Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part IV)

Tadanobu Nakayama

Center for Global Environmental Research

National Institute for Environmental Studies, Japan
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Foreword

The Center for Global Environmental Research (CGER) at the National Institute for Environmental Studies (NIES) was established in October 1990, with the main objectives of contributing to the scientific understanding of global change and identifying solutions to critical environmental problems. CGER conducts environmental research from an interdisciplinary, multi-agency, and international perspective, and provides an intellectual infrastructure for research activities in the form of databases and a supercomputer system. CGER also ensures that data from its long-term monitoring of the global environment is made available to the public.

CGER installed its first supercomputer system (NEC SX-3, Model 14) in March 1992, and this was subsequently upgraded to an NEC Model SX-4/32 in 1997, an NEC Model SX-6 in 2002, and an NEC Model SX-8R/128M16 in 2007. In June 2013, the system was further upgraded with the inclusion of an NEC Model SX-9/A(ECO), in order to provide an increased capacity for speed and storage. We expect our research to benefit directly from this upgrade.

The supercomputer system is available for use by researchers from NIES and other research organizations and universities in Japan. The Supercomputer Steering Committee consists of leading Japanese scientists in climate modeling, atmospheric chemistry, ocean environment, computer science, and other areas concerned with global environmental research, and one of its functions is to evaluate proposals of any research requiring the use of the Supercomputer system. In the 2013 fiscal year (April 2013 to March 2014), seventeen proposals were approved.

To promote the dissemination of results, we publish both an Annual Report and occasional Monograph Reports. Annual Reports deliver results for all research projects that have made use of the supercomputer system in a given year, while Monograph Reports present the integrated results of a particular research program.

This Monograph Report presents results following the previously published 11th publication (Part I), the 14th publication (Part II), and the 18th publication (Part III). The new process-based catchment model, named the National Integrated Catchment-based Eco-hydrology (NICE) model, was applied to various catchments in East Asia. The results obtained in this research will allow us to clarify the various interactions occurring between human activities and water–heat–mass cycles, and their subsequent impacts on environmental degradation. This will improve our ability to plan for sustainable development in catchments. This integrated system also contributes to the development of process-based tipping-point early warning systems and the improvement in boundless biogeochemical cycles along the terrestrial-aquatic continuum.

In the years to come we intend to continue our support of environmental research by enabling the use of our supercomputer resources and continue to disseminate practical information based on our results.

January 2014

Hitoshi Mukai
Director
Center for Global Environmental Research
National Institute for Environmental Studies
Preface

This volume of the CGER’S SUPERCOMPUTER MONOGRAPH REPORT series is the 20th publication of research outcomes achieved by users of the supercomputer facilities at the Center for Global Environmental Research (CGER) at the National Institute for Environmental Studies (NIES).

The author has developed an advanced process-based model, known as the National Integrated Catchment-based Eco-hydrology (NICE) model, for use in the evaluation of ecosystem dynamics in catchments. NICE is a 3-D, grid-based eco-hydrology model that simulates the complex interactions between forest canopy, surface water, unsaturated zones, aquifers, lakes, and rivers, and also simulates iteratively nonlinear interactions between hydro-geomorphic and vegetation dynamics. The model is also able to couple with complex subsystems to simulate systems such as irrigation, urban water usage, stream junctions, and dams/canals, to develop integrated human and natural systems and to analyze the impact of anthropogenic activity on eco-hyrdologic change. Water resources are vital for human activity and their overuse has caused serious environmental degradation, economic stagnation, and an immense burden on the surrounding environment. This is particularly evident in Asia, where it is crucial to find a solution for such integrated environmental pollution from many aspects.

This monograph (Part IV) succeeds the previously published 11th publication (Part I), the 14th publication (Part II), and the 18th publication (Part III). This volume reviews the NICE processes that have been newly developed since Part III was published, and describes how the model has been applied for the scaling-up of both the Changjiang and Yellow River Basins in China on a continental scale. Results of the application indicate that the effective management of water resources is necessary in decision-making and adaptation strategies. The results also suggest the strong need for trans-boundary and trans-authority solutions for sustainable development, with sound socio-economic conditions that will contribute to national and global securities.

NICE is now being expanded to include an up-scaling process through a transformation from a rectangular to a longitude-latitude coordinate system, which will be applicable on a global scale by the application of a map factor and non-uniform grid. Because recent research has begun to reconsider how inland water might play a role in continental carbon cycling, a further improvement of the simulation system will play an important role in the evaluation of spatio-temporal hot spots on a regional scale, and boundless biogeochemical cycles on a global scale. This subsequent research will be reported in the next monograph (Part V) in the near future. The author hopes that the publication presented here will facilitate further research on the sustainable development in catchments. In particular, the author hopes that the publication will help highlight ways of solving the complex nature of water-related problems and support decision-making on sustainable development.

