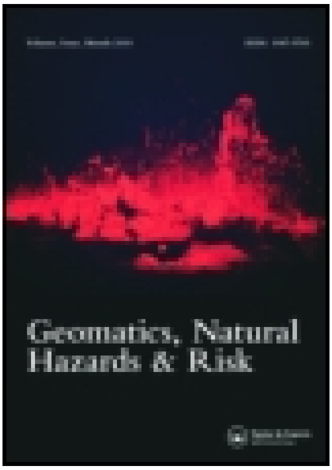

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A drought monitoring operational system for China using satellite data: design and evaluation

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A drought monitoring operational system for China using satellite data: design and evaluation

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Droughts occur frequently in China and their real-time monitoring and timely reporting are required for prevention and mitigation. This paper presents a method for developing an operational drought monitoring system for China. The method is based on various components such as Moderate Resolution Imaging Spectroradiometer data access, data processing, indices calculations, drought monitoring and analysis, and information dissemination. The system was tested by monitoring drought conditions in the early spring of 2009 in the Hai Basin of China. Results were compared with the *in situ* data-based indices. It was found that the system was capable of monitoring spatial variation in vegetation conditions attributed to droughts. The traditional meteorological drought index and yield data were collected to evaluate the system performance. A stronger relationship was found between the vegetation health index and the three-month standard precipitation index for the rainfed cropped areas. The relationship between the drought-area percentage and the winter wheat yield reduction percentage for 16 counties was stronger for the April–May period than for the February–March period. The drought monitoring system could explain about 60% of the variance in the winter wheat yields.

1. Introduction

Drought is one of the major natural disasters that occur in China. The frequency of drought occurrence can be as high as 70% in some regions as reported by Huang and Zhou (2002) following the 40 years of data analysis. Drought impacts agriculture, people's lives, and the economy. The impacts on agricultural production are especially outstanding. A direct result of drought includes the reduced production of food and commercial crops leading to decline in farm earnings. During the 1950–2001 period, the average drought-affected area in China was 21.73 million hectares per year and the average grain loss was 14.13 million tons per year which accounted for 4.68% of the overall grain production. The grain crops include mainly rice, wheat, maize, and beans. The grain loss exceeded 20 million tons in 12 different years (Cheng 2002). During 2004–2007, each year drought impacted about 16% of farmers nationwide, which resulted in an income loss of about 20% (You 2009).

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The traditional drought monitoring methods used in China are based on data on precipitation, temperature, and soil moisture collected from the meteorological stations. The spatial resolution of these stations is coarse and the data coverage is incomplete on a temporal scale. Therefore, such data-sets fail to monitor drought conditions accurately and in a timely fashion. Remote sensing technology, which provides continuous data both spatially and temporally, has been found useful to improving drought monitoring. Sensors such as Advanced Very High Resolution Radiometer (AVHRR) onboard National Oceanic Atmospheric Administration (NOAA) satellites, vegetation sensor (VGT) onboard Satellite Pour l'Observation de la Terre (SPOT) satellites, and Moderate Resolution Imaging Spectroradiometer (MODIS) onboard TERRA and AQUA satellites have been used for the large-scale drought monitoring (Kogan 1990, 1995; McVicar & Jupp 1998; Boken et al. 2005; Bayarjargal et al. 2006; Rhee et al. 2010).

Some of the indices derived from satellite data and used for drought monitoring include vegetation condition index or VCI (Kogan 1990), crop water stress index or CWSI (Jackson et al. 1988), vegetation temperature condition index or VTCI (Wang et al. 2001), drought extreme index or drought severity index (Su et al. 2003). The Australian Drought Watch System (ADWS) for Australia was developed in the late 1980s (Wilhite & Glantz 1985). The drought monitor for the United States was developed in 1999 jointly by the NOAA, the United States Department of Agriculture (USDA), and the National Drought Monitoring Center (NDMC) (Svoboda 2000). Lourens and Jager (1997) developed a real-time drought monitoring system for South Africa, which helped monitor crop conditions and estimate crop yields. The National Integrated Drought Information System (NIDIS) developed for the United States uses a biweekly vegetation health index (VHI) and weather data (Brown et al. 2008). Mu et al. (2005) used VCI derived from the NOAA AVHRR data to develop the National Drought Monitoring System. Yang et al. (2009) developed the wheat drought monitoring system for the Shandong province in China using CWSI derived from the MODIS data. The National Environmental Satellite, Data, and Information Service (NESDIS) provided the weekly global VHI products generated following a method developed by Kogan (1997). Bai and Di (2012) and Deng et al. (2013) reported a Global Agricultural Drought Monitoring and Forecasting System (GADMFS) which is a web-based service system developed for researchers and policy-makers.

