Ecohydrology in water-limited environments using quantitative remote sensing – the Heihe River basin (China) case

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CHAPTER 1

Introduction

1.1 Background

Arid, semiarid and subhumid regions occupy approximately 50% of the global land surface (Parsons and Abrahams, 1994). These regions and their environments are considered to be water limited because annual precipitation is typically less than the annual potential evapotranspiration (Guswa et al., 2004). Although variable with respect to physiography, geology and soils, these environments are often sensitive and vulnerable because of low and highly variable precipitation, limited water resources and sparse vegetation. The environmental changes occurring over vast areas in these arid regions include land desertification, groundwater depletion, salinization, and soil erosion (De Fries et al., 2004), amongst others. These environmental changes increasingly affect human societies and have a growing influence on global biogeochemical cycles (Schlesinger et al., 1990; Bonan, 2002).

Vegetation, both native and cultivated, strongly influences the environment and is influenced itself by the environment (Sabins, 1996). The vegetation is an environmental indicator in water-limited ecosystems and is often linked to both the causes and consequences of arid land degradation. The role of vegetation in the dynamics of soil moisture, runoff, and streamflow has been acknowledged to be very important (Wilcox et al., 1997, 2003b; Newman et al., 1998, 2004; Neave and Abrahams, 2002; Porporato et al., 2002; Ridolfi et al., 2003; Fernandez-Illescas and Rodriguez-Iturbe, 2004; Cayrol et al., 2000; Kerkhoff et al., 2004b). Understanding the influence of vegetation on hydrological changes is part of the foundational basis of ecohydrology (Newman et al., 2006). Therefore, studies on quantifying the relationship between the vegetation and water resources represent a critical step in developing advanced ecohydrological approaches, supporting resource management and environmental change.

The above-mentioned arid regions occupy a vast area in north-western China, covering about 2.5 million km² or one-quarter of the Chinese territory. In these regions, mean annual rainfall is less than 250 mm, and even decreasing towards the western plains (50-150 mm) and the Ejina area (less than 40 mm). The annual potential evaporation is in general more than 1,400 mm, and can exceed 2,000-3,000 mm in the desert areas. Because of the arid climate, about 70% of the total arid regions are unusable for human activities, such as sandy deserts, gravel deserts, and other sorts of xeric shrublands. During recent years, the recession of the vegetated parts of the ecosystems appeared to be extensive in Northwest China. They caused a series of environmental problems, like the shrinking of the oasis area and land desertification resulting in increasing sources of sandstorms. Water resources are the essential factor influencing the vegetation variability (Dawson, 1993; Burgess et al., 1998; Caldwell et al., 1998; Brooks et al., 2002; Zou et al., 2005; Santanello et al., 2007). In the northwestern arid area of China, all the oases are fed by surface rivers and their extent has a close relationship with runoff of the river and the groundwater depth. However, due to little population density, inconvenient transportation and shortage of available long-term monitoring data, traditional methods performing qualitative ecohydrological analysis that usually employ point observations and are only representative for local scales, cannot be extended to large areas. The use of remote sensing can provide continuous and representative measurements of several relevant physical parameters at scales from point to continent. These methods are still used in a limited fashion in hydrology for a quantitative assessment of the eco-environmental changes in China (Li et al., 2001; Lu et al., 2003; Guo and Cheng, 2004; Kang, et al., 2007). The purpose of this study is to develop a method to quantitatively assess the eco-environmental changes using remote sensing methods and applying it to ecohydrological applications in China.

The Heihe River basin, located in the middle of the Hexi Corridor of the Gansu Province, is one of the two largest inland river basins in China. Its watershed covers an area of 14.3×10^4 m^2 and the upper, middle and lower reaches of the Heihe River stretch from the middle of the Hexi corridor to the western Inner Mongolia Municipality. In the southern part of the Heihe River basin the Qilian Mountains are located representing the upstream area, which are steep mountains with an altitude ranging from 3000 m to 5000 m above sea level. Due to the cold climate and the sufficient precipitation, the runoff generated from this area is the main source of the surface water and groundwater for the Heihe River basin, and finally ends in two terminal lakes of the Ejina Oasis (the downstream area), namely, West Juyan Lake and East Juyan Lake. The middle stream area, called the Zhangye basin, is a very important agricultural area in northwest China. With growing population and farmland expansion in the middle stream area, the water consumption has increased gradually and most water is nowadays used for irrigation. This is causing a decrease of incoming water in the downstream area resulting in a serious recession of the eco-environment in that region. The Chinese government puts significant importance on improving the eco-environment of the downstream area by balancing the water consumption and has therefore implemented a new policy for the allocation of available water resources. An applicable method for a quantitative analysis of the eco-environmental changes as well as providing scientific evidence for protecting and improving the eco-environment in these Chinese Northwestern arid regions is the final goal of this study.

1.2 Remote sensing in ecohydrology

Remote sensing has long been suggested as being a time- and cost-efficient method for monitoring changes in arid environments. It can detect and monitor landscape change and degradation in arid and semiarid regions. The use of remote sensing for deriving process-relevant environmental information from optical remote sensing data in arid areas is highlighted in several environmental degradation studies (Okin and Roberts, 2004; Bai et al., 2008). Therefore, using remote sensing methods to understand eco-environmental changes has emerged to be a current research topic of wide interest.

The complexity and heterogeneity of hydrological processes exist over a wide range of scales in space and time. Traditional techniques measuring hydrological variables rely on point sensors collecting information which is assumed to be representative for large areas. However, this approach is not particularly helpful in complex or heterogeneous environments where the point measurements cannot be assumed to represent large areas. The surface-atmosphere interface is an example of a system that is highly variable in both space and time (Cooper et al., 1992, 2000; Eichinger et al., 2000). Remote sensing, broadly defined as a collection of noncontact observational methods, offers the potential to capture information on some of the spatial and temporal ecohydrological processes. We propose to establish an integrated remote sensing method where research across the spectrum of hydrologic remote sensing can be integrated with hydrological processes occurring at large scales. Historically, remote sensing products have been used to evaluate short-term processes focusing on the retrieval of a singular geophysical variable. To improve this approach, we suggest the use of remote sensing for the estimation of water-energy-ecosystem variables be performed as an integrated method. This method can be used to address fundamental hydrological research questions at local to global scales. It is clear that satellites have proven their capability to monitor many aspects of the total Earth system on a global scale. Aircraft- and ground-based systems play a vital role in improving our understanding of hydrological processes and their interactions.

For over 20 years, research on spatial hydrological processes has been developed through modeling or scaling studies (Wood et al., 1988; Gupta and Waymire, 1990; Famiglietti and Wood, 1995; Blöschl and Sivapalan, 1995; Gupta et al., 1996; Rodriguez-Iturbe and Rinaldo, 1997; Crow et al., 2000; Brown et al., 2002; Miline et al., 2002; Rietkerk et al., 2004). Many of these developments have been related to the space-time organization of ecosystem fields and their influence on hydrological processes. The theories can be further developed and tested by adding multiscale views of the landscape. It appears that remote sensing is the only approach that has the potential to translate measurements from one scale to another scale. The integration of remote sensing and hydrological data at various spatial scales will further produce the hydrological predictions that our society needs.

The main hydrological variables of interest include precipitation, evapotranspiration, extent of surface water reservoirs and river discharge, soil moisture, groundwater storage capacity, and ecosystem variables like vegetation cover. A lot of research suggests that hydrologic forecasts can be improved if hydrological variables, like precipitation, soil moisture, river runoff and snow cover, along with ground observations, can be assimilated in hydrological models (Houser et al., 1998; Reichle et al., 2002; Crow and Wood, 2003; Margulis and Entekhabi, 2003; Drusch et al., 2005; Duune and Entekhabi, 2005; Walker and Houser, 2005).

Therefore, it should be investigated how remote sensing data can be combined with hydrological data to improve hydrological predictions, and how these can be quantified. To illustrate how to approach this question, we use the example of predicting evapotranspiration. Accurate measurement of evapotranspiration at the watershed scale is a major challenge in hydrology. Evapotranspiration is one of the largest components of the surface water balance and remains a major source of uncertainty in the estimation of groundwater recharge. Because of the spatial variability of evapotranspiration and its influence on soil water storage, it also strongly influences the estimation of runoff. Ideally, remote sensing can estimate evapotranspiration at a large scale because it is able to map the spatial distribution of vegetation cover and surface temperature, which are two quantities closely related to evapotranspiration. Based on the surface energy balance, regional scale land surface models use input variables such as surface meteorological parameters and detailed soil and vegetation information to estimate the heat flux and the evapotranspiration of the surface. Although models have been proposed to estimate regional evapotranspiration, the reliability of the results still requires validation before they can be used for water resources assessment in a specific region. In most of the studies, the accuracy of the evapotranspiration estimation is validated by monitoring data at local scale (Wilson et al., 2002; Sun et al., 2004; Salazar and Poveda, 2006; Zwart and Bastiaanssen, 2007). Therefore, the proper validation of the reliability of the evapotranspiration estimates at regional scales is a critical issue in properly integrating remote sensing and hydrological data.

The main goal of ecohydrology is to explain (1) how hydrological processes influence the distribution, structure, function, and dynamics of biological systems and (2) how feedbacks from biological systems affect the water cycle (Baird and Wilby, 1999; Rodriguez-Iturbe, 2000; Bonell, 2002; Eagleson, 2002; Kundzewicz, 2002; Nuttle, 2002; Zalewski, 2002; Bond, 2003; Hunt and Wilcox, 2003; Newman et al., 2003; Van Dijk, 2004; Hannach et al., 2004; Breshears, 2005). Consequently, ecohydrology is a discipline linking hydrology and ecology. Vegetation is the most important factor to characterize the variability of an ecosystem and understanding and quantifying the relationship between the vegetation and water resources is an important step in developing an ecohydrological approach for water resources management. Much of the early and classic work in watershed management of arid regions focused on this topic (Hibbert, 1983) and it remains a topic of importance today, especially as water supplies become increasingly limited. If specific correlations among groundwater recharge, runoff, hydraulic factors, and variation of vegetation could be defined through coordinated measurement and monitoring activities, the vegetation could be used as a proxy for recharge and water demand (Walvoord and Phillips, 2004; Kwicklis et al., 2005). The important role of vegetation in the dynamics of groundwater recharge and runoff in arid environments has been studied using remote sensing methods (Cayrol et al., 2000; Kerkhoff et al., 2004b). Vegetation mapping, based on ground, aerial, or satellite approaches, can be used to predict surface flow and groundwater recharge in stead of surface and subsurface sampling and analysis. Therefore, incorporating remote sensing methods in ecohydrological approaches or models will be useful for predicting both the response of vegetation to changes in water input and the effects of vegetation on water fluxes and storage. Enhanced satellite remote sensing capabilities can improve our ability to quantify vegetation responses to changes in hydrological processes. Combining remote sensing methods with hydrology will yield new insights in ecohydrological processes.

1.3 Objectives

The main objective of this thesis is to develop a methodology for the quantitative assessment of eco-environmental changes at a large scale in arid regions by integrating remote sensing methods in ecohydrological approaches. The Heihe River basin, which is located in northwest China, is selected as the study area because of its obvious changes in water resources management that are typical for a water-limited region: assessing the vegetation distribution and the close correlation between vegetation change and precipitation in the upstream area, further understanding of the water resources variation in the whole river basin, resolving the conflict of water consumption between the middle stream area and the downstream area, balancing the water allocation, improving and protecting the eco-environment of the river basin. To achieve this objective, the following specific research questions are formulated:

A. Can we use remote sensing methods for quantitatively assessing both the vertical and horizontal distribution of vegetation in a mountainous area and assess the main impact factors on vegetation growth?

B. Can regional evapotranspiration be precisely estimated by using a model based on the surface energy balance including remotely sensed data input and how can we validate the reliability of the evapotranspiration results at larger scales?

C. Can we use remote sensing methods for understanding the quantitative relationship between the runoff of a river towards an oasis landscape and the vegetation growth in the oasis, and can these relationships be used for estimating the water demand of the oasis?

D. Can we integrate remote sensing methods into ecohydrological approaches to study the effect of groundwater depth on vegetation growth in the oasis area, and use this to determine the range of groundwater depth for vegetation growth?

1.4 Outline

The main chapters of this thesis (chapter 2 to 5) are assigned to answering the research questions as mentioned in the previous section and have been prepared as peer reviewed publications. The study area of the Heihe River basin is divided into three parts in response to the upstream, middle stream and downstream area, respectively. Every chapter includes an introduction related to one of the specific research questions, a detailed description of the corresponding study area and the datasets used, a discussion of the obtained results and the conclusions.

In Chapter 2, both the vertical and horizontal distribution of vegetation in the Qilian Mountain area, representing the upstream area of the Heihe River basin, is quantified based on MODIS NDVI images from the years 2000 to 2006. The main impact factors, such as elevation, aspect, precipitation and land surface temperature are analyzed in detail in this chapter (Question A).

Chapter 3 presents a practical method to estimate the annual evapotranspiration in the Zhangye basin (representing the middle stream area) based on the Surface Energy Balance System (SEBS) algorithm and the accuracy of the evapotranspiration result has been validated using the water budget. NOAA/AVHRR measurements ranging from 1990 to 2004 are used for the evapotranspiration estimation (Question B).

In Chapter 4, the long-term vegetation change of the downstream area (the Ejina Oasis) is analyzed in two periods, one before and one after the implementation of a new government policy for water allocation. The GIMMS NDVI and MODIS NDVI datasets are used to evaluate the long-term vegetation change. A one year hysteresis effect of the runoff of the river on the oasis vegetation is also discussed and the water demand for sustaining the eco-environment of the downstream area is estimated (Question C).

Chapter 5 continues on the research of chapter 4 and focuses on quantifying the relationship between the groundwater depth and vegetation growth in the Ejina Oasis by combining MODIS NDVI measurements and groundwater observation data. The threshold for the groundwater depth affecting the vegetation growth is defined and the range of groundwater depths suitable for vegetation growth is discussed in the Ejina area (Question D).

Chapter 6 concludes this thesis with the results and main findings of all previous chapters and offers suggestions for the future work.

Finally, the thesis closes with an overview of all references used and summaries in English, Dutch and Chinese.

CHAPTER 2

Quantification of spatial distribution of vegetation in the Qilian Mountain area with MODIS NDVI*

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* Based on: Jin, X.M., Wan, L., Zhang, Y-K., Hu, G.C., Schaepman, M.E., Clevers, J.G.P.W., Su, Z., 2008. Quantification of spatial distribution of vegetation in the Qilian Mountain area with MODIS NDVI. *International Journal of Remote Sensing* (in press).

Quantification of spatial distribution of vegetation in the Qilian Mountain area with MODIS NDVI

Abstract

The spatial distribution of vegetation in the Qilian Mountain area was quantified with remote sensing data. The MODIS NDVI values for June, July, August, and September are the best indicators for the vegetation growth during a year in this area and thus were used in this study. The results obtained by analyzing the NDVI data for seven years from 2000 to 2006 clearly indicated that elevation and aspect, as a proxy for precipitation and temperature, are two very important factors for the vertical distribution of vegetation in Qilian Mountain area. In the Qilian Mountain area: the vegetation growth is optimal between the elevations of 3200 m and 3600 m with the NDVI values larger than 0.50 and a peak value of > 0.56 around 3400 m. It is the combination of plentiful precipitation and suitable land surface temperature that provides less soil moisture stress and thus suitable conditions for vegetation growth in this range of elevations. The optimal vegetation growth is found in the shady slope between NW (340º) to NE (70º) with the largest NDVI value (> 0.56) within the elevation range of 3200 m and 3600 m. The methodology developed in this study should be useful for similar ecological studies on vegetation distribution.

Keywords: MODIS NDVI, Elevation, Aspect, Precipitation, Ground surface temperature, Qilian Mountain area

2.1 Introduction

The importance of vegetation cover, especially forests, in mountain areas can not be overstated. Forests and other plants provide an environment for many species living in these areas. Vegetation cover affects local and regional climate and reduce erosion. Economy of local communities and millions of people in mountain areas depend on forests and plants. Vegetation cover also effectively protects people against natural hazards such as rockfall, landslides, debris flows, and floods (Brang et al., 2001). For example, the vegetation cover in alpine regions protects the settlement and transportation corridors, providing wind sheltering and landslide prevention (Agliardi and Crosta, 2003). Therefore, understanding of distribution and patterns of vegetation growth along with their affecting factors in those areas are important and have been studied by many researchers (e.g., Oliver and Webster 1986; Weiser et al. 1986; Stephenson 1990; Turner et al. 1992; Henebry 1993; Endress and Chinea 2001; Bai et al. 2004).

Elevation, aspect, and slope are the three main topographic factors that affect the distribution and patterns of vegetation in mountain areas indirectly (Huang 2002). Among these three factors, elevation is important (Leak and Graber 1974; Busing et al. 1993) because it serves as a proxy for precipitation and temperature. Elevation along with aspect and slope in many respects determines the microclimate and the microclimate affects the spatial distribution and patterns of vegetation (Geiger 1966; Day and Monk 1974; Johnson 1981; Marks and Harcombe 1981; Allen and Peet 1990; Busing et al. 1992).

One of the powerful tools to study the spatial distribution of vegetation is remote sensing. Remote sensing has traditionally been used in large-scale global assessments of vegetation distribution and land cover with the Normalized Difference Vegetation Index (NDVI) data from Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Chen and Brutsaert 1997; Defries and Townshend 1994; Defries et al. 1995; Friedl et al. 2002; Loveland et al. 1999, 2000). The NDVI is an index derived from reflectance measurements in the red and infrared portions of the electromagnetic spectrum to describe the relative amount of green biomass from one area to the next (Deering 1978). This index is an indicator of photosynthetic activity of plants and has been widely used for assessing vegetation phenology and estimating landscape patterns of primary productivity (Sellers, 1985; Tucker and Sellers, 1986). The NDVI was designed to quantitatively evaluate vegetation growth: higher NDVI values imply more vegetation coverage, lower NDVI values imply less or non-vegetated coverage, and zero NDVI indicates rock or bare land.

Most studies with remote sensing data were concentrated on two-dimensional horizontal patterns although some were focused on the effect of elevation on the vertical distribution of vegetation in mountain areas (Franklin 1995; Edwards 1996; Guisan and Zimmermann 2000;

Hansen 2000; Miller et al. 2004; Lookingbill et al. 2005). Zhao et al. (2006) predicted Qinghai spruce (Picea crassifolia) distribution in the Qilian Mountains based on meteorological data and the GIS-modeling. The result indicated that the suitable niche of Qinghai spruce ranged from 2650 m to 3100 m. The objectives of this study are two-fold: 1) to quantitatively assess both vertical and horizontal distribution of vegetation in the Qilian Mountain area and its main controlling factors, i.e., elevation and aspect or precipitation and land surface temperature, and 2) to demonstrate the usefulness of the methodology which may be used for other environmental and ecological studies. The study area is described first and followed by the dataset description and results presentation and discussion. The conclusions are provided at the end.

2.2 Study area

Located in the upstream of the Heihe River basin, the Qilian Mountain area has a steep topography with an elevation range from 1680 m to 5100 m (Figure 2.1). Geomorphologically,

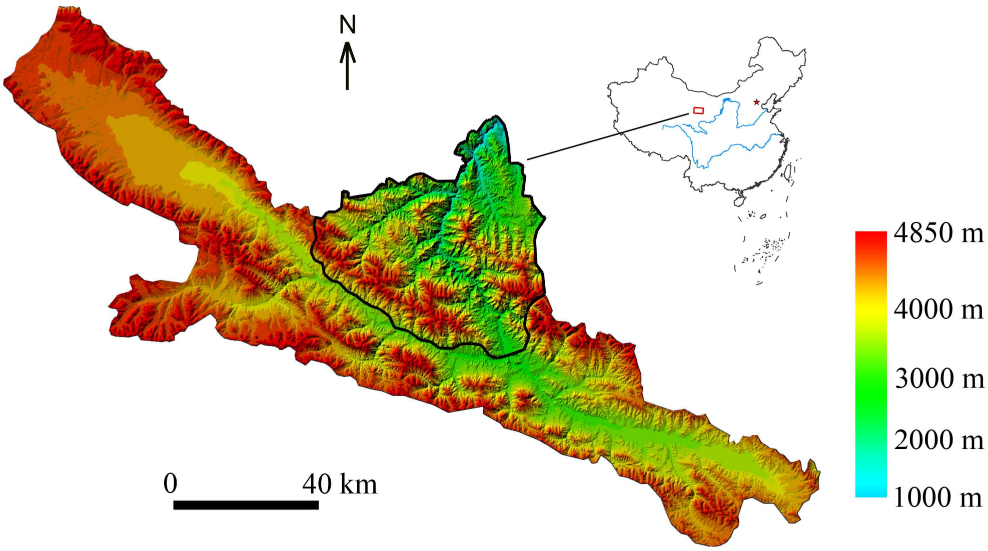


Figure 2.1 The DEM (digital elevation model) map of the Qilian Mountain area with the spatial resolution of 100 m. The area surrounded by watershed of Heihe tributaries in east and west boundary (outlined with bold black line) was selected as the study area.

the intermountain basin and longitudinal valley are widely developed in the area. The northern part of the Qilian Mountains, surrounded by tributaries of Heihe River to the east and west, was selected to be the study area which was outlined with the bold black line in Figure 2.1 because this area represents a typical mountain range and reflects the typical vegetation change with elevation in this region. With a total area of 2,968 km^2, the study area is characterized by typical high plateau continental climate. The average annual temperature is 0.6 °C and the amount of precipitation increases with the elevation. Due to complex topography, the climate is diverse and has distinct vertical characteristics: from the lower elevation area to the higher elevation area, the temperature decreases and the precipitation increases. The climate in higher mountain areas is cold and humid while the climate in lower mountain areas is warm and arid. These vertical climate characteristics have important impacts on the soil development and vegetation growth in the areas as they do in many other mountains.

The vegetation distribution in this area exhibits an obvious vertical gradient due to the climatic changes with elevation. From the low altitude to high altitude the vegetation types are: desert-grassland vegetation (1800 – 2100 m), dry shrub-grassland vegetation (2100 – 2400 m), mountain forest-grassland vegetation (2400 – 3400 m), sub-alpine shrub-grassland vegetation (3400 – 3900 m), and cold-desert alpine meadow vegetation (> 3900 m). The mountain forest-grassland vegetation is the main vegetation type and the main component of the Qilian Mountains ecosystem. The range of elevations (1800 – 5100 m) in study area was divided into a total of 31 intervals with 100m in each of the interval and the aspect angle was divided into a total of 72 intervals with 5° in each of the interval. The changes in the number of pixels with elevation and aspect are shown in Figure 2.2 and 2.3, respectively. These two figures should show that there are enough data points in the elevation range between 2100 m and 4700 m and in the aspect angles between 0º and 360º to draw statistically significant conclusions regarding the spatial distribution of the vegetation.

The vegetation in the Qilian Mountain area plays an important role in the local water cycle by affecting hydrological processes, e.g., evapotranspiration (ET) and runoff, and is an important ecological storage for water resources. Qilian Mountains supplies water for the Hexi Corridor which is the most important agricultural region and settlement in northwest China. The vegetation in the Qilian Mountain area significantly affects the oases in the region and protects the middle and downstream area of Heihe River against desertification.

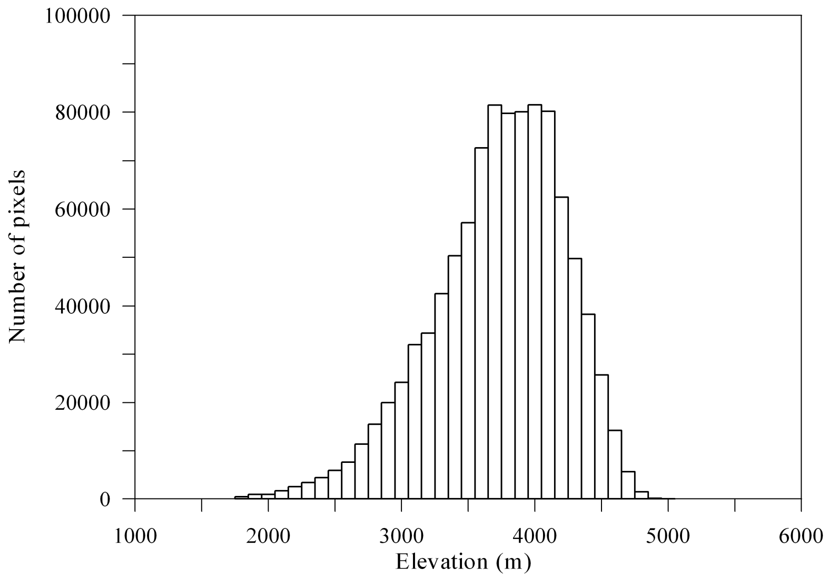


Figure 2.2 The distribution of the pixel number over the elevation intervals of 100 m in the study area. It shows that the most elevations are between 1800 m and 4800 m and that there are enough data points (at least a few thousands) for each interval between 2100 m and 4700 m to warrant statistical significance in the results.

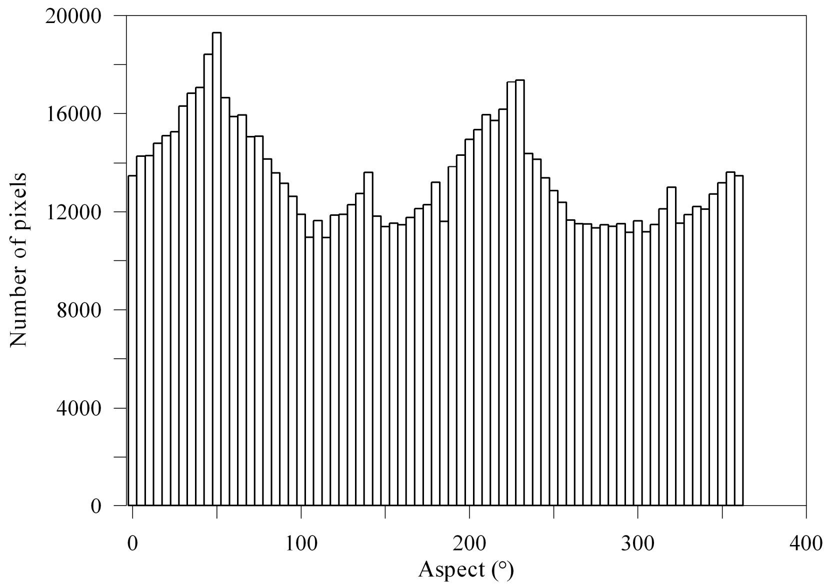


Figure 2.3 The distribution of the pixel number over the aspect intervals of 5° in the study area. It shows that there are enough data points (more than 10,000) for each interval to warrant statistical significance in the results.

