GROUNDWATER LEVEL MONITORING MODEL USING MULTI-TEMPORAL IMAGES IN ARID REGION OF NORTHWEST CHINA

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Commission VIII, WG VIII/7

KEY WORDS: Hydrology, Ecological Environment, Multi-temporal Images, Model, Monitoring.

ABSTRACT:

For the frangible ecological environment, it is very important to reasonably develop and utilize groundwater resources in Northwest China. Shallow groundwater level is an essential factor related to the eco-environmental problems such as oasis degeneration and land salinification. The lack of groundwater dynamic data is a critical concern for water resources management in the arid region. This paper aims at the development of groundwater level information model with remotely sensed data, combined with the well observations and field investigation. The method is based on the basic fact that the surface soil water moisture is observably related to the shallow groundwater level because of the very few precipitation in the lower plain of inner arid land basin. The analysis models for soil water content and radiation of remote sensing image are established, and then the remotely sensed data based groundwater level monitoring model is developed by using multi-temporal MODIS images. The models are demonstrated in the Shule River Basin which is located in Hexi Corridor, Gansu province of China. The research results could provide effective tools for the hydrology research, and support the sustainable water resources development and management in arid regions.

1. INTRODUCTION

1.1 Background

Shule river basin, with total area about 15000 square kilometres, is located in the west part of Hexi Corridor, Gansu province of China (see Figure 1). This is an extremely dry area with the mean annual precipitation is only about 40 mm in the lower plain while the potential evaporation reaches 2500mm. The annual river runoff, mainly formed in the mountainous area where the mean annual precipitation reaches 200mm, is about 1.63 billion cubic meters. Larger irrigation districts had been developed by the implementing of Shule River Basin Agriculture Development and Resettlement Project, supported by both the central government and the World Bank.

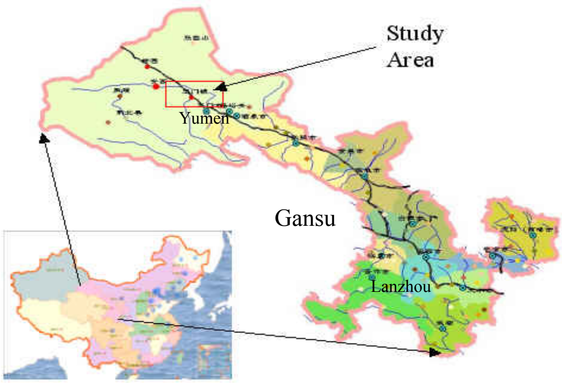

Figure 1 Location of Study Area

By building the Changma reservoir, rehabilitating the irrigation and drainage system and enhancing water use efficiency, this project aims at to reclaim about 29000ha of land in this region and to resettle 75,000 population from the poor mountainous area in the middle and south of the province. It is expected that the project will greatly promote the economic development for the whole province. It was verified that the land and water resources are enough for the agricultural development, the major concern is that if the development will cause negative impacts on the ecosystem in this region (Pan S.B., et.al., 2004).

Shallow groundwater level is an essential factor related to the eco-environmental problems such as oasis degeneration caused by groundwater level declining, and land salinification due to the groundwater level rising. The lack of detailed groundwater dynamic data is a critical problem for scientific water resources management in this region. Remote sensing technique may take an important role in obtaining dynamic information of water level in a large basin scale. Early researchers used airborne thermal infrared data and synthetic- aperture radar imagery to monitor groundwater (Whiting J.M., 1976; Dobrynnin N. P., et al.,1998). Rodell M., et.al.(2002) utilized GRACE (Gravity Recovery And Climate Experiment) to monitor groundwater storage changes for long term in high plains aquifer in central US. Maeleen Noomen (2007) also presented the groundwater monitoring techniques using both GRACE and ERS satellite images in continental or global scale. Suphan S. et.al. (2004) also proposed a method for estimation of spatial variation of subsurface water level change caused by crop growth from Landsat TM images, by simply using Normalized Difference Vegetation Index (NDVI) relationship with groundwater level in an irrigation project in Thailand. Tashpolat Tiyip et.al. (2005)

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discussed the thermal infrared data of Landsat TM application to groundwater level estimation in the oasis-desert ecotone in an arid area of Northwest of China. For a long-term groundwater monitoring, special considerations should be taken to a higher temporal resolution of remote sensors with an appropriate spatial resolution. This paper mainly discusses the development of groundwater level information model with multi-temporal MODIS images and field observations, for the purpose of monitoring shallow groundwater level.

