Hydroinformatics and ecohydrology tools for ecologically sustainable development in northern China

HUILI GONG, JING ZHANG, DEMIN ZHOU, XIAOJUAN LI & YUN PAN

3D Information Acquisition and Application Key Laboratory of Education Ministry, College of Resource Environment and Tourism, Capital Normal University, #105 West 3rd Ring Road North, 100048 Beijing, China
maggie2008zj@yahoo.com

Abstract Due to natural and human disturbances (e.g. urban expansion), ecosystems have been changed dramatically on time scales ranging from years to decades. Especially in recent years, the ecohydrological system in northern China (including Inner Mongolia and around the Beijing area) has faced several environmental issues such as the shrinking of wetlands, water table decline, water quality deterioration, grassland degradation, dune expansion and the urban heat island effect. These merging issues make it necessary to consider the social context of interactive processes linking hydrology and ecology; hence the need for the Ecohydrology Approach. This transdisciplinary challenge requires an integration of various types of information, knowledge and techniques referred to as hydroinformatics for ecologically-sustainable development. In this study, the current conditions and problems of ecohydrology in northern China are reviewed. A transdisciplinary ecohydrological framework is proposed for future research, which incorporates remote sensing, geographic information systems and geographic positioning systems to extract hydro-ecological information for coupling ecohydrological models of different scale and resolution to simulate regional environmental change over time under various climate, land-use and environment management scenarios. The remote sensing (RS) monitoring of resources and the eco-environment around the Beijing area are also introduced. The large-scale remote sensing data processing system CASMImageInfo can be used to fast process hydro-ecological elements monitored by RS for the system. The proposed research plan is to study long-term regional hydrological change in the metropolitan and surrounding areas, and to determine the functionality and water cycle changes under controlled environment conditions in response to vegetation growth. The framework provides an opportunity for linking hydrology and ecology, as well as integration with modern information technology, leading to ecologically sustainable development of the region.

Key words remote sensing; geographic information system; hydro-ecological model; monitoring; human disturbance

INTRODUCTION

With the global shortage of freshwater resources, freshwater ecosystems continue to be stressed, and the traditional single discipline approaches have difficulty addressing the complexity of the new challenges of global environmental change. Hence it is very difficult to effectively solve these problems through either hydrology or ecological science. Ecohydrology emphasizes the interaction between hydrological processes, ecosystems and social systems. The UNESCO IHP VII Strategic Plan (2008–2013) "Water dependencies: Systems under Stress and Societal Responses" is bringing together transdisciplinary approaches for future action. It is of great importance to establish regional sustainable development plans to balance regional development needs and protection for aquatic natural resources.

The quantum leap in the development of computer science and geo-information technology provides an objective basis for truly integrated transdisciplinary approaches using hydro-informatics. Global Earth observation systems combining aerospace, aviation and ground coordination with multi-temporal and spatial resolution have been more and more widely applied in hydrological, ecological and environmental studies. The precision of the parameters acquired and data inversion are getting higher and higher (Groeneveld *et al*., 2007). Remote sensing technology can provide information on the community structure and individual canopy layer from an ecosystem to the biological community (resolution from 1 m to 1 km), and accurate access to all kinds of complex features of ecosystem properties and biochemical parameters, to meet the multi-type and high-precision requirements for model inputs.

In this study, an interdisciplinary framework is proposed for future research, which incorporates high-tech hydroinformatics methods such as RS, GIS and GPS to extract hydro-ecological environment information, and coupling of ecohydrological models with different scales

and resolution to simulate regional environmental change over periods of years under the impacts of climate, agriculture and ecology. The remote sensing monitoring and spatial data acquisition and application of geo-information techniques for resources and the eco-environment around the Beijing area are introduced. The objectives of this paper are to propose a transdisciplinary framework to determine the functionality and correlation between the water cycle under the controlled environment and the response of vegetation growth, to understand scientifically the regional hydrological processes and ecosystem changes in the future. It will enrich the eco-hydrological theory as well as offer valuable data for future environmental and hydrological research.