This paper focuses on the design and performance evaluation of a drought monitoring system, DroughtWatch, developed for monitoring drought conditions in China. A detailed design of the system is described. The performance of this satellite data-based system was evaluated using the traditional meteorological drought index and the crop yield data. The system using the MODIS satellite data with a higher spatial resolution (compared to AVHRR) was found suitable for meeting accuracy needs for drought monitoring at a national level.

2. System configuration

DroughtWatch consists of four modules and a system database as shown in figure 1. The four modules include data acquisition, data processing, drought monitoring and analysis, and information dissemination. The system database, the foundation of DroughtWatch, saves the input and output parameters of these modules and provides connectivity among different modules.

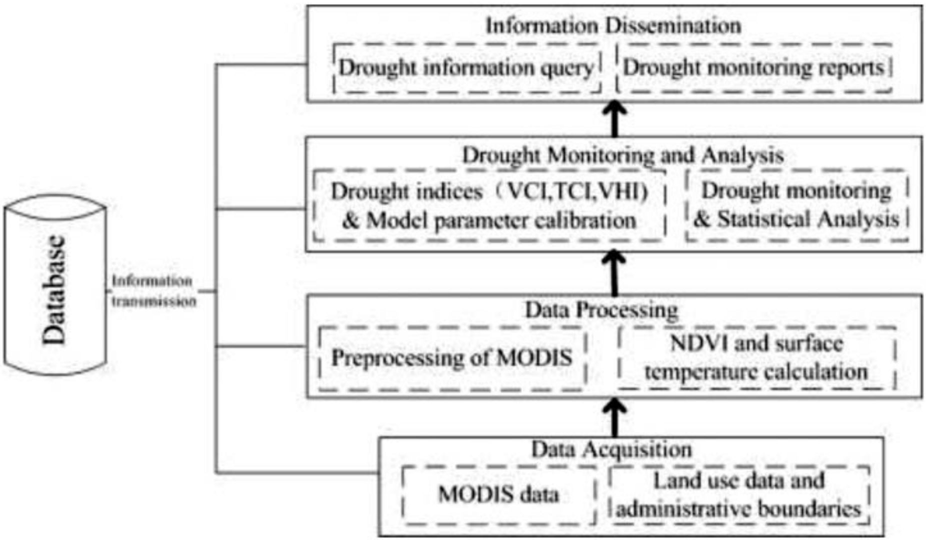

Figure 1. A configuration of the DroughtWatch system.

2.1. *Data acquisition*

The data acquisition module is responsible for collecting the MODIS data and the geographical data as required by the system. The land use data and the administrative boundaries were directly entered into the system from the system interface. The diurnal MODIS data were downloaded from the "very small aperture terminal" (VSAT), which is a very small transmitting and receiving station and is able to reliably transfer data, video, and voice via satellite. Because of the high storage requirement (20–40 gigabyte on a daily basis), the timely data transmission was performed via a file transfer protocol (FTP) for the data acquisition module.

2.2. *Data processing*

The data processing module comprises two sub-modules: (1) the MODIS preprocessing and (2) the normalized difference vegetation index (NDVI) and surface temperature computing.

The preprocessing includes the radiometric, geometric, and atmospheric corrections, and the cloud detection. The MRTSWATH program released by the USGS EROS Data Center[1] was integrated into the sub-module to perform a geometric correction. The radioactive transfer model 6S released by NASA was used to perform an atmospheric correction (Vermote & Vermeulen 1999). Another algorithm developed by NASA was also used for cloud detection (Ackerman et al. 2002).

