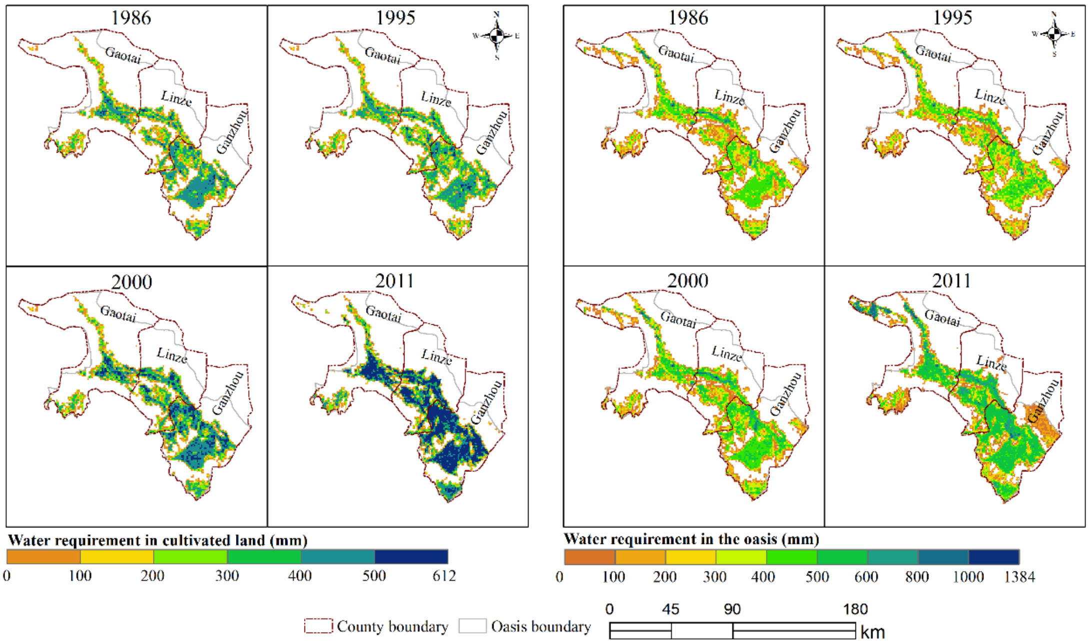


Figure ~~7~~5. The spatial distribution of the water requirement ~~per unit area~~ in the cultivated land and oasis at the spatial resolution of 1 km in the middle Heihe River Basin in 1986, 1995, 2000, 2011.

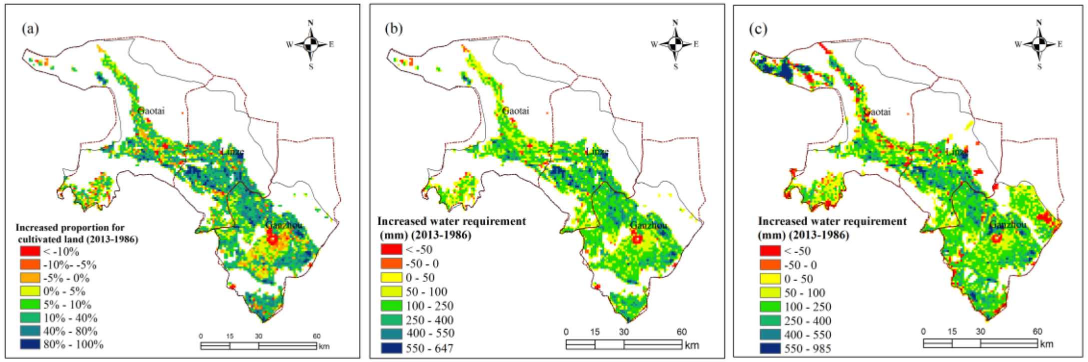


Figure 6. The difference between (a) the proportion of cultivated land, (b) water requirement in the cultivated land, and (c) water requirement in the oasis, at the spatial resolution of 1 km in 1986 and 2013 in the middle Heihe River Basin.