2.3 Dataset

The MODIS NDVI data, the vegetation index maps depicting spatial and temporal variations in vegetation activities, was derived by monitoring the Earth's vegetation. These vegetation index maps have been corrected for molecular scattering, ozone absorption, and aerosols. The MODIS NDVI data is based on 16-day composites and its spatial resolution is 250 m. Currently, the MODIS NDVI products have been used throughout a wide range of disciplines, such as inter- and intra-annual global vegetation monitoring, climate and hydrologic modeling, and agricultural activities and drought studies (Zhan et al. 2000; Jin and Sader 2005; Sakamoto et al. 2005; Knight et al. 2006; Lunetta et al. 2006). In this study the NDVI values from 28 MODIS NDVI images of the 16-day composites of June, July, August, and September in seven years from 2000 to 2006 were used because these four months consist of the most productive season for vegetation growth during a year and thus the NDVI values of these four months can best reflect the pattern of the vegetation cover in the region.

The MODIS LST (land surface temperature) data for the same four months, i.e., June, July, August, and September from 2000 to 2006 were used in this study to be consistent with the NDVI data. The MODIS LST data are 8-day composites and its spatial resolution is 1 km. The mean gridded rainfall data from June to September is given monthly and its spatial resolution is 1 km. The monthly rainfall data was published by the Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.naturalresources.csdb.cn). This database contains the monthly rainfall data from year 1971 to 2001 of 700 land meteorological stations in China. The interpolation algorithm in the ANUSPLIN4.3 software was used which was published by Centre for Resources and Environmental Studies, the Australian National University (http://cres.anu.edu.au/). This method considers the impact of climate and topography. In order to be consistent with the NDVI data, the rainfall data of June, July, August, and September from 2000 to 2001 were used in this study and the precipitation of these four months are at maximum. A monthly mean precipitation chart from 2000 to 2001 illustrates that these four months are the wet periods in a year and are sensitive for the vegetation growth (Figure 2.4). The Digital Elevation Model (DEM) data was downloaded from the Digital River Basin website (http://heihe.westgis.ac.cn) and its spatial resolution is 100 m. The MODIS NDVI, land surface temperature, and rainfall data were resampled and interpolated to have the same spatial resolution as the DEM data in this study.

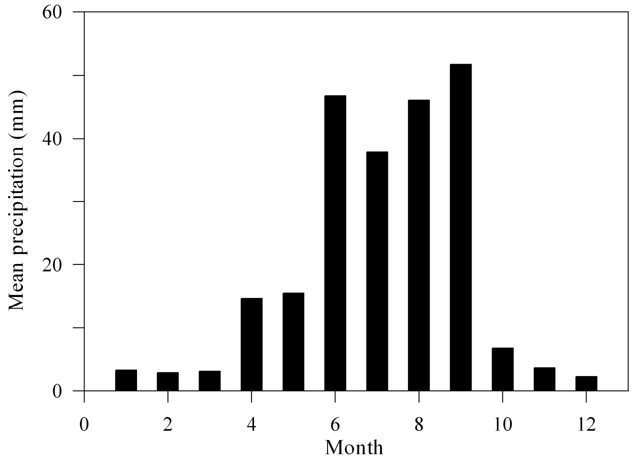


Figure 2.4 The monthly mean precipitation chart from 2000 to 2001. It shows June, July, August and September are the wet seasons in study area.

2.4 Results and Discussion

It is well known that elevation serves as a proxy for precipitation and temperature, and affects the spatial distribution of vegetation cover indirectly. Most of the vegetation in the northern Qilian Mountain area is distributed between the elevations of 1800 m and 4500 m. To the best of our knowledge, however, the obvious spatial distribution and patterns have not been studied quantitatively. We show in this study that the readily available NDVI data can be used to quantify the spatial distribution of vegetation. The range of elevations from 1800 m and 4500 m was divided into a total of 270 intervals with 10m in each of the interval. The aspect angle of 360º were divided into a total of 72 intervals with 5º in each of the interval. These divisions result a total of 19360 cells among which 19060 cells with the NDVI values larger than zero. In each cell the NDVI values from year 2000 to 2006 were averaged. The mean values represent the general conditions of the vegetation growth in different elevations and aspects. A contour map of the mean NDVI values with elevation and aspect in the northern part of Qilian Mountains was plotted in Figure 2.5. A Gaussian smooth filter was used and a low pass convolution was performed on the gridded data to obtain the more consistent and smooth map in Figure 2.5.

Several observations can be made in Figure 2.5 regarding the effects of elevation and aspect on the vegetation growth in the mountain area. First of all, it is clearly seen that the elevation is very important for the vegetation growth through its control on precipitation and temperature discussed later. The NDVI value increases with the elevation and reaches its maximum value around 3400 m and then decreases as the elevation increases beyond 3400 m. The NDVI values are mostly larger than 0.50 (the dark green region in Figure 2.5) when the elevation is between 3200 m and 3600 m which is the optimal vertical zone in terms of vegetation growth. The NDVI values are less than 0.50 when the elevation is lower than 3200 m and higher than 3600 m or the vegetation growth is poorer in these elevations than in the zone between 3200 m and 3600 m.

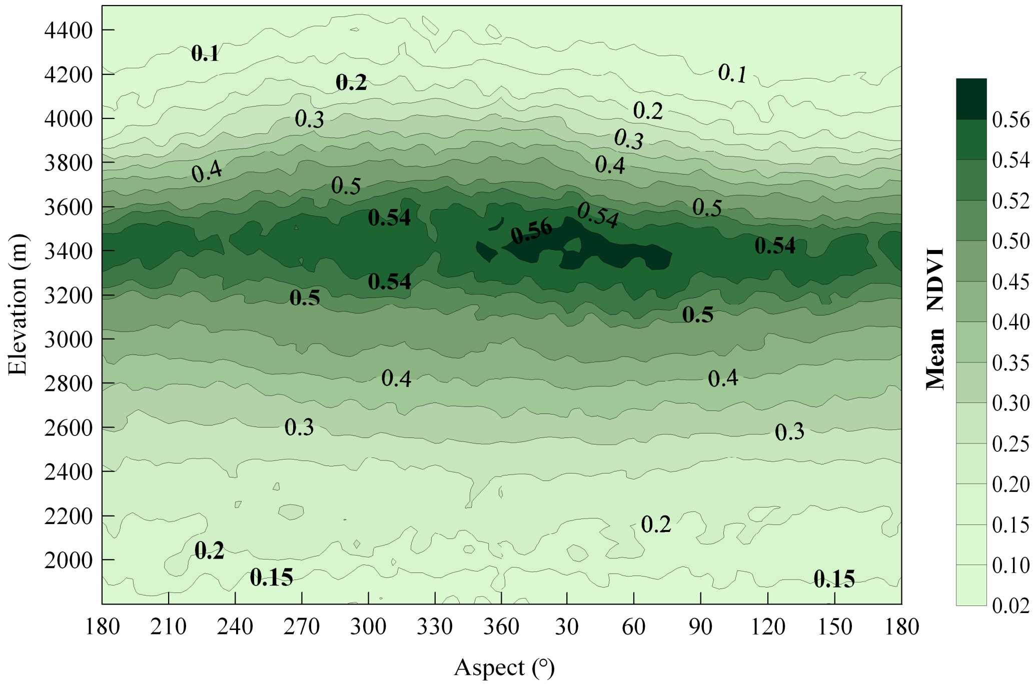


Figure 2.5 The change of the mean NDVI values with elevation and aspect in the northern part of Qilian Mountains. A Gaussian smooth filter was used and a low pass convolution was performed on the grid data to present a more consistent and smooth map. Note: a refiner scale (0.02) was used when the NDVI value is larger than 0.5.

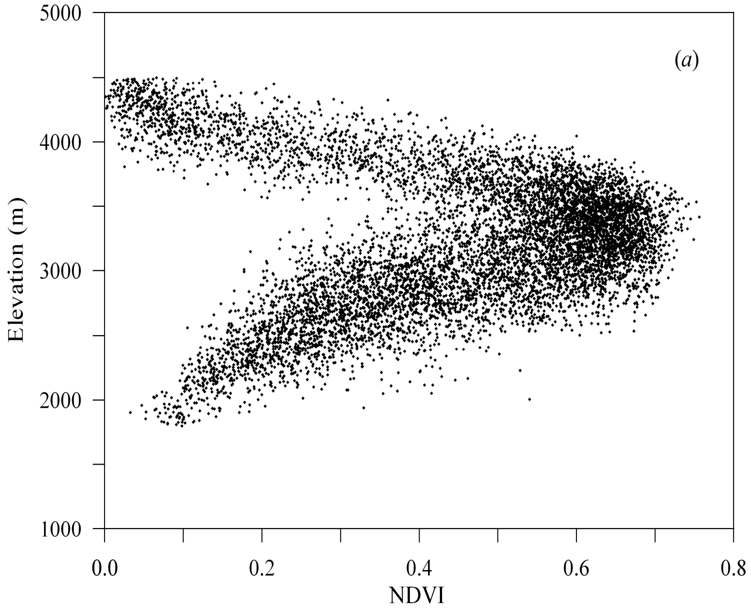
Secondly, the vegetation growth in the Qilian Mountain area is significantly affected by aspect. The impact of aspect on the vegetation growth is most significant in the vertical zone of 3200 m and 3600 m. The optimal vegetation in this zone is distributed between NW 340º and NE 70º (the darkest green area in Figure 2.5 with the NDVI value larger than 0.56). In other words, the optimal vegetation growth is on the shady side of the mountain. This is because of less evapotranspiration (ET) due to less radiation on the shady side which results less soil moisture stress. The less soil moisture condition can also be produced by less snow sublimation during the winter, lower temperatures and higher relative humidity. The less soil moisture stress on the shaded side is important for the vegetation growth in the Qilian Mountain area since it is located in a semi-arid region. It is also observed in Figure 2.5 that a better vegetation growth occurs over a larger elevation range on the side facing north and northeast. At the aspect of N 0º, for example, the NDVI value of 0.50 or larger are observed over the vertical zone from 3100 m to 3700 m while at the aspect of S 180° the same NDVI values are observed in a smaller zone from 3200 m and 3600 m. The much wider vertical zone with better vegetation growth on the shady side of Qilian Mountains may significantly affect the local water cycle and climate.

Third observation made in Figure 2.5 is the rate of change in the NDVI values with elevation. This rate varies more gently at lower elevations from 2000 m to 3400 m and more quickly when elevation is higher than 3400 m, implying that the vegetation growth is more sensitive in high altitude area. On the average, for example, it takes about 300 m (roughly from 2600 m to 2900 m) for the NDVI value to change from 0.3 to 0.4 at the lower altitude zone and only about 200 m at the higher altitude zone.

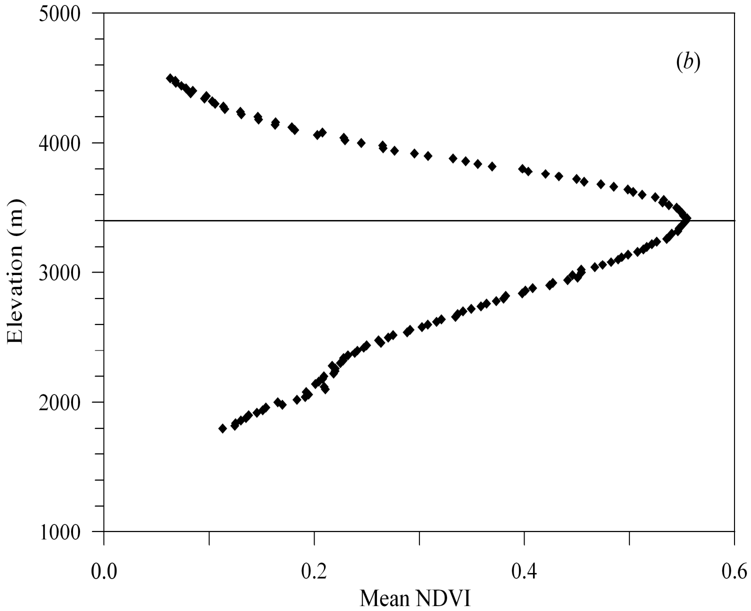
The relationship between NDVI values and the corresponding elevation is clearly shown in Figure 2.6a although the points scatter around. Nevertheless, the NDVI values corresponding to the same elevation were averaged to better show the relationship between the vegetation growth and elevation. A total of 221142 pairs of NDVI and elevation were obtained based on the 28 MODIS NDVI images of the 16-day composites of June, July, August, and September from 2000 to 2006. It is clearly shown in Figure 2.6b: the averaged NDVI increases with elevation and reaches its maximum value of about 0.56 at 3400 m and then decreases as the elevation increases beyond 3400 m, an clear indication that the vegetation growth is at its best at the elevation of 3400 m.

The effect of aspect on the vegetation growth is more clearly demonstrated in Figure 2.7 where the change of the NDVI values with aspect between the elevations of 3200 m and 3600 m was plotted. It is seen in Figure 2.7 that the NDVI value is larger than 0.55 or the vegetation growth is optimal in the aspect range of NW 340º to NE 70º. The NDVI value is less than 0.54 or the vegetation is worse between E 90º to W 270º. As we discussed above, this shows that the aspect of the mountain slopes significantly affects the vegetation growth in the study area. In general, the vegetation coverage on the sunny side in the semi-arid Qilian mountain area is less developed than that on the shady side because of more ET and thus higher soil moisture stress in the sunny side than in the shady side due to the differences in their solar radiation and higher land surface temperature.

Temperature and precipitation are probably the two most important primary climatic factors that control differences in the Earth's vegetation cover by affecting growth rate and plant reproduction (Wang et al., 2001). The relationships between eco-climatic conditions and vegetation growth are often complex and indirect. A better understanding of this relationship is needed for modeling regional atmosphere-biosphere processes (Martin, 1993). The difference in the vegetation growth of the two sides of Qilian Mountains can be explained by the difference in the solar radiation they receive or the difference in the land surface temperature (T). Similar to Figure 2.7, Figure 2.8 shows the change of land surface temperature with aspect for the vertical zone between 3200 m and 3600 m. It is seen in the figure that T on the sunny side between SE 155º and SW 235º is larger than 21.6 °C while T



(a)



(b)

Figure 2.6 (a) The change of the NDVI values with elevation in the northern part of the Qilian Mountain area before NDVI averaging in the same elevation; (b) The change of the NDVI values with elevation in the study area after NDVI averaging in the same elevation.

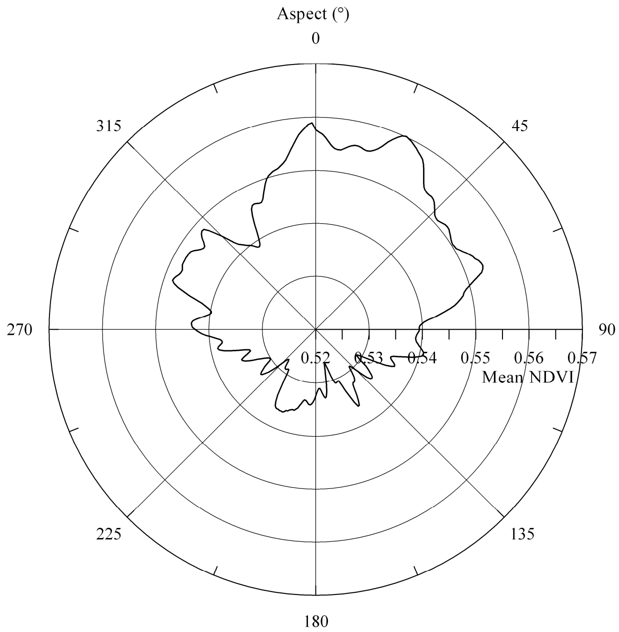


Figure 2.7 The change of the NDVI value with aspect for the elevation range of 3200 m to 3600 m in northern part of Qilian Mountain area.

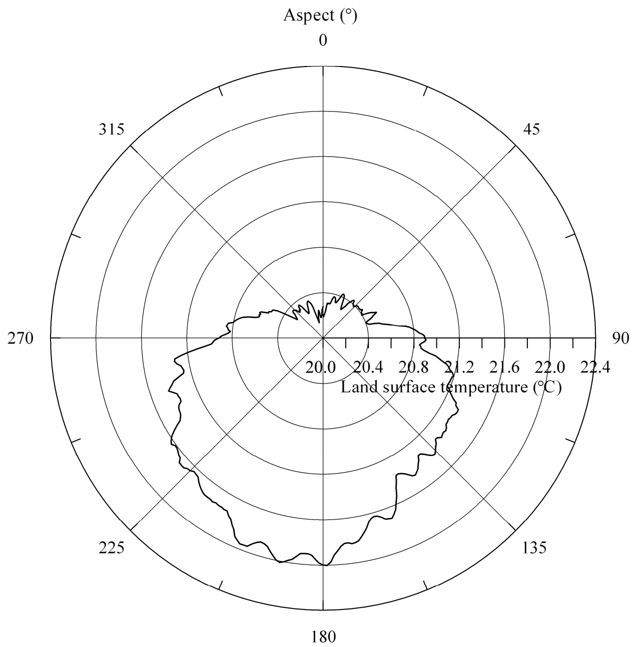


Figure 2.8 The change of the NDVI value with the land surface temperature for the elevation range of 3200 m to 3600 m in northern part of Qilian Mountain area.

on the shady slope between NE 55º and NW 310º is below 20.4 °C. A negative correlation exists between the NDVI values and the land surface temperature when the elevation is between 3200 m and 3600 m, as shown in Figure 2.9 where a straight line fits well to the data points. The aspect angle of 360º were divided into a total of 360 intervals with 1° in each interval and in each cell the land surface temperature from 2000 to 2006 were averaged in Figure 2.9. It is thus concluded that the vegetation growth in the Qilian area is significantly affected by the hillslope aspect with different solar radiation and land surface temperature.

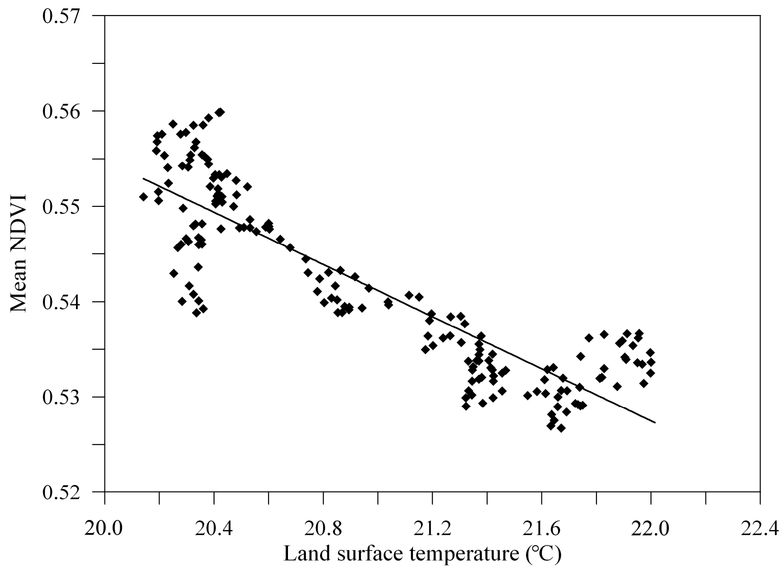


Figure 2.9 The relationship between the NDVI and the land surface temperature. The solid line is the best fit to the data with the linear regression line ($R^2 = 0.77$).

The precipitation values corresponding to the elevation interval of 10 m were averaged and the relationship between the mean precipitation and elevation was plotted in Figure 2.10 (the diamonds). The measured precipitation is positively correlated with the elevation and can be well fitted with the linear equation (the solid straight line in Figure 2.10):

$$P = 0.0058H + 26.4 \tag{2.1}$$

where P is the monthly mean precipitation of June, July, August, and September in mm from 2000 to 2001 and H is the elevation in m. It can be easily calculated based on Equation (2.1) that the monthly P increases 0.58 mm for every 100 m increase in elevation from June to September. The change of the land surface temperature with elevation was also obtained and plotted on the same graph (the triangles in Figure 2.10). The land surface temperature is negatively correlated with the elevation and is fitted well with a straight line (the dashed line in Figure 2.10). The relationship between land surface temperature and elevation is given by:

$$T = -0.0063H + 42.9 \tag{2.2}$$

where T is the mean land surface temperature of June, July, August, and September in °C from 2000 to 2006. Equation (2.2) indicates that the mean land surface temperature decreases 0.63 °C for every 100 m increase in elevation. A straight line at the elevation 3400 m is drawn in Figure 2.10 which intersects with the value of T around 21 °C and the value of P around 46 mm per month, indicating the optimal temperature and precipitation for the vegetation growth at the elevation of 3400 m in the northern part of the Qilian Mountain area.

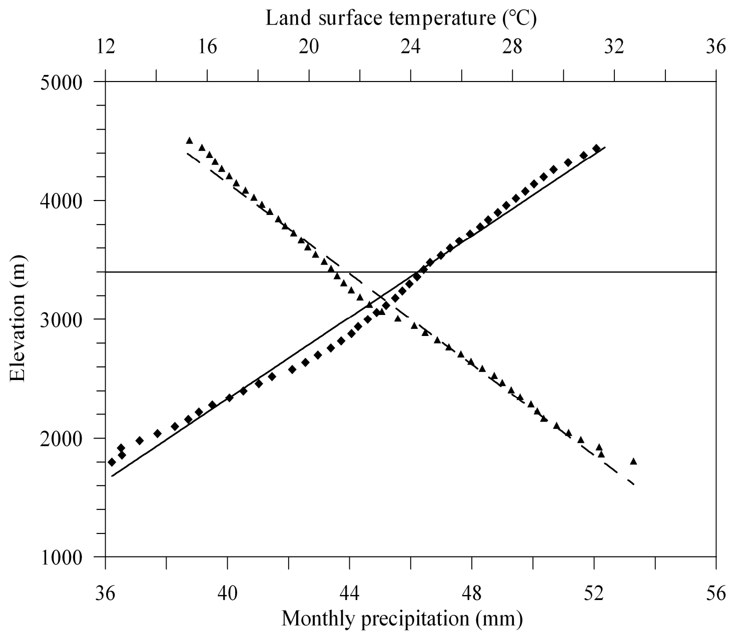


Figure 2.10 The change of precipitation (diamonds) and land surface temperature (triangles) with elevation. The solid line is the best fit with regression ($R^2 = 0.99$) to the precipitation and the dashed line is the best fit with regression ($R^2 = 0.98$) to the land surface temperature.

The change of the mean NDVI with the monthly P was plotted in Figure 2.11 which shows that the NDVI increases with P and reaches its peak value around 0.56 at P = 46mm per month and then decreases even though P increases. The relationship between the NDVI and P in Figure 2.11 can be well fitted with two straight lines, one for P < 46 mm with $R^2 = 0.96$ and

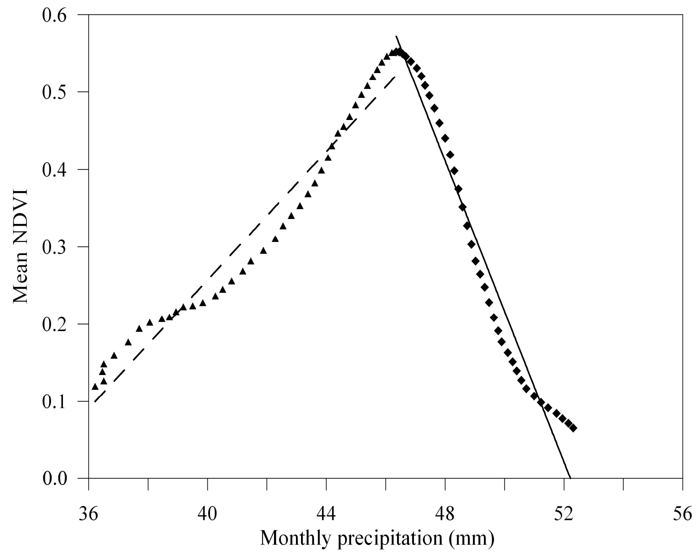


Figure 2.11 The change of the NDVI with the monthly precipitation. Two straight lines are fitted to the data, one for P < 46 mm ($R^2 = 0.96$) and the other for P > 46 mm ($R^2 = 0.99$).

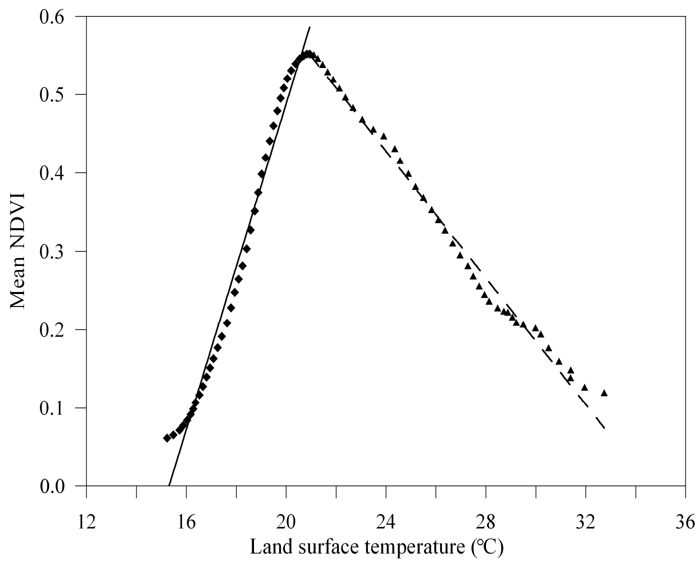


Figure 2.12 The change of the NDVI with the land surface temperature. Two straight lines are fitted to the data, one for T < 21 °C ($R^2 = 0.98$) and the other for T > 21 °C ($R^2 = 0.95$).

the other for P > 46 mm with R^2 = 0.99. A similar plot to Figure 2.11 is provided in Figure 2.12 for the change of the mean NDVI with the land surface temperature. It is seen that the NDVI increases with T and reaches its peak value at T = 21 °C and then decreases even though T increases. The relationship between the NDVI and T in Figure 2.12 can also be well fitted with two straight lines, one for T < 21 °C with R^2 = 0.98 and the other for T > 21 °C with R^2 = 0.95. Figure 2.11 and 2.12 clearly show that the largest NDVI values or the optimal conditions for the vegetation growth in the Qilian Mountain area are given by a monthly P around 46 mm and T around 21 °C. This best combination of precipitation and temperature exists at the elevation of 3400 m in the Qilian Mountain area. The vegetation at lower elevation (< 3200 m) does not grow well due to less precipitation and higher temperature while the vegetation cover at higher elevation (> 3600 m) is poor due to lower temperature. In fact, the land surface is covered by snow for two-thirds of a year when the elevation is higher than 3900 m which is certainly not suitable for vegetation growth even though there is plenty precipitation.