1.2 Geological Setting and Groundwater System

The whole basin is separated to several sub-basins by outcrops of bedrock. Three sub-basins, Yumen, Anxi and Huahai, with similar geological conditions. Only Yumen basin (see Figure 2), the largest sub-basin, is considered for discussion in details in this paper. Groundwater, which is relatively rich in alluvial and floodplain, is mainly recharged by river water's infiltration in upper desert plain areas and discharged by ways of both springs and envp-transpiration in lower plain areas. In the lower plain, formed mainly by fine sand, silt and clay, the aquifer system can be schematically subdivided into two layers, i.e. the shallow groundwater, the upper layer with depth of from 30 m to 50 m, and the deep groundwater, the lower layer with bottom depth from about 60m to 160m. Shallow groundwater is the only water source on which the oasis depends. Groundwater becomes one of the most critical and sensitive factors that affect the ecological environment, because of the dry climate in this region. The dynamic of shallow water influences the development of ecological system. The variations of ground-water level are directly related to the changes of inflow from upper areas and the evap-transpiration. In May and June, groundwater level is higher because of infiltration recharge of river as well as irrigation utilizing surface water, while from July to September, water level is much lower because of the large evap-transpiration. From November to March of next year, water level rises because of the underground inflow of upper areas (see Figure 3).

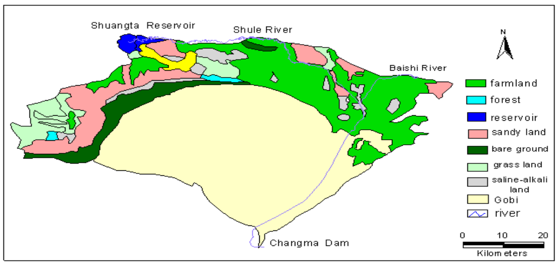


Figure 2 Yumen basin landuse classifications by Landsat TM

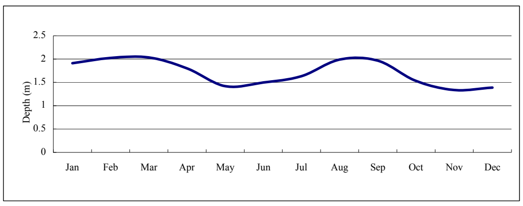


Figure 3 Shallow groundwater level annual dynamic curve (2002, well 4-4)

2. DATA AND MODEL

2.1 Data

The Moderate Resolution Image Spectro-radiometer (MODIS) on the Terra (Aqua) spacecrafts provides twice daily wide area coverage at 36 spectral channels for various detecting proposes. For this research, only channel 1,2 and channel 31, 32 were utilized for modelling (see Table 1).

Band No.	Wave length range (μm)	Resolution (m)	Detection objectives
1	0.620-0.670	250	cloud & land
2	0.841-0.876	250	cloud & land
31	10.78-11.28	1000	temperature
32	11.77-12.27	1000	temperature

Table 1 MODIS Typical Band Parameters

Total 12 periods of cloud free MODIS images of 2002 (about one month interval) was used to acquire the surface reflectance under the changes of shallow water level. The topographic maps with scale 1:50000 were used from the National Survey Bureau. Observation data of 19 wells were collected for the model development. The locations of groundwater observation wells were determined by using GPS in the field (see Figure 4).

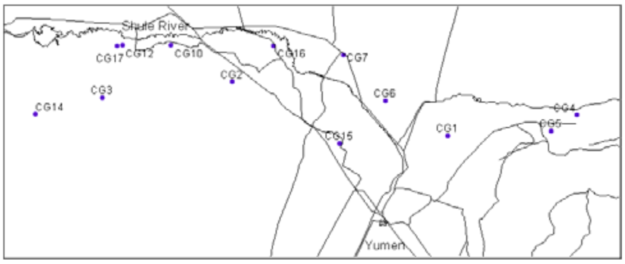


Figure 4 Location of observation wells in Yumen Irrigation District, lower plain of Shule River Basin

2.2 Model Methodology

The method is based on the basic fact that the surface soil water moisture is observably related to the shallow groundwater level because of the very less precipitation in the lower plain of inner arid land basin. The higher surface soil moisture, the higher shallow water level (see Figure 5). The land surface reflectance which can be obtained from the image varies with the surface soil moisture. Therefore, the relationship between the reflectance and groundwater level depth could be estimated using the well observation of same time period.