Various vegetation indices, such as the simple vegetation index (SVI), ratio vegetation index (RVI), NDVI, and soil calibration vegetation index (SCVI), have been developed to monitor vegetation conditions effectively. Out of these indices, NDVI, as defined below, has been widely used.

$$\mathrm{NDVI} = \frac{(\rho_{\mathrm{nir}} - \rho_{\mathrm{red}})}{\rho_{\mathrm{nir}} + \rho_{\mathrm{red}}} \tag{1}$$

where ρ_{nir} is the reflectance in the near infrared band (band2 in MODIS) and ρ_{red} is the reflectance the red band (band1 in MODIS).

The surface temperature was calculated using a split window algorithm developed by Mao et al. (2005) and using the thermal infrared information as explained below:

$$Ts = a\,BT_{31} + b\,BT_{32} + c \tag{2}$$

where BT_{31} is the brightness temperature of band31 in MODIS, while BT_{32} is the brightness temperature of band 32 and a, b, and c are the coefficients.

2.3. *Drought monitoring and analysis*

The drought monitoring and analysis module comprises two sub-modules: (1) drought indices and model parameter calibration and (2) drought monitoring and statistical analysis.

2.3.1. Drought indices and model parameter calibration.

(1) VCI. Kogan (1990) proposed a VCI based on the NDVI and its maximum and minimum values for a long multi-year period as expressed in the following equation:

$$\mathrm{VCI}_j = \frac{\mathrm{NDVI}_j - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}} \times 100\,\% \tag{3}$$

where VCI_j is the vegetation condition index at time j, NDVI_j is the NDVI value at time j, $\mathrm{NDVI}_{\max}$ is the maximum NDVI value found in all of the images, while $\mathrm{NDVI}_{\min}$ is the minimum NDVI value found in all of the images. $\mathrm{NDVI}_{\max}$ and $\mathrm{NDVI}_{\min}$ were extracted every 10 days using the MODIS NDVI data since 1999 (Yan et al. 2005). Higher values of VCI correspond to the more healthy and less stressed vegetation. However, the red channel and the near-red channel reflectance rather overlap during the crop sowing period as well as during the crop harvesting period. Hence, the VCI is less capable of monitoring the fallow land. Therefore, the period from March to September was selected for which Feng et al. (2003) carried out a national drought monitoring analysis using VCI.

(2) Temperature condition index (TCI). The plant canopy temperature changes due to water-stressed or drought conditions. When the air temperature rises, stomata closure can reduce water loss caused by transpiration. As a result, the surface latent heat flux will decline and the sensible heat flux will increase, leading to an increase in the canopy temperature. Based on this principle, Kogan (1995) proposed TCI as defined below.

$$\mathrm{TCI}_j = \frac{T_{\max} - Ts_j}{T_{\max} - T_{\min}} \times 100\,\% \tag{4}$$

where TCI_j is the temperature condition index at time j, Ts_j is the surface temperature at time j, $T_{\max}$ is the maximum surface temperature found in all of the images, while $T_{\min}$ is the minimum surface temperature found in all of the images. Low TCI values indicate the vegetation stress due to dryness by high temperatures. TCI is not limited by the crop-growing season and can be used for the entire year as it is based only on the surface temperature.

(3) VHI. VCI and TCI characterize the moisture condition and the thermal condition of vegetation, respectively (Kogan 2001). To represent the overall vegetation health, the VHI, defined as below, was developed using VCI and TCI (Kogan 2001).

$$\mathrm{VHI} = a\mathrm{VCI} + (1 - a)\,\mathrm{TCI} \tag{5}$$

where a is the weight coefficient for the VCI, which represents the contribution of VCI to VHI. For the convenience of data storage, VHI is scaled from 0–1 to 0–250 through multiplying the number of 250. Since the moisture and temperature contribution during a vegetation cycle is currently not known, it is difficult to determine the value of a, so an equal weight has been generally assumed and assigned to calculate VHI (Kogan 2001). Mu (2006) proposed a method to estimate the value of a through a correlation analysis between VCI, TCI, and soil moisture; a was defined as

$$a = \frac{R^2_{\mathrm{VCI}}}{R^2_{\mathrm{VCI}} + R^2_{\mathrm{TCI}}} \tag{6}$$

where R^2_{VCI} is the coefficient of determination between the VCI and the soil moisture. R^2_{TCI} is the coefficient of determination between the TCI and the soil moisture. According to Mu (2006), the value of a was found to be 0.44.