2.5 Conclusions

The spatial distribution of vegetation in the Qilian Mountain area was quantified with remote sensing data. The MODIS NDVI values for June, July, August, and September are the optimal indicators for the vegetation growth during a year in this area and thus were used in this study. Based on the results obtained by analyzing the NDVI data for seven years from 2000 to 2006, the following important conclusions can be drawn.

1) Elevation and aspect are two very important factors for the vertical distribution of vegetation in Qilian Mountain area because of their control on precipitation and temperature;

2) In the Qilian Mountain area the vegetation was at a maximum between the elevations of 3200 m and 3600 m with the NDVI values larger than 0.50 and a peak value of larger than 0.56 around 3400 m. The optimal vegetation growth with the largest NDVI value (> 0.56) is found in the shady side between NW (340º) to NE (70º) within the elevation range of 3200 m and 3600 m;

3) Better vegetation growth occurs over a larger elevation range on the shady side than the sunny side in this area because of the reduced ET and less soil moisture stress on the shady side;

4) The vegetation growth is more sensitive in high altitude area since the rate of change in the NDVI values with elevation varies gently at lower elevations from 2000 m to 3400 m and more quickly at higher elevations than 3400 m;

5) The monthly mean precipitation of 46 mm (552 mm/year) and the land surface temperature of around 21 °C provide the optimal conditions for the vegetation growth between 3200 m and 3600 m in the northern part of the Qilian Mountain area.

CHAPTER 3

Impact and consequences of evapotranspiration changes on water resources availability in the arid Zhangye basin (China)*

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* Based on: Jin, X.M., Wan, L., Schaepman, M.E., Clevers, J.G.P.W., Su, Z., 2008. Impact and consequences of evapotranspiration changes on water resources availability in the arid Zhangye basin (China). *International Journal of Remote Sensing* (in press).

Impact and consequences of evapotranspiration changes on water resources availability in the arid Zhangye basin (China)

Abstract

Evapotranspiration (ET) plays an important role in the hydrological cycle and it is essential to estimate ET accurately for the evaluation of available water resources. This is most critical in (semi-)arid regions. In this paper, the long-term change of daily ET in the semi-arid Zhangye basin in northwest China and its impact factors were studied. The spatial distribution of ET was assessed by using the energy balance approach SEBS (Surface Energy Balance System). Cloud free NOAA-AVHRR September images over the Zhangye basin from the year 1990 to 2004 were used in combination with SEBS to estimate ET at a spatial resolution of 1.1 km. This daily ET was converted to a monthly ET (for September) using daily pan evaporation values from a meteorological station in the study area. Spatial aggregation of all pixels yielded the total monthly ET for the whole study area. Subsequently, the monthly ET was extrapolated to annual ET values using the pan evaporation data. Results were validated with ground-based measurements on the water balance for the whole Zhangye basin. The annual ET increased gradually from 23.7×10^{8} m^{3} in 1990 to 26.9×10^{8} m^{3} in 2004 for the Zhangye basin. The main cause appeared to be vegetation change.

Keywords: Evapotranspiration, Surface Energy Balance System (SEBS), Water resources, NOAA-AVHRR data, Zhangye basin

3.1 Introduction

Sustainable development of arid and semi-arid areas, like the arid inland basins in Northwest China, will largely depend on the availability of water resources. For the assessment of water resources in a large arid inland basin one usually needs to quantify the inflows from high mountains to the basin and the evapotranspiration (ET) loss in the basin. Both quantities are highly variable in time and space. River gauging stations can be established in large rivers to measure river discharges, but the discharges in smaller tributaries discharging directly in the river basin are usually difficult to quantify. In an inland basin, ET is the only major loss term occurring that is relevant for the water balance. ET plays an important role in the hydrological cycle. It is site specific and varies with local meteorological conditions (radiation, wind, temperature, humidity of the air) and surface conditions (surface type, soil wetness, vegetation development stage, etc.) (Hare, 1980; Willmott et al., 1985; Mintz and Walker, 1993; Potter et al., 1993; Sun et al., 2004).

The Heihe river basin is the second largest inland river basin in China, covering an area of 128,283 km^2. With the increase of population and farmland in the Zhangye basin, which is the middle stream area of the Heihe river basin, the water consumption has increased gradually during recent years. Most water is used for agriculture in the Zhangye basin and the irrigation rate is more than 90% of the agricultural water consumption. The water consumption increases continuously and part of the water resources cannot be used effectively because of net ET loss. It is causing a decrease of incoming water in the downstream area resulting in a shrinking of the Ejina oasis area that is located downstream. The eco-environment of the downstream area is degrading and it is causing a series of environmental problems, like land desertification. In order to properly estimate the decrease in water consumption and the net ET loss in the Zhangye basin, the amount of water going into the atmosphere should be estimated first. Subsequently, the incoming water in the downstream area should be estimated as well. Concerning the water balance, precipitation is the only recharge resource and the ET is the only loss term in the inland river basin. Therefore, quantitative estimation of ET for the Zhangye basin and finding the impact factors on it can significantly contribute to improving the eco-environment, balancing the water consumption and properly allocating available water resources.

To date, there are a series of methods available for ET estimation, such as the energy balance method, the aerodynamic resistance method and the eddy correlation method (Ke et al., 1995; Mo and Liu, 1997; Kim, 1998; Mo, 1998; Liu and Sun, 1999). These approaches generally rely on ground meteorological observations on a point basis. In order to estimate the spatial distribution of ET, a network of ‘point’ data have to be interpolated to a regional scale. As an alternative, methods using remote sensing information to estimate ET have been proposed. Because remotely sensed data have the advantage of a large area coverage, frequent update and consistent quality, remote sensing based ET estimation has been a subject of many studies (Rango, 1989; Kuittinen, 1992; Kite and Pietroniro, 1996; Stewart et al., 1996; Sorooshian et al., 1997; Rango and Shalaby, 1999; Mu et al., 2007; Liu et al., 2007; Sobrino et al., 2007; Santanello et al., 2007; Wang et al., 2007). As ET cannot be directly measured by remote sensing methods, indirect estimation of ET using remotely sensed data has been explored with several approaches, such as the energy balance approach (Choudhury, 1997; Seguin, 1997) and the Priestley-Taylor or modified Priestley-Taylor approach (Jiang and Islam, 2001).

In recent years, methods for deriving surface fluxes using remote sensing data have been developed, such as the model SEBAL (Surface Energy Balances Algorithm for Land) (Bastiaanssen et al., 1998; Bastiaanssen, 2000; Bastiaanssen et al., 2002, 2005), SEBS (Surface Energy Balance System) (Su, 2002), TSEB (Two-Source Energy Balances) (Norman, et al., 1995) and S-SEBI (Simplified Surface Energy Balances Index) (Roerink et al., 2000). SEBAL is a robust remote sensing model that can be applied to estimate the different components of the energy balance of the earth surface and thus also actual evapotranspiration (ET). TSEB modeling scheme has been developed to use either microwave-derived near-surface soil moisture or radiometric surface temperature as the key remotely sensed surface boundary condition for computing spatially distributed heat fluxes. The SEBS system was developed by Su (2002) in order to estimate land surface fluxes using remotely sensed data and available meteorological observations. Being applied to many case studies in Europe and Asia (Oku et al., 2007; Ma et al., 2007; Jia et al., 2007; Su, 2002), SEBS was selected to be the methods of ET estimation in this study.

Although these models have been proposed to estimate regional ET, the accuracy of the results still requires validation before they can be used for water resources assessment in a certain region. In most of the researches, the results of ET estimation are validated by monitoring data at local scale (Wilson et al., 2002; Sun et al., 2004; Salazar and Poveda, 2006; Zwart and Bastiaanssen, 2007). The purpose of this study is to estimate the ET of the Zhangye basin in Northwest China and to validate the ET result by using the water balance of the basin. The specific objectives are: (1) to estimate the ET of the Zhangye basin using the SEBS model, (2) to validate the accuracy of the ET result using the water balance, and (3) to analyze the long-term change of ET and the major impact factors on this ET.

3.2 Material and Methods

3.2.1 Study area

The study area is the Zhangye basin, which is located in the middle stream area of the Heihe river in Northwestern China, roughly ranging between 97°12’-102°20’E and 37°28’-39°57’ N. The total area is 24,060 km^2 and it is lying between the Yingluo gorge and the Zhengyi gorge (Figure 3.1). With a typical continental arid climate, the precipitation in the study area is small and concentrated from June to September. The mean annual precipitation is spatially varying between 54.9 and 436.2 mm.

The Heihe river is the longest river in the study area. It flows along the south slope of the Qilian mountains and flows out of the mountains from the Yingluo gorge and enters into the Zhangye basin. After that, the Heihe river flows through the Zhengyi gorge into the Ejina oasis in Inner-Mongolia, and finally discharges into the east and west Juyan lakes (Figure 3.1). The length of the stream is 821 km. The Zhangye basin is located in the Heixi Corridor between the Yingluo gorge and the Zhengyi gorge.

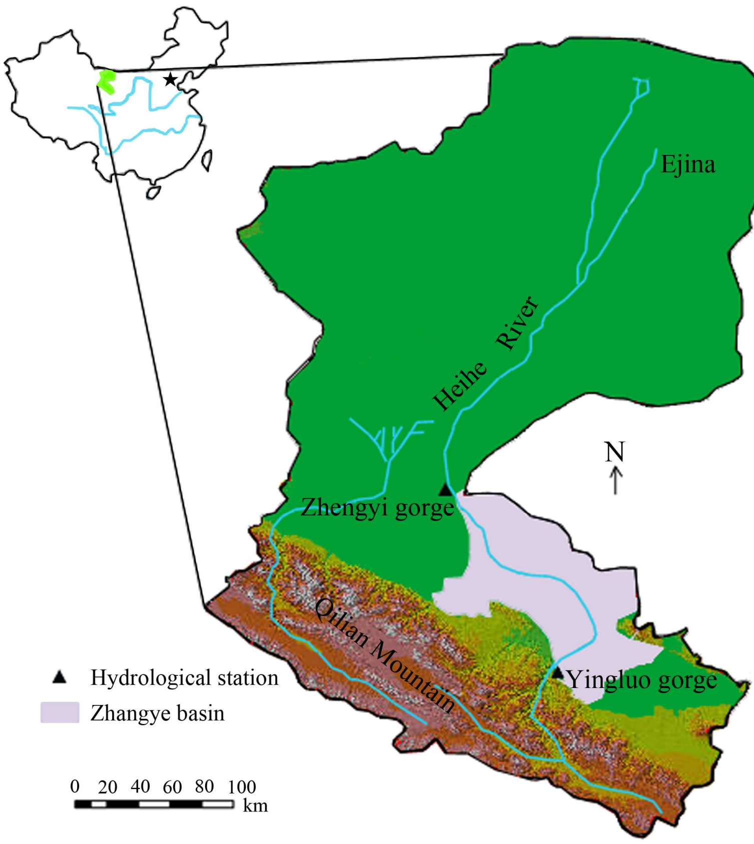


Figure 3.1 The location of the study area. The Zhangye basin is between the Yingluo gorge and the Zhengyi gorge. The Yingluo gorge is in the hill-side of the Qilian Mountains which is upstream of the Heihe River. The Zhengyi gorge is in the middle stream of the Heihe River.

3.2.2 Methodology

The surface energy balance is commonly written as

$$R_n = G + H + \lambda E \tag{3.1}$$

where R_n is the net radiation, G_0 is the soil heat flux, H is the turbulent sensible heat flux, and λE is the turbulent latent heat flux (λ is the latent heat of vaporization and E is the actual evapotranspiration).

The equation to calculate the net radiation is given by

$$R_n = (1-\alpha)\cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4 \tag{3.2}$$

where α is the surface albedo, ε is the emissivity of the surface, R_{swd}, R_{lwd} are incoming shortwave and longwave radiation respectively, σ is the Stefan-Bolzmann constant, and T_0 is the surface temperature. α, ε and T_0 are physical parameters and can be derived from satellite data. The same estimation procedure as described by Su et al. (1999) was used in this study. R_{swd} and R_{lwd} are measured by a meteorological measurement system.

The equation to calculate the soil heat flux is parameterized as follows

$$G_0 = R_n \cdot [\Gamma_c + (1-f_c)\cdot(\Gamma_s - \Gamma_c)] \tag{3.3}$$

where Γ_c and Γ_s are empirical coefficients. For most bare soil conditions a Γ_s value of 0.315 is valid (Kustas and Daughtry, 1989), and for full vegetation often Γ_s is assumed to be 0.05 (Monteith, 1973). An interpolation is then performed between these cases using the fractional canopy coverage f_c. f_c can be derived by following equation:

$$f_c = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{3.4}$$

The surface energy balance computation with the SEBS algorithm is based on the determination of the relative evaporative fraction. To determine the relative evaporative fraction, the energy balance solution at limiting cases is used. At the dry-limit, the latent heat (or the evaporation) becomes zero due to the limitation of soil moisture, and the sensible heat flux is at its maximum value. It follows from Eq. (3.1) that

$$\begin{aligned} \lambda E_{dry} &= R_n - G_0 - H_{dry} \equiv 0, \quad or \\ H_{dry} &= R_n - G_0 \end{aligned} \tag{3.5}$$

At the wet-limit, where the evapotranspiration takes place at potential rate, λE_{wet} (i.e. the evapotranspiration is only limited by the available energy under the given surface and atmospheric conditions), the sensible heat flux takes its minimum value, H_{wet} i.e.

$$\lambda E_{wet} = R_n - G_0 - H_{wet}, \quad or$$

$$H_{wet} = R_n - G_0 - \lambda E_{wet} \tag{3.6}$$

The relative evaporation then can be estimated as

$$\Lambda_r = 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}} \tag{3.7}$$

The evaporative fraction is finally given by:

$$\Lambda = \frac{\lambda E}{H + \lambda E} = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \cdot \lambda E_{wet}}{R_n - G} \tag{3.8}$$

Eqs. (3.1) – (3.8) constitute the basic formulation of SEBS. The actual sensible heat flux H in SEBS is obtained by solving a set of non-linear equations and is constrained in the range set by the sensible heat flux at the wet limit H_{wet}, and the sensible heat flux at the dry limit H_{dry}.

It is assumed that the daily evaporative fraction is approximately equal to the instantaneous value. The daily evaporation can be determined as (Su, 2002)

$$E_{daily} = 8.64 \times 10^7 \times \frac{\Lambda \cdot \overline{R_n}}{\lambda \rho_w} \tag{3.9}$$

where E_{daily} is the actual evaporation on a daily basis ($mm.d^{-1}$), λ is the latent heat of vaporization (JKg^{-1}), ρ_ω is the density of water (Kgm^{-3}) and $\overline{R_n}$ is the daily net radiation flux.

3.2.3 Dataset

The Advanced Very High Resolution Radiometer (AVHRR), onboard the National Oceanic and Atmospheric Administration's (NOAA) Polar Orbiting Environmental Satellites (POES), has unique characteristics in terms of spectral response, image geometry, frequency of coverage, and accessibility that make it useful for applications in oceanography, terrestrial sciences, and meteorology. AVHRR is a broad-band, four or five channel (depending on the model) scanner, sensing in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum. NOAA/AVHRR remote sensing data were used for evapotranspiration estimation in this study. The data were retrieved from NOAA's Satellite Active Archive (SAA). SAA is a digital library of real-time and historical satellite data and the data can be downloaded free. 11 Sets of cloud free NOAA satellite images over the Zhangye basin from the year 1990 to 2004 were used to estimate the daily ET at a spatial resolution of 1.1 km. For each of the years a September image was used. Due to cloud cover, there was no image available in 1992, 1994, 1999 and 2000. In order to relate results to meteorological and runoff data, four sets of cloud free NOAA satellite images from September in the year 1995 to 1998 were used for the validation of ET in the Zhangye basin.

The meteorological dataset used in this study includes the altitude of the Zhangye station, sea level pressure, air temperature, wind speed, wind direction, relative humidity and pan evaporation (open water surface evaporation). Pre-processing of the data was done to derive the variables at satellite passing time needed as inputs for SEBS.

The mean gridded rainfall data from 1995 to 1998 are given on a monthly basis and its spatial resolution is 1 km. The monthly rainfall data was published by the Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.naturalresources.csdb.cn). This database contained the monthly rainfall data from 1971 to 2001 from 700 meteorological stations in China. The interpolation algorithm in the software was used which was published by the Centre for Resources and Environmental Studies, the Australian National University (http://cres.anu.edu.au/). The software package provides a facility for transparent analysis and interpolation of noisy multi-variate data using thin plate smoothing splines. The package provides comprehensive statistical analyses, data diagnostics and spatially distributed standard errors. It also supports flexible data input and surface interrogation procedures. Thin plate smoothing splines can in fact be viewed as a generalization of standard multi-variate linear regression, in which the parametric model is replaced by a suitably smooth non-parametric function. The degree of smoothness, or inversely the degree of complexity, of the fitted function is usually determined automatically from the data by minimizing a measure of the prediction error of the fitted surface given by the generalized cross validation (GCV). Recent applications of thin plate smoothing splines to annual and daily precipitation data have been described by Hutchinson (1995, 1998ab). This method considers the impact of climate and topography.

3.3 Result and discussion

3.3.1 Spatial distribution of daily ET in the Zhangye basin

The spatial distribution patterns of daily ET as estimated using SEBS over the Zhangye basin can be observed in Figure 3.2. Figure 3.2a shows the spatial distribution of daily ET on 28 September 1995, having a mean value of 1.37 mm day^{-1}. The daily ET is between 0 and 1 mm day^{-1} in the mountainous areas and this area is 42.39% of the total study area. The value is between 1 and 3 mm day^{-1} in the corridor area with better vegetation and this area is 48.66% of the Zhangye basin. The highest daily ET is between 3 and 4 mm day^{-1} and it is distributed in the hillside area of the Qilian mountains.

The distribution patterns of the other three years are similar to the year 1995. The daily ET is relatively higher on 15 September 1996. The range of values in the corridor area is between

3 and 4 mm day^{-1} and this area is 10.05% of the total study area. The daily ET is very high on 4 September 1998. Most of the ET in the corridor is higher than 4 mm day^{-1} and this area is 23.88% of the Zhangye basin. The mean daily ET values on 15 September 1996, 3 September 1997 and 4 September 1998 are 1.31, 1.18, and 2.00 mm day^{-1}, respectively. The statistics of daily ET for 1995, 1996, 1997 and 1998 are given in Table 3.1.

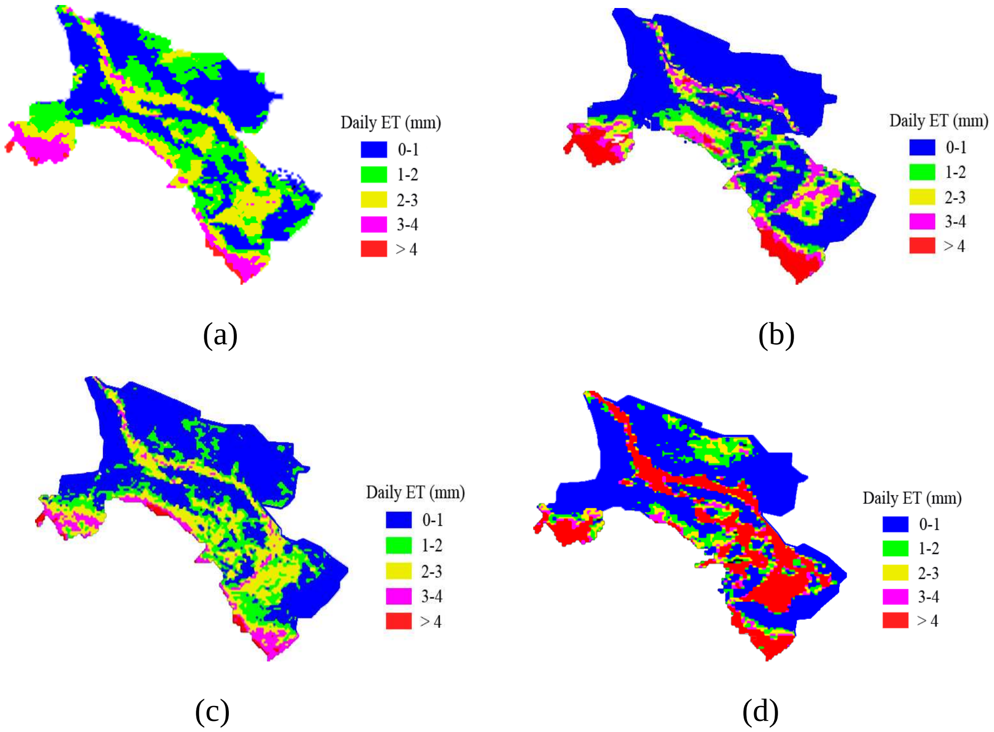


Figure 3.2 The spatial distribution pattern of daily ET in the Zhangye basin on 28 September 1995 (a), 15 September 1996 (b), 3 September 1997 (c), and 4 September 1998 (d). The legend provides the ET in mm day^{-1}.

Table 3.1 Statistics of daily ET for the study area

Daily ET (mm/d)	09-28-1995 Percentage of area	09-28-1995 Mean value	09-15-1996 Percentage of area	09-15-1996 Mean value	09-03-1997 Percentage of area	09-03-1997 Mean value	09-04-1998 Percentage of area	09-04-1998 Mean value
0-1	42.39	0.35	57.50	0.14	52.44	0.23	51.83	0.12
1-2	30.02	1.47	12.82	1.48	20.12	1.50	11.01	1.51
2-3	18.64	2.46	11.93	2.50	19.54	2.44	7.90	2.46
3-4	7.70	3.41	10.05	3.45	6.40	3.40	5.39	3.48
> 4	1.25	4.29	7.70	5.13	1.51	4.29	23.88	5.84

3.3.2 Annual ET estimation

Monthly ET estimation based on daily ET

The daily ET values of the SEBS results were averaged for all pixels of the study area in each image and this mean value was considered to be the daily ET of the whole Zhangye basin. There are in total 6221 pixels in the study area. Due to cloud cover, there are only very few NOAA satellite images available in one month and the daily ET for each day could not be obtained. The extension of daily ET to monthly ET, and further to annual ET is very important. In this study, the monthly ET was estimated by combination of the SEBS results and the daily data of meteorological stations. Take the year 1995 as example. The SEBS result of mean daily ET is 1.37 mm on 28 September 1995, and the pan evaporation value from the meteorological station is 6.9 mm for the same day. The daily ET of other days in September can be obtained by Equation (3.10) and the summation is the monthly ET of September.

$$ET_{S.i} = \frac{ET_{S.d}}{ET_{M.d}} \times ET_{M.i} \qquad (3.10)$$

where i is the number of days from 1 to 30 in September; $ET_{S.i}$ is the predicted SEBS daily ET for day i in September after calculation; $ET_{S.d}$ is the mean daily ET from the SEBS result and this value is 1.37 mm on 28 September 1995; $ET_{M.d}$ is the observed pan evaporation of the meteorological station on the same day, and it is 6.9 mm on 28 September 1995; $ET_{M.i}$ is the observed daily pan evaporation of the meteorological station for day i in September.

The Zhangye basin is in arid area and the vegetation, wind speed and temperature in September is in the average values among a year. The variation of the vegetation, wind speed and temperature in September is relatively small. Therefore, the quotient of $ET_{S.d}/ET_{M.d}$ was assumed not change in a month in this study. The predicted daily ET of SEBS for each day in September can be calculated by Equation (3.10) and the summation yields the monthly SEBS ET of September. The amount of monthly ET of the total basin was estimated by multiplying the area of the Zhangye basin. The area can be obtained based on the total number of pixels of the study area (6221 pixels) multiplying the resolution of the NOAA data (1100×1100 km^2).

Annual ET estimation

Based on the observed daily pan evaporation at the Zhangye meteorological station, the monthly evaporation of every September and the annual evaporation of each year from 1995 to 1998 were calculated. The monthly evaporation of September from 1995 to 1998 are 9.4%, 9.6%, 9.5% and 9.6% of the annual value, respectively. Therefore, the predicted annual ET based on SEBS can be obtained using Equation (3.11).

$$ET_y = ET_m / K \tag{3.11}$$

where ET_y is the predicted annual ET from SEBS; ET_m is the predicted monthly ET from SEBS in September obtained by Equation (3.10); K is the rate of monthly evaporation of September to the annual value.

The predicted annual ET from the SEBS result based on Equation (3.11) is shown in Table 3.2. We see the lowest annual ET values for 1995 and 1997 and a relatively high value in 1998.

Table 3.2 Predicted annual ET by SEBS in the Zhangye basin from 1995 to 1998.

Year	Monthly ET of September (10^8 m^3)	Annual ET(10^8 m^3)
1995	2.30	24.47
1996	2.74	28.54
1997	2.37	24.98
1998	3.35	34.90

3.3.3 Validation of ET

The Zhangye basin is considered as an isolated hydrological unit where recharge, runoff and discharge occur. Impermeable and weakly permeable layers are distributed around the base and boundary of the basin. The precipitation in the Qilian mountain area recharges the groundwater in the drainage area, and it discharges by the ET and the spring in the discharge area. The Zhangye basin is a downfaulted basin and there are water-resisting faults around it. The main recharge of the groundwater is from the leakage of the surface water of the rivers and the precipitation. Therefore, the total amount of water resources in the Zhangye basin is consists of the outflow of the mountain-gap (Yingluo gorge), the precipitation and the lateral runoff outside the basin. In this hydrological unit, a water resources system of river-groundwater-spring-river is constituted by the mutual change between the surface water and the ground water (Figure 3.3). In this closed basin of Zhangye, the inflow and outflow are equal in a hydrological budget. Considering the water balance for a large watershed, the hydrological balance equation can be given as (Gupta, 1989)

$$E = P + R \pm \Delta W \tag{3.12}$$

where E is the land ET, P is the precipitation, R is the water consumption and ΔW is the change of water storage in the Zhangye basin.