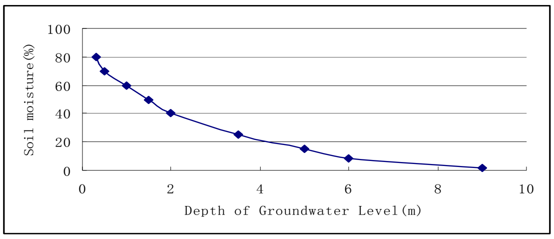


Figure 5 Relationship between groundwater level depth and surface soil moisture

2.2.1 Calculation of radiance: Firstly, the primitive data are processed to eliminate the BowTie effect, and transferred to WGS-84 projection. The radiance can be calculated for later application, the formula is written as following,

$$Rsi = D_{Ri}(DN_i - D_{RSi}) \qquad (1)$$

where, Rs presents radiance, DN_i is DN value of the pixel, D_{Ri} and D_{RSi} are the radiance constants which could be obtained from the head file of MODIS data, i is the serial number of the bands.

2.2.2 NDVI Calculation: Normalized Difference Vegetation Index (NDVI) describes the surface vegetation coverage, the quality or condition of being dense. The higher density is represented by larger NDVI, which can be stated as following,

$$NDVI = (Rs_2 - Rs_1)/(Rs_2 + Rs_1) \qquad (2)$$

where Rs_1 and Rs_2 are the radiance of band 1 and band 2 respectively.

2.2.3 Simulation of Surface Temperature and Soil Moisture: The surface temperature could be estimated by the method of the split window technique by using thermal infrared band data.

$$T_s = Rs_{31} + a(Rs_{31} - Rs_{32}) + c \qquad (3)$$

where T_s surface temperature, Rs_{31} and Rs_{32} are the radiance of band 31 and band 32 respectively, a is model parameter, and c is split window coefficient. The surface soil moisture could be described by using the land surface temperature and NDVI.

$$Sw = f(Ts, NDVI) \qquad (4)$$

where Sw is surface soil moisture.

2.2.3 Simulation of Groundwater Level Depth: Shallow groundwater level depth is observably related to the surface soil moisture. According to the field test, the relationship between the level depth and soil moisture is stated as following,

$$Sw = a_0 + c_1 \exp(Dw) \qquad (5)$$

where, Dw denotes the depth of groundwater level. Combined formulas (4) and (5), a mathematical model for water level depth analysis is established as following,

$$Dw = k \times Ln(NDVI \times Ts) + b \qquad (6)$$

where, k, b are equation coefficients which could be obtained by the fitting method using groundwater level observations. The depth of groundwater level could be estimated by using the radiances of band 1 and band 2, as well as band 31 and band 32 of MODIS data.

3. MODEL RESULTS AND DISCUSSIONS

3.1 -Model Results

The thematic map NDVI and land surface temperature (LST) of Yumen basin in June of year 2002 were shown in Figure 6 and Figure 7. The NDVI and LST at observation wells were calculated monthly (see Figure 8 and Figure 9). Both NDVI and LST at different locations varied in similar pattern with the highest values in June, July and August, and lowest values from January to March. The lowest values of groundwater level depth appear in August, September and October, about 60 days backward.