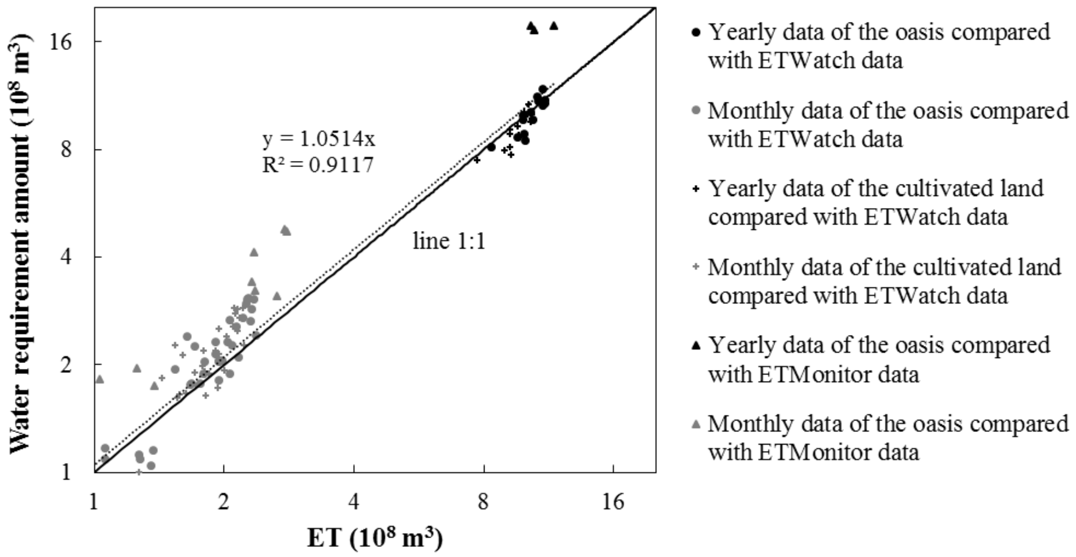
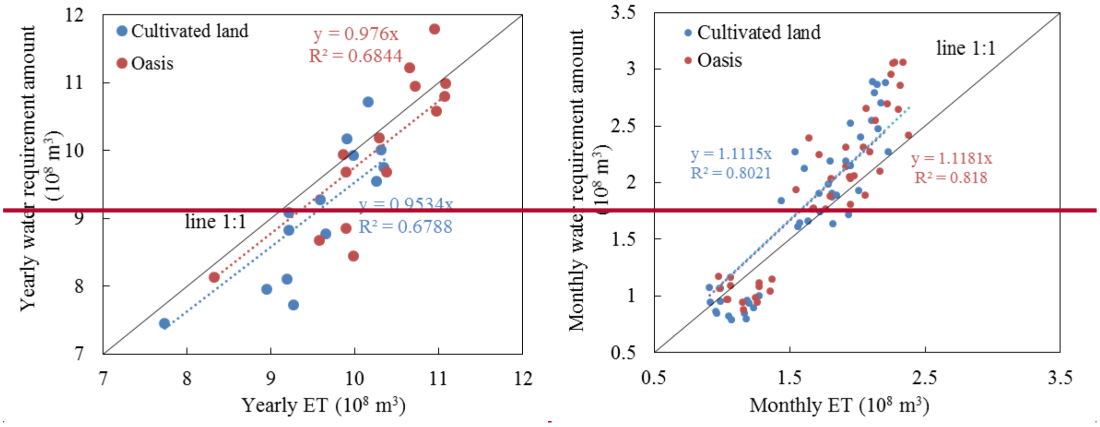
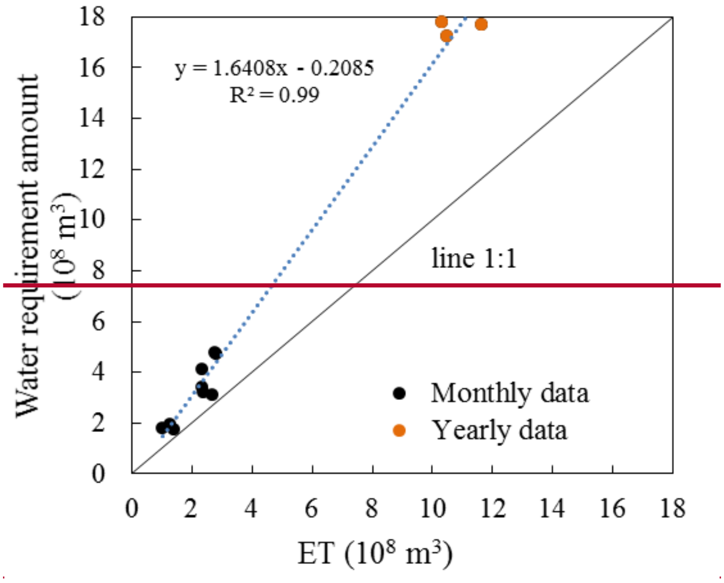