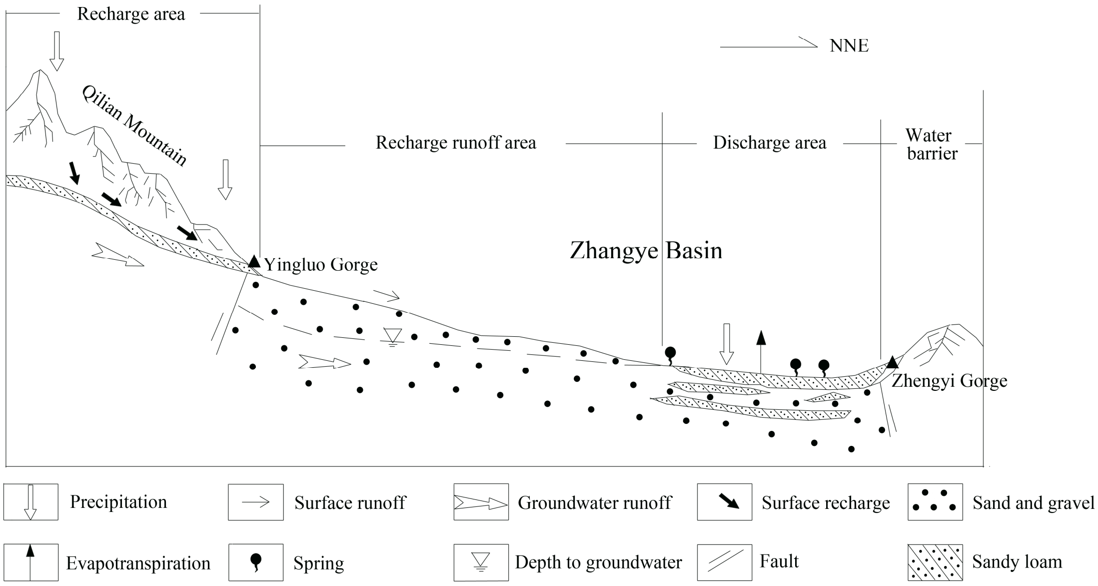


Figure 3.3 Cross section of the water resources system for the Zhangye basin in the middle stream of the Heihe River basin. The Zhangye basin is located between two faults. The recharge of the system is the precipitation of Qilian Mountains, the runoff of the Heihe River and groundwater. The discharge path is evapotranspiration and a spring. The Yingluo gorge is the upstream of the Heihe River and the Zhengyi gorge is in the middle stream. The difference between the runoff at the two gorges is the water consumption of the Zhangye basin.

Over a long period of time (≥1 year), water storage stays more or less the same ($\Delta W \approx 0$) and thus $ET = P + R$. The inflow of the Zhangye basin is mainly from the Yingluo gorge upstream of the Heihe river basin, and the outflow of the Zhangye basin is equal to the runoff at the Zhengyi Gorge in the middle stream of the Heihe river basin. Equation (3.12) can now be rewritten as

$$E = P + R_y - R_z \tag{3.13}$$

where R_y is the runoff at the Yingluo gorge and R_z is the runoff at the Zhengyi gorge.

The annual mean runoff at the Yingluo gorge is 15.98×10^8 m^3/a, the mean runoff of other small rivers was 6.277×10^8 m^3/a in total, so the summation of the inflow in the Zhangye basin was 22.257×10^8 m^3/a. Based on the statistics, the rate of the annual mean runoff at the Yingluo gorge to the total inflow of the Zhangye basin is 0.718 (15.98/22.257). Therefore, the annual inflow of the Zhangye basin can be estimated by the following equation

$$R_i = R_y / 0.718 \tag{3.14}$$

where R_i is the total annual inflow of the Zhangye basin and R_y is the annual runoff at the Yingluo gorge.

The annual ET of the Zhangye basin from 1995 to 1998 based on the water balance equation is given in Table 3.3. This ET was determined by the inflow plus the precipitation minus the outflow (Table 3.3). As can be seen, the annual ET based on the water balance compared well with the SEBS result (Table 3.2 and 3.3). Thus, the SEBS algorithm can be used to effectively estimate annual ET in the Zhangye basin.

Table 3.3 The annual ET (10^8 m^3/a) of the Zhangye basin from 1995 to 1998 based on the water balance

Year	Inflow	Outflow	Precipitation	ET
1995	18.25	7.54	12.44	23.15
1996	25.18	9.55	11.91	27.55
1997	19.28	5.13	8.84	22.98
1998	30.06	9.46	12.84	33.43

3.4 Annual ET change and the impact factor

3.4.1 Annual ET change

The daily ET values of September from 1990 to 2004 in the Zhangye basin were calculated using the SEBS model, and extrapolated to estimate monthly ET and annual ET based on observation data from the meteorological stations. Due to cloud cover, there was no NOAA satellite image available in 1992, 1994, 1999 and 2000. Figure 3.4 illustrates the annual ET

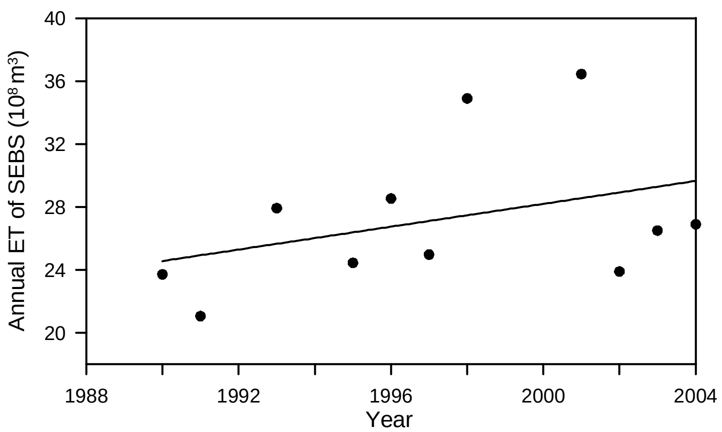


Figure 3.4 The annual ET change in the Zhangye basin from the year 1990 to 2004. The solid line is the fitted line.

change in the Zhangye basin from the year 1990 to 2004. The result indicates that the annual ET increased gradually from 1990 to 2004. The annual ET increased from 23.7×10^{8} m^{3} in 1990 to 26.9×10^{8} m^{3} in 2004 and the increase rate is 0.21×10^{8} m^{3} per year in the Zhangye basin.

3.4.2 Impact factor

Vegetation is one of the important impact factors on evapotranspiration. The NDVI is an index derived from reflectance measurements in the red and infrared part of the electromagnetic spectrum to describe the relative amount of green biomass per pixel (Deering, 1978). This index is an indicator of photosynthetic activity of plants and has been widely used for assessing vegetation phenology and for estimating landscape patterns in terms of primary productivity (Sellers, 1985; Tucker and Sellers, 1986). The NDVI was designed to quantitatively evaluate vegetation growth: higher NDVI values imply more vegetation coverage, lower NDVI values imply less or non-vegetated coverage and zero NDVI indicates rock or bare land.

Due to the arid and semi-arid climate in the Zhangye basin, most of the vegetated areas concern agricultural land. In general, this means vegetation growth occurs if NDVI is larger than 0.1 and an NDVI value greater than 0.3 represents agricultural land. In this study, the NDVI values of each September from 1990 to 2004 were calculated based on NOAA satellite data. The number of pixels with an NDVI greater than 0.1, 0.2 and 0.3 were counted for each image (Figure 3.5). The frequency can represent the area of vegetation coverage.

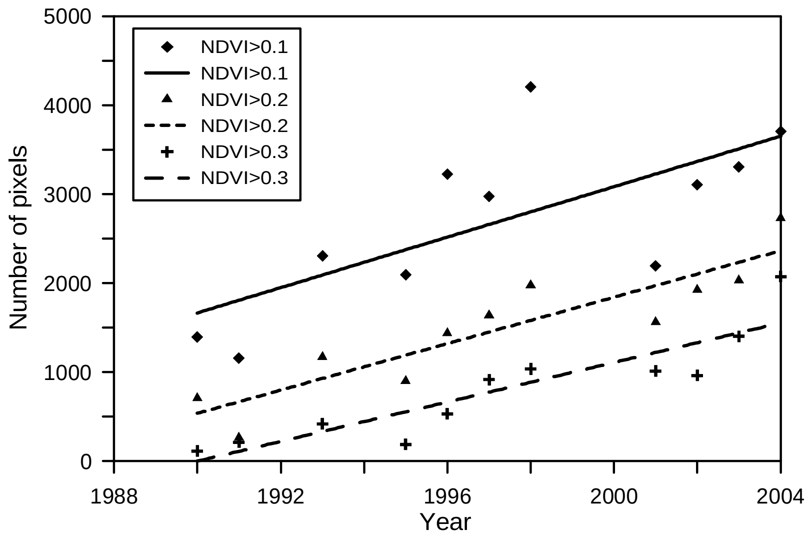
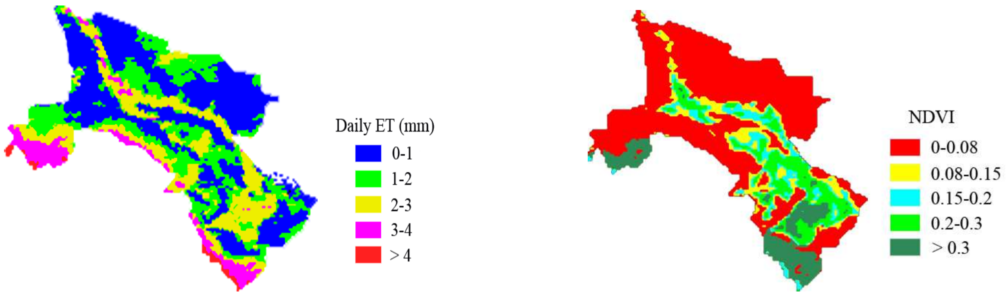


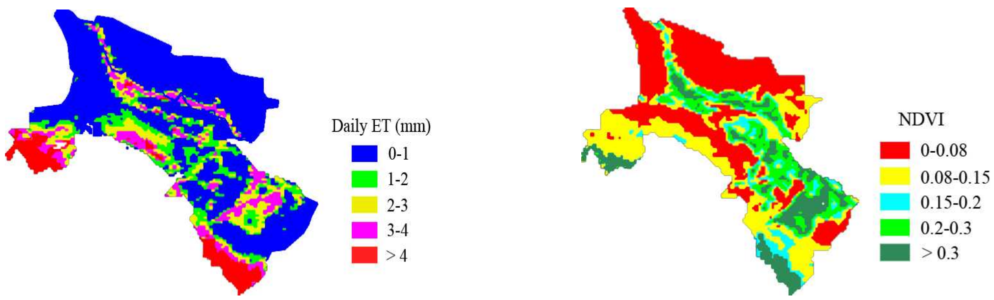
Figure 3.5 The variation of pixel numbers from 1990 to 2004 with NDVI greater than 0.1, 0.2 and 0.3, respectively.

Figure 3.5 illustrates that the areas of NDVI greater than 0.1, 0.2 and 0.3 increased gradually with time and this result indicated that the vegetation growth of the Zhangye basin in September has become better with time. The increase in NDVI greater than 0.3 showed that the agricultural land has increased gradually from 1990 to 2004. The Zhangye basin is one of the most important agricultural areas in the Hexi Corridor. The increase of agricultural area caused an increase of the water demand and resulted in an increase of evapotranspiration. Therefore, the vegetation change, especially the increase of agricultural area, is the main factor explaining the increase of ET in the Zhangye basin.

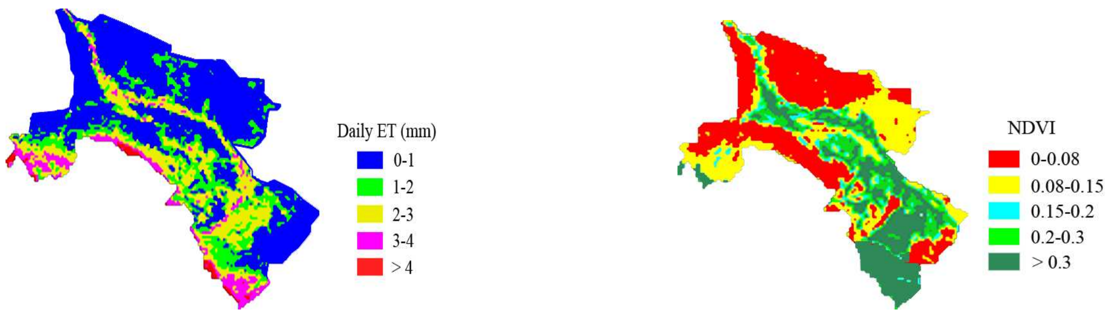
In order to further explain the impact of vegetation on the ET, the spatial correlation between the SEBS daily ET and the corresponding NDVI is shown in Figure 3.6. Figure 3.6a illustrates the correlation between the SEBS daily ET and the NDVI on 28 September 1995 in the Zhangye basin. The result indicates that the area with a large ET value was in the area with good vegetation growth (large NDVI values) and it was mainly occurring in the corridor area. The daily ET value is between 1 and 3 mm day^{-1} and the NDVI is larger than 0.2 in the corridor area. The ET in the southern area (close to Qilian mountains) is very large and the daily ET is between 3 and 4 mm day^{-1}. Figure 3.6b shows the correlation between the daily ET and the NDVI on 15 September 1996 and it has a similar result as Figure 3.6a. Figure 3.6c compares the daily ET and the NDVI on 3 September 1997. As can be seen, the NDVI of 1997 is larger than that of 1995 and 1996. The vegetation in the Zhangye basin is mainly agricultural land, the crop has matured and changed into the ripening phase at the end of September. The NDVI results of 1995 and 1996 were in the middle and the end of the September, respectively. The one of 1997 was still at a full green crop. Therefore, the NDVI of 1997 has a relatively large value. Figure 3.6d shows that the vegetation is better in 1998 and the daily ET is higher than in the other three years. In 1998, the precipitation was very large and this made the inflow of the Yingluo gorge higher, which resulted in a good vegetation growth and high ET in the Zhangye basin. The SEBS daily ET was larger than 4 mm day^{-1} in the corridor area. Based on the above analysis, the area with a large daily ET is corresponding to the large NDVI area and this result validated spatially that vegetation is a very important impact factor for the ET.



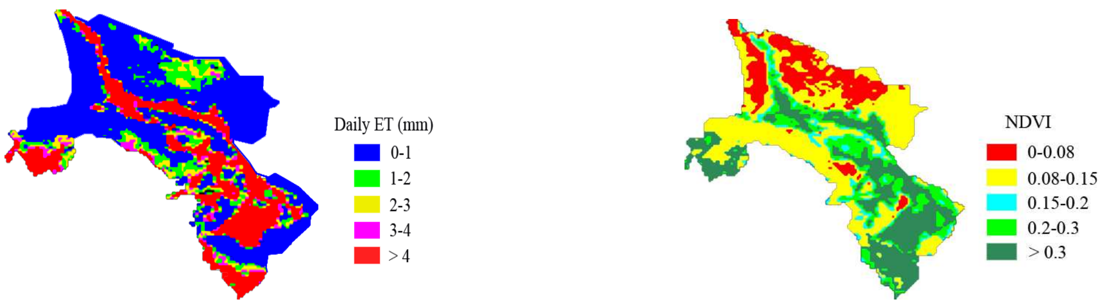
(a)



(b)



(c)



(d)

Figure 3.6 The spatial correlation between the SEBS daily ET and the NDVI in the Zhangye basin on 28 September 1995 (a), 15 September 1996 (b), 3 September 1997 (c), and 4 September 1998 (d).

The relation between the annual ET result obtained by using SEBS and the mean NDVI based on NOAA satellite data from 1990 to 2004 is shown in Figure 3.7. The annual ET increased with an increase of the mean NDVI. The increase rate of the annual ET is 0.21×10^8 m^3 and the increase of the mean NDVI is 0.01 per year. This result proved temporally that vegetation is a very important impact factor for the ET.

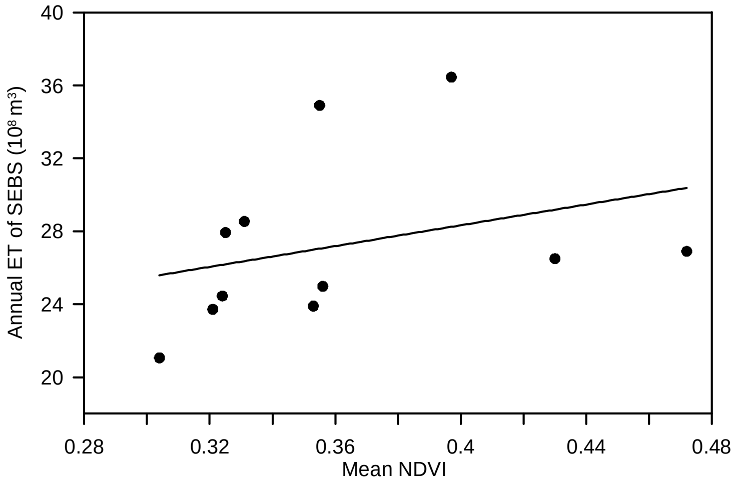


Figure 3.7 The relation between the annual ET based on SEBS and the mean NDVI based on NOAA satellite data from 1990 to 2004 in the Zhangye basin (Y=28.5X + 16.93, R^2=0.10).

3.5 Conclusions

As a key component in the water and energy budget, the long-term change of ET in the semi-arid Zhangye basin in China and its impact factors were analyzed in this paper. The following conclusions can be drawn based on the results obtained.

1) The annual ET was estimated based on the SEBS algorithm (Surface Energy Balance System) and increased gradually from 1990 to 2004. The annual ET increased from 23.7×10^8 m^3 in 1990 to 26.9×10^8 m^3 in 2004 and the increase rate is 0.21×10^8 m^3 per year in the Zhangye basin;

2) The accuracy of annual ET results based on the SEBS model was validated using a water balance for the whole Zhangye basin from 1995 to 1998. Results show that the SEBS algorithm can be used to effectively estimate annual ET in the Zhangye basin;

3) The main impact factor of the long-term increase of annual ET was the vegetation change. The annual ET increased with the mean NDVI and the area with a large daily ET is corresponding to the area with large NDVI values in the Zhangye basin;

4) The result of this study can provide reference for the government to decide on a new policy of water resources allocation in the Heihe River basin.

CHAPTER 4

Runoff hysteresis effects of the Heihe River on the vegetation cover in the Ejina Oasis (China)*

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* Based on: Jin, X.M., Wan, L., Schaepman, M.E., Clevers, J.G.P.W., Su, Z., 2008. Runoff hysteresis effects of the Heihe River on the vegetation cover in the Ejina Oasis (China). *Journal of Hydrology* (in review).

Using the method as defined in: Jin, X.M., Hu, G.C., Li, W.M., 2008. Hysteresis effect of runoff of the Heihe River on vegetation cover in the Ejina Oasis in Northwestern China. *Earth Science Frontiers*, 15(4), 198-203.

Runoff hysteresis effects of the Heihe River on the vegetation cover in the Ejina Oasis (China)

Abstract

In arid regions an oasis plays an important role. It is nearly the only support of living and economic development for the local people. In recent years, the recession of the oasis areas appeared to be significant in Northwest China. It caused a series of environmental problems and part of the area even became the cradleland of sandstorms. In this paper, the long-term vegetation change of the Ejina Oasis, which is located in the downstream area of the Heihe River basin, was analyzed based on remote sensing data. The quantitative relation between the runoff of the Heihe River and the vegetation change of the Ejina Oasis from 1989 to 2006 was established using AVHRR and MODIS time series. The vegetation growth of the Ejina Oasis depends on the runoff of the Heihe River. The time lag of the impact of the runoff on the vegetation of the Ejina Oasis is one year. The smallest water amount which can sustain the demand of the eco-environment of the Ejina area was estimated. The result can serve as a reference for decision making processes at governmental level, finally allowing a better allocation of water resources in the Heihe River basin.

Keywords: Runoff, Vegetation change, Hysteresis effect, GIMMS NDVI, MODIS NDVI, Ejina Oasis

4.1 Introduction

In a desert area with an arid climate, like in the arid inland areas in Northwest China, sustainable social development will largely depend on the availability and sustainability of an oasis ecosystem. An oasis is nearly the only support of living and of economic development for the local people. Although they occupy only 4%-5% of the total area of the region, over 90% of the population and over 95% of social wealth are concentrated within the oases. The oasis is not only the most concentrated area of human activities in arid regions but also the largest area where disturbances are happening at the regional scale. Thus the oases, which are fragile ecosystems, play an important role in arid regions. During recent years, the recession of oases areas appeared to be extensive in Northwest China.

The Heihe River basin is the second largest inland river basin in China, covering an area of 128,283 km^2. With the continuous increase of economic activities in the Zhangye area, which is the middle stream area of the Heihe River basin, the water consumption increased gradually. It caused a decrease of incoming water in the downstream area resulting in a shrinking of the Ejina oasis area downstream. As a result, in that region the eco-environment is degrading and it causes a series of environmental problems like land desertification and part of the area even became the cradleland of sandstorms. Therefore, research on the spatial and temporal regulations and the control factors of the oasis areas has great significance for protecting and optimal use of the oasis resources, sustainable development of regional economy and social stability of the inland area.

However, due to little population, inconvenient transportation and shortage of long-term monitoring data, no quantitative analysis could be carried out using traditional methods by employing point measurements. Newly developed methods based on remote sensing data provide representative measurements of several relevant physical parameters at scales from point to continent. Currently, remote sensing is extensively used in crop assessment, natural disaster monitoring and land use mapping (Quarmby et al., 1993; Hayes & Decker, 1996; Unganai and Kogan, 1998; Mendoza and Etter, 2002; Berardino et al., 2003; Crowley et al., 2003; Kogan et al., 2003; Pinter et al., 2003; Canuti et al., 2004; Shalaby et al., 2004; Metternicht et al., 2005; Giri et al., 2005; Prasad et al., 2006; Shalaby and Tateishi, 2007), but it is ample used in research towards regulations of oasis variability in arid areas.

An oasis is the most important landscape in arid areas. The vegetation cover and the vitality of the oasis can be used as indices to characterize the regional ecological environment. Some approaches have been proposed since the 1980s. For example, Faragalla et al. (1988) discussed the relationship between agricultural development and oasis evolution. With the development of remote sensing techniques, the dynamic monitoring of the variability of the oasis has become possible. Some Chinese studies used Landsat Thematic Mapper satellite data for analysing the variability of the Ejina oasis. Some other studies used meteorological satellite data to monitor the variability of Hexi oasis. Tucker et al. (1991, 1994) studied the long-term variation of the oasis vegetation in the Sahara Desert using daily AVHRR data from the year 1980 to 1992. Several studies have shown vegetation cover change in arid areas using remote sensing (Elmore et al., 2000; McGwire et al., 2000; Dube, 2001; Okin et al., 2001; Diouf and Lambin, 2001; Larsson, 2002; Bruelheide et al., 2003). In addition, protection of the natural oasis also attracts more attention (Bornkamm, 1986). However, most of the studies are based on only small scale, qualitative analysis or only use short time series of satellite data. There is little focus on large scale studies towards oasis variation or studies using long time series.

Water is the essential factor that influences the oasis variability (Devitt et al., 1997; Bruelheide et al., 2003; Gries et al., 2003; Kang et al., 2007; Thomas et al., 2006). In the northwest arid area of China, all the oases depend on surface rivers and have a close relationship with the runoff of the river. With the increase of population and economic development, more and more human activities, like hydraulic structures and irrigation of cropland, cause a large area of useless evaporation and result in shortage of oasis water availability. The purpose of this study is to establish the quantitative relationship between the runoff of the Heihe River and the vegetation change of the Ejina Oasis, and furthermore, to estimate the water demand of the Ejina area. The specific objectives are: (1) to study the long-term change of the Ejina Oasis based on large scale remote sensing data; (2) to establish the quantitative relation between the runoff of the Heihe River and the vegetation change of the Ejina Oasis; and (3) to estimate the yearly water demand of the Ejina Oasis.

4.2 Study area

The Heihe River Basin, located in the north of the Qilian Mountains and the middle part of the Hexi Corridor, is one of the biggest inland river basins in arid northwest China. Being the oases of the Hexi Corridor and the desert plain, the middle stream area of the Heihe River is the most important developing area for agriculture and the base for commodity grain in Gansu province (Figure 4.1). The downstream area north of the Langxinshan gorge forms the oasis area of Ejina in Inner Mongolia. In recent years, development of industry and agriculture and the consumption of water in the middle stream area largely increased. According to the runoff data of the Langxinshan hydrological station, the discharge of the Heihe River has decreased since 1950 (Table 4.1), and the shortage of water caused the Ejina oasis to shrink considerably.

Table 4.1 The annual runoff at Langxinshan station in different decades

Time	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999
Runoff ($10^8 m^3$)	8.66	7.4	6.53	6.64	3.47

Ejina oasis is chosen as a pilot area in this research. Ejina, covering an area of 114,000 km^2, is located at the end of the Heihe River and in the west of Inner Mongolia of China. The Gobi desert occupies over 90% of the Ejina area. Around the downstream area of the Heihe River and near the lakes of West and East Juyanhai, it forms the only oasis with a long history. The territory of the oasis stretches from 100.90º to 101.42° east longitude and from 41.85° to 42.50° north latitude, forming an important ecological line of defense in the foreland of West China. With extremely arid conditions, the study area belongs to the north temperate zone. The mean annual precipitation in Ejina is around 40.8 mm; whereas the pan evaporation ranges between 3700 and 4000 mm. The main vegetation in this area is poplar.

From 1960 onwards, with the decrease of discharge downstream of the Heihe River, the oasis of Ejina began to shrink and caused a series of environmental problems. The areas of the lake of West and East Juyanhai were 267 km^2 and 35 km^2, respectively, and became dry in 1961 and 1992 one after the other. The oasis area drastically reduced from 6,440 km^2 to 3,200 km^2 and the area of the Gobi desert increased over 460 km^2.

As people's life depends on it, the oasis not only supports the social-economic development, but also characterizes the eco-environmental condition of the northwest area of China. The Chinese government pays great importance to the eco-environmental aspect of the northwest area and has implemented a long-term development program. In order to suppress the recession trend of the eco-environment of the downstream area of the Heihe River Basin, the State Council of the People's Republic of China started to perform a system for distribution and management of the water resources for the Heihe River from the year 2000 onwards and implemented an allocation scheme of the limited water resources.