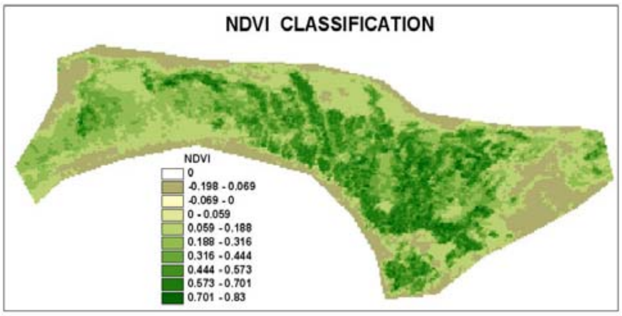


Figure 6 Thematic map NDVI of Yumen basin in June, 2002

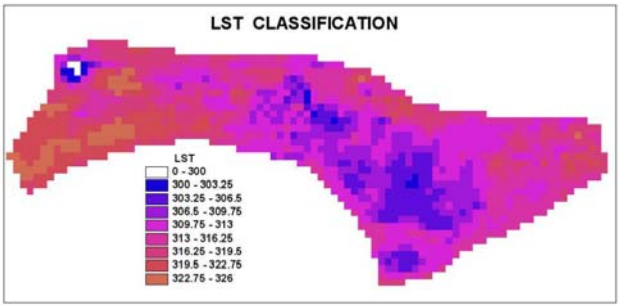


Figure 7 Thematic map LST of Yumen basin in June, 2002

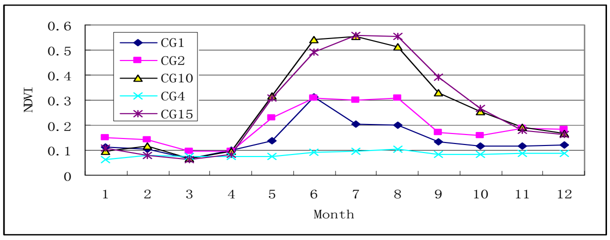


Figure 8 Variation of NDVI at observation well in 2002

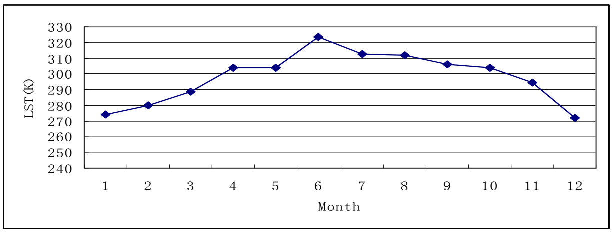


Figure 9 Variation of LST in the Yumen basin in 2002

Therefore the stepwise regression analysis method was used to obtain the relationship between groundwater level depth with NDVI / LST. The mathematical model is stated as following,

$$Dw(t_{i+2}) = k \times Ln\sum_{j=1}^{3}[w_j NDVI(t_{i+j-1}) \times Ts(t_{i+j-1})] + b \qquad (7)$$

where, i denotes time step (one month), k and b are model parameters, W_j weight for three time steps, w_1, w_2 and w_3 are 0.2, 0.4 and 0.4 respectively.

The parameters of the model for 5 typical observation wells are listed in Table 2, and the fitting curve of water level depth for observation well CG10 was illustrated in Figure 10.

No. obs. well	*k*	*b*	R^2	*average depth, m*
CG1	0.453	-0.233	0.782	1.43
CG10	0.224	0.538	0.845	1.47
CG2	0.327	0.672	0.678	3.87
CG4	0.636	2.479	0.534	4.53
CG15	0.040	6.385	0.033	6.21

Note: R= correlation coefficient

Table 2 Model parameters for different observation wells

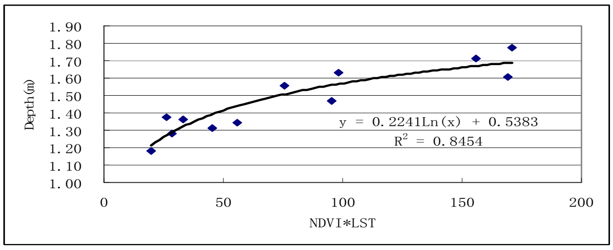
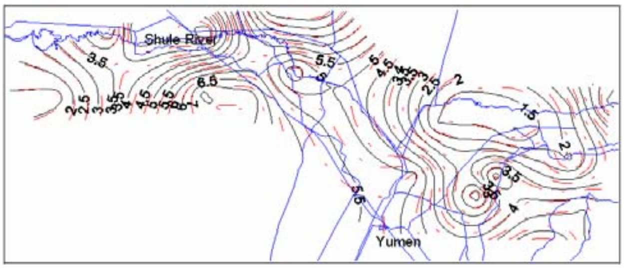