January 2014

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(Some of the figures in Chapter 5 are reprinted from Nakayama T. [2013a] For improvement in understanding eco-hydrological processes in mire. Ecohydrology and Hydrobiology, 13, 62-72, doi: 10.1016/j.ecohyd.2013.03.004.)
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Chapter 1

General Introduction
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1.1 Background

Ecosystem dynamics in East Asia have been drastically changed by the human alteration of land use from areas of wilderness to areas of urban or agricultural lands. Furthermore, anthropogenic activities resulting in environmental pollution have degraded water environments, causing contamination and an imbalance in both the hydrologic cycle and the thermal environment. In addition to surface water shortages, the depletion of groundwater resources is also becoming a serious problem in many areas, including the High Plains of the central United States, the North China Plain (NCP), northern India, the Sahel, South Africa, and Australia, although most people are unfamiliar with the dynamic nature of groundwater, and its use as an important storage and reservoir of water resources (Alley et al., 2002; Milly et al., 2008; Wada et al., 2010). Lack of water now threatens potentially 80% of the world’s population, due to the rising demands from population growth, urbanization, and industrialization (Gleick and Palaniappan, 2010). It is clear that a cumulative threat diagnosis framework is needed as a tool for the prioritization of policy and for management responses to assure global water security for human existence and ecosystem biodiversity (Jackson et al., 2001; Baron et al., 2002; Vorosmarty et al., 2010). For the facilitation of sustainable development, it is necessary to quantify the mechanisms of ecosystem change through an integrated approach, and to carry out an adaptation strategy to ensure sustainable development and to actively recover local natural environments.

There is a need to solve territorial disagreements over water resources peacefully, through trade and international agreements (Barnably, 2009). It is, therefore, possible that water market based policy instruments could help to attain targets in the most cost-effective manner. Numerical models are powerful tools for use in a river–basin wide initiative approach. Although the assumption of stationarity (the idea that natural systems fluctuate within an unchanging envelope of variability) has long been applied to human disturbance of river basins, research has indicated that stationarity should no longer serve as a central, default assumption in water-resource risk assessment and planning, and that non-stationarity approaches are needed to predict global pattern of streamflow and to ensure sustainable water availability under global climate changes (Milly et al., 2005, 2008). Recently, interesting studies have been made using virtual and real water transfers (water saved in one region by the importation of goods produced from water used in another region), and their relationship to actual water demand, water scarcity, and water conflicts (Yang and Zehnder, 2001; Hoekstra and Hung, 2005; Ma et al., 2006). It is of considerable interest that, in the long term, the globalization of water resources might reduce societal resilience with respect to water limitations; that is, it leaves fewer options available to cope with exceptional droughts and crop failure (D’Odorico et al., 2010), while it is generally recognized that in the short term, the globalization of water resources may prevent malnourishment, famine, and conflict.
Fig. 1.1  Droughts in northern China (Yellow River) and floods in southern China (Changjiang River).

This report considers the areas surrounding the Changjiang (Yangtze), Yellow (Huanghe), and Hai Rivers (Fig. 1.1), which are among the “seven big rivers” of China. In China, the hydroclimate differs between the northern and southern regions (Nakayama, 2011a-b, 2012c; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2008b). The semi-arid north is heavily irrigated, and the use of water combined with an increase in food demands, along with a diminishing availability of water, creates substantial pressure in the region of the Yellow River (Brown and Halweil, 1998; Yang et al., 2004; Nakayama et al., 2006, 2010; Nakayama, 2011a-b). The North China Plain (NCP), located downstream of the Yellow River, is one of the country’s most important agricultural regions, and experiences critical water shortages (Brown and Halweil, 1998; Shimada, 2000; Chen et al., 2003; Nakayama et al., 2006). In addition, this region includes vast metropolitan areas, such as Beijing and Tianjin. The demand for water here has intensified usage conflicts between the upstream and downstream areas, and similar conflicts have occurred between agricultural and municipal–industrial sectors. Several researchers have stated that China’s demand for natural resources already exceeds the environment’s capacity to sustain this densely populated land (Varis and Vakkilainen, 2001).

However, in the humid southern region the hydroclimate is very different and severe flooding causes considerable economic loss and serious damage to towns and farms, in particular, across the middle and lower regions of the Changjiang River. Although some severe floods have been attributed to abnormally high rainfall events, (such as those of 1954 and 1998), the changes in the landscape related to human activity have been the main cause of...
the increasing severity of major floods (Cheng, 1999; Yin and Li, 2001; Piao et al., 2003; Zhao and Fang, 2004; Zhao et al., 2005; Nakayama and Watanabe, 2008b; Nakayama and Shankman, 2013a). To compensate for this imbalance in water resources, China is accelerating preparatory work on its ambitious project for the transference of water from the Changjiang to the Yellow River (South-to-North Water Transfer Project; SNWTP) (Yang and Zehnder, 2001; Li et al., 2007).