Figure 7. The comparison between the yearly and monthly (May, June, July) water requirement amounts and ET data, which included the ET data estimated by ETWatch model from 2000 to 2013 for the cultivated land and the oasis, and the ET data estimated by ETMonitor model from 2009 to 2011 for the oasis.



~~**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.~~

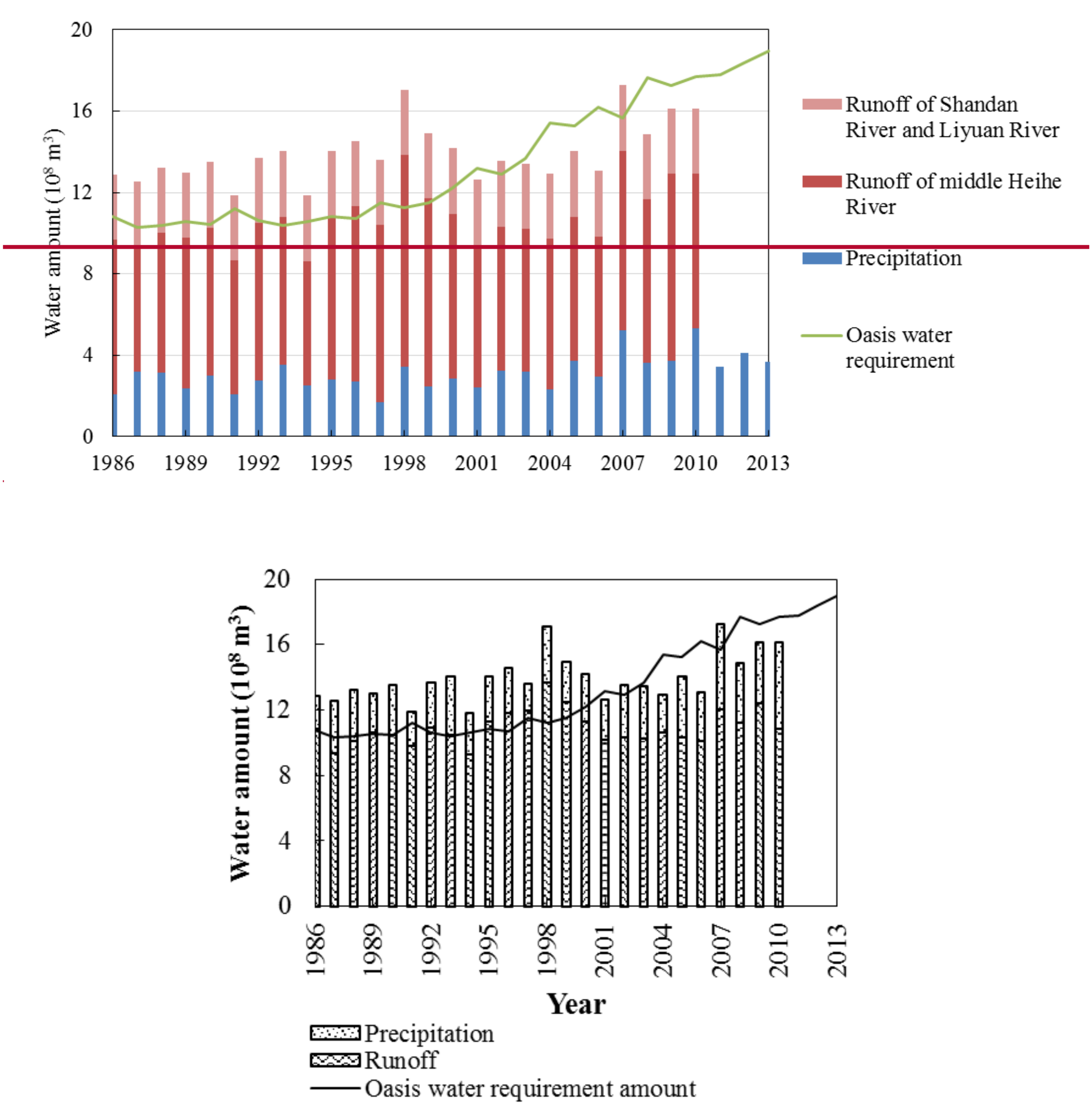
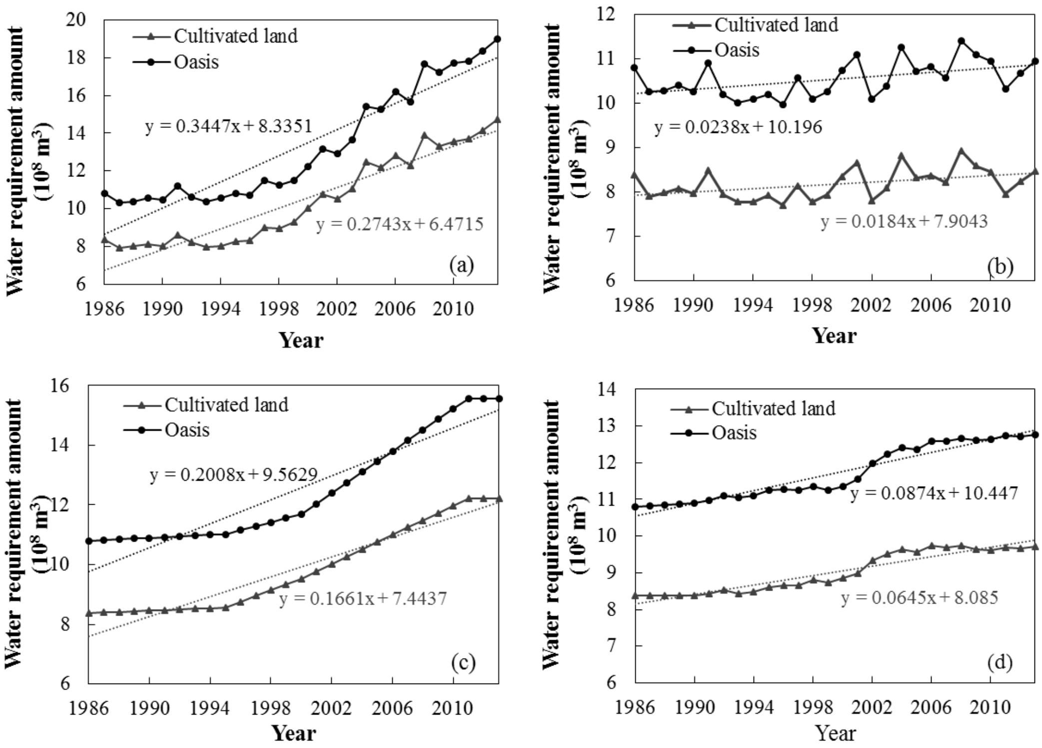


Figure ~~10~~8. The water requirement amount and the surface water supply including the precipitation and runoff data for the oasis in the middle Heihe River Basin. The runoff data included the runoff from the mainstream of middle Heihe River, Shandan River and Liyuan River.