The soil moisture data were collected from the agro-meteorological stations for point locations. The drying method was used to measure soil moisture at depths of 10 and 20 cm every 10 days. The relative soil moisture (RSM) was computed by dividing the actual soil moisture by the field capacity. The soil moisture for point locations was averaged within the 3×3 pixel windows. For the corresponding windows, VCI, TCI, and VHI were also averaged using the zonal statistics tool of the ArcGIS software. The soil moisture at the depth of 10 cm had a better correlation with indices than the soil moisture at 20 cm (Mu 2006).

(4) Model parameter calibration. Since VHI represents an overall vegetation health and has a stronger relationship with soil moisture than with VCI or TCI, the soil moisture data from the stations across China need to be collected to calibrate the weight coefficient of a in order to enhance the model's regional adaptability (Mu 2006). Therefore, the system designed a sub-module by including more regional observations to calibrate the model parameters for some regions.

2.3.2. Drought monitoring and statistical analysis. The RSM, presented by the Agricultural Climate Center of Weather Bureau (Yao et al. 2007) was used to classify the spatial extent of drought. Using the soil moisture data provided by the National Meteorological Bureau for more than 100 agricultural and meteorological

Table 1. The drought categories of vegetation health index (VHI) and relative soil moisture (RSM).

RSM (%)	VHI	R^2	Drought grades
0–30	1–23	0.36	extreme drought
30–40	24–41	0.42	severe drought
40–50	42–63	0.66*	moderate drought
50–60	64–85	0.55*	mild drought
60–80	86–125	0.61*	normal

Note: * represents statistical significance at alpha equal to 0.05.
Source: Mu (2006).

observation sites for the period from 2001 to 2004, Mu (2006) established statistical relationships between the drought categories and the VHI as shown in table 1. This study showed that the coefficient of determination (R^2) between VHI and the soil moisture was in the range of 0.3–0.6 for different categories (table 1). The correlation coefficient changes between the indices (VCI, TCI, and VHI) and RSM in Shanxi province during the period from March to October are presented in figure 2.

In addition, the overlay analysis and zonal statistics methods were applied on grid data to estimate the drought-affected area within different provinces and counties. The tools to apply these methods are available in the ArcGIS software. Using these methods, the average value of VCI, TCI, and VHI was calculated for a given county in a province.

2.4. *Information dissemination*

The Information dissemination module runs queries for historical and real-time drought monitoring results and provides reports every 10 days.

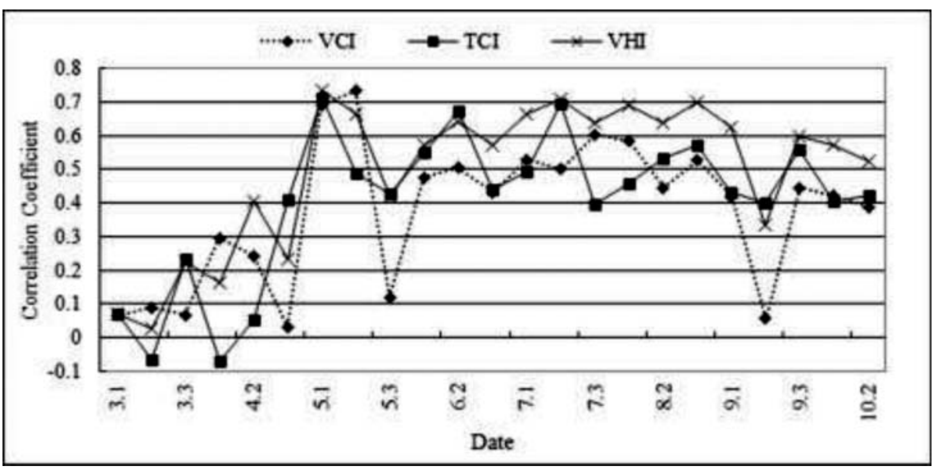

Figure 2. Relations between vegetation condition index (VCI), temperature condition index (TCI), vegetation health index (VHI), and relative soil moisture in Shanxi province. Source: Mu (2006).

The drought maps and statistical tables of drought are provided through a network. A colour drought map is also produced. The drought statistical data for counties and provinces are imported into the database.