Although it is estimated that the Three Gorges Dam project (TGD) and the SNWTP would greatly reduce these imbalances (Yang and Zehnder, 2001; Li et al., 2007), there is an urgent need to clarify the relationship between these two extremes affected by human activity. Therefore, it is essential to make an accurate evaluation of the optimum amount of transferred water, and the socioeconomic and environmental consequences affecting both basins. The development of a process-based model presents an integrated approach for appropriate water resource management, for the achievement of sustainable development on a regional scale (Nakayama, 2012c; Nakayama and Shankman, 2013a-b), and makes it possible to: evaluate water-heat-mass dynamics; predict future changes caused by human activity; and aid an accurate estimation of the amount of water required for transference between the catchments.

The current monograph (Part IV) succeeds our 11th publication (Part I) of 2006 (Nakayama and Watanabe, 2006b), 14th publication (Part II) of 2008 (Nakayama, 2008c), and 18th publication (Part III) of 2012 (Nakayama, 2012d). The catchments, or basins, described in this monograph are the Changjiang and Yellow River Basins in China, where two huge national projects, the TGD and the SNWTP are under construction (or are almost completed), in order to diminish flood risk and to compensate for the imbalance of environmental resources as much as possible. Although water resources are vital for human activity, their overuse causes significant hydrologic changes, ecosystem degradation, and sometimes a severe environmental burden in the surrounding areas. Therefore, the effective management of water resources is important for planning and sustainable development strategies and for developing an urgent solution to the intertwined environmental pollution problems. The eco-hydrological model is a powerful tool for the evaluation of an optimum amount of transferred water, and the socio-economic and environmental consequences from such a transfer. From this perspective, this monograph is further expanded to a continental scale from the 18th publication (Part III) of 2012 (Nakayama, 2012d) which showed the possibility for a sound recovery of the hydrologic cycle with the simultaneous creation of thermally stable environments on a local/regional scale. An evaluation of the water-heat-mass cycle in China, as described in the above, is also necessary relative to the national security of Japan and international contributions (Nakayama, 2011a-b; Nakayama and Watanabe, 2008b; Nakayama et al., 2006, 2010). Such an integrated approach will not only aid an evaluation of the complex processes involved from the viewpoint of hydrologic and biogeochemical cycles, but will also clarify how the substantial pressures caused by such intricately-woven problems can be overcome by effective trans-boundary solutions.
1.2 Model Description of Process-based Model Applicable to Continental Scale

In a previous study, the author developed the National Integrated Catchment-based Eco-hydrology (NICE) model, which includes surface-unsaturated–saturated water processes and assimilates land-surface processes, describing phenology variations on the basis of satellite data (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012) (Fig. 1.2). NICE is a 3-D, grid-based eco-hydrology model, and simulates iteratively nonlinear interactions between hydro-geomorphic and vegetation dynamics.

The NICE model has been coupled with complex subsystems in irrigation, urban water usage, stream junctions, and dams and canals, to develop integrated human and natural systems and to analyze the impact of anthropogenic activity on eco-hydrologic change. In the Simple Biosphere model 2 (SiB2), the unsaturated layer vertically divides the canopy into two layers and the soil into three layers (Sellers et al., 1996). In the saturated layer, NICE solves 3-D groundwater flow for both unconfined and confined aquifers. The hillslope hydrology, including freezing–thawing processes, can be expressed by the two-layer surface runoff model. NICE links each submodel by considering water–heat fluxes, including the gradient of hydraulic potential between the deepest unsaturated layer and the groundwater, effective precipitation, and seepage between the river and groundwater.

![Diagram of NICE model](image-url)