4.3 Material and methods

The Global Inventory Modeling and Mapping Studies (GIMMS) normalized difference vegetation index (NDVI) data sets (Tucker et al., 2005) were generated to provide a 23-year satellite record of monthly changes in terrestrial vegetation. The NDVI is an index derived from reflectance measurements in the red and infrared portions of the electromagnetic spectrum to describe the relative amount of green biomass present (Deering, 1978). The NDVI was designed to quantitatively evaluate vegetation growth: higher NDVI values imply more vegetation coverage, lower NDVI values imply less or non-vegetated coverage and zero NDVI indicates rock or bare land. The GIMMS-NDVI dataset includes corrections for variation in NDVI caused by solar zenith angle changes due to orbital drift (Pinzon et al., 2004; Piao et al., 2003; Pinzon, 2002). It also has been corrected for distortions caused by cloud cover (Vermote et al., 1997), sensor inter-calibration differences (Vermote and Kaufman, 1995), solar zenith angle and viewing angle effects, volcanic aerosols and interpolation for missing data in the Northern Hemisphere during winter. The GIMMS dataset

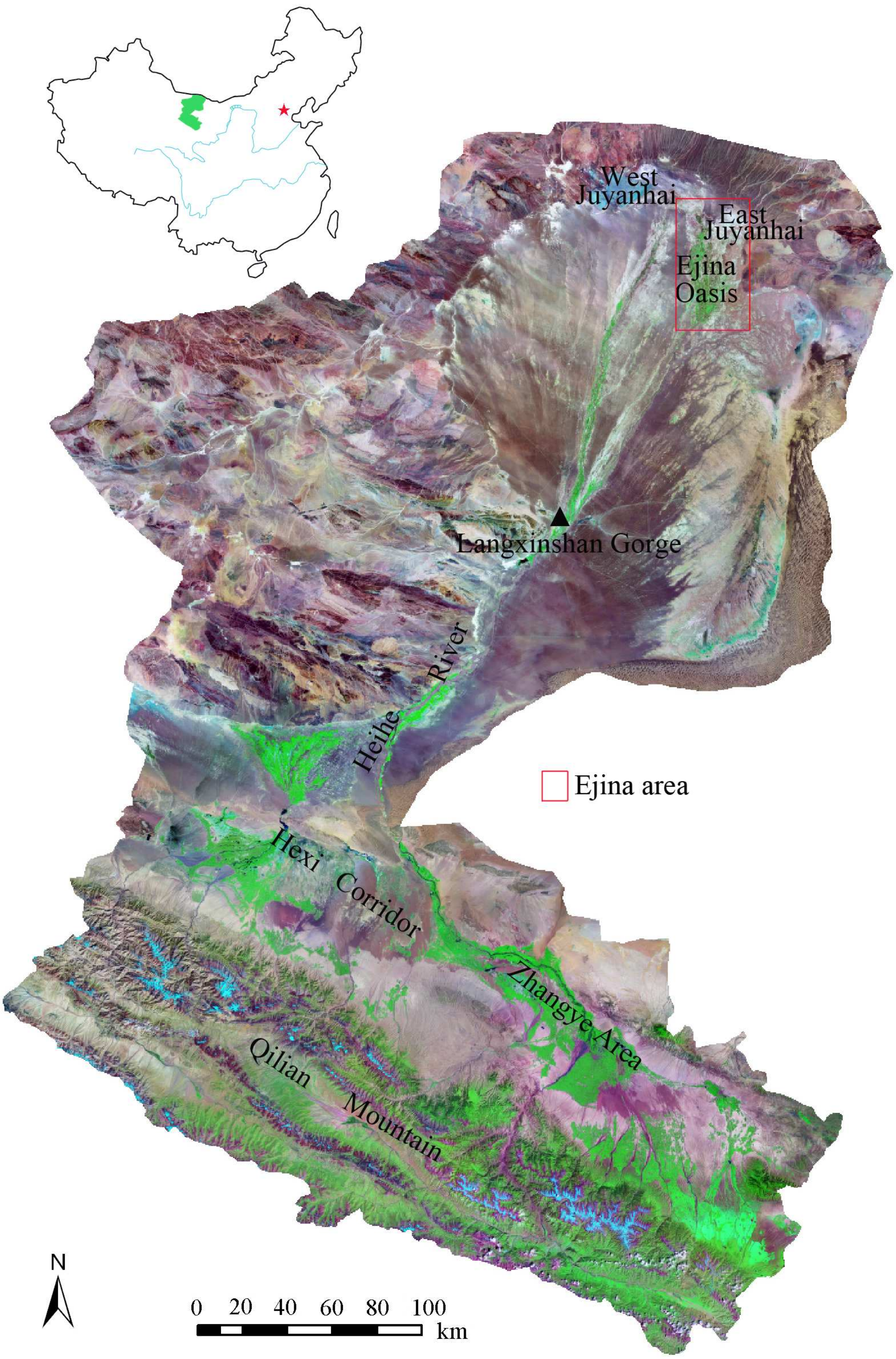


Figure 4.1 The location of the study area. The Ejina Oasis is in the downstream area of the Heihe River and it is close to the East Juyanhai lake.

is based on 15-day composites and its spatial resolution is 8 km. The data set used for this research consisted of 336 15-day GIMMS-NDVI composites for the Ejina Oasis from 1989 to 2002.

Vegetation changes seasonally and is affected by climatic conditions. According to the seasonal variations, the vegetation in China is best developed in most areas from June to September. The vegetation variation is usually small from October to next May, especially in northern China, and thus may not reflect the possible trend of long-term vegetation development. June, July, August and September are the most productive periods of vegetation growth during a year and thus the NDVI values of these four months may best reflect the long-term pattern of vegetation cover. Therefore, the NDVI from June to September of each year was averaged and this mean value was used as indicator for the annual vegetation growth of the study area.

Since the GIMMS-NDVI dataset only runs until 2003, the NDVI product from the Moderate Resolution Imaging Spectroradiometer (MODIS) of NASA’s Earth Observing System was used to complement this former time series. The MODIS NDVI dataset (MOD13 product) is based on 16-day composites and its spatial resolution is 250 m. These vegetation index maps have been corrected for molecular scattering, ozone and aerosol absorption. Currently, the MODIS NDVI product has been used throughout a wide range of disciplines, such as inter- and intra-annual global vegetation monitoring, climate and hydrologic modeling, agricultural activities and drought studies (Zhan et al., 2000; Jin and Sader, 2005; Sakamoto et al., 2005; Knight et al., 2006; Lunetta et al., 2006). In this study the NDVI values from 28 MODIS NDVI 16-day composites of June, July, August, and September in seven years from 2000 to 2006 were used to study the spatial distribution of vegetation in the Ejina Oasis.

The pan evaporation (open water surface evaporation) of the Ejina meteorological station and the runoff at the Langxinshan hydrological station were used in this research to study the quantitative relation between the runoff and the vegetation change.

4.4 Result and discussion

4.4.1 The long-term vegetation change of the Ejina Oasis in the period 1982-2002

Figure 4.2 illustrates the long-term change of the mean annual GIMMS NDVI of the Ejina Oasis in the period 1989-2002. The result indicates the recession trend of the vegetation growth during the 14 years period.

The impact of water resources on the vegetation is very important in the downstream plain in an arid area. Most of the incoming water recharges the groundwater in the downstream area of the Heihe River Basin. In recent years, the vegetation growth has become worse and the vegetation area has decreased in the downstream area because of decreased incoming water and the increasing depth of the groundwater. It caused land desertification and some salt-enduring vegetation species have been replaced by halophytic vegetation. The oasis landscape has changed into a desert landscape.

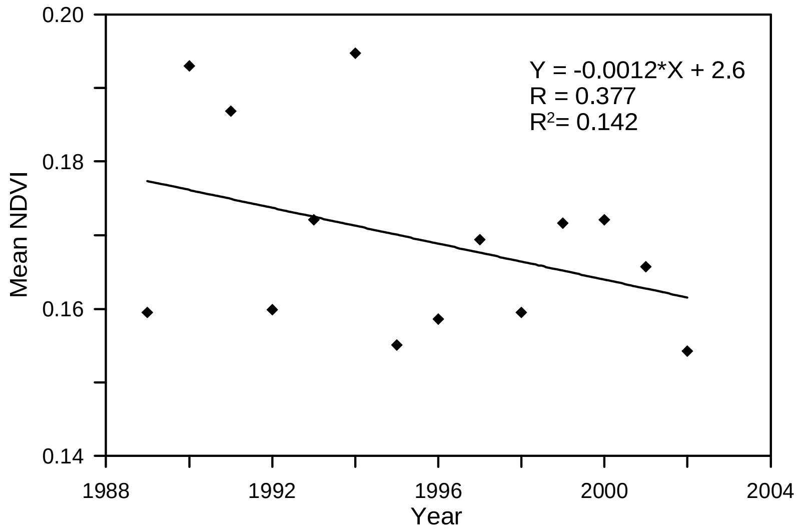


Figure 4.2 The long-term vegetation change of the Ejina Oasis in the period 1989-2002 based on GIMMS NDVI.

4.4.2 The relation between the runoff of the Heihe River and the vegetation change in the period 1989-2002

A regression analysis was performed whereby the mean annual GIMMS NDVI from the year 1989 to 2002 was the dependent variable (y) and the runoff of the current year (x_0), the runoff of the previous year (x_1) and the runoff of two years ago (x_2) at the Langxinshan station were the independent variables. Stepwise regression showed that the runoff of the previous year (x_1) was the only relevant independent variable in the regression equation. The result indicates that the mean NDVI and the runoff of the previous year at the Langxinshan station are linearly correlated (Figure 4.3) with a correlation coefficient of 0.835. The equation can be written as

$$y = 0.004x + 0.1525 \tag{4.1}$$

Where y is the mean annual GIMMS NDVI between the year 1989 and 2002 and the x is the yearly runoff at the Langxinshan station between the year 1988 and 2001. The relationship is significant at 5% significance level, so the vegetation growth of the oasis is related to the runoff of the Heihe River. The time lag of the impact of the runoff on the vegetation of the Ejina Oasis is one year.

According to the hydrological characteristics of the downstream area of the Heihe River, the incoming water of the Ejina Oasis in the winter was the result of recharge by agricultural irrigation in the middle stream area in the previous year. In the summer, the recharge from the middle stream area can arrive in the downstream area and the groundwater was recharged efficiently. The groundwater table shows a big increase along the two sides of the river. However, the peak in growth of the vegetation has finished at that time and the increased groundwater table produces a good condition for the oasis vegetation in the next year.

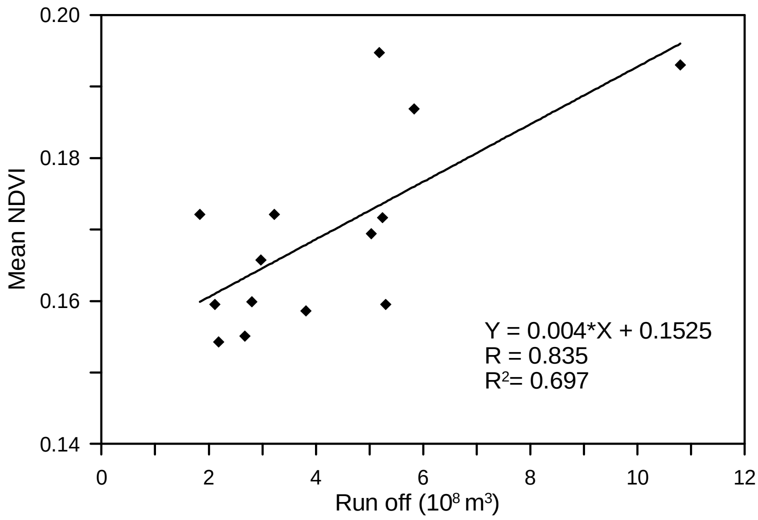


Figure 4.3 The correlation between the mean NDVI of the Ejina Oasis and the runoff of the previous year at the Langxinshan station between the year 1989 and 2002.

4.4.3 The vegetation change of the Ejina Oasis in the period 2000-2006

In order to suppress the recession trend of the eco-environment of the downstream area of the Heihe River Basin, the State Council of the People's Republic of China started to perform a distribution and management plan of the water resources for the Heihe River and implemented an allocation scheme of the limited water resources after the year 2000. The water again flowed into the East Juyanhai in 2002, the flow length of the channel increased and the water entered into more regions along the two sides of the Heihe River. The oasis vegetation was irrigated and the groundwater of the Ejina Oasis recharged and recovered efficiently. The eco-environment along the downstream of the Heihe River improved and the recession trend of the eco-environment was suppressed.

The MODIS NDVI was used to analyze the vegetation change after the year 2000. Figure 4.4 shows the temporal change of the annual mean NDVI of the Ejina Oasis from 2000 until 2006. The result indicates a positive trend of growth of the Ejina Oasis vegetation. Figure 4.5 illustrate the spatial change of the annual mean NDVI of the oasis from 2000 to 2006. It can be seen from the result that the oasis area increased with time and the vegetation growth was best in 2004. There was no water in the East Juyanhai lake (the red color area in Figure 4.5) before 2002 and there was permanent water after 2003. The area of the East Juyanhai lake increased with time.

The runoff (incoming water) of the Langxinshan station in 1999 was relatively large (3.74×10^8 m^3). Due to the hysteresis effect of the runoff, the vegetation growth of the Ejina Oasis was better in 2000 (Figure 4.4). The runoff in 2000 and 2001 was smaller than 3×10^8 m^3 and the mean NDVI of 2001 and 2002 was lower than that of 2000. The runoff of the Langxinshan station was highest in 2003 (7.12×10^8 m^3), which resulted in the highest NDVI in 2004. The runoff of 2004 and 2005 was smaller than that of 2003, the vegetation growth of these two years was worse than that of 2004. Therefore, there is close relationship between the runoff and the vegetation change in the Ejina area.

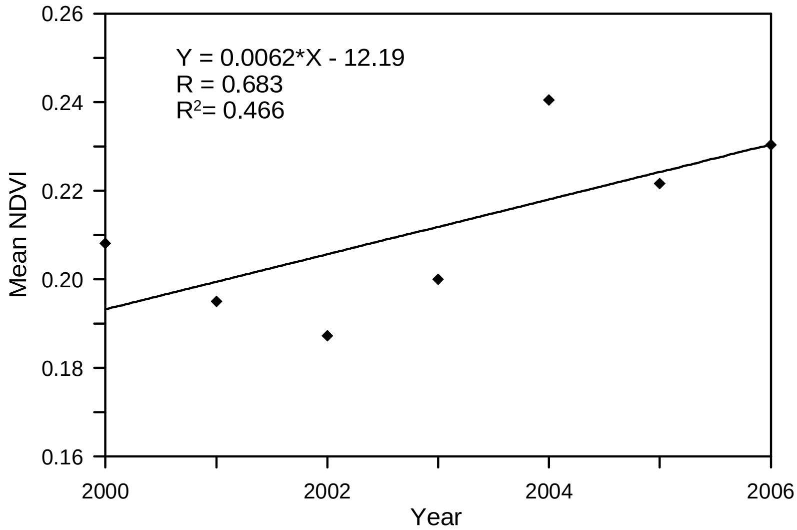


Figure 4.4 The vegetation change of the Ejina Oasis in the period 2000-2006 based on MODIS NDVI.

4.4.4 The relation between the runoff of the Heihe River and the vegetation change in the period 2000-2006

Also for the MODIS dataset a regression analysis was performed for NDVI with the runoff data. The mean annual MODIS NDVI from the year 2000 to 2006 was the dependent variable (y) and the runoff of the current year (x_0), the runoff of the previous year (x_1) and the runoff of two years ago (x_2) were the independent variables. The runoff of the previous year and the runoff of two years ago exceeded the significance level and entered into the regression equation after stepwise regression. The regression coefficient of the runoff of the previous year (x_1) is the largest and most significant and this result further proved that the runoff of the previous year has most impact on the vegetation growth of the current year. Figure 4.6 illustrates the correlation between the runoff of the previous year and the mean NDVI of the current year. The correlation coefficient is 0.906. The equation can be written as

$$y = 0.0106x + 0.1691 \tag{4.2}$$

Where y is the mean annual MODIS NDVI between the year 2000 and 2006 and the *x* is the yearly runoff of the Langxinshan station between the year 1999 and 2005.

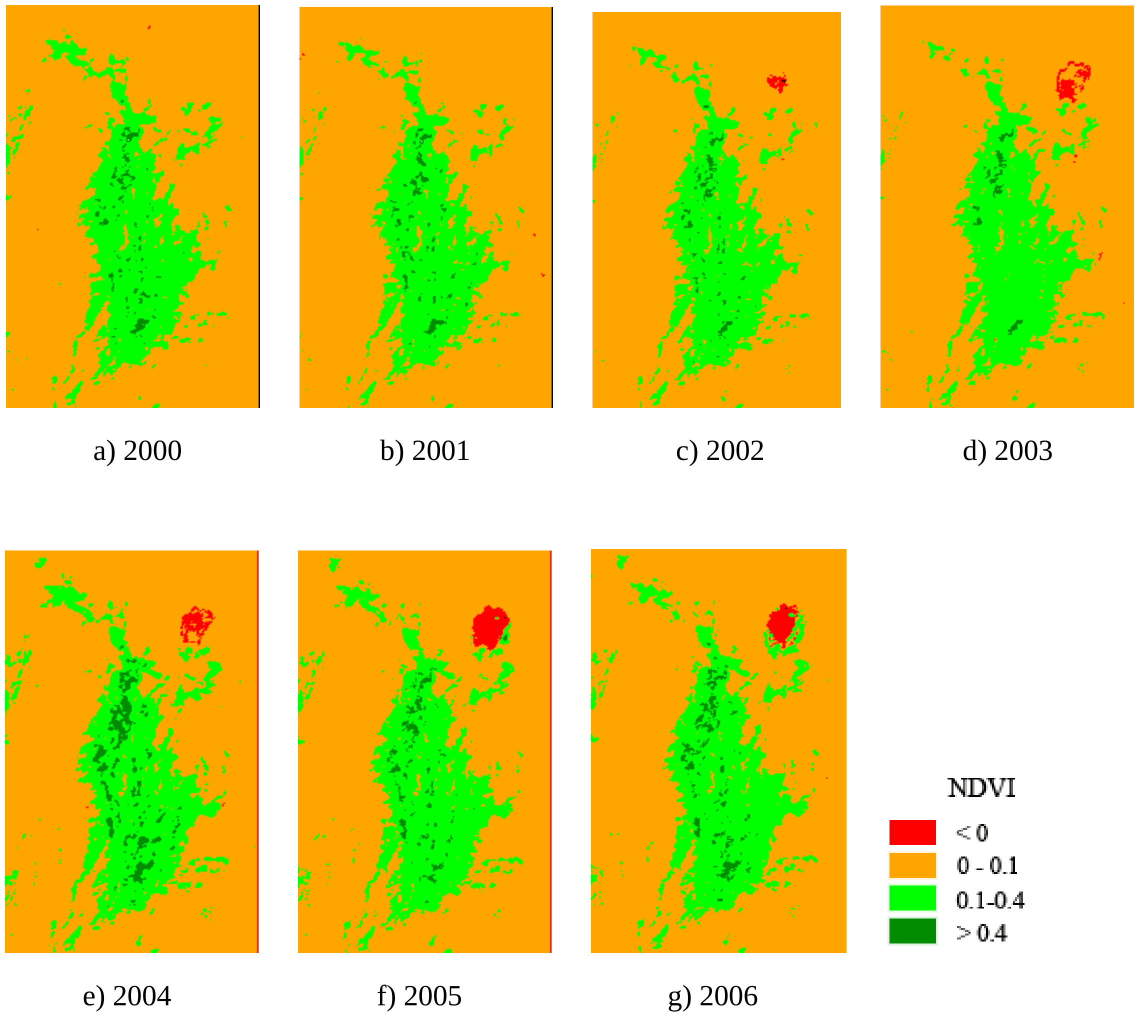


Figure 4.5 The spatial pattern and change of the Ejina area between 2000 and 2006. The red area represents the water in the Juyanhai lake and the orange area is gobi and desert area. The green and dark green area represents the vegetation of the Ejina Oasis.

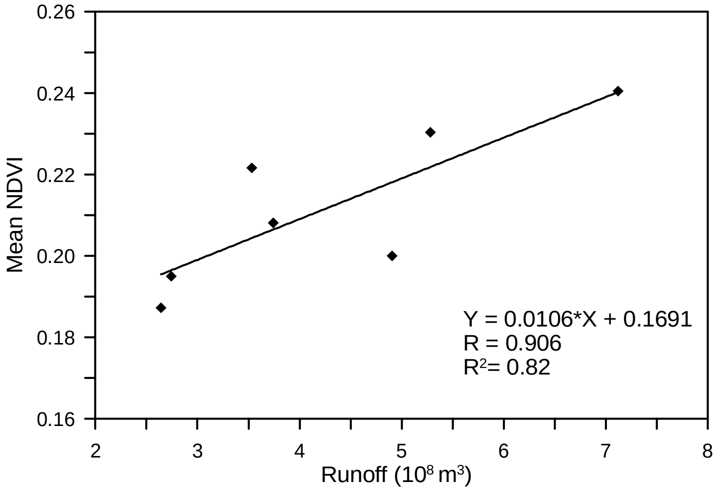


Figure 4.6 The correlation between the mean NDVI of the Ejina Oasis and the runoff at the Langxinshan station in the previous year between the year 2000 and 2006.

4.4.5 The water demand of the Ejina area

The government started to organize distribution and management of the water resources for the Heihe River in 2000. The water discharges from the middle stream and has entered into the East Juyanhai lake since 2002. Before 2002 all the water was consumed on its way and couldn't arrive at the lake. Due to water shortage for many years, the water evaporated before it entered into the lake and the East Juyanhai lake was dry until the year 2002. Due to the increase of discharge from the middle stream area, the East Juyanhai lake has water permanently since 2003. The water was dispatched into the East Juyanhai lake twice a year based on the bulletins published by the Ministry of Water Resources of the People's Republic of China. In 2002, the first time was from 17 July to 29 July and the second time was from 22 September to 20 October. Based on the MODIS images from July to September, the lake became dry around 16 September after the first time of dispatching in 2002. In other words, the evaporation time was about 45 days from 30 July to 16 September after the first time of dispatching water. The amount of water that entered into the lake was 0.23×10^8 m^3 for the first time of dispatching in 2002 and most of the water was evaporated in about 45 days because of the shallow depth of the groundwater. Therefore, the mean monthly evaporation was about 0.15×10^8 m^3 and most of the evaporation happened in August. Based on the pan evaporation measurements at the Ejina meteorological station from 1986 to 2004, the mean monthly evaporation of August is 14% of the total year. So, the predicted annual evaporation of the East Juyanhai lake is about 1.1×10^8 m^3. On the basis of these result, the smallest water demand of the East Juyanhai lake, which can sustain the demand of the eco-environment, is 1.1×10^{8} m^{3}.

There was permanent water in the East Juyanhai lake after 2003. Based on the vegetation change of the Ejina Oasis in the period 2000-2006, the mean MODIS NDVI was 0.2 in 2003 and we assume that this value is the smallest value which can sustain normal growth of the oasis vegetation. According to Equation (4.2), the smallest runoff corresponding to this NDVI is 2.9×10^{8} m^{3} and this water amount is considered to be the smallest water demand of the Ejina Oasis. Therefore, the smallest water amount which can sustain the demand of the eco-environment of the Ejina area is 4×10^{8} m^{3}. The eco-environment will show a recession trend if the water amount from the middle stream is smaller than 4×10^{8} m^{3} per year in the Ejina area.

4.5 Conclusions

The long-term change of the Ejina Oasis vegetation and the relation between the vegetation and the runoff of the Heihe River were analyzed in this paper. The following conclusions can be drawn based on the results obtained.

1) The vegetation growth decreased from 1989 to 2002 and increased from 2002 to 2006 in the Ejina Oasis. The most important impact factor causing the vegetation change is the discharge from the middle stream area;

2) The relation between the oasis vegetation and the runoff of the Heihe River was established. The time lag of the impact of the runoff of the Heihe River on the Ejina Oasis was one year;

3) The smallest water amount which can sustain the demand of the eco-environment of the Ejina area is 4×10^{8} m^{3} per year.

CHAPTER 5

Effects of groundwater depth on vegetation growth in the Ejina area (China)*

* Based on: Jin, X.M., Schaepman, M.E., Clevers, J.G.P.W., Wan, L., Su, Z., Hu, G.C., 2008. Effects of groundwater depth on vegetation growth in the Ejina area (China). *International Journal of Applied Earth Observation and Geo-Information* (submitted).

Using the method as defined in: Jin, X.M., Wan, L., Zhang, Y-K., Xue, Z.Q., Yin, Y., 2007. A study of the relationship between vegetation growth and groundwater in the Yinchuan Plain. *Earth Science Frontiers*, 14(3), 197-203.

Effects of groundwater depth on vegetation growth in the Ejina area (China)

Abstract

The relationship between vegetation growth and groundwater depth in arid areas is one of the most active research topics in ecohydrology. Due to little precipitation, vegetation growth is closely related to groundwater depth in the arid inland areas of northwest China. Research on the ecological effects of groundwater depth at larger scales has great significance for policy decisions on eco-environmental recovery and protection of the occurring vegetation. In this study we investigate the relationship between vegetation growth and depth of the groundwater table in June 2000 in the Ejina area, located in the northwest arid region of China, by combining remote sensing with in-situ groundwater observations. We demonstrate with our results that the groundwater depth suitable for vegetation growth in this region ranges from 2.8 to 5 m, depending on species composition. Hardly any vegetation growth occurs when the groundwater depth is below 5 m because the rooting depth of the present species is limited and therefore cannot maintain adequate water supplies to their canopies. On the other hand, a groundwater depth less than 2.8 m causes excessive salt accumulation in the rooting zone. Field excavation experiments confirm that present species develop a maximum rooting depth between 2 and 5 m in the Ejina area. The vegetation change after implementation of a new water allocation scheme since 2000 was also analyzed in this study. The result indicates that the mean NDVI increased and the annual conversion of bare land into vegetated land is about 38 km^2 per year during the period 2000 – 2008. It explains a potential recovery of the eco-environment of the Ejina area.

Keywords: Groundwater depth, Vegetation growth, MODIS NDVI, Salt concentration, Ejina area

5.1 Introduction

About 47% of the total area of China consists of arid and semi-arid regions. The environment in these regions is vulnerable because of little precipitation, limited water resources and sparse vegetation. There, an oasis is the only place to sustain life and social development for local people. The area occupied with the land cover type ‘oasis’ represents only 5% of the total area of northwestern China, but supports over 95% of the population with natural supplies in that area. Among many influencing factors, groundwater is the most important one in sustaining the ecological environment of an oasis. Vegetation succession and cover patterns are primarily controlled by the groundwater table (Stromberg et al., 1996). However, patterns of vegetation cover also exhibit an important feedback on the water quantity.