Drought reports are provided in a fixed template along with drought maps showing the drought-affected areas for the six selected regions – the north-west, the North China Plain, the north-east, the south-west, and the eastern and southern parts of China.

3. Performance evaluations

3.1. *Study area*

Drought had occurred in the north of China in the spring of 2009. The Hai Basin, an important food base of China, was chosen for evaluating the performance of DroughtWatch. The Hai Basin is located between east longitudes of 112.0° and 119.8°, and between north latitudes of 35.0° and 42.8° (figure 3). It has a total area of 318,000 km^2, which accounts for 3.3% of the total land area of China. Grain production in this basin accounts for approximately 10% of the national grain production. The corn production accounts for 20% and the wheat production 16% of the total grain production of the basin.

3.2. *Data used*

DroughtWatch used two data-sets: the MODIS satellite data-set and the geographical data-set. Different MODIS products were used. MOD02 products (MODIS 1B data) were downloaded from the NASA website[2] or obtained from VSAT. There are 36 bands for the MOD02 product, but only 11 bands in MOD02 were preprocessed for drought monitoring. MOD11 and MOD13 products were used to calculate the maximum NDVI, the minimum NDVI, and the surface temperature, for the period from 2000 to 2008.

The geographical data provided by the Earth System Scientific Data Sharing Network (ESSDSN) with the resolution of 1 km included the shape files of the land use map, and the national, the provincial, and the county boundaries.

3.3. *Drought monitoring results*

DroughtWatch system was operated to produce the daily VHI and the 10-day VHI during the spring of 2009. The daily VHI data were used to calculate the monthly VHI by an averaging method. Figures 3 and 4 show the drought map for February-to-May period of 2009 and 2013. The results showed that drought occurred across the Hai Basin in 2009, while it did not occur in 2013.

The number of consecutive days without precipitation was up to 80 during winter in the northern region and therefore in February, the drought covered most of this area, including the Shandong, Hebei, Henan, and Shanxi provinces. The proportion of drought area in the arable land accounted for more than 35%. The drought extent declined in March due to the arrival of natural rains towards the end of February and due to the artificial rains created in some areas. During the period from April to May, droughts were detected only in regions in the south-eastern part of the Hebei

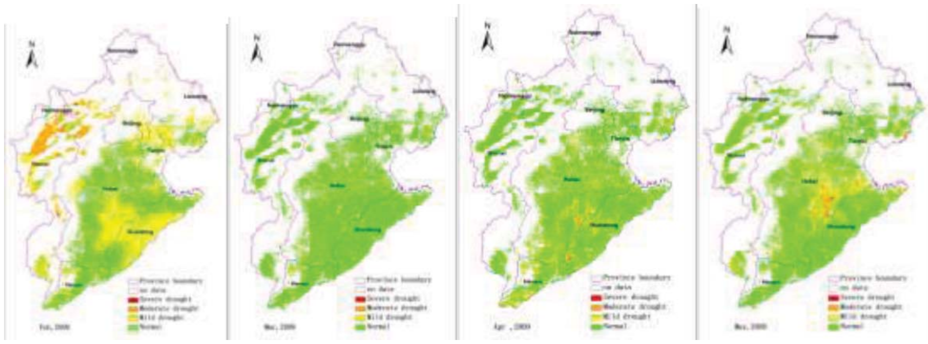

Figure 3. The drought monitoring maps during the period from February to May in the Hai Basin based on DroughtWatch 2009.

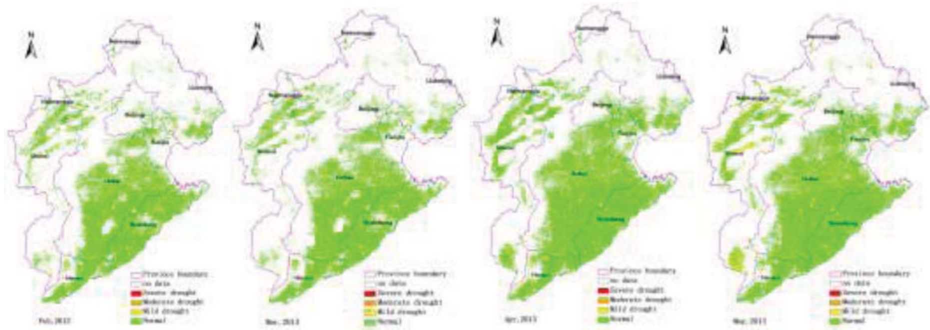

Figure 4. The drought monitoring maps during the period from February to May in the Hai Basin based on DroughtWatch 2013.

province, the north-western part of the Shandong province, and the north-eastern part of the Shanxi province. The drought in the spring of 2009 impacted agriculture production as analysed in Section 3.5.