OVERVIEW OF CURRENT ECOHYDROLOGY CONDITIONS IN NORTHERN CHINA

Study area

In this research, three typical study areas were selected in northern China (Fig. 1). One is the Guishui River watershed, the rural plain area in the capital city of China, Beijing, which has a distinct water ecosystem protection function and experiences periods of drought and wetness annually. The area is 1064 km^2 including Guanting Reservoir and the Yeya Lake natural wetlands. The long-term average precipitation is 429 mm. This area has a unique ecological environment function within Beijing.

The second selected area is typical of grassland in northern China, located in the central region of Xilingol League, Inner Mongolia, with an area of 42 276 km^2. The average precipitation is between 300 and 450 mm. This area has been facing grassland degradation issues in recent decades.

The Hunshandake sand land, one of the five biggest sand lands in Inner Mongolia, China, was chosen as the third study area. It is located in the eastern part of Asia's mid-latitude desert belt

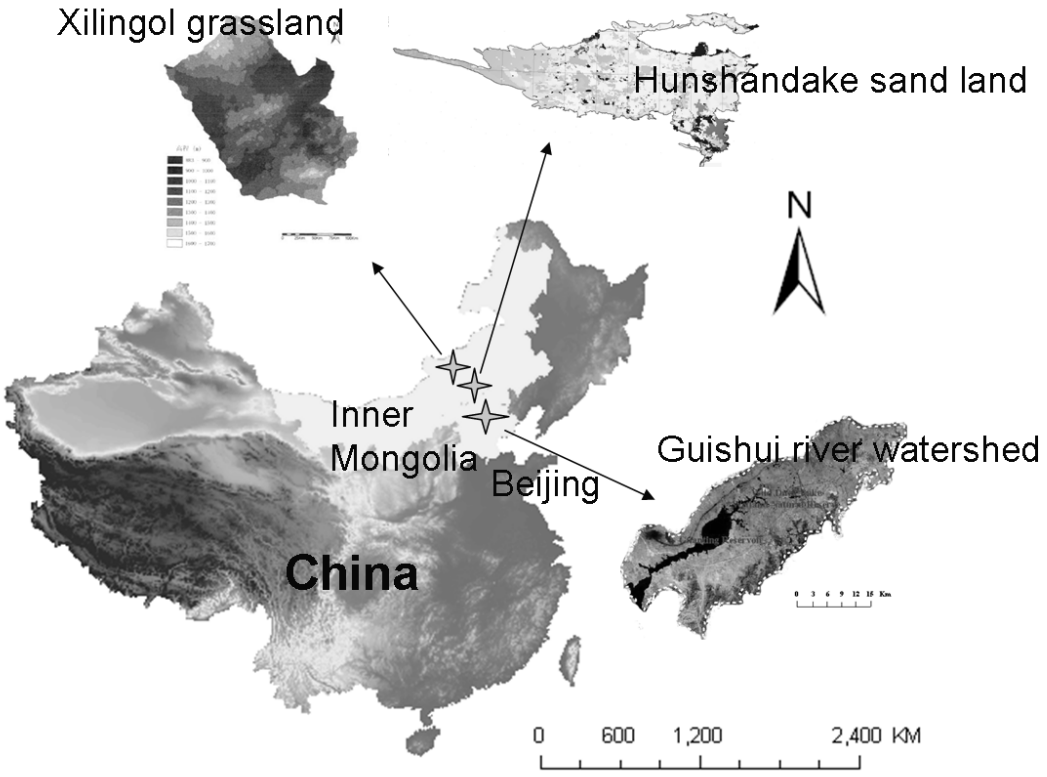

Fig. 1 The map of study areas.

and is 32 149 km^2 in area. The annual precipitation ranges considerably from 350–400 mm in the eastern region, to 100–200 mm in the west, with a mean annual ET as high as 2000–2700 mm. The wind velocity and intensity are quite high in the study area. The Hunshandake sand land has been fighting against desertification for years.

Water resources issues

In response to natural and human disturbances (e.g. urban expansion), ecosystems have been changing dramatically on time scales from years to decades. Especially in recent years, the eco-hydrological system in northern China (including Inner Mongolia and the area around Beijing) has faced several key issues needing societal responses: wetland shrinkage, water table decline, water quality deterioration, grassland degradation and the urban heat island effect. Figure 2 shows the dynamic evolution of wetland resources in Beijing for >20 years, 1984–2008. It can be seen that, generally, the total wetland areas have been decreasing; the areas of wetland in 1996 and 1998 were larger than those of the other years, and after 1998 the wetland resource rapidly degenerated, especially paddy wetland. From 1998 to 2008, the area of wetland dropped by 50%. Furthermore, the water quality of five different types of wetland has a declining tendency, mainly due to human disturbances (e.g. urban expansion) and precipitation decrease.