Figure 10 Fitting curve of water level depth for well CG10

3.2 Discussions

The relationship model correlation coefficients vary from 0.033 to 0.845. The model accuracies are much higher for shallower ground-water level, for cases of observation well CG1, CG10 and CG2, the correlation coefficients are larger than 0.67. The depth of groundwater level is not significantly related to NDVI and LST, when the water level depth is larger than 6 meters, for the case of observation well CG15. It has been verified that the evaporation of shallow water could be ignored at the depth of larger than 6 meters. Therefore, the model developed at the Yumen Basin is suitable only for shallower groundwater with a level depth not larger than 5 meters.

The groundwater level depth contour based on the relationship model of MODIS data is shown in Figure 11. The large depths of water table, varied from 4m to 5m, are mainly distributed along the ecotone between the oasis and the desert. Along Shule river, the depths of water level are also larger, about 5 m, because of the deeply cutting of the river. The depths of water table in the lower inner basin vary from 0.5m to 2.5m. The results are consistent with the actual situation in Yumen basin.



Note: dot-dash line in red, simulated value; solid line, observed.

Figure 11 Shallow groundwater level depth contour based on the simulation model of MODIS data (August of 2002)

4. CONCLUSIONS AND FUTURE DIRECTIONS

Remote sensing images could provide the available information for groundwater dynamic monitoring. This research suggested that MODIS, with a higher temporal resolution as well as an appropriate spatial resolution, is a very suitable data source to establish the groundwater level depth analysis model. In this paper, the series of band 1 and band 2, as well as band 31 and band 32 of MODIS data were used to calculate the NDVI and land surface temperature (LST). And the relationship between groundwater level depth and soil moisture which simulated by NDVI and LST was developed by using a series of MODIS data to simulate the water level variation monthly.

The model should be verified by using longer series of images. The precision of the analysis model needs to be further improved, by considering more factors such as soil and vegetation types, as well as irrigation activities. In future research, models with consideration of the factors mentioned above could be developed for analysis of the groundwater dynamic. Sub-regions with the different water level dynamic characteristics could be divided according to these factors. Various models for different sub-regions could be separately developed to improve the model simulation accuracy. Other remote sensing data with a higher spatial resolution could be tested for the dynamic monitoring purposes in the arid areas.

REFERENCES

Dobrynnin N. P., et al.,1998, Mapping of lands with a rising water table from synthetic-aperture radar imagery, Mapping Science and Remote Sensing, 35 (1) pp.31-40.

Liu P., et.al., 1997. A method for monitoring soil water contents using satellite remote sensing. Jour. of Remote Sensing, 1(2), pp.135-138 (in Chinese).

Maeleen Noomen, 2007, Groundwater Monitoring Using GRACE and ERS Satellite Image, Proceeding of the 28th Asian Conference on Remote Sensing, Malaysia

Pan S.B., Wang Z.J. et.al. 2004, Impact of water resources development on the environment system in Shule River basin of China, Proceeding of 25th Asia Conference Remote Sensing, Thailand, Vol.1: pp.824-829.

Rodell, M., 1999. Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. Water Resources Research, 35 (9), pp. 2705-2723.

Rodell M., et.al., 2002, The potential satellite-based monitoring of groundwater storage changes using GRACE: High Plains aquifer, Central US, Jour. of Hydrology, 263, pp.245-256 .

Suphan S. et.al. 2004 Estimation of subsurface water level change from satellite data, Proceeding of 25th Asia Conference Remote Sensing, Thailand, Vol.1: pp.512-516.

Tashpolat Tiyip et.al., 2005, Groundwater distribution in the oasis-desert ecotone in an arid area by using thermal infrared data, Arid Land Geography, 28(2): pp.252-257(in Chinese)

Whiting J.M., 1976, Airborne thermal infrared sensing of soil moisture and groundwater [A], Canadian Aeronautics and space institute, Remote sensing of soil moisture and groundwater[C].

ACKNOWLEDGEMENTS

This research is supported by the National Natural Science Foundation Committee (NSFC). The authors would like to thank NSFC for its financial support to this research. The authors would also like to thank the Bureau of Shule River Water Resources Management for providing the key data and useful information of Shule River basin.