3.4. Comparison between VHI and standardized precipitation index

DroughtWatch was evaluated by comparing its performance with the performance of the standardized precipitation index（SPI） that is widely used by the Hydrological Bureau of Ministry of Water Resources and the National Climate Centre of the China Meteorological Administration (Zhang & Gao 2004). The SPI, developed by McKee et al. (1993), is calculated by standardizing the probability of observed precipitation for any duration of months or years. A probability density function and an inverse normal (Gaussian) function are applied to the long-term precipitation data (Guttman 1999). Duration in months can be used to apply the SPI for agricultural or meteorological purposes, and the longer durations can be used for hydrological and water management purposes (Guttman 1999).

The 1979–2009 precipitation data collected from 34 meteorological stations were used to calculate a one-month SPI, a three-month SPI, and a six-month SPI. The monthly VHI was compared against the SPI during the period from February to May in 2009 for all of the selected meteorological stations. Relationships between the VHI and the different categories of SPI were established. The coefficients of determination in case of the one-month SPI, the three-month SPI, and the six-month SPI were 0.07, 0.11, and 0.08, respectively. None of the meteorological drought indices were found to be strongly correlated with the VHI.

However, there is a significant spatial variability in the above relationships. Figure 5 shows the spatial variability in the relationship between the VHI and the three-month SPI for all meteorological stations. Generally, there are much stronger relationships between the VHI and three-month SPI for meteorological stations located in the north than in the south or along the Bohai coast (figure 5).

The Xinxiang, Kenli, Huimin, Linxian, and Changyang stations in the south plain show negative relationships between VHI and SPI. These areas are included in the region irrigated by the Yellow River, and therefore, their vegetation growth was guaranteed. Similar relationships were found for the Shijiazhuang, Xingtai, and Anyang stations in the plains. These areas form the alluvial plain of the mountains, and the precipitation as well as the groundwater resources available in these areas adequately supported the vegetation growth. Huailai, Yuxian, Datong, and Yuanping stations in the western mountains show the stronger positive relationships. The area represented by these stations is considered dryland where crop yields rely only on precipitation; crops such as potatoes and sorghum are planted in this area. Therefore, it can be concluded that the relationship between VHI and drought is affected by the land cover, climate, and the irrigation from the surface as well as the ground water resources.

3.5. *Impact of drought on the winter wheat yield*

Drought impacts crop yields in arable lands. The winter wheat is the main crop of the Hai Basin and is planted in October and harvested in May. Winter wheat passes through three critical periods of water requirement – regreen-jointing (February), heading-flowering (April), and filling-ripening (May). DroughtWatch quantifies the drought information during these critical periods for the counties included in the Hai Basin. In order to examine drought impact on crop yields, the winter wheat yield data weres collected from the agro-meteorological stations for 16 counties for the period from 2005 to 2009. Considering the yield averaged for the 2005–2009 period as a reference yield, it was found that droughts had impacted winter wheat yields in approximately 70% of the counties. The coefficient of determination (R^2) between the percentage of the drought area and the yield loss of winter wheat for 16 counties was 0.0 for February, 0.33 for March, 0.635 for April, and 0.433 for May (figure 6). This relationship was statistically significant for April and May, indicating that the drought had much stronger impact on yields in April and May than in February or March. Although the period of regreen-jointing is also a critical water-requirement period, the growth of winter wheat needs less than 10% of the total water requirement during this period. In addition, due to the timely availability of water supplies in February and March, the drought had a declining impact on yield during these two months (figure 6).