Fig. 1.2 Process-based National Integrated Catchment-based Eco-hydrology (NICE) model.
For agricultural applications, NICE is coupled with the Decision Support Systems for Agro-technology Transfer (DSSAT) (Ritchie et al., 1998), in which an automatic irrigation mode supplies the crop water requirements for field cultivation (Nakayama et al., 2006; Nakayama, 2011a-b) and for the cultivation of paddy fields (Nakayama and Shankman, 2013a; Nakayama and Watanabe, 2008b). This model includes the various functions of representative crops such as wheat, maize, soybean, and rice and automatically simulates their dynamic growth processes. Plant growth is based on biomass formulation, which is limited by various reduction factors such as light, temperature, water, and nutrients (Nakayama, 2011a-b, 2012c; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2008b; Nakayama et al., 2006). Most of the water supplied to major cities and cultivated fields in the NCP and Dalian is transported through a network of reservoirs and canals (Nakayama, 2011a; Nakayama et al., 2006, 2010). Because limited data are available on the discharge control at most of the dams adjacent to these reservoirs, a constant ratio of inflow to outflow—instead of the more complicated storage–runoff function model—is used for the major dams for which no data were available (Nakayama, 2011a). NICE was also coupled with the urban canopy model (UCM) (Nakayama and Fujita, 2010) to include the effects of the hydrothermal cycle on various pavements, and with the Regional Atmospheric Modeling System (RAMS) (Pielke et al., 1992) to include hydrothermal interaction in urban areas (Nakayama and Hashimoto, 2011; Nakayama et al., 2012). Downward short- and long-wave radiation, precipitation, atmospheric pressure, air temperature, air humidity, and wind speed simulated by the atmospheric model were input into the UCM, whereas momentum, sensible, latent, and long-wave flux simulated by the UCM were input into the atmospheric model at each time step. This procedure ensures that the feedback process of water and heat transfers between the atmospheric region and the land surface are implicitly included in the simulation process.

The NICE series has further expanded to include additional processes such as geomorphic change and vegetation succession, to evaluate various ecosystems and their relation to surrounding regions. These complex compartments are necessary for the application of NICE to evaluate ecosystem dynamics on a continental scale, in addition to local or regional scales. The details of the existing NICE series are presented in the following references.

1.3 Objective and Method

To study the ecosystem dynamics in catchments of East Asia, the author previously developed a method to combine a grid-based numerical model, ground-truth observation network, satellite data, and statistical analysis (Fig. 1.2). In this monograph (Part IV), the author reviews the new processes of NICE developed after Parts I (Nakayama and Watanabe, 2006b), Part II (Nakayama, 2008c), and Part III (Nakayama, 2012d), and describes how these models are applied to the broader catchments or basins wherein the relationship between the environment and water resources, economic growth, and ecosystem degradation require an urgent evaluation. The main study areas are the Changjiang and Yellow River Basins in China (Nakayama, 2011b, 2012c; Nakayama and Shankman, 2013a-b), and this is an extension of the author’s previous research in China (Nakayama, 2011a; Nakayama and Watanabe, 2008b; Nakayama et al., 2006, 2010). Some methodologies from the previous papers relating to Japan are considered valuable for use in this study (Fig. 1.3) (Nakayama, 2008a-b, 2010a, 2012a-b, 2013a; Nakayama and Watanabe, 2004, 2006a, 2008a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama et al., 2007, 2012).
The final objective of the current monograph is to evaluate the eco-hydrological processes in both the Changjiang and the Yellow River Basins, and predict the impact of anthropogenic activities such as the TGD and SNWTP on eco-hydrologic change on a continental scale, with the view of working towards trans-boundary and -authority solutions for sustainable development under sound socio-economic conditions, contributing to national and global security. During this evaluation and prediction, the monograph also presents an advanced method by which a combination of numerical models, satellite imagery, observation data, and statistical analysis clarify the relationship between water resources and economic growth, which adversely affects the ecological balance on a continental scale. Furthermore, this procedure offers an integrated assessment system for effective strategies which could reveal methods for solving the complex nature of water-related challenges and support plans for sustainable development. This new simulation system would also describe the development of process-based tipping-point early warning systems, and the improvement of an understanding of boundless biogeochemical cycles, related to recent research that has begun to reconsider how inland water may play a role in continental/global carbon cycling.

Fig. 1.3  Ecosystems highlighted within various regions in East Asia. Orange circles show representative megalopolis.
References


Chapter 2

Effect of Irrigation on the Hydrologic Cycle in a Semi-Arid Yellow River Basin
Abstract

To gain an understanding of the complex and diverse water systems involving river dry-up, groundwater degradation, agricultural/urban water use, and dam/canal effects in the heavily irrigated Yellow River Basin, the study related in this chapter coupled the National Integrated Catchment-based Eco-hydrology (NICE) model series with more complex sub-models (NICE-DRY).

The NICE-DRY made a reasonable reproduction of the hydrologic cycle with the inclusion of phenomena such as evapotranspiration, irrigation water use, groundwater level, and river discharge during spring/winter wheat, summer maize, and summer rice cultivations. Two scenario analyses predicted the impact of irrigation on both surface water and groundwater, which had previously been difficult to evaluate. The simulated discharge with irrigation was improved in terms of the mean value, standard deviation, and coefficient of variation.