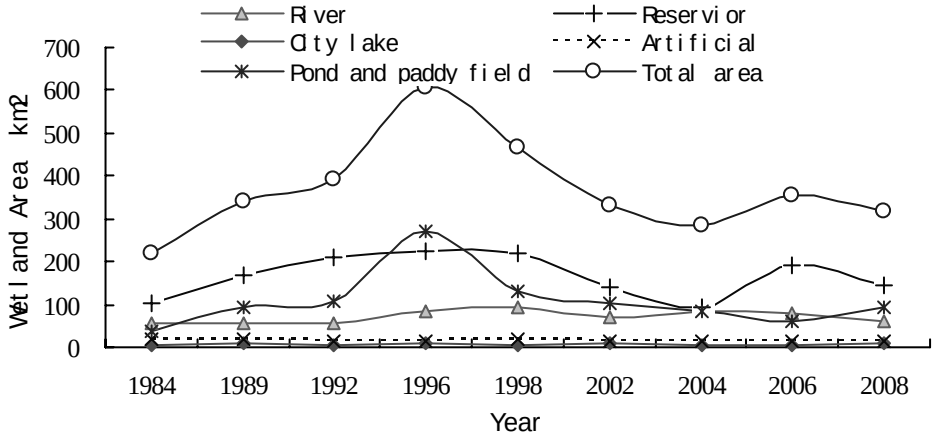

Fig. 2 The dynamic evolution of wetland resources in the last >20 years, Beijing.

Degradation of typical grassland has profoundly changed hydrological-ecological processes, which increased the surface runoff and accelerated further deterioration of the environment. Figure 3 shows the spatial change of degraded communities in a typical grassland in the central region of Xilingol League, Inner Mongolia (Wang *et al*., 2009). Figure 3 clearly shows that from the late 1970s to the beginning of this century there have been important changes in vegetation. The area of unchanged vegetation communities was only a third of the total area 30 years earlier. The vegetation has changed toward more severe degraded types; some of them have developed towards the trend of salinization under the mutual effect of strong rainfall and strong evaporation.

Wang *et al*. (2008) used 16 meteorological stations' data in the Hunshandake sand land and a neighbouring region since 1965, to undertake preliminary research on the spatial correlation between the seriously sand damaged zone and the drought gradient in Hunshandake sand. In the study, six different types of subarea were categorized. The results showed that the mobility of the sand soil means that agriculture cannot be sustainable in some sub-areas. Large areas of the sand land were cultivated for farming, but have since been abandoned to become bare sand land. Wang *et al.* (2008) report on another sub-area showing the most serious sand damage in Hunshandake sand land. The Hunshandake sand land has become a source of sandstorms in northern China, and has an especially severe influence on the Beijing-Tianjin and surrounding areas.