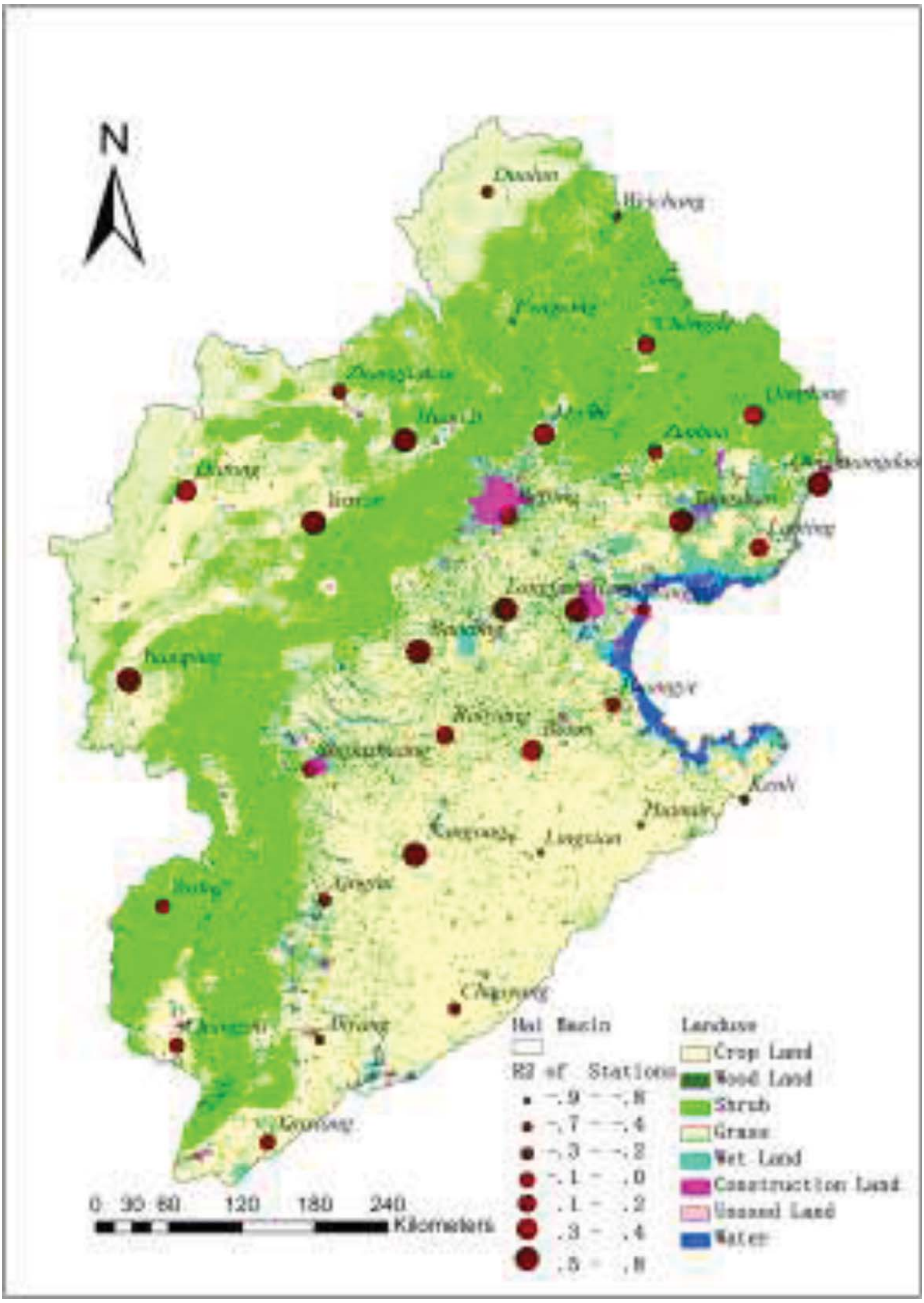

Figure 5. Meteorological stations and the land use map of the Hai Basin showing the coefficients of determination between the VHI and the three-month SPI from March to May in 2009.