The scenario analysis of a conversion from dryland to irrigated fields predicted that the effect on groundwater from irrigation was most severe in the middle and downstream areas of the Yellow River, and the quantity of the groundwater diminished in areas where the surface water was considerably limited. The simulated dry biomass of both wheat and maize were linearly related to the Time-Integrated Normalized Difference Vegetation Index (TINDVI) estimated from satellite images. The temporal gradient of the TINDVI between 1982 and 1999 showed a spatially heterogeneous distribution with increasing trends in the wheat and maize fields, indicating that the increases in production were related to the application of irrigation water and the resultant hydrologic changes.

The Yellow River Basin experienced substantial river dry-up and groundwater degradation at the end of the 20th century. By use of this integrated approach, it is potentially possible to estimate the close relationship between crop production, the hydrologic cycle, and water availability, and the heterogeneity of vulnerable water resources could be predicted. The application of this approach could therefore help to overcome substantial pressure to meet increasing demands for food with a declining availability of water, and to decide on appropriate measures to be taken for the management of whole water resources, in order to achieve sustainable development under sound socio-economic conditions.

Keywords: irrigation, hydrologic cycle, TINDVI, integrated catchment-based eco-hydrology model, water availability, sustainable development
2.1 Introduction

Water use in the Yellow River Basin has altered considerably in line with the development of regional economies (Fig. 2.1). The region is now heavily irrigated, and a combination of increased food demands and declining water availability are creating substantial pressures on the region. Tang et al. (2008a) indicated that climate change is the dominant contributor to changes in annual streamflow in the upper area of the basin, whereas human activities (such as the withdrawal of water for irrigation) dominate the downstream changes in annual streamflow. The North China Plain (NCP), located in the downstream area of the Yellow River, is one of the most important grain-cropping areas in China. As water resources are essential for agricultural development, the demand for groundwater has been increasing. Levels of groundwater have declined dramatically over the previous half century due to over-pumping and drought, and an area of saline-alkaline land has now expanded (Brown and Halweil, 1998; Shimada, 2000; Chen et al., 2003b; Nakayama et al., 2006).

Since the completion of a large-scale irrigation project in 1969, a noticeable cessation of flow has been observed in the Yellow River (Yang et al., 1998b; Fu et al., 2004), resulting from the increasing, and intense, competition between water supply and demand. The ratio of irrigation water use (defined as the ratio of the annual gross use for irrigation relative to the annual natural runoff) has increased steadily from 21% to 68% over the last 50 years, indicating that the current water shortage is closely related to irrigation development (Yang et al., 2004). This shortage also reduces the water renewal time (Liu et al., 2003) and the renewability of water resources (Xia et al., 2004), and such a reduction has been accompanied by a precipitation decrease in most parts of the basin (Tang et al., 2008b). It is evident that to ensure sustainable water resource use it is important to understand the contribution of human intervention to climate change within this basin (Xu et al., 2002), in addition to clarifying the rather complex and diverse water system in this highly cultivated region.

The research described in this chapter focuses on the impact of irrigation on the hydrologic cycle in the Yellow River Basin, which is an arid to semi-arid environment with intensive cultivation. A combination of the National Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012) and more complex components (sub-models) simulating processes such as irrigation, urban water use, and dam/canal systems, has led to the development of the NICE-DRY model, which simulates the balance of both the water budget and the energy in the entire basin with a resolution of 10 km.

The objective of this study was to evaluate the complex hydrological processes of river dry-up, agricultural/urban water use, groundwater pumping, and dam/canal effects, and to reveal the impact of irrigation on both surface water and groundwater in the basin. Based on the relationship between satellite images of the Normalized Difference Vegetation Index (NDVI) and Time-Integrated NDVI (TINDVI), along with the simulated dry biomasses of wheat and maize, a temporal gradient of TINDVI was estimated from 1982 - 1999. This was then linearly correlated with changes in crop production and indirectly correlated with changes in irrigation water use and the resulting hydrologic changes. It is considered that this integrated approach will help to clarify how the substantial pressures that the country faces from a combination of increased food demand and declining water availability, can be overcome, and how effective decisions can be made regarding sustainable development under sound socio-economic conditions in the basin.
Chapter 2  Effect of Irrigation on the Hydrologic Cycle in a Semi-Arid Yellow River Basin

2.2 Regional Overview

The Yellow River is 5,464 km long and has a basin area of 794,712 km² (including the Erdos inner flow area) (Fig. 2.1). The basin is divided into: the upper region (3,472 km, 428,235 km²) from the headwater to Toudaoguai in Inner Mongolia (R–4 in Table 2.1); the middle region (1,206 km, 343,751 km²) from Toudaoguai to Huayuankou in Henan province (R–6 in Table 2.1); and the lower region (786 km, 22,726 km²) from Huayuankou to the estuary. The upper region can be further divided into two sub-regions: the source area (upstream of Tangnaihai) and the downstream area (between Tangnaihai and Toudaoguai). The river is well known for its high sediment content, frequent floods, the unique channel characteristics of the downstream area where the river bed lies above the surrounding land, and its limited water resources. It is confined to a levee-lined course in the downstream area as it flows across the NCP, a giant alluvial plain formed by deposition from the Yellow, Hai, and Luan Rivers and their tributaries, with many palaeochannels of different stages forming various geomorphological features (Chen, 1996), and is one of the most important grain cropping areas in China because of its large area (about 13,600 km²) and huge population (about 112 million).
Table 2.1  Lists of observation stations for calibration and validation shown in Fig. 2.1.