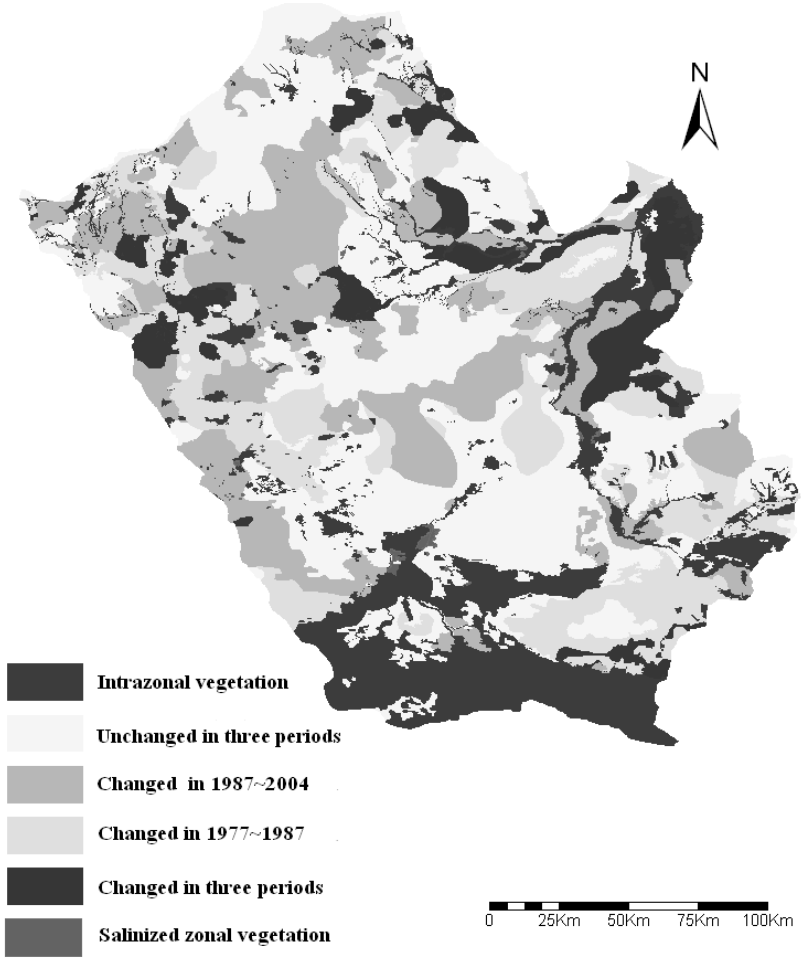

Fig. 3 Dynamic map of grassland in Xilingol League, Inner Mongolia, 1977–2004 (modified from Wang *et al*., 2009).

HYDROINFORMATICS FOR UNDERSTANDING THE ECOHYDROLOGY OF NORTH CHINA

Theory of ecohydrological modelling

Ecohydrology is a discipline that refers to the science which seeks to describe the hydrological mechanisms that underlie ecological patterns and processes (Rodriguez-Iturbe, 2000). The existing ecosystem parameters are usually very limited in ecohydrological models; most models are based on biomass, or plant leaf area index (LAI) as the connecting parameter between hydrology and ecology. The scale problem of coupling hydrological sciences and ecological sciences has still not been solved. Meanwhile, quantitative description is required of wetlands habitat structure, plant species characteristics and changes involved at transitions between land and water. Establishment of a clear quantitative relationship between water depth and other habitat elements, and the distribution of plants involve complex mechanisms (Baird, 2005; Boswell *et al*., 2007). The current research level is not able to express all of the processes by strict mathematical equations, which is a basic difference between ecohydrological models based on ecological response and eco-hydrological models based on hydrological processes.

Framework of ecohydrology

The aim of the proposed research is to develop a distributed ecohydrological model for the selected typical areas. The authors wish to reveal the processes and mechanisms of regional

hydrological changes over long-term periods in the suburbs of metropolitan Beijing and Inner Mongolia, and to determine the links between the water cycle, the anthropogenically controlled environment and the response of wetland vegetation. Finally, the authors wish to develop scenarios for different climatic and ecological conditions. The framework of the proposed research plan (Fig. 4) includes three major parts: firstly, data collection and establishment of a parameter system for regional integrated hydrological modelling and parameter generation for the regional change and human disturbance spatial-temporally, based on remote sensing and field surveys and continuous observation for ecohydrological environmental elements. Regional multi-parameters, remote sensing inversion and integration technology are used. Secondly, the study of the integrated water cycle process and vegetation response. Lastly, the assessment of the interaction between the water cycle and wetland vegetation. The key issues that need to be solved are:

1 The transformation of the spatial and temporal discipline of the regional water cycle. An analysis of the transformation of spatial and temporal discipline as "rainfall; surface-water, soil-water and shallow-groundwater".
2 The regional hydrological processes influenced by environmental changes.