The main factors controlling vegetation growth are solar irradiation, temperature, water and soil condition (Wang et al., 2001). Vegetation growth varies with space and time due to the spatial and temporal variations of these factors. The seasonal changes of vegetation growth are the results of differences in temperature and solar irradiation. The spatial variations of vegetation growth are mainly determined by the soil characteristics and the landform, among which the soil moisture is the most influential factor. Due to little precipitation in arid areas, the soil moisture maintaining a vegetation root system is largely supplied by groundwater through capillarity. The shallower the groundwater depth, which is defined as the distance from the soil surface to the groundwater table, the more soil moisture is available, and vice versa (Rodriguez-Iturbe, 2000; Farmer et al., 2003; Pan et al., 2008). On the other hand, salinization may happen at the soil surface and thus hinder vegetation growth if the groundwater depth is too shallow (Mirlas et al., 2003; Benyamini et al., 2005; Jalali 2007).

The groundwater depth influences the abundance, age structure and species composition of vegetation, particularly in semi-arid and arid regions (Stromberg et al., 1992; Busch and Smith, 1995; Stromberg, et al., 1996; Mahoney and Rood, 1998; Scott et al., 1999; Castelli et al., 2000; Scott et al., 2000; Horton et al., 2001a, b; Muñoz-Reinoso, 2001; Amlin and Rood, 2002, 2003; Cooper et al., 2003; Elmore et al., 2003; Naumburg et al., 2005; Stromberg et al., 2007). It has been recognized that groundwater depth is a critical parameter determining the species composition in arid areas (Allen-Diaz, 1991; Ridolfi et al., 2006). Impacts on these species by a gradual groundwater decline initially will be expressed through loss of young age classes, and ultimately through death of older trees. Although a small groundwater decline is not expected to cause large changes in abundance of these species, it might affect factors such as structure and productivity. Relationships between groundwater depth and riparian plants have been studied frequently (Stromberg et al., 1996; Baker et al., 2004; Baird et al., 2005; Loheide and Gorelick, 2007). However, certain aspects still remain underexplored, in particular the effect of groundwater depth on riparian vegetation change at regional scales.

Hydrological processes vary over a wide range of scales in space and time. It is widely accepted that remote sensing, broadly defined as a collection of non-intrusive observational methods, offers the potential to capture some of the characteristics of these spatial and temporal processes. Traditionally, techniques of measuring hydrologic variables rely on point measurements for collecting information, which is then assumed to be representative for larger areas. In some cases, a point measurement does represent a ‘hydrologically integrated’ catchment area if it is a homogeneous one. Point measurements are not particularly useful in complex or heterogeneous environments where the point data cannot be assumed to represent a larger area. Part of the problem is that the Earth’s surface is usually not homogeneous in terms of topography, geology, soil moisture availability, soil type, or canopy cover. Remote sensing may play a critical role towards addressing this problem. These methods have the ability to produce high resolution spatial measurements over large areas. Moreover, remote sensing data often allow us to visualize complex dynamic processes because the spatial data can be captured at regular time intervals (Tenhunen and Kabat, 1999; Krajewski et al., 2006).

Vegetation in arid and semi-arid environments has received a lot of attention because of its sensitivity to changes in groundwater depth, need for management, and potential for restoration (Chambers and Miller, 2004; Baker et al., 2004; McKinstry et al., 2004). Vegetation is particularly important because it is an important part of the eco-environment, playing a critical role in the hydrological cycle. The vegetation-groundwater relationship and long-term shifts in the vegetation species community composition resulting from changes in the groundwater table are discussed in Elmore et al. (2003). Baird et al. (2005) demonstrated advanced groundwater modeling techniques for estimating groundwater use by vegetation. Initial efforts of linking groundwater flow and vegetation response models for predicting riparian vegetation patterns are discussed by Rains et al. (2004) and Stromberg et al. (2007). These recent advances can help us to understand the relationship between vegetation cover and groundwater conditions. The growing interest in interactions between groundwater and vegetation, particularly in arid and semi-arid areas, reflects a current trend towards integrated management of natural resources (Le Maitre et al., 1999; Walvoord et al., 2002; Newman et al., 2006).

In water-limited environments, temporal variability of meteorological conditions, spatial variability of geologic and topographic settings, and different ways that plants use water present particular challenges when local field data need to be scaled to regional scales. The purpose of this study is to understand the hydrologic link between the groundwater depth and vegetation by analyzing both hydrological data gathered in the field and remote sensing data. The study area is the Ejina oasis in northwest China, representing an arid to semiarid environment, including an oasis. The specific objectives of this paper are two-fold: (1) to study the effect of groundwater depth on vegetation growth in the Ejina area in order to determine the range of groundwater depth suitable for vegetation growth, and (2) to investigate the relationship between different vegetation types and groundwater depth. The outcome of this study should be input to the water resources management in order to maintain a certain groundwater table enabling sustainable vegetation growth in the oasis.

5.2 Material and Methods

5.2.1 Study Area

Ejina, covering an area of 114,000 km^2, is located at the end of the Heihe River in the west of Inner Mongolia of China (Figure 5.1). The Gobi desert occupies over 90% of the Ejina area. In the downstream area of the Heihe River, just before the East Juyan lake the Ejina oasis is located. North-east of the oasis, a second lake is present, the West Juyan lake. The Ejina oasis has been existing for a long time already. The territory of the oasis extends from 100.90º to 101.42° east longitude and from 41.85° to 42.50° north latitude, forming an important ecological buffer in the foreland of west China. With extremely arid conditions, the mean annual precipitation in Ejina is around 40.8 mm, whereas the pan evaporation ranges between 3700 and 4000 mm (Zhang et al., 2002).

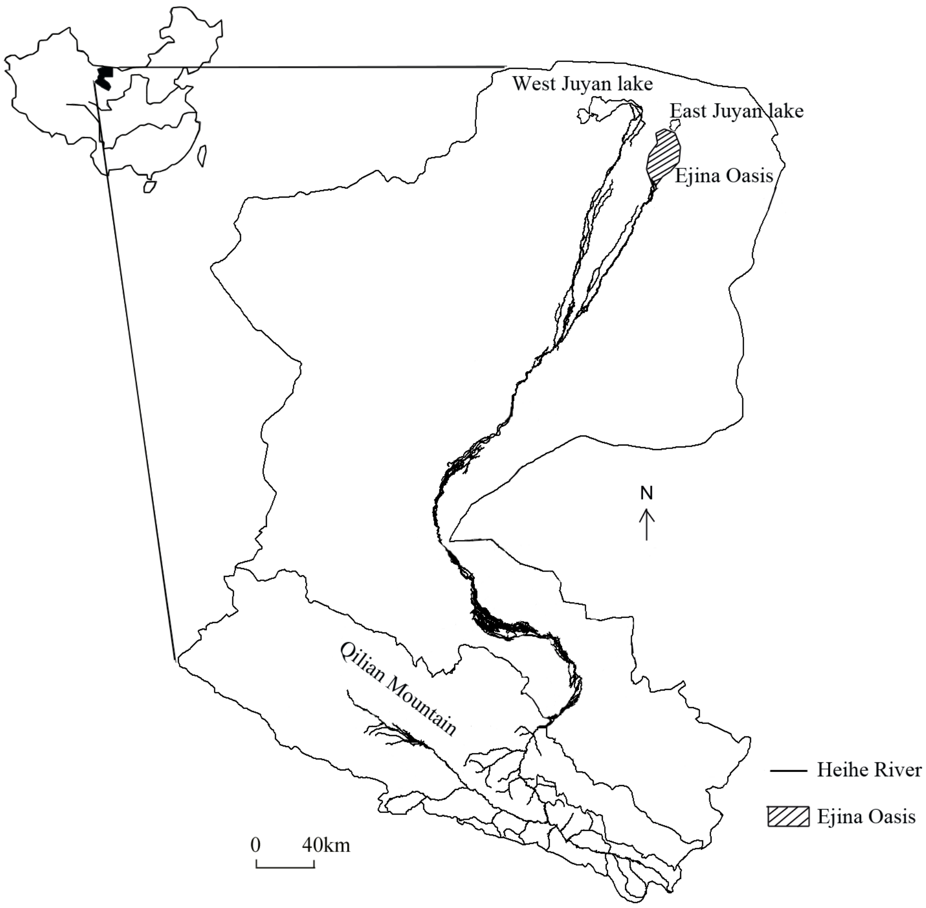


Figure 5.1 Location map showing the Heihe River basin and the Ejina area, China.

The main vegetation of the oasis is dominated by xerophytic plants, such as *Populus euphratica* Oliv., *Elaeagnus angustifolia* L., *Haloxylon ammodendron* (C.A.Mey.) Bunge, and *Tamarix ramosissima* Ledeb. The development of this xeric, salt-enduring vegetation depends on the groundwater depth. During recent years, the development of industry, agriculture and the consumption of water in the middle stream area of the Heihe River has increased a lot and resulted in a decrease of incoming water into the oasis in the downstream area. According to the runoff data of the hydrological station at the river, the discharge of the Heihe River has decreased since 1950. The annual incoming water into the Ejina area was 8.66×10^8 m^3 and 6.53×10^8 m^3 during the period 1950-1959 and 1970-1979, respectively (Zhang et al., 2002). Finally, the amount of runoff decreased to 3.47×10^8 m^3 in the 1990s (Figure 5.2) and the shortage of water caused shrinking of the oasis and land desertification resulting in increasing numbers of sandstorms. In 1950 the area of the West and East Juyan lakes still covered 267 km^2 and 35 km^2, respectively. They fell dry in 1961 and 1992 one after the other. The oasis area drastically reduced from 6,440 km^2 to 3,200 km^2, the area of the Gobi desert increased over 460 km^2 and some of the hygric, mesophytic and light salt-enduring plants were replaced by xeric and halophile plants. During the 1982 – 1995 period the decrease in vegetation cover was severe, the areas of *Populus euphratica* and *Elaeagnus angustifolia* decreased with 3.1% and 57.45%, respectively, while the areas of *Haloxylon ammodendron* and *Tamarix ramosissima* decreased with 39.17% and 7.28%, respectively. 78% of the *Populus euphratica* is over-aged, covered with blight and dehydrated. Most of the herbaceous communities and 180 wildlife species have disappeared in the Ejina area (Wang, 2007).

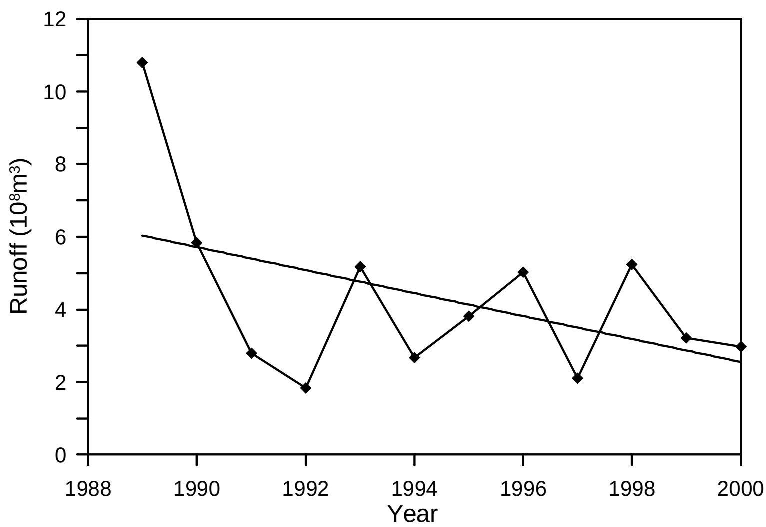


Figure 5.2 Decreasing runoff of the Heihe River in the Ejina area (1989-2000).

The Ejina area is fully dependent on incoming water from the Heihe river. The water quantity and water quality not only affect the groundwater, but also change the eco-environment. Decrease of incoming water resulted in a drop of the groundwater table, falling below 3 - 4 m in the 1990s. Meanwhile, it was observed that decrease of the water quantity combined with a strong evapotranspiration caused accumulation of salt at the surface and in the root zone (Wang, 2007). The deterioration of the root zone influenced the vegetation development and further altered the hydrological environment of the Ejina area.

5.2.2 Satellite data

One of the primary interests of the Earth Observing System (EOS) programme of the National Aeronautics and Space Administration (NASA) is to study the role of terrestrial vegetation in large-scale global processes in order to understand how the Earth functions as a system. One of the EOS products is the Normalized Difference Vegetation Index (NDVI) of the Moderate Resolution Imaging Spectroradiometer (MODIS), which is referred to as the "continuity index" to the NDVI derived from the existing National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR). The NDVI is an index derived from reflectance measurements in the red and near-infrared portions of the electromagnetic spectrum to describe the relative amount of green biomass (Deering, 1978). This index is an indicator of photosynthetic activity of plants and has been widely used for assessing vegetation phenology and estimating landscape patterns of primary productivity (Sellers, 1985; Tucker and Sellers, 1986). The NDVI was designed to quantitatively evaluate vegetation growth: higher NDVI values imply more vegetation coverage, lower NDVI values imply less or non-vegetated coverage, and zero NDVI indicates rock and bare land.

In this paper, we use the MODIS Vegetation Index product (MOD13) that is based on the MODIS surface reflectance product (MOD09). This product is corrected for molecular scattering, ozone absorption, and aerosols, and adjusted to nadir with use of a Bidirectional Reflectance Distribution Function (BRDF) model. The MODIS NDVI data are based on 16-day composites (MOD13Q1 product) and the spatial resolution is 250 m. The gridded vegetation indices include quality assurance (QA) flags with statistical data that indicate the quality of the NDVI product and input data (Huete et al., 1996). Currently, the MODIS NDVI product is used throughout a wide range of disciplines, such as inter- and intra-annual global vegetation monitoring on a periodic basis, global biogeochemical, climate, and hydrologic modeling, agricultural activities and drought studies (Zhan et al., 2000; Jin and Sader, 2005; Sakamoto et al., 2005; Knight et al., 2006; Lunetta et al., 2006). A case study with mean NDVI data of June 2000 (Figure 5.3) was used to analyze the relationship between groundwater depth and vegetation growth in this study. Monthly MODIS NDVI data was obtained by averaging two 16-day composites. Vegetation changes were monitored by using MODIS NDVI data from June 2000 until 2008.

5.2.3 Ground observations

Most of the groundwater table in the Ejina area remained relatively stable in 2000 and the main flow direction of the regional groundwater was from south to north. Groundwater finally discharged into the East and West Juyan lakes. A total of 13 groundwater observation wells were distributed over the Ejina area (Figure 5.4) and observations of groundwater depth from 1989 - 2000 are available. In this study the measurements from 2000 were combined with satellite data. A map of the groundwater depth of the Ejina area was calculated at the same resolution as the MODIS NDVI image by interpolating the groundwater depth measurements in June 2000 to a 250 m × 250 m grid using kriging (Isaacs and Srivastave, 1989). More than 1,000,000 pairs of groundwater depth measurements and MODIS NDVI values were obtained for the study area. In order to study the relationship between the groundwater depth and the vegetation growth, the oasis area was used as a subset area and groundwater depth data were extracted (Figure 5.5). 18,801 pairs of groundwater depth measurements and MODIS NDVI values remained after the oasis area was extracted. The NDVI values corresponding to the same groundwater depth were then averaged and the averaged NDVI value represents the vegetation growth at this depth. The relationship between the averaged NDVI and the corresponding groundwater depth in the area was then established. Since this relationship showed strong local variations, a low-pass (5×5) filter was applied to the curve depicting the relationship. Finally, the groundwater depth suitable for vegetation growth was derived from this analysis.

For validation, seven root systems were analyzed in terms of rooting depth by performing excavations (Table 5.1).

Table 5.1 Suitable groundwater depth for different plants in the Ejina Oasis.

Species	suitable groundwater depth [m]	threshold depth [m]
Populus euphratica Olive.	2-5	5.5
Elaeagnus angustifolia L.	2-5	5.5
Tamarix ramosissima Ledeb	2-5	5
Haloxylon ammodendron (C.A.Mey.) Bunge	2-4	4
Phragmites australis (Cav.) Trin. ex Steud	2-3	3
Glycyrrhiza glabra L.	2-4	4
Apocynum venetum L.	2-4	4

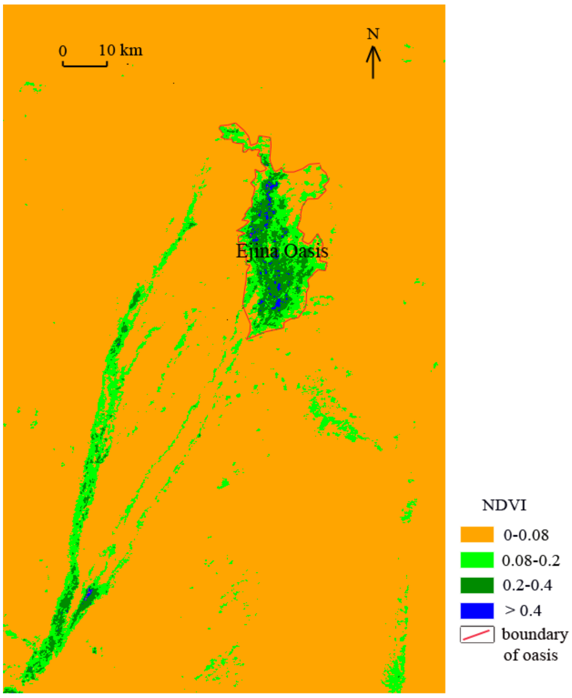


Figure 5.3 MODIS NDVI image of the Ejina area (June 2000). The oasis is located within the red boundary.

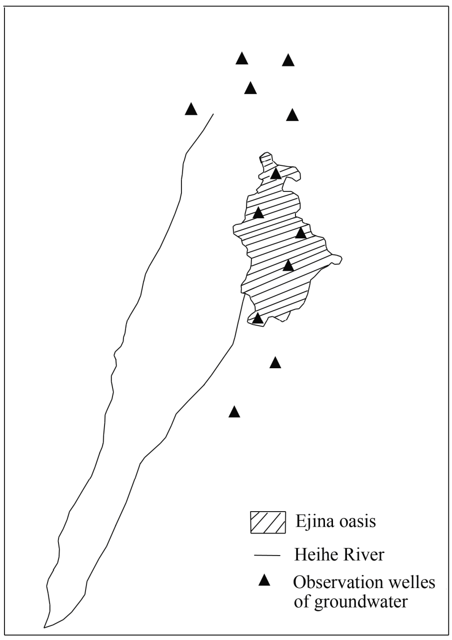


Figure 5.4 Distribution of groundwater observation wells in the Ejina oasis.

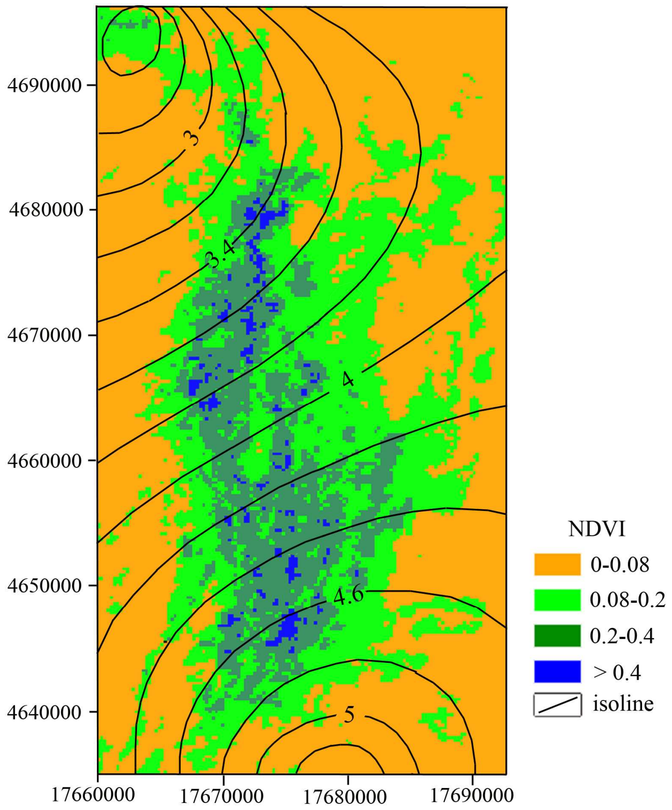


Figure 5.5 Contour map of the groundwater depth in the Ejina oasis overlaid over the NDVI map. Contours are in [m] and range from 2.6-5.2 m.

5.3 Results and Discussions

5.3.1 Relationship between vegetation and groundwater depth in June 2000

All the observation wells showed a continuous decline in the water table level during the measurement period (1989 – 2000). Overall, the groundwater depth dropped 0.8 m according to field data of five observation wells in the Ejina oasis (Figure 5.6). However, the Ejina area has seen little increase in human pressure over time, because of its poor sandy soils and the difficulty to grow crops. The human groundwater exploitation of the area remained therefore at a low level and its impact on the regional groundwater is considered to be low. The dynamics of groundwater depth for each well over the years is between 0.5 m and 1.5 m and most of the groundwater depths also showed no big change within one year in the oasis (Figure 5.6). The standard deviation of groundwater depth for these five observation wells is shown in Figure 5.7. This standard deviation is between 0.14 and 0.40, whereby the northern observation well at Saishe has the smallest value and the other four wells of the oasis have a similar value. These results confirm that the groundwater depth is relatively stable in the study area, indicating a low level of human influence.

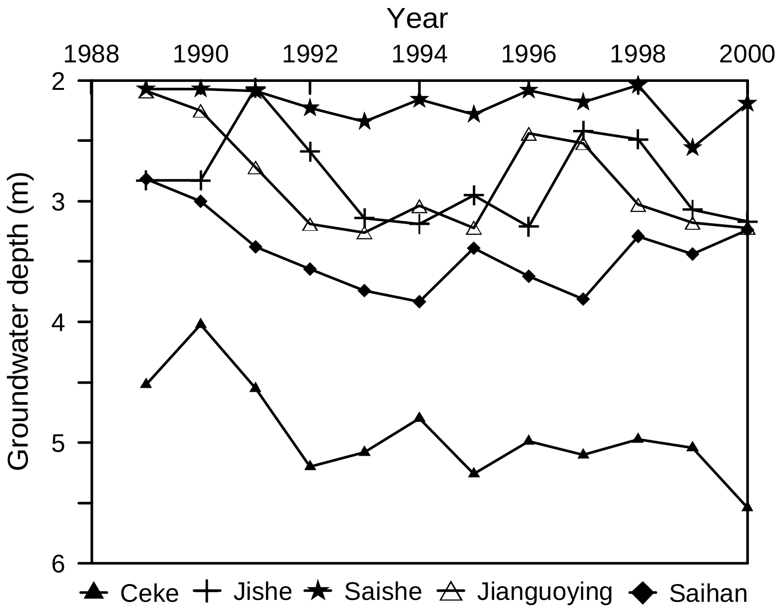


Figure 5.6 Groundwater depth fluctuations in wells of Ceke, Jishe, Saishe, Jianguoying and Saihan during the period 1989-2000 in the Ejina area.

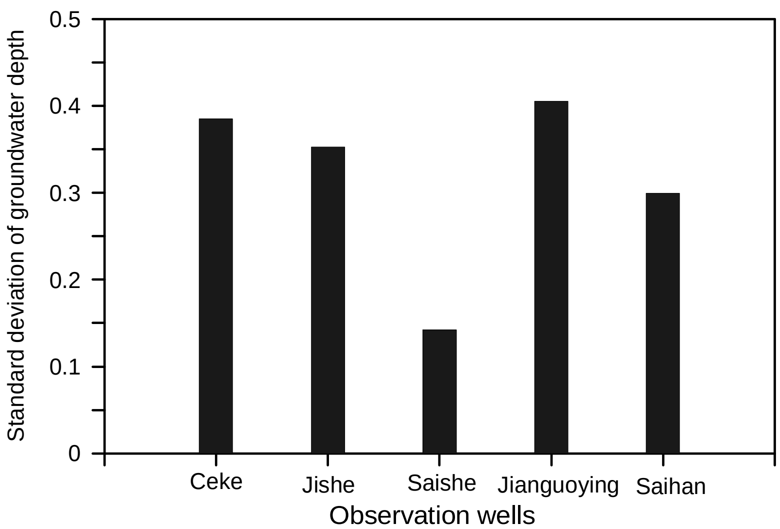


Figure 5.7 Standard deviation of groundwater depth for the observation wells of Ceke, Jishe, Saishe, Jianguoying and Saihan during the period 1989-2000 in the Ejina oasis.

The MODIS NDVI image of June 2000 showed that 90% of the Ejina area was covered with desert sand and bare soil. The oasis in this area corresponds well to NDVI values larger than 0.08 (Figure 5.5). A histogram of the number of pixels and the corresponding groundwater depth for the oasis is presented in Figure 5.8. Most pixels were in the depth range between 2.6 m and 5.5 m. The relationship between the groundwater depth and the corresponding average NDVI is plotted in Figure 5.9 using depth intervals of 0.1 m. This figure shows that the NDVI values were generally larger than 0.10 when the groundwater depth was between around 2.8 and 5 m with a maximum NDVI of about 0.20 for a groundwater depth of 3.4 m. The NDVI value decreased to less than 0.10 when the groundwater depth was larger than 5 m. Beyond this depth hardly any vegetation is growing because the water simply is too far away for the root system to maintain adequate water supplies to an extensive canopy. On the other hand, when the groundwater depth becomes less than 2 – 3 m, transpiration from the soil becomes significant, causing increased salt concentrations at and near the surface (in the root zone). Obviously, there is a fine balance between a too shallow and a too deep groundwater table for the present vegetation, resulting in a limited range of suitable groundwater depths for vegetation growth.

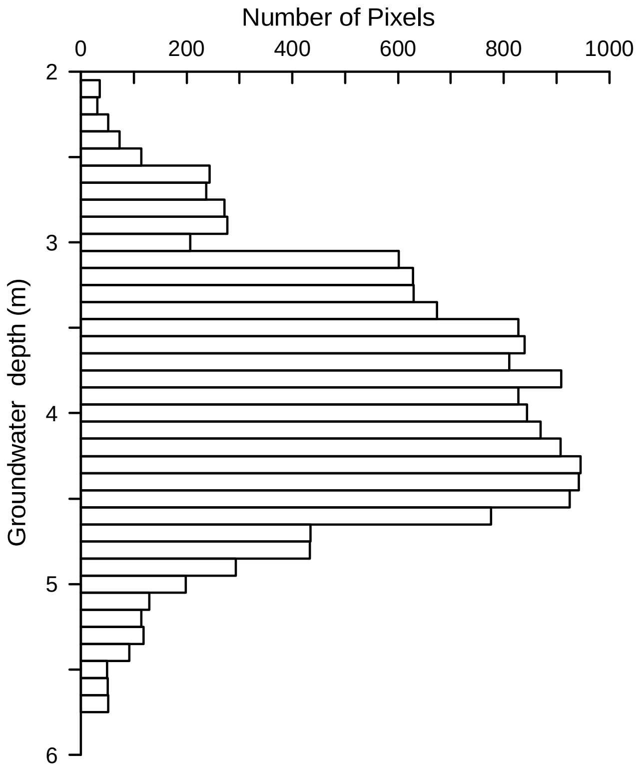


Figure 5.8 Number of pixels corresponding to different groundwater depths in June 2000.