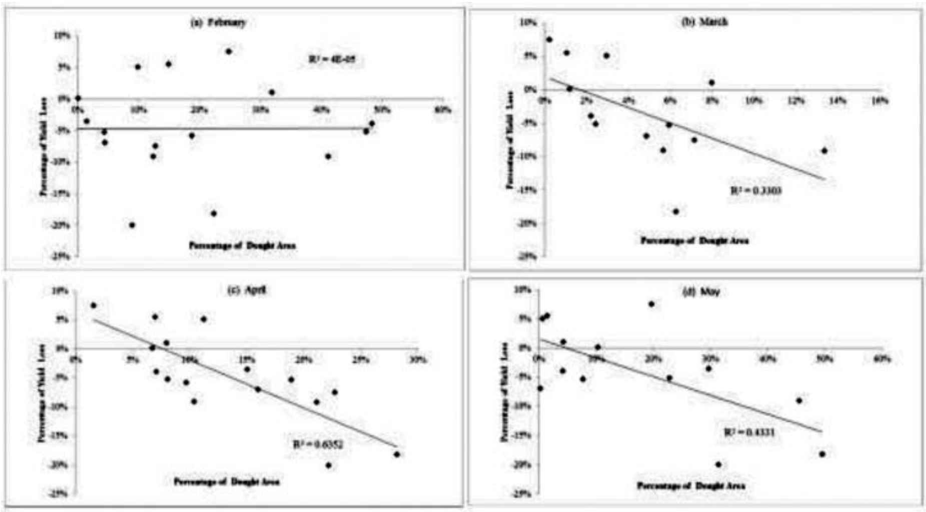

Figure 6. Relationships between the winter wheat yield and the drought-affected area in 2009 in the months of (1) February, (2) March, (3) April, and (4) May.

4. Discussion

The application of the remote sensing technology makes drought monitoring possible for various administrative offices and drought management departments. DroughtWatch plays an important role in two major ways: first, it provides a near real-time monitoring. MODIS data covering large areas are accessed daily and processed timely, while the *in situ* data usually are not available on a real-time basis because of the absence of automation in weather recording. Second, it provides detailed information on spatial variability of drought across nation. The spatial resolution of drought indices calculated from the *in situ* data depends on the density of the data collection network. Satellite data with relatively higher spatial resolution cover large areas. Therefore, DroughtWatch provides information about drought conditions in greater and multi-dimensional details. The VHI had strong relationships with the three-month SPI in the rainfed areas. The lagged response of the VHI to weather variations occurred because the vegetation growth withstood a short period of below-normal precipitation. This finding indicates that VHI can be used for monitoring a meteorological drought of three-month period for rainfed areas. Piao et al. (2003) also found a three-month lag between NDVI and weather variations in China. On the contrary, a weak relationship between VHI and a three-month SPI was observed for irrigated areas indicating that SPI is not capable of detecting drought conditions for irrigated areas. Drought had also occurred in irrigated areas due to inadequate frequency or amount of irrigation on account of inadequacy of water resources.

The relationships between droughts and the winter wheat yields for the Hai Basin showed that the yields were impacted more significantly by the April-to-May drought than by the February-to-March drought. Droughts in April and May explained about 60% of the variance in yields. Nevertheless, other factors relating to disease, insects, and fertilizers also caused yields to decline. However, such factors are difficult to examine. The satellite data with the spatial resolution higher than the MODIS' will help further improve the drought monitoring capability of DroughtWatch in the future.

5. Conclusion

In this paper, DroughtWatch for China, an operational drought monitoring system that uses satellite and meteorological data, was described. The satellite-based drought indices were calculated every 10 days and the monthly drought conditions were studied from February to May in 2009. The system was evaluated by comparing its performance with SPI, a widely used drought indicator. Although the correlations between the VHI and SPI were relatively low for all 34 stations, the strength of the relationship varied spatially. These relationships were stronger in the north than in the south or along the Bohai coast. A significant positive relationship was observed between VHI and the three-month SPI, which indicated that the VHI was able to detect meteorological droughts for the dryland cropped areas; the VHI detected agricultural droughts more accurately than SPI did, for irrigated areas.

While assessing the drought impact on winter wheat yields, it was found that the percentage of the drought-affected area during April–May caused yields to decline more significantly. These droughts could explain about 60% of the variance in the winter wheat yields.

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Notes

1. https://lpdaac.usgs.gov/tools/modis_reprojection_tool_swath
2. http://lasweb.nascom.nasa.gov

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