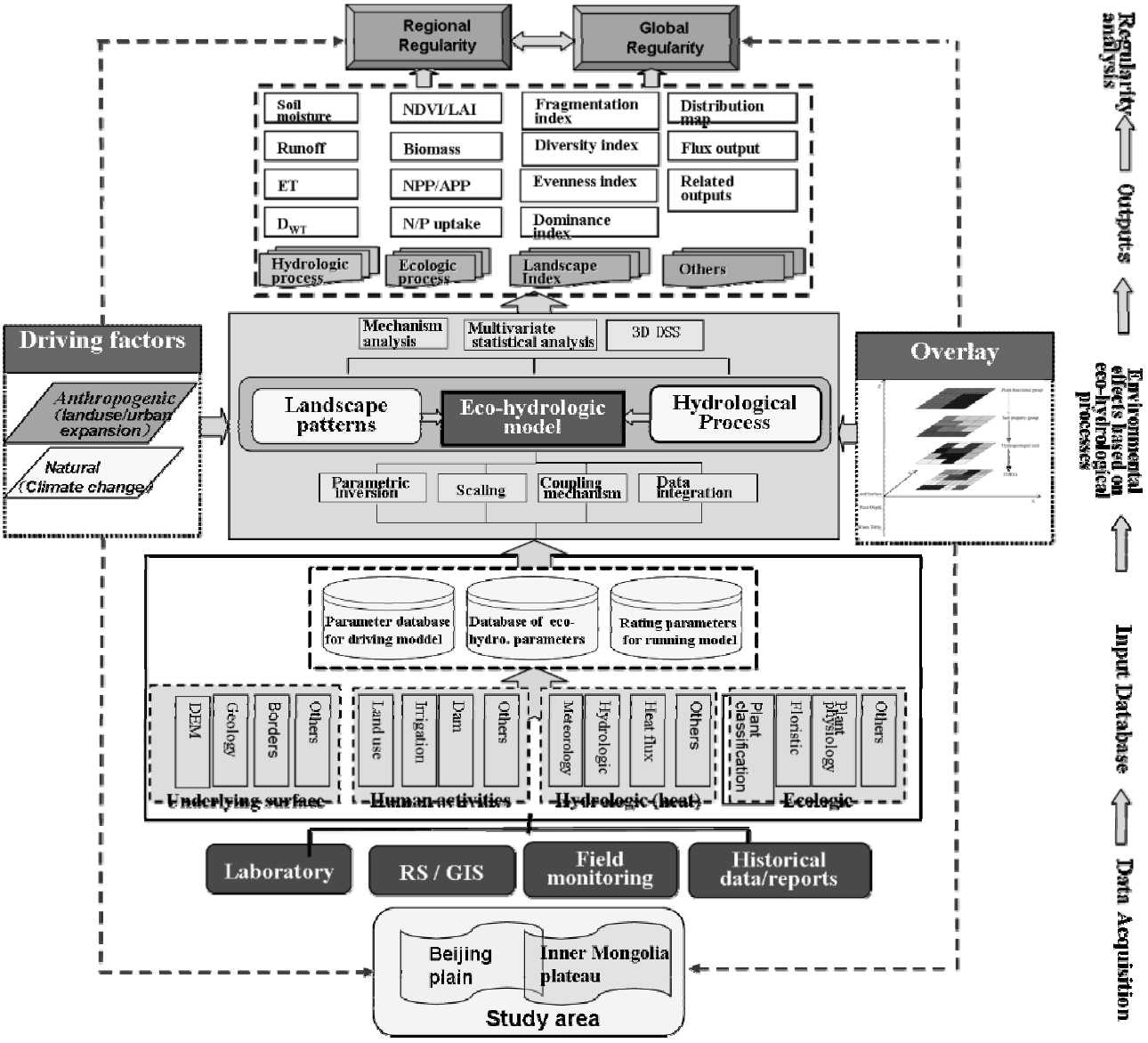

Fig. 4 Framework of the research plan.

3 The interaction between the water cycle process and wetland vegetation. It also includes the impact of the human activities.

The multi-level cross-cutting nature of the methodologies proposed is the most significant feature of this proposed research plan. The proposed tools bring forward the dual regulation of flow and biota through the ecohydrology approach and state-of-the-art hydroinformatics for data acquisition, assimilation and analysis. Multi-interface time-series data will be assimilated into the study area to assess spatial and temporal states of the hydro-ecological systems. Hence, this can form a mechanism for holistic treatment of water and ecological interactions to scope systems solutions for Ecologically Sustainable Development in peri-urban and rural environments.