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<th>No.</th>
<th>Point Name</th>
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2.3 Methods

2.3.1 NICE Model Series in Natural and Agricultural Regions

The author developed the NICE series of process-based catchment models for applicability to natural, agricultural, and urban regions in various catchments and basins (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012). The NICE models link surface-unsaturated–saturated water and land-surface processes, and describe variations in phenology on the basis of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. The surface hydrology model of NICE consists of a hillslope hydrology model based on kinematic wave theory, and a distributed stream network model based on both kinematic and dynamic wave theories. NICE also solves a partial differential equation describing three-dimensional groundwater flow for both unconfined and confined aquifers. The submodels consider water and heat fluxes from the ground to the surface, including: the gradient of hydraulic potential between the deepest layer of unsaturated flow and the groundwater level; the effective precipitation calculated from actual precipitation, infiltration into the upper soil moisture store, and evapotranspiration; and the seepage between river water and groundwater. In the agricultural field, NICE is coupled with Decision Support Systems for Agro-technology Transfer (DSSAT) (Ritchie et al., 1998), in which an automatic irrigation mode supplies crop water requirements for the cultivation of fields (Nakayama et al., 2006; Nakayama, 2011a-b) and paddy fields (Nakayama and Watanabe, 2008b). The model includes various functions for representative crops such as wheat, maize, soybean, and rice, and automatically simulates their dynamic growth processes. The details are described in Chapter 1 and in previous related papers (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012).
2.3.2 Coupling of NICE with Various Irrigation Procedures (NICE-DRY)

Irrigation withdrawals in the basin account for about 90% of total surface abstraction and 60% of groundwater withdrawal (Chen et al., 2003a). The higher use of irrigation water from the river is attributed to the geographical ease of access and water availability, rather than the crop water requirements (Yang et al., 2004).

NICE-DRY was further developed from previous NICE series for its application to irrigated fields where water is withdrawn from both groundwater and river, thereby satisfactorily reproducing river drying-up processes. The initial conditions for the ratios of river to aquifer irrigation were set at constant values (basin average = 74% and 26%, respectively; upper = 80% and 20%; downstream = 65% and 35%) (Yellow River Conservancy Commission, 2002). These initial condition values were then changed in the calibration procedure, to reproduce the observation data as closely as possible after repeated trial and error (Oreskes et al., 1994). A validation procedure was then conducted to confirm the simulation under the same set of parameters, (including the ratios of river to aquifer irrigation), and to closely reproduce the observed values.

Spring/winter wheat, summer maize, and summer rice were automatically simulated in succession in the sequence analysis mode by inputting both previous point data for each crop type (Wang et al., 2001b; Liu et al., 2002; Tao et al., 2006) and spatial distribution data (Chinese Academy of Sciences, 1988; Fang et al., 2006). The automatic irrigation mode supplied the crop water requirement at all times, assuming that the average available water in the top layer of soil fell below the soil moisture at field capacity for wheat and maize, and that the water level in the rice fields was maintained in accordance with the irrigation schedule of irrigated water depth (submerged depth) in previous research (Huang et al., 1998), as a representative of single rice. The water volume deficit in the irrigated fields was automatically withdrawn and supplied from the river or the aquifer, in order to satisfy the observed soil moisture, river discharge, groundwater level, LAI (Leaf Area Index), evapotranspiration, and crop coefficient. In doing so, NICE simulates the impact of drought and implicitly includes the effect of water stress. Details are given in Nakayama et al. (2006) and Nakayama and Watanabe (2008b).