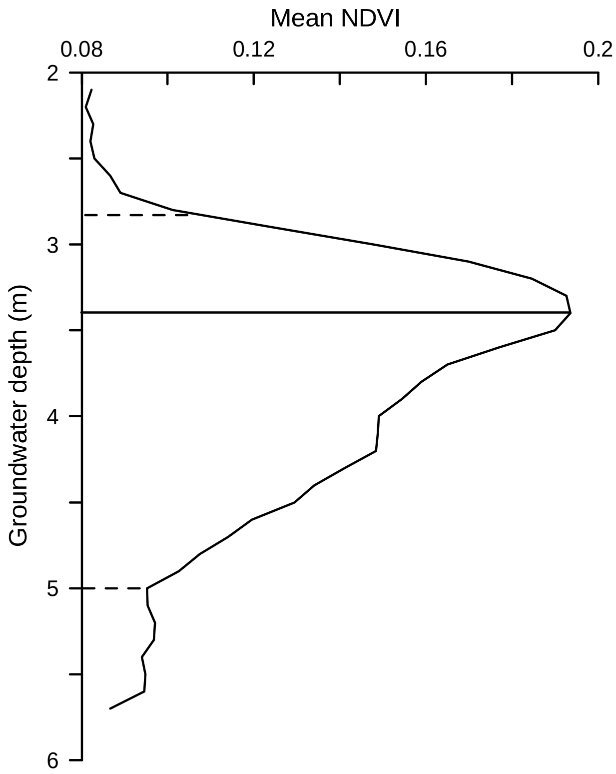


Figure 5.9 Relationship between groundwater depth and mean NDVI in the Ejina area. The solid line represents the groundwater depth. At the maximum NDVI, the groundwater depth corresponds to 3.4 m. The dashed lines indicate the depth range between 2.8 m and 5 m.

5.3.2 Vegetation type and groundwater depth

Indications in the literature exist that root depth is generally only limited by the water table or by soil characteristics that prevent rooting (Stone and Kalisz, 1991; Nepstad et al., 1994; Canadell et al., 1996; Jackson et al., 1996; Le Maitre et al., 1999). The variation of groundwater depth can affect the soil salt content and further control the surface vegetation growth. Different plants extract water from different depths in the Ejina oasis. Root excavation studies in June 2000 in the Ejina area showed that seven main plants developed strong sinker roots to a groundwater depth between 2 and 5 m (Table 5.1).

Populus euphratica, *Elaeagnus angustifolia* and *Tamarix ramosissima* are relatively deep-rooting, drought tolerant tree species in the Ejina area. Their suitable range of groundwater depth is between 2 and 5 m, and the maximal rooting depth is 5 to 5.5 m. The corresponding depth interval of dense coverage of these three species is between 3 and 5 m. The plant develops well in a relatively large interval of groundwater depths. The root can not extract enough water and the plant has difficulty to survive if the groundwater depth exceeds 5.5 m. *Haloxylon ammodendron*, *Glycyrrhiza glabra* and *Apocynum venetum* are three shrub species with a depth range for dense vegetation coverage between 2 and 4 m. *Phragmites australis* (Cav.) Trin. Ex Steud. is a relatively shallow-rooted type in the Ejina area and the suitable depth interval is between 2 and 3 m. It develops in a small range of groundwater depth. Indeed, species like *Phragmites australis*, *Glycyrrhiza glabra* and *Apocynum venetum* have nearly completely disappeared in this area.

5.3.3 Vegetation and groundwater salt concentration

The vegetation growth in the Ejina oasis is not only affected by groundwater depth, but also controlled by groundwater salinity. In general, *Populus euphratica* can develop well in the Ejina area if groundwater salt concentration is lower than 5 g/L, and the thresholds of salt concentration for *Tamarix ramosissima*, *Phragmites australis* and *Glycyrrhiza glabra* are 10 g/L, 10 g/L and 7.5 g/L, respectively (Zhang et al., 2002). However, strong evapotranspiration and the decrease of incoming water in the Ejina area resulted in little groundwater recharge and caused increased salt concentrations at the surface of the soil and an increase of groundwater salt concentrations. Our experimental results indicate that *Tamarix ramosissima* is the most halophile species in the Ejina area and it can survive when the groundwater salt concentration is larger than 22 g/L. Most plants can develop well if the groundwater salt concentration is lower than 3 g/L and their growth is restrained if the salt concentration is between 5 and 10 g/L. In the Ejina area, most of the plants start to die when the salt concentration is larger than 10g/L except *Tamarix ramosissima*. The extent of this species has been increasing since the beginning of the 1990s.

5.3.4 Vegetation change after 2000

The Ejina oasis not only supports the social-economic development, but also characterizes the eco-environmental condition of the northwestern area of China. The drastic degradation of the eco-environment in the Ejina area has raised much concerns in the past. A new scheme of water allocation in the Heihe River basin was put in place after the year 2000 and the incoming water of the Ejina area increased to more than 7×10^8 m^3 lately, bringing back a situation as before 1990 (cf. Figure 5.2) (Zhang and Dong, 2005). The increased amount of incoming water results in a steady recovery of specific parts of the eco-environment of the Ejina area and permanent water came back to the East Juyan lake in 2003. Some of the hygric and light salt-enduring species like *Phragmites australis* also recovered in the area. Although no observations of the groundwater depth after 2000 are available for this study to analyze the change of the depth, the indicated vegetation change reflects also the variation of the groundwater depth as discussed earlier. We use the oasis area to analyze the long-term change of the vegetation after 2000. Figure 5.10 illustrates the change of the mean NDVI between June 2000 to 2008. This NDVI figure shows an increasing greening trend, ranging from 0.156 to 0.179 during the period 2000 – 2008. Figure 5.11 shows the long-term change of the NDVI classes based on the classification used in Figure 5.3. According to this analysis, bare land (defined as 0 < NDVI < 0.08) covers nearly 74% of the Ejina area, low NDVI values (0.08 < NDVI < 0.2) cover 18%, moderate NDVI values (0.2 < NDVI < 0.4) cover 7%, and high NDVI values (NDVI > 0.4) make up the smallest area of about 1% surface cover. Trend analysis in this period reveals a decrease – or land improvement – of bare soil, whereas the other three NDVI classes show an increasing trend during the period 2000 – 2008. The annual conversion of bare land into improved land (measured by an increasing greenness trend) is about 608 pixels/year (Figure 5.11a). This result reveals a net land improvement of 38 km^2 ± 2.6 km^2 (Figure 5.11a) per year since 2000 with the most significant improvement in the NDVI class ranging from 0.08 – 0.2 of 16 km^2 (Figure 5.11b). The moderate NDVI class improved by 13 km^2 (Figure 5.11c) and the improvement of the high NDVI class is 6 km^2 (Figure 5.11d) in the Ejina area. The above NDVI change analysis indicates an increasing greening trend in the Ejina oasis since the new water allocation scheme was put in place in the year 2000.

Given the established link between groundwater depth and NDVI as indicated in Figure 5.9, signs are that the groundwater table has been successfully expanded and is recovering to depth levels that are more vegetation friendly.

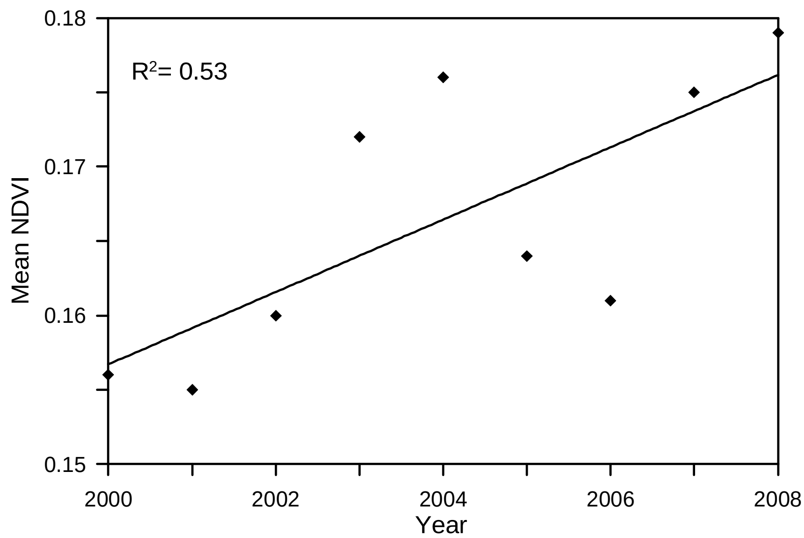
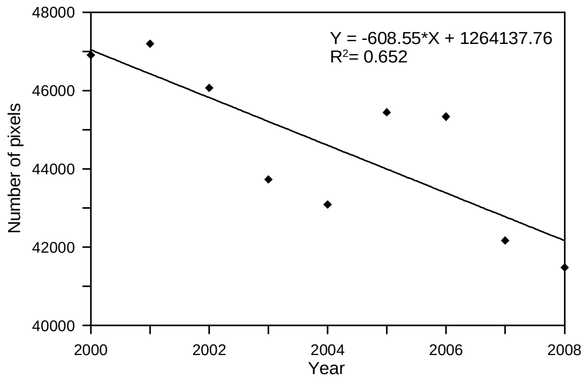
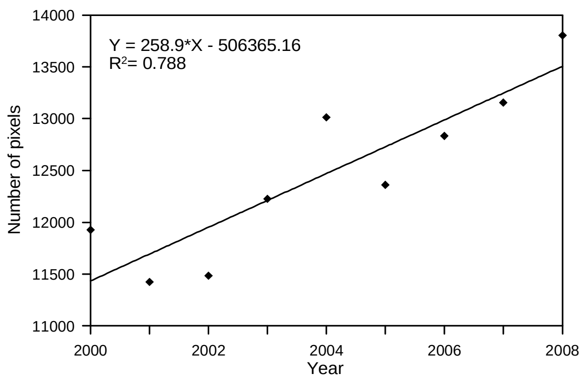


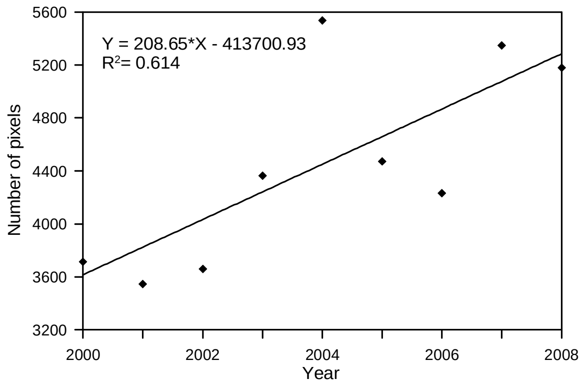
Figure 5.10 Mean NDVI changes as of June 2000 until 2008 in the Ejina area, expressing a general upward trend (y = 0.00243*x – 4.71) over that period.



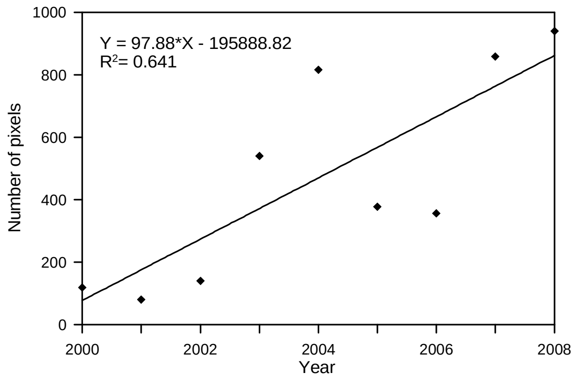
(a)



(b)



(c)



(d)

Figure 5.11 Annual changes of NDVI classes as used in Figures 5.3 and 5.5 in pixel counts for the Ejina oasis: (a) represents 0 < NDVI < 0.08 (‘no vegetation’), (b) represents the low NDVI area (0.08 < NDVI < 0.2), (c) corresponds to the moderate NDVI class (0.2 < NDVI < 0.4) and (d) to the high NDVI class area (NDVI > 0.4).

5.4 Conclusions and outlook

In this study the quantitative relationship between groundwater depth and vegetation cover in the Ejina area in June 2000 was derived by combining remote sensing and groundwater observation data. Further we used the above established relation to monitor greenness in the Ejina area in the subsequent years, where extensive groundwater depth measurements are missing. The following conclusions can be drawn based on the results obtained.

(1) The threshold for the groundwater depth affecting the vegetation growth in the Ejina area varies around about 5 m. The vegetation growth in the Ejina area is mainly controlled by groundwater when the groundwater depth is less than 5 m and hardly any vegetation growth occurs when the groundwater depth is larger than 5 m;

(2) The range of groundwater depth suitable for vegetation growth in the Ejina area varies between 2.8 m and 5 m. Deep groundwater depth will cause shortage of water for the root system that thus it is not able to supply adequate water for the canopies. With a shallow groundwater depth, salinization will occur at the surface and this is also not suitable for vegetation growth in the Ejina area either;

(3) The excavation experiments in the Ejina area show that many plants developed strong sinker roots to a groundwater depth between 2 and 5 m below ground level. Species like *Phragmites australis*, *Glycyrrhiza glabra* and *Apocynum venetum* have nearly disappeared from the Ejina area because of a shallow rooting system;

(4) In the Ejina area, vegetation can develop well if the groundwater salt concentration is lower than 3 g/L. Their growth is restrained if the salt concentration is between 5 and 10 g/L and most of the plants start to die when the salt concentration is higher than 10 g/L. *Tamarix ramosissima* is a halophile species occurring in the Ejina area and its extent has increased since the beginning of the 1990s.

(5) The mean NDVI shows an increasing greening trend in the Ejina area during the period 2000 – 2008. The long-term change of the bare land area ($0 < NDVI < 0.08$) shows a decreasing trend and that of all the other three NDVI classes show an increasing trend during the period 2000 – 2008. It reveals a net land improvement of 38 km^2 ± 2.6 km^2 per year since 2000 with the most significant improvement in the NDVI class ranging from 0.08 – 0.2 of 16 km^2. The analysis supports the hypothesis that the Ejina oasis is gradually recovering its eco-environment.

This study on the impact of groundwater depth on vegetation growth can provide reference for protecting the water depth from declining, balancing the water quantity allocation, controlling the water salinity and finally slowing down the rate of degradation in the Ejina area. In future work, we will continue quantifying the relationship between groundwater depth and vegetation growth after implementation of an updated water allocation scheme. New observation data of the groundwater wells will be needed, in combination with remote sensing data, to analyze further the spatial and temporal changes of the groundwater depth and its relationship with vegetation growth. In particular, the relation between structural vegetation components (e.g., grassland, shrubs, trees) will be of prime interest.

CHAPTER 6

Synthesis

6.1 Conclusions

The main objective of this thesis is to develop a methodology for large scale quantitative assessment of the eco-environmental changes in arid regions by integrating remote sensing methods with ecohydrology approaches. Each of the chapters of this thesis concentrates on answering one of the research questions proposed in section 1.3, subsequently achieving this overall objective.

Question A: Can we use remote sensing methods for quantitatively assessing both the vertical and horizontal distribution of vegetation in a mountainous area and assess the main impact factors on vegetation growth? The Qilian Mountains are located in the southern part of the Heihe River basin representing the upstream area. The runoff generated by precipitation in this area is the main water source for the total river basin. The vegetation cover is one of the most important indicators for the ecosystem in this area, it can affect local climate and further it has an important effect on water resources. Amongst the many impacting factors affecting vegetation cover, the effect of topography is most significant because it serves as a proxy for precipitation and temperature. Therefore, elevation and aspect determine the microclimate and the microclimate affects the spatial distribution of vegetation.

In Chapter 2, the spatial distribution of vegetation in the Qilian Mountains is quantified using remote sensing. Seven years of MODIS NDVI data from 2000 to 2006 were used serving as an indicator for vegetation growth in this study. Our analysis shows that elevation and aspect are two important impact factors responsible for the vertical distribution of vegetation in mountainous areas. A contour map representing the relationship between NDVI and the elevation and aspect is generated based on a combination of MODIS NDVI and DEM data. The ranges of elevation and aspect corresponding to the best vegetation growth were assessed. In general, the NDVI increases with the elevation and reaches its maximum value at a certain elevation threshold, and then decreases as the elevation increases beyond this threshold. The optimal vegetation growth is on the shady side of the mountains because of reduced evapotranspiration losses. Furthermore, the effect of two primary climatic factors, temperature and precipitation, on vegetation growth was also very important. The monthly precipitation and land surface temperature providing optimal conditions for the vegetation growth were assessed in this chapter.

Question B: Can regional evapotranspiration be precisely estimated by using a model based on the surface energy balance including remotely sensed data input and how can we validate the reliability of the evapotranspiration results at larger scales? The Zhangye basin, located in the middle stream area of the Heihe River basin, is a very important agricultural area in northwest China. With the increase of population and farmland, the water consumption of this basin increased gradually during recent years. Most water is used for agricultural purposes and 90% of the water consumption is used for irrigation purposes. The water consumption increased continuously during the past years and parts of the water resources disappear through net evapotranspiration (ET) loss. This caused a decrease of the incoming water in the downstream area resulting in a recession of the eco-environment of the downstream area. In order to properly estimate the increase of water consumption and the net ET loss in the Zhangye basin, the amount of water evaporated to the atmosphere should be estimated first.

Chapter 3 demonstrated the use of the SEBS algorithm (Surface Energy Balance System) to estimate the regional ET in a basin. The SEBS algorithm requires cloud free satellite images as one of the input variables and there are only very few useful NOAA/AVHRR satellite images available in one month for the study area. Consequently, the daily ET could not be modelled. A new efficient method to estimate the monthly ET, and subsequently the annual ET, was proposed by using a combination of daily SEBS results and measurements of ground meteorological stations. First, the daily ET for each individual day in one month was calculated based on SEBS results and the observed pan evaporation at the meteorological station. Then the monthly ET for the whole basin was estimated by multiplying with the area of the basin, and finally the annual ET was computed by using again the pan evaporation data. The results indicate that the annual ET increased gradually during the period 1990-2004 and the main impact factor on the long-term increase of annual ET was the vegetation change.

The reliability of the ET result based on the SEBS algorithm requires validation before it can be used for water resources assessment in a certain region. In this research, the study area is an isolated hydrological unit where recharge, runoff and discharge occur. The inflow and outflow are equal in this closed basin. The accuracy of the ET result was validated by using a water balance for the whole watershed. Although there were still some uncertainties in the SEBS algorithm, the validation indicated that the SEBS algorithm can be used to effectively estimate annual ET. Further, it is expected that these results can serve as a basis for the government to decide on a new policy of water resource allocation in the Heihe River basin.

Question C: Can we use remote sensing methods for understanding the quantitative relationship between the runoff of a river towards an oasis landscape and the vegetation growth in the oasis, and can these relationships be used for estimating the water demand of the oasis? The decrease of incoming water in the downstream area of the Heihe River basin resulted in a shrinking of the Ejina oasis. It caused a series of environmental problems like land desertification and because of this process the chance of sandstorms occurring increased. Water resources availability is essential for a continuous oasis development. In northwest China, all the oases depend on surface rivers and have a close relationship with the runoff of the river.

The quantitative relationship between the runoff of the Heihe River and the long-term vegetation change of the Ejina oasis was studied in Chapter 4. The research was divided into two stages corresponding to before and after the implementation of a new allocation scheme of the limited water resources in the Heihe River basin. For the first period from 1989-2002, the GIMMS NDVI dataset was used to quantify the long-term change of the oasis vegetation, and a good correlation between the runoff of the river and the vegetation change was established based on stepwise regression analysis. Complementing the first stage, we used MODIS NDVI in the second stage to analyze the vegetation change and the relationship between the runoff of the river and the vegetation variation (2000-2006). The results illustrate a decreasing trend of vegetation growth from 1989-2002 and an increasing trend from 2000-2006. A good correlation between the runoff of the river and vegetation growth was found in both stages and the time lag of the hysteresis effect of the runoff of the river on the oasis vegetation development is one year. In addition, the yearly smallest amount of water which can sustain the demand of the downstream area was estimated as well on the basis of these MODIS images.

Question D: Can we integrate remote sensing methods into ecohydrological approaches to study the effect of groundwater depth on vegetation growth in the oasis area, and use this to determine the range of groundwater depth for vegetation growth? Groundwater is the most important impact factor in sustaining the ecological environment of an oasis. Decrease of incoming water caused a drop of the groundwater table in the Ejina area and the hygrophytic, mesophytic and light salt-enduring vegetation was replaced by xerophytic, halophilic vegetation. Understanding the hydrological link between the groundwater depth and vegetation cover is important for eco-environmental recovering and protection activities for the vegetation in the Ejina area.

Chapter 5 explored a method to quantify the effect of the groundwater depth on the vegetation growth in the year 2000 in the oasis by combining MODIS NDVI with groundwater observation data. The groundwater depth of the downstream area was calculated at the same resolution as the MODIS NDVI image by interpolating the measured groundwater depth using a kriging method. The quantitative relationship between the NDVI and the corresponding groundwater depth in the oasis area was determined and the range of groundwater depth suitable for vegetation growth was derived from this relationship. Finally, the process of vegetation change after the implementation of a new water allocation scheme in 2000 was analyzed in this study. The results indicate that the mean NDVI increased and the annual conversion of bare land into vegetated land is about 38 km^2 per year during the period 2000 – 2008. This indicates a potential recovery of the eco-environment in the Ejina area. The result of this study can be used as an example to develop a new method for assessing the impact of groundwater changes on large-scale vegetation growth by using remote sensing.

General conclusions. Based on the studies of the four previous chapters, it can be concluded that:

- The spatial (vertical and horizontal) distribution of vegetation in mountainous areas can be successfully quantified using MODIS NDVI. The elevation and aspect, serving as a proxy for precipitation and temperature, are two very important factors for the vertical distribution of vegetation in the Qilian Mountains. The vegetation was at a maximum between an elevation of 3200 m and 3600 m and the peak value of NDVI was around 3400 m. Vegetation growth is better on the shady side of the mountain than on the sunny side. A preferred precipitation of 46 mm/month and a land surface temperature of 21°C may provide suitable conditions for optimal vegetation growth.

- The SEBS (Surface Energy Balance System) algorithm can successfully estimate the regional evapotranspiration of the inland basin using it in combination with observed pan evaporation of a meteorological station. The annual ET increased gradually during the period 1990-2004 and the main impact factor on the long-term increase of annual ET was the vegetation change.
- GIMMS NDVI and MODIS NDVI data are two important time series allowing the assessment of the long-term vegetation changes in an oasis area located in an arid region. With the support of stepwise regression, the hysteresis effect of the runoff of the river on the oasis vegetation was efficiently evaluated based on these two time series in this study. The vegetation growth decreased during the period 1989-2002 and increased from 2000 to 2006 in the Ejina Oasis. The time lag of the impact of the runoff of the river on the oasis vegetation is one year. Furthermore, the smallest water demand which can sustain the need of the eco-environment of the oasis area is 4×10^8 m^3 per year based on the series of MODIS images.
- The significant impact of groundwater on vegetation growth in an arid area can be quantitatively assessed at regional scale by integrating MODIS NDVI data with in-situ groundwater observations. The range of groundwater depth suitable for vegetation growth in a certain region can be found by means of data mining. The range of groundwater depth for vegetation growth is between 2.8 m and 5 m and hardly any vegetation growth occurred when the groundwater depth is below 5 m because the rooting depth of the present species is limited and therefore cannot provide adequate water supply to their canopies in the Ejina area.

6.2 Reflection

In this section, we discuss the general contribution of this research integrating remote sensing methods with eco-hydrology approaches. In particular, we refer to the here developed methodology applied to the eco-environment in the Heihe River basin.

The overall objective of this research is to find a sound and robust method evaluating the eco-environmental changes in an arid oasis area. Vegetation and water are two significant factors and intimately coupled in an arid eco-system: changes in one factor automatically imposes changes on the other. Although this coupling has been studied for many years within various earth science and biological disciplines (Bonell, 2002), our understanding of the interdependencies and interaction of these two factors is still far from complete. The merger of ecology and hydrology into a science of "ecohydrology" is aiming at understanding environmental systems in a more integrated and comprehensive way (Newman et al., 2006). This study successfully integrates remote sensing methods with ecohydrology in quantifying the relationship between water resources and vegetation at larger scale. The first achievement of this thesis (Jin et al., 2008a, b) resides in quantitatively assessing the spatial distribution of vegetation and the topographic impact on the vegetation with remote sensing data in a mountainous area. The result can help us to study the interaction between vegetation and microclimate, and subsequently understanding the interdependence between vegetation and water resources.

The second step of this thesis (Jin et al., 2008c) is developing an innovative and efficient method to estimate the annual evapotranspiration at regional scale by combination of the SEBS (Surface Energy Balance System) algorithm with meteorological observations. Subsequently, one of the key issues addressed in this thesis is the validation of the accuracy of the evapotranspiration result using a water balance. The work of the thesis indicates that the continuous increase of farmland and irrigation resulted in the ET increase.

In general, the distribution, growth, and mortality of vegetation is more sensitive to the hydrologic cycle than to any other factor (Weltzin and Tissue, 2003). Although significant progress has been made in analyzing the interdependence between vegetation and water resources at local scale, quantitative methods relating vegetation change to hydrologic processes at regional scale are still in earlier stages of development. A main effort presented in this thesis is the conceptual and quantitative understanding of how the surface water and groundwater impact the vegetation growth in a large arid area using remote sensing data (Jin et al., 2007; 2008d; 2008e; 2008f). Selecting time series of remote sensing data with a moderate spatial resolution suitable for evaluating eco-environmental changes not only benefits from mapping the vegetation area over large regions, but it is also possible to detect long-term vegetation change using multi-temporal images (Jin et al., 2008f). The large amount of remote sensing data can be used efficiently to find potential variations and regulations of the eco-environment by means of data mining (Jin et al., 2008a; 2008f).

Therefore, the main contribution of this work is the development of new methods for (i) quantitative assessment of the spatial distribution of vegetation and its impact factors in a mountainous area; (ii) accuracy estimation of the regional evapotranspiration and the validation of the evapotranspiration with a water budget; (iii) quantifying the important effects of surface water and groundwater on the vegetation growth. Furthermore, a new particularly useful framework for evaluating the eco-environmental changes at large scale in an arid area was presented in this work.