~~The precipitation, runoff, and oasis water requirement in the middle Heihe River Basin.~~



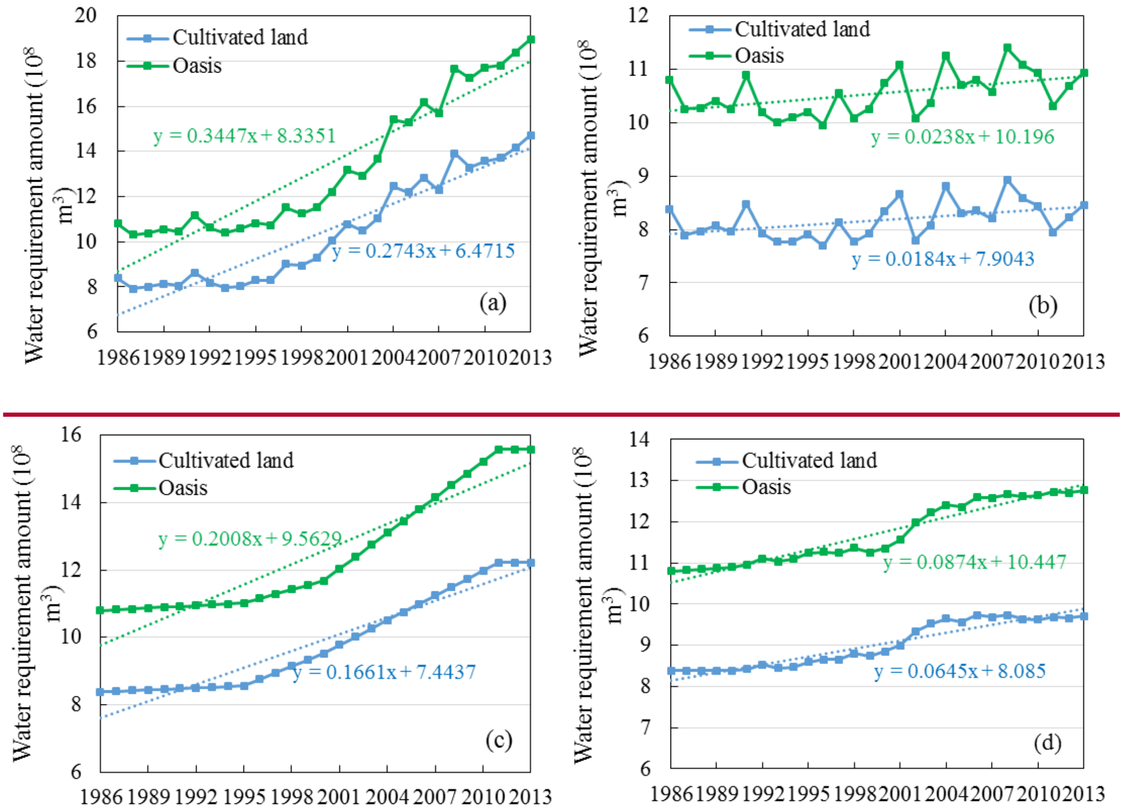


Figure ~~11~~9. The long-term trend of the water requirement for the cultivated land and oasis under different situations during 1986-2013. ~~when the climate, total area of the oasis (cultivated land), and area proportions of the land structure were changing~~(a) Under a situation of climate change and human agricultural activities~~(a)~~; (b) under the situation that only the climate was changing, but the total area of the oasis (cultivated land) and ~~area proportions of the~~ land structure were stable ~~(b)~~; (c) Under the situation that the total area of the oasis (cultivated land) was changing, but the climate and ~~area proportions of the~~ land structure were stable ~~(c)~~; (d) Under the situation that ~~area proportions of~~ the land structure was changing, but the climate and the total area of the oasis (cultivated land) were stable ~~(d)~~.

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)		1986-1989	1990-1999	2000-2013
Water requirement	Agricultural vegetation	8.32	8.84	12.61
	Ecological vegetation	2.19	2.07	3.26
Runoff consumed in the middle Heihe River Basin	Mainstream of the middle Heihe River	6.99	8.00	7.66[a]
	Shandan and Liyuan Rivers	3.22	3.22	3.22
Precipitation	Landing on the agricultural vegetation	2.22	2.22	2.88
	Landing on the ecological vegetation	0.53	0.48	0.67
Groundwater consumed in the middle Heihe River Basin		0.6[b]	1.13	3.25[c]

([a] the average value during 2000-2010, [c]the average value during 2000-2007; [b] the data referred to Yang and Wang (2005).)