There are a large number of dams and canals along the mainstream of the Yellow River and across the NCP, to meet the huge demand for agricultural, industrial, and domestic water use (Ren et al., 2002) (Fig. 2.1). The main river has six large dams: Longyangxia, Liujiaxia, Qingtongxia, Wanjiazei, Sanmenxia, and Xiaolangdi (Yang et al., 2004). Because there are few available data on the discharge control at most of these dams, the model uses a constant ratio of dam inflow to outflow, which is a more simple approach than that of the storage-runoff function model (Sato et al., 2008). There are also many complex canals in the three large irrigation zones (Qingtongxia in Ningxia Hui, Hetao in Inner Mongolia, and Weisan in Shandong Province), in addition to on the NCP, making it very difficult to evaluate the flow dynamics in these areas, and it is impossible to obtain the observed discharge and data related to the control of the weirs and gates on every canal. In reality, it is not necessary to evaluate the flow dynamics of all canals, but it is effective to estimate the flow dynamics in the main canals for the first approximation, when attempting to evaluate the hydrologic cycle in the entire basin. Therefore, NICE simulates the discharge only in the main canals, assuming that this is defined as the difference in the hydraulic potential at both junctions, (similar to the stream junction model) (Nakayama and Watanabe, 2008b).

Heavy sedimentation in the downstream area of the Yellow River causes the river bed to agrade by 5 to 10 cm a year, thus elevating it relative to the surrounding landscape, although
this sedimentation has decreased with the increase in dam numbers and the consequent
decrease of river discharge, (which promotes river drying), and by the considerable leakage
through the levee banks (Zhang et al., 1990; Yang et al., 1998b; Ren et al., 2002). The
dynamic wave effect is also important when simulating meandering rivers and smaller slopes,
because the backwater effect is predominant (Nakayama and Watanabe, 2004). When a river
has a very low flow (almost zero at some points in the simulation), the dynamic wave theory
requires a longer computational time, and in the process can become unstable. NICE therefore
applies a threshold water level of 1 mm to ensure simulation stability and to include the
drying-up process, and also includes a seepage process, which is decided by parameters such
as the hydraulic conductivity of the river bed, cross-sectional area of the groundwater section,
and river bed thickness.

2.3.3 Satellite Analysis using NOAA/AVHRR Data

NDVI was calculated from NOAA/AVHRR satellite data with a resolution of 1.1 km
collected over East Asia between 1982 and 1999. The original data were downloaded from
WebPaNDA (2008) and re-sampled to alter the resolution to 6.0 km, using the
nearest-neighbor method. Theoretical research by Sellers et al. (1997) provided the following
relationship between NDVI and primary production, \( P (\text{g/m}^2) \), defined as dry biomass by unit
of surface, by using Light Use Efficiency (LUE) model (Gower et al., 1999):

\[
P = \int_0^t (a \cdot NDVI + b) \cdot PAR \cdot \varepsilon \cdot W \, dt
\]

(2.1)

where \( \varepsilon \) is the efficiency for converting radiant energy into dry biomass, and \( W \) is the water
stress index. Assuming that parameters \( \varepsilon \), PAR, and \( W \) are constant for each developmental
stage, the above (Eq. 2.1) makes it possible to introduce the concept of Time-Integrated
NDVI (TINDVI), which is defined as the area under the curve described by NDVI with time
(Yang et al., 1998a), as follows:

\[
P = m \times TINDVI + n
\]

(2.2)

The above (Eq. 2.2) indicates that dry biomass is linearly related to TINDVI, and that crop
growth rate CGR (g/m²/day) can be related to NDVI, as discussed on the basis of
experimental field data (Calera et al., 2004). The dry biomass production \( P (\text{g/m}^2) \) simulated
by NICE-DRY was compared with NDVI and TINDVI for winter wheat in the 1986-1987
growing season, and for summer maize in the 1987 growing season in the downstream area of
the Yellow River (R–6 in Table 2.1) (Fig. 2.2). It can be seen that the simulated dry biomass,
which agrees well with the observed value from previous field experiments (Nakayama et al.,
2006), has a linear relationship to the TINDVI, with a high correlation (\( r^2 \) is more than 0.950)
(Fig. 2.2b) and with similar coefficients to those reported by Calera et al. (2004). The figure
also implies that the maximum growth rate generally occurs when the NDVI reaches a plateau
stage (Fig. 2.2a). These results mean that Eq. (2.2) is useful for estimating the potential rate of
primary production in the basin, and also indicates that the simulated evapotranspiration is
indirectly affected by the hydrologic change in NICE.
Fig. 2.2 Comparison of dry biomass simulated by NICE-DRY (open circle) with: (a) NDVI; and (b) Time-Integrated NDVI (TINDVI), for winter wheat in the 1986-1987 growing season (top) and summer maize in the 1987 growing season (bottom) (filled triangle), in the downstream area of the Yellow River (R6 in Table 2.1).