Application of hydroinformatics for ecological monitoring

Over recent years a range of multi-disciplinary technologies have been applied. A combination of remote sensing data and GIS spatial analysis tools is an important technical base for developing landscape ecology theory (Fu *et al*., 2008). Distributed hydrological models can be built using the hydroinformatic methods such as digital terrain maps (DTM) and geographic information systems (GIS), and integration of remote sensing (RS) and geographic positioning systems (GPS) can help in parameter calibration in such complex models. In recent years, data assimilation techniques have been developed which can assimilate surface observations, satellite and radar data, optimize the surface and root zone soil moisture, temperature, surface energy fluxes and other estimates (Porporato *et al*., 2002). These new developments provide support to coupled research with multi-interface, multi-element regional hydrological processes and ecological response under the influence of human disturbance.

In order to meet the current needs for research on the hydrological-ecological processes based on remote sensing technology (Gong *et al*., 2009), a new monitoring technology system is proposed (see Fig. 5) to detect hydrological-ecological response. The hydroinformatics employs a three-in-one framework which combines rapid management of remote sensing information of hydro-ecological processes, ecohydrological process simulation, and 3-D visualization for understanding hydro-ecological environments. The framework of the system uses the large-scale remote sensing data processing system CASMImagelnfo to fast process hydro-ecological elements monitored by RS. Based on a plug-in open system structure such as Visual Studio, ArcGIS Engine,

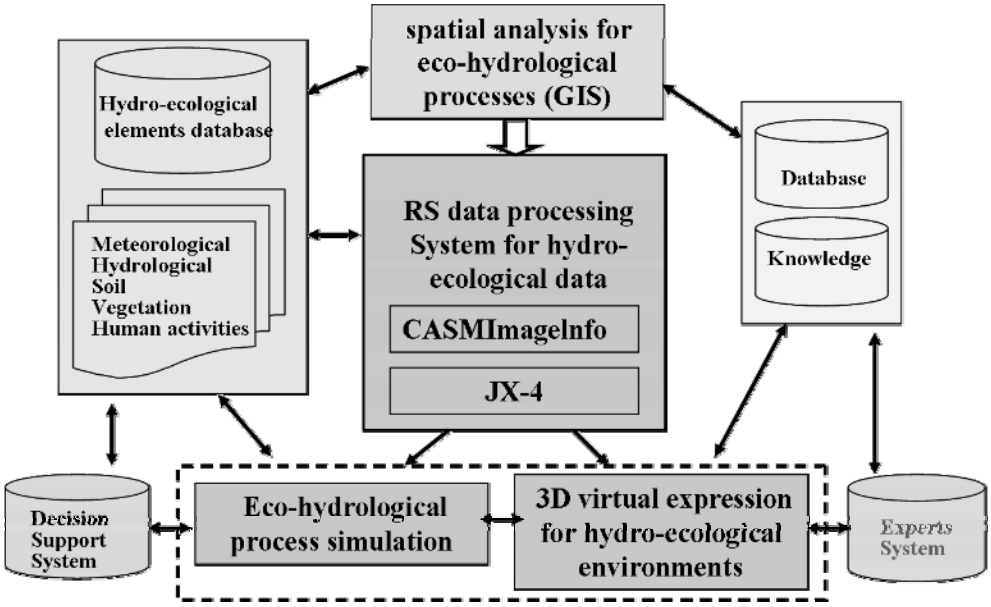

Fig. 5 RS based monitoring technology system for the hydro-ecological process.

and SQL Server2000, spatial analysis modules have been developed for understanding the eco-hydrological processes which include simulation modules and an ecohydrological database management system. In addition the system takes full advantage of the JX-4 full digital photogrammetry system to acquire DEM and other data using virtual reality technology to mimic the ecohydrological environment in a virtual 3-D visualisation. It provides a fully digital pipelined processing for researchers to study ecohydrological process based on the RS technology.

SUMMARY

Several environmental issues such as the shrinking of Yeya Lake wetland in Beijing, grassland degradation in Xilingol League, dune expansion in Hunshandake sand land, Inner Mongolia, and the urban heat island effect surrounding the Beijing-Tianjin region have been the focus of the research. Although climate change could be a reason for desertification in Inner Mongolia and water table decline in Beijing, anthropogenic factors such as overgrazing, overcultivation, urban expansion and over-irrigation also contribute to degradation in grassland areas, sand land expansion and reduced wetland area, respectively. All these problems indicate that ecologically sustainable development is very necessary given the burden of natural and human disturbances; promotional and support programmes, services and policies for sustainable development are also important. An advanced framework describing hydro-ecological processes and an RS-based hydroinformatics monitoring system are proposed in the paper. Compared to other studies, the advances of this proposed study plan are: At the theoretical level, there are few studies in eco-hydrology about how hydrological processes are impacted by change in the vegetation. This proposed research focus on regional hydrological process changes influenced by human activities and the associated wetland vegetation response, is innovative.