The importance of this work also lies in the choice of the study area, being the Heihe River basin. The Heihe River basin, located in middle part of the Hexi Corridor in China, is one of the most important agricultural areas in northern China and it is also one of the inland basins which is most strongly affected by human activities. The entire river basin can be divided into three parts based on three different landscapes - the upstream mountainous area, the middle stream cropland area and the downstream desert area. Due to sufficient precipitation, the runoff generated from the upstream mountainous area is the main water resource supporting the middle stream and downstream areas. There are close relations amongst these three systems and their composition represents a very typical vegetation-water-ecosystem in an arid region. The depletion of the water resources in middle stream area caused serious eco-environmental problems in the downstream area and it has become a threat to the eco-safety of the whole river basin. The Heihe River basin was approved to be the first generation of a national protection area of the ecological function in 2001. The study of eco-environmental changes in the Heihe River basin shows consistent and significant impact originating from human activities, which has been discussed widely in many scientific contributions (e.g., Lu et al., 2003; Lan et al., 2004; Zhou et al,, 2004; Luo et al., 2005; Qi and Luo, 2005; Qi et al., 2007; Wang, 2007). However, little progress has been made on the study of the quantitative relationship between vegetation change and water resources availability at regional scales in China. The main work of this thesis discussed the successive scientific issues as different parts and then combined them systematically. It provides a methodology to evaluate the long-term vegetation change and the impact of water resources using remote sensing methods. On the other hand, river basins in water-limited landscapes are particularly well suited for studying environmental feedbacks and responses because they contain long and relatively complete records of past environmental change. Available eco-environmental results originating from the total river basin analysis of this thesis can be synthesized to build a comprehensive reconstruction of the hydrological and vegetation history of the Heihe River basin. This iterative, retrospective, and process-oriented approach of vegetation dynamics, runoff and groundwater change can lay a solid foundation for predicting the effects of future environmental changes. Therefore, this study provides a sound scientific reference to policy makers and may help to further support adaptation activities in order to carry out sustainable environmental protection in the Heihe River basin.

6.3 Outlook

In this section we put our findings into perspective and we outline possible improvements in future work. We segment the efforts into the following domains:

- Partitioning of evaporation and transpiration,
- Vegetation and streamflow,
- Vegetation change and groundwater recharge, and
- Evaporation and groundwater.

Partitioning of evaporation and transpiration. The amount of available water is the driver of many plant and microbiological processes in water-limited environments. The amount of available water is determined by the spatial and temporal distribution and amount of precipitation, but it is also determined by how precipitation is redistributed via processes such as interception, infiltration, evaporation, and runoff. Most hydrological studies have estimated water budgets by combining canopy interception, soil evaporation (E), and transpiration (T) into a single term, evapotranspiration (ET) (Reynolds et al., 2000; Yepez et al., 2003; Loik et al., 2004; Huxman et al., 2005). Although combining E and T is very useful for some applications, the biological processes play a significant role in regulating the hydrological cycle directly or indirectly. Soil evaporation and transpiration all depend on vegetation cover, but in different ways. Therefore, study on evaporation and transpiration processes separately can help us to better understand how they are affected by vegetation cover and what their influence is on ecohydrological dynamics. Furthermore, partitioning E and T can help us to estimate the water demand and to improve our ability to quantify the effect of biological processes on the hydrological cycle.

The E and T constitute more than 95% of the water budget in water-limited ecosystems (Wilcox et al., 2003a) and some studies quantified this partitioning for different ecosystems and temporal scales (Reynolds et al., 2000; Unsworth et al., 2004; Huxman et al., 2005; Scanlon et al., 2005a). The stochastic variation of precipitation is a very critical factor on this partitioning of E and T. The spatial and temporal stochasticity of precipitation in water-limited environments results in highly dynamic patterns of soil water distribution and vegetation properties (Porporato et al., 2002; Knapp et al., 2002; Rodriguez-Iturbe and Porporato, 2004). Assessment of controls on E and T and further partitioning of E and T will be needed in the future.

Vegetation and streamflow. Understanding the effect of vegetation on streamflow is one of the most important tasks in ecohydrology. The role of vegetation in the dynamics of soil moisture, runoff and streamflow in arid environments has been studied through field observations, hydrological modeling and remote sensing (Wilcox et al., 1997, 2003b; Newman et al., 1998, 2004; Cayrol et al., 2000; Neave and Abrahams, 2002; Porporato et al., 2002; Ridolfi et al., 2003; Kerkhof et al., 2004b). Few studies have attempted to quantify relationships between the type and pattern of vegetation and streamflow. These relationships are a significant step in developing an ecohydrological approach to water resources management and environmental change. In some water-limited areas, the streamflow is derived mostly from precipitation and melting snow, and it has close relationship with vegetation cover (Hibbert, 1983; Baker, 1984; Williamson et al., 2004). Therefore, study on the influence of vegetation on streamflow using remote sensing will remain a main topic of interest and importance in ecohydrology in the near future.

Vegetation change and groundwater recharge. The important link between vegetation and groundwater has been shown in water-limited environments. The relation between groundwater recharge and vegetation type could enable vegetation to be used as a proxy for recharge to some extent (Walvoord and Phillips, 2004; Kwicklis et al., 2005). Vegetation mapping generated by using airborne- or satellite based approaches could then be used to predict subsurface flow and recharge and these methods can improve local to regional estimates of recharge. Hydrological processes in the thick infiltration zones of water-limited environments demonstrate longer timescales than those in surface soils. Changes in groundwater recharge brought about by changes in vegetation (caused by climate variation, land use, etc) can be predicted through a substitution of space by time. Although some important progress has been made on the relationship between vegetation dynamics, soil water storage, and precipitation in predictive models of groundwater recharge, the specific relation among recharge, hydraulic factors and vegetation type should be further assessed through coordinated hydrological measurements and monitoring using various remote sensing based methods (Allison et al., 1990; Smith et al., 2000; Walvoord et al, 2002; Scanlon et al., 2003, 2005a; Seyfried et al., 2005).

Phreatic evaporation and groundwater depth. Evaporation is the main discharge path of groundwater in the hydrological cycle for water-limited areas. The groundwater moves up due to capillary forces and enters into the atmosphere through the unsaturated zone. Therefore, the groundwater depth and soil properties of the unsaturated zone have significant impact on phreatic evaporation. Quantifying the relation between groundwater depth and surface evaporation can improve our understanding of factors determining phreatic evaporation. The relationship between groundwater depth and phreatic evaporation for different soil properties have been studied through the use of various in-situ methods (Duell, 1990; Nichols, 1994; Laczniak et al., 1999; Berger et al., 2001; Steinwand, 2001, 2006). However, most studies focused on experimental measurements for certain soil types at local scale. Groundwater depth, soil property, vegetation type and evaporation are all spatially dynamic at regional scales. The regional phreatic evaporation can be efficiently estimated by using a remote sensing model, but quantifying the relationship between groundwater depth and phreatic evaporation at large scale in an arid region is still an open research question.

This study summarizes and puts various points of discussion for future work forward. Implementation of the above efforts will need further integration of remote sensing and hydrological data at various spatial, temporal and spectral scales. A successful integration will further promote the development of even more powerful approaches for environmental problem assessment. Even though past calibration and now-casting are important methods supporting this assessment, further data collection will need to include methods allowing forecasting models to be used, ultimately allowing us to address unforeseen upcoming environmental problems.

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Summary

Water-limited environments exist on all continents of the globe and they cover more than 30% of the Earth's land surface. The eco-environments of these regions tend to be fragile and they are changing in a dramatic way through processes like land desertification, shrinking of oases, groundwater depletion, and soil erosion. These are either human induced or results of a changing climate. Implications of these changes for both the regional hydrologic cycle and the vegetation have been documented. Since these changes occur over a wide range of scales in space and time, remote sensing methods are needed to monitor the land surface characteristics, to observe changes in vegetation and hydrological states, and to compare these with predictions from hydrological models. It is widely accepted that remote sensing methods offer the ability to acquire spatially continuous measurements over large areas. Remote sensing can also help to visualize complex processes because the spatial data can be captured regularly over time.

China is one of several countries with large arid and semi-arid areas. The Heihe River basin, situated in the arid inland of northwestern China, is one of the areas severely affected by eco-environmental degradation and recovery. The problem of the degraded environment is due to overexploitation of surface and ground water leading to shrinking of oases, including the decline and death of natural vegetation, and the lowering of the groundwater table. Exhaustive (over-)use of water resources is the main cause of land degradation in the lower reaches of the basin, called the Ejina oasis. The whole Heihe River basin is therefore selected as study area in this thesis to analyze the long-term eco-environmental changes. What happens in this river basin is likely to have a growing influence on regional hydrological cycles, even affecting human life. Effective management of eco-environmental problems in this critical zone of water-limited conditions will provide scientific evidence for protecting and improving the eco-environment in these Chinese northwestern arid regions, eventually resulting in land improvement.

Studies on quantifying the relationship between the vegetation and the water resources are a critical step in developing an ecohydrological approach to resources management in order to minimize environmental degradation. Remote sensing measurements can help us to better understand the effects of changes in water management on hydrological processes and their subsequent feedback to the eco-environment at the regional scale. Remote sensing methods can also provide information to quantify heterogeneity and change at a large scale. Therefore, the main objective of this thesis is to develop a methodology for the quantitative assessment of eco-environmental changes at a large scale in arid regions by integrating remote sensing methods in ecohydrological approaches.

Chapter 1 outlines the significance of quantitative assessment of eco-environmental changes using remote sensing methods and applying them for ecohydrology in northwestern China, resulting in the specific research objectives of this thesis.

Chapter 2 quantifies both the vertical and horizontal distribution of vegetation in the Qilian Mountains area, representing the upper reaches of the Heihe River basin, based on MODIS NDVI images from the year 2000 - 2006. Our analysis reveals that elevation and aspect are two important impact factors for the vertical distribution of vegetation in a mountainous area. The NDVI increases with the elevation and reaches a maximum value at a certain elevation threshold, and then decreases as the elevation increases beyond this threshold. The optimal vegetation growth is on the shady side of the mountains because of less evapotranspiration. The best combination of temperature and precipitation is assessed providing good conditions for vegetation growth.

Chapter 3 presents an efficient method to estimate the regional annual evapotranspiration (ET) based on the SEBS algorithm (Surface Energy Balance System) in the Zhangye basin, representing the middle reaches of the Heihe River basin. The method proposed is a combination of the daily SEBS results and data collected by meteorological stations. The result shows that the annual ET increased gradually during the period 1990-2004 and the main impact factor on the long-term increase of annual ET was the vegetation change. The accuracy of the ET result is validated using a water balance for the whole watershed and the validation reveals that the SEBS algorithm can be used to effectively estimate annual ET in the Zhangye basin.

Chapter 4 establishes the quantitative relationship between the runoff of the Heihe River and the long-term vegetation change of the Ejina oasis, located in the lower reaches of the Heihe River. In this part, two time periods are distinguished corresponding to before and after the implementation of a new water allocation scheme in the Heihe River basin. The GIMMS NDVI and MODIS NDVI data sets are used to quantify the long-term change of the oasis vegetation in the first period 1989-2002 and the second period 2000-2006, respectively. The vegetation change shows a decreasing trend from 1989 to 2002 and an increasing trend between 2000 and 2006. Good relation between the runoff of the river and the vegetation growth are found at both stages and the time lag of the observed hysteresis effect of the runoff of the river on the oasis vegetation is one year. In addition, the yearly smallest water amount which sustains the demand of the eco-environment of the Ejina area is estimated to be 4×10^8 m^3 based on MODIS images.

Chapter 5 explores a method to quantify the effect of the groundwater depth on the vegetation growth in the year 2000 in the oasis area by combining MODIS NDVI with groundwater observation data. The result demonstrates that the groundwater depth suitable for vegetation growth in this region ranges from 2.8 to 5 m, depending on species composition. Hardly any vegetation growth occurs when the groundwater depth is below 5 m because the rooting depth of the occurring species is limited and cannot maintain adequate water supplies to their canopies when the water depth is below 5 m. The situation changes after implementation of the new water allocation scheme since 2000. The mean NDVI increased and the annual conversion of bare land into vegetated land is about 38 km^2 per year during the period 2000 – 2008. It reflects a potential recovery of the eco-environment of the Ejina area.

Chapter 6 comprises the main conclusions and the outlook for possible improvements in future research. The main contribution of this study is the successful integration of remote sensing with ecohydrology in quantifying the relationship between water resources and vegetation occurrence at large scale. It provides a methodology to evaluate the long-term vegetation change and the water resources impact using remote sensing data in water-limited areas. The approach of vegetation dynamics, runoff and groundwater impacts presented in this thesis serves as a sound foundation for predicting the effects of future environmental changes.

Samenvatting

Milieus met beperkte waterhoeveelheden bestaan op alle continenten en ze beslaan meer dan 30% van het landoppervlak op aarde. Het eco-milieu van deze regio's is meestal kwetsbaar en verandert op een dramatische wijze door middel van processen zoals woestijnvorming, het inkrimpen van oases, uitputting van het grondwater en bodemerosie. Deze processen zijn ofwel door de mens veroorzaakt of het gevolg van een veranderend klimaat. De gevolgen van deze veranderingen voor zowel de regionale hydrologische cyclus als de vegetatie is reeds beschreven. Omdat deze veranderingen plaatsvinden over een breed scala aan ruimte- en tijdschalen, zijn remote sensing methoden nodig voor het monitoren van eigenschappen van het landoppervlak, voor het waarnemen van veranderingen in de vegetatie en de hydrologische toestand, en voor het vergelijken hiervan met voorspellingen uit hydrologische modellen. Het is algemeen aanvaard dat remote sensing methoden de mogelijkheid bieden om ruimtelijk continue metingen over grote oppervlakten te verkrijgen. Remote sensing kan ook helpen bij het visualiseren van complexe processen, omdat de ruimtelijke gegevens met regelmatige tussenpozen kunnen worden verkregen.

China is een van de landen met grote aride en semi-aride gebieden. Het stroomgebied van de Heihe rivier, gelegen in het aride binnenland van het noordwesten van China, is een van de gebieden die sterk beïnvloed zijn door degradatie en herstel van het eco-milieu. Het probleem van degradatie van het milieu is te wijten aan overmatig gebruik van het oppervlaktewater en het grondwater dat leidt tot het inkrimpen van de oases, met als gevolg achteruitgang en afsterven van de natuurlijke vegetatie, en verlaging van het grondwaterpeil. Overmatig gebruik van de watervoorraden is de belangrijkste oorzaak van bodemdegradatie in de benedenloop van het stroomgebied, de zogenaamde Ejina oase. Het hele stroomgebied van de Heihe rivier is daarom geselecteerd als studiegebied in dit proefschrift om de lange termijn veranderingen in het eco-milieu te onderzoeken. Wat er gebeurt in dit stroomgebied zal waarschijnlijk een groeiende invloed op de regionale hydrologische cycli hebben, en zelfs het leven van de mensen ter plaatse beïnvloeden. Effectief beheer van de problemen van het eco-milieu in deze kritische zone met beperkte waterhoeveelheden zal wetenschappelijke aanwijzingen leveren voor de bescherming en verbetering van het eco-milieu in de noordwestelijke aride gebieden van China, uiteindelijk resulterend in landverbetering.

Studies naar de kwantificering van de relatie tussen vegetatie en de watervoorraad zijn een essentiële stap in de ontwikkeling van een ecohydrologische aanpak voor het beheer van hulpbronnen met het oog op het minimaliseren van de degradatie van het milieu. Remote sensing metingen kunnen ons helpen bij het beter begrijpen van de effecten van veranderingen in het waterbeheer op hydrologische processen en vervolgens van hun feedback op het eco-milieu op regionale schaal. Remote sensing methoden kunnen ook informatie leveren om heterogeniteit en veranderingen op grote schaal te kwantificeren. Daarom is de belangrijkste

doelstelling van dit proefschrift het ontwikkelen van een methodiek voor de kwantitatieve bepaling van veranderingen in het eco-milieu op grote schaal in aride gebieden door de integratie van remote sensing methoden in ecohydrologische benaderingen.

Hoofdstuk 1 geeft een overzicht van de betekenis van de kwantitatieve bepaling van veranderingen in het eco-milieu met behulp van remote sensing methoden en de toepassing daarvan voor de ecohydrologie in het noordwesten van China, resulterend in de specifieke onderzoeksdoelstellingen van dit proefschrift.

Hoofdstuk 2 kwantificeert zowel de verticale als de horizontale verdeling van de vegetatie in het gebied van het Qilian gebergte, dat de bovenloop van het stroomgebied van de Heihe rivier vertegenwoordigt, gebaseerd op MODIS-NDVI beelden uit het jaar 2000 – 2006. Ons onderzoek toont aan dat hoogte en hellingsrichting twee belangrijke factoren voor de verticale verdeling van vegetatie in een bergachtig gebied zijn. De NDVI neemt toe met de hoogte, bereikt een maximale waarde op een bepaalde hoogte en neemt vervolgens weer af als de hoogte nog verder toeneemt. De optimale vegetatiegroei is aan de schaduwzijde van de bergen omdat daar minder evapotranspiratie plaatsvindt. De beste combinatie van temperatuur en neerslag voor goede vegetatiegroei is bepaald.

Hoofdstuk 3 beschrijft een efficiënte methode voor het schatten van de regionale jaarlijkse evapotranspiratie (ET) op basis van het SEBS algoritme ("Surface Energy Balance System") in het Zhangye bekken, de middenloop van het stroomgebied van de Heihe rivier. De voorgestelde methode is een combinatie van de dagelijkse SEBS resultaten en gegevens van meteorologische stations. Het resultaat toont aan dat de jaarlijkse ET geleidelijk toenam in de periode 1990 – 2004 en dat de belangrijkste impact factor op de stijging van de jaarlijkse ET op de lange termijn de verandering in vegetatie was. De nauwkeurigheid van het ET resultaat is gevalideerd met behulp van een waterbalans voor het gehele stroomgebied en uit deze validatie blijkt dat het SEBS algoritme gebruikt kan worden om effectief de jaarlijkse ET in het Zhangye bekken te schatten.

Hoofdstuk 4 stelt de kwantitatieve relatie tussen de afvoer van de Heihe rivier en de vegetatieveranderingen in de Ejina oase, gelegen in de benedenloop van de Heihe rivier, op de lange termijn vast. In dit deel worden twee perioden onderscheiden die overeenkomen met voor en na de invoering van een nieuw systeem voor toekenning van water in het stroomgebied van de Heihe rivier. De GIMMS-NDVI en MODIS-NDVI gegevens zijn gebruikt voor het kwantificeren van de lange termijn verandering van de vegetatie in de oase in respectievelijk de eerste periode 1989 – 2002 en de tweede periode 2000 – 2006. De vegetatieverandering vertoont een dalende trend tussen 1989 en 2002 en een stijgende trend tussen 2000 en 2006. Er is een goede relatie gevonden tussen de afvoer van de rivier en de vegetatiegroei in beide perioden. De tijdsvertraging van het waargenomen hysteresis-effect van de afvoer van de rivier op de reactie van de vegetatie in de oase is een jaar. Verder wordt de minimale jaarlijkse hoeveelheid water die nodig is om te voldoen van de vraag van het eco-milieu in het Ejina gebied geschat op 4×10^8 m^3 (gebaseerd op MODIS beelden).

Hoofdstuk 5 onderzoekt een methode om het effect van de grondwaterdiepte op de groei van de vegetatie in het jaar 2000 in de oase te kwantificeren door het combineren van MODIS-NDVI beelden met grondwatermetingen. Het resultaat toont aan dat de grondwaterdiepte geschikt voor vegetatiegroei in deze regio varieert van 2,8 tot 5 m, afhankelijk van de soortensamenstelling. Er vindt bijna geen vegetatiegroei plaats als het grondwaterpeil dieper is dan 5 m, omdat de bewortelingsdiepte van de voorkomende soorten beperkt is en niet voldoende water kan leveren aan het bladerdak als het waterpeil dieper is dan 5 m. De situatie is sinds 2000 veranderd na invoering van het nieuwe systeem voor toekenning van water. De gemiddelde NDVI is toegenomen en de jaarlijkse omzetting van kale grond in begroeid land is ongeveer 38 km^2 per jaar in de periode 2000 – 2008. Dit geeft een eventueel herstel van het eco-milieu van de Ejina gebied aan.

Hoofdstuk 6 omvat de belangrijkste conclusies en een vooruitblik op mogelijke verbeteringen in toekomstig onderzoek. De belangrijkste bijdrage van deze studie is de succesvolle integratie van remote sensing met de ecohydrologie bij het kwantificeren van de relatie tussen watervoorraden en het voorkomen van vegetatie op grote schaal. Het biedt een methodologie om de vegetatieveranderingen op de lange termijn en de impact van watervoorraden vast te stellen met behulp van remote sensing data in gebieden met beperkte waterhoeveelheden. De aanpak van vegetatiedynamiek, afvoer en grondwatereffecten beschreven in dit proefschrift dient als een goede basis voor het voorspellen van de gevolgen van toekomstige veranderingen in het milieu.

内容概要

干旱、半干旱地区在世界上分布广泛，占据了全球陆地约 30%的面积。这些地区的生态环境极其脆弱, 由于人类活动及气候变化的影响导致土壤沙漠化、绿洲萎缩、地下水位下降以及土壤侵蚀等生态环境地质问题, 许多学者研究了这些变化对区域水循环及植被的影响。由于这些变化跨越大范围的时间和空间尺度, 遥感技术以其大范围区域内可获取实时监测数据的优越性, 被广泛用于观测这些地面特征参数、植被及水文状态参数, 并可以与通过水文模型模拟得到的参数进行对比验证。由于能够获取实时的空间数据, 遥感技术可以帮助我们透视复杂的变化过程。

中国是世界上干旱与半干旱区域广泛分布的国家之一。位于中国西北内陆的黑河流域, 是受生态环境变化影响最大的地区之一, 其环境退化的主要原因是水资源的不合理开发导致的绿洲萎缩, 包括自然植被的退化、死亡以及地下水位的下降, 特别是不合理应用水资源导致了黑河流域下游额济纳绿洲的退化。因此, 本篇论文选择了黑河流域作为研究区分析生态环境的长时期变化。流域内生态环境所发生的变化不仅影响了区域水循环, 而且影响了人们的生活。因而在黑河流域这个典型干旱区内有效解决生态环境问题, 既可以为中国西北干旱地区的生态环境保护提供科学依据, 也可以促进区域土地改良。

研究植被与水资源之间的定量关系是应用生态水文学进行资源管理, 有效遏制环境退化的关键一步。遥感技术不仅可以帮助我们更好地理解水资源管理对水文过程的影响, 及其在区域尺度上对生态环境的影响, 还可以为我们定量研究大尺度上的不均一性提供信息。因此, 本篇论文的主要研究目标是: 提出一种科学方法, 将遥感技术与生态水文学相结合, 定量评价干旱区大尺度生态环境的变化。

论文第一章主要介绍了将遥感方法应用于生态水文学中定量评价生态环境变化的重要意义, 并提出本篇论文具体的研究目标。

基于 2000 至 2006 年的 MODIS NDVI 遥感数据, 定量研究黑河流域上游祁连山地区植被在垂直和水平方向上的空间分布, 是论文第二章的主要内容。研究结果表明: 高程与坡向是山区植被空间分布的两个重要影响因素, 植被指数 NDVI 随着高程的增加而增大, 在一个高程处达到峰

值; 之后, 植被指数又随着高程的增加而减小。由于蒸发蒸腾较低, 植被在阴坡发育最好。同时, 温度和降雨的最佳耦合可以为山区植被发育提供良好的条件。

论文第三章提出了一种有效方法, 即基于表面能量平衡原理 (SEBS) 估算黑河流域中游张掖盆地的年蒸散量。此方法是将计算出的日蒸散量与气象站的观测数据相结合, 推算出月蒸散量, 进而估算区域年蒸散量。从结果可以看出: 张掖盆地的年蒸散量在 1990 至 2004 年间呈逐渐增加的趋势, 其主要影响因素是植被的变化。本章的最后运用水均衡法验证了表面能量平衡原理估算张掖盆地年蒸散量的可靠性。

论文在第四章建立了黑河流量与下游额济纳绿洲植被生长之间的定量关系。本章中, 我们根据黑河流域新的配水方案将研究分为两个阶段。在 1989 - 2002 年及 2000 - 2006 年这两个阶段分别采用 GIMMS NDVI 和 MODIS NDVI 数据进行定量分析。在第一阶段植被变化呈下降趋势, 而在第二阶段则呈现上升趋势。在这两个阶段, 黑河前一年流量与当年植被生长之间均显示有良好的相关性, 即河流流量对绿洲植被生长的影响滞后, 其滞后期是一年。另外, 基于 MODIS 数据, 本文计算出维持额济纳绿洲生态环境正常的最小需水量是 4 亿方。

论文第五章提出了一种方法, 结合 2000 年额济纳绿洲 MODIS NDVI 与地下水位观测数据, 定量评价地下水位埋深对植被生长的影响。研究结果表明: 额济纳地区适宜于植被生长的地下水位埋深范围是 2.8 至 5 m。当水位埋深低于 5 m 时, 由于植被根系深度有限无法供给叶片充足的水分, 故而植被很难存活。自 2000 年新的配水方案施行之后, 情况已有所好转, 额济纳绿洲的植被指数开始呈现增大的趋势, 而且在 2000 至 2008 年间植被面积在每年以 38 km^2 的速度增长, 这从另一侧面反映出额济纳地区的生态环境正在逐步恢复。

论文最后是主要结论及对未来工作的展望。这篇论文的主要贡献是将遥感与生态水文学较好地结合在一起, 定量评价了大尺度范围内水资源与植被生长之间的关系。所得结果为干旱区运用遥感方法评价植被的长期变化及水资源对植被变化的影响提供了一种科学方法, 同时本文对植被动态变化、地表水及地下水的影响研究也为预测未来生态环境的变化提供了科学基础。

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD Candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

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Review of Literature (5.6 ECTS)

- The Surface Energy Balance System (SEBS) for estimation of evaporation fraction (2004)

Laboratory Training and Working Visits (15.6 ECTS)

- Application of GIS in water resources development; China University of Geosciences (Wuhan), China (2005)
- Application of IDL language; Peking University, China (2005)
- Vegetation change and the effect on the water shed hydrology in Mississippi River basin; University of Iowa, USA (2007)

Discussion Groups / Local Seminars and Other Scientific Meetings (6.1 ECTS)

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- 34th Congress of International Association of Hydrogeologists (IAH); Beijing, China (2006)
- International Groundwater Forum, Nanjing, China (2007)
- 21st Congress of International Society for Photogrammetry and Remote Sensing (ISPRS); Beijing, China (2008)
- 33rd International Geological Congress (IGC); Oslo, Norway