At the methodology level, the proposed research is coupled with remote sensing technology, field surveys and modelling methods based on integration of various hydrological processes and associated wetland vegetation ecology, which are regarded as part of a system and hence should be studied using the transdisciplinary ecohydrology approach. It is innovative to integrate multiple disciplines, processes and technology to solve real-world problems. At the application level, currently, regional natural resource management theory is based on either water resources or ecological resources and lacks linkages between these scientific disciplines and in-depth social response.

The paper has presented a new paradigm for scoping options for ecologically sustainable development. The hydrological models HSPF and SWAT, and the ecological model MOVER, are the useful tools for the hydro-ecological process simulation. Through artificial testing and field monitoring, ecological response patterns can be established. Using fuzzy theory and other statistical methods, an expert knowledge base can be built to determine the frequency of plant species. In the GIS platform connecting the habitat spatial-temporal database, a regional vegetation response model for the three study areas can be established. The large-scale remote sensing data processing system CASMImagelnfo can be used to fast process hydro-ecological elements monitored by RS. With the use of satellite, aerial and other remote sensing data, combined with field survey data and historical data, plant response models can be calibrated and validated in order to reveal the regional regularities of hydro-ecological processes in northern China for the purpose of ecologically sustainable development in the future.

Acknowledgement This research is sponsored by NSFC (nos 40771170 and 40901026). We also thank Prof. Yongli Wang from Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences; and Dr Xiaoyu Guo, Dr Zhaoning Gong and Dr Dan Meng from Capital Normal University for their valuable suggestions for improving this research plan.

REFERENCES

Baird, K. J., Stromberg, J. C. & Maddock, T. (2005) Linking riparian dynamics and groundwater: an ecohydrologic approach to modeling groundwater and riparian vegetation. *Environ. Manage.* **36**(4), 551–564.

Boswell, J. S. & Olyphant, G. A. (2007) Modeling the hydrologic response of groundwater dominated wetlands to transient boundary conditions: Implications for wetland restoration. *J. Hydrol.* **332**, 467–476.

Fu, B. J., Lv, Y. H., Chen, L. D., Su, C. H., Yao, X. L & Liu, Yu (2008) The latest progress of landscape ecology in the world. *Acta Ecologica Sinica* **28**(2), 798–804 (in Chinese).

Gong, H. L, Zhu, L., Li, X. J. & Pan, Y. (2009) Eco-hydrological information acquisition, simulation and 3D expression. *Progress in Natural Science* **19**(11), 1249–1254 (in Chinese).

Groeneveld, D. P. & Baugh, W. M. (2007) Correcting satellite data to detect vegetation signal for eco-hydrologic analyses. *J. Hydrol.* **344**, 135–145.

Porporato, A. & Rodriguez-Iturbe, I. (2002) Ecohydrology – a challenging multidisciplinary research perspective. *Hydrol. Sci. J.* **47**(5), 811–821.

Rodriguez-Iturbe, I. (2000) Ecohydrology: a hydrologic perspective of climate–soil–vegetation dynamics. *Water Resour. Res.* **36**, 3–9.

UNESCO (2006) Draft Strategic Plan for the 7th Phase of the IHP (2008–2013). The Document of the 35th Session of the IHP Bureau, IHP/IC-X VII/Inf.9 2006.

Wang, Y. L., Yun, W. L., Wang, W. & Liang, C. Z. (2008) A primary study on the space correlation between serious sand damaged zone and drought gradient in Hunshandake Sand Land. *J. Arid Land Resour. Environ.* **22**(4), 122–126 (in Chinese).

Wang, Y. L., Yun, W. L., Liang, C. Z. & Wang, W. (2009) Analysis of the spatial change of degraded communities in typical steppe using statistical enumeration method. *Chinese J. Grassland* **31**(1), 92–97 (in Chinese).