2.4 Input Data and Boundary Conditions for Simulation

2.4.1 Meteorological Forcing Data

The simulation period used in this study was between 1987 and 1988, and at that time, MODIS data were too new to be applicable. Therefore, six-hour reanalyzed data for downward short- and long-wave radiation, precipitation, atmospheric pressure, air temperature, air humidity, wind speed at a reference level, fraction of photosynthetically active radiation (FPAR) and LAI, were input into the model after interpolation of the International Satellite Land Surface Climatology Project (ISLSCP) data with a resolution of 1° × 1° (Sellers et al., 1996) in inverse proportion to the distance back-calculated in each grid cell. Because the ISLSCP precipitation data was the least reliable, and it underestimated the observed values at peak times, rain gauge daily precipitation data collected at 3,352 meteorological stations throughout the study area were used to correct this data. The ISLSCP maximum and minimum temperatures and radiation were previously compared with observed data and were shown to be relatively reliable (Nakayama et al., 2006).

2.4.2 Vegetation and Geological Properties

Mean elevation of each 10-km grid cell was calculated from the spatial average of a global digital elevation model (DEM; GTOPO30), with a horizontal grid spacing of 30 arc–seconds (~1 km) (U.S. Geological Survey, 1996). Digital land cover data produced by the
Chinese Academy of Sciences (CAS), based on Landsat TM data from the early 1990s (Liu, 1996), were categorized for the simulation (Fig. 2.1). Forests, grasslands, bushes, and shrubs cover the mountainous and hilly areas in the upper regions of the basin. Vegetation class and soil texture were categorized and digitized into 1-km mesh data by using 1:4,000,000 and 1:1,000,000 vegetation and soil maps of China (Chinese Academy of Sciences, 1988, 2003), and these finer-resolution products are highly correlated with the ISLSCP (Sellers et al., 1996). Approximately 50 vegetation and soil parameters were calculated in each cell. The major parameters included: vegetation cover, green fraction, albedo, surface roughness length and zero displacement height, soil conductivity, and soil water potential at saturation. In addition, several parameters were also included for stomatal resistance, as these are associated with environmental factors. From the soil texture and soil organic matter input, the model calculated the hydrological parameters of the soil layers, such as the water saturation content, the lowest water content required for crop growth, and the upper water content after free drainage and saturated water conductivity.

The geology of the basin encompasses a broad range of tectonic series, ranging from ancient metamorphic rocks to modern fluvial–lacustrine sediments (Huang et al., 1992). Schist, gneiss, marble, magmatite, and metamorphosed volcanic and detrital rocks of the basement are exposed sporadically in the north-west and south of the basin. Carbonate (Cambrian-Ordovician), coal series (Carboniferous-Permian and Jurassic), and detrital rocks (Triassic-Cretaceous) from the Palaeozoic to the Mesozoic eras occur in the highlands and in deeply cut valleys along the river’s course. Quaternary loess deposits cover an area of 300,000 km² in the middle section (approximately 40% of the total basin area), with a thickness of up to 200 m (Huang et al., 1992). In the downstream area, the river drains the Quaternary alluvial plains (principally the NCP), which are composed of thick lacustrine and delta deposits at depths of 100 m to 500 m. These geological structures were determined from the Geological Atlas of China (2002), which includes core–sampling data at some points. The geological structures can be divided into four types, based on parameters about their hydraulic conductivity, specific storage of porous materials, and specific yield, as described by Nakayama et al. (2006).

2.4.3 Irrigation and Urban Water Use

The irrigation area was calculated from GIS data based on Landsat TM data from the early 1990s (Liu, 1996), and the calculated value agrees well with the previous results from that period (Yang et al., 2004) ($r^2 = 0.996$, BIAS = 1.4%, RMSE = $8.2 \times 10^4$ ha, RRMSE = 0.053, MSSS = 0.995) (Table 2.2), where BIAS is the mean bias, RMSE is the root-mean-square error, RRMSE is the relative root-mean-square error, and MSSS is the mean square skill score (Tang et al., 2007). Most of the irrigated fields are distributed in the middle and lower regions of the Yellow River mainstream and in the NCP (Fig. 2.3). The agricultural areas in the upper regions and on the Erdos Plateau are dominated by dryland fields, and the large Qingtongxia and Hetao irrigation zones have been described above. Spring/winter wheat was predominant in the upper and middle areas of the arid and semi-arid regions, and double cropping of winter wheat and summer maize was usually practiced in the middle and downstream areas, and in the relatively warm and humid environment of the NCP (Wang et al., 2001b; Liu et al., 2002; Fang et al., 2006; Nakayama et al., 2006; Tao et al., 2006).
Table 2.2 Comparison of irrigation areas: Simulated conditions and conditions from previous research.

<table>
<thead>
<tr>
<th>Reaches(^a)</th>
<th>Irrigation area ((\times 10^4 \text{ ha}))</th>
<th>GIS database (Liu, 1996)</th>
<th>Previous research (Yang et al., 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above LZ</td>
<td>46.8</td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>LZ – TDG</td>
<td>342.1</td>
<td>344.1</td>
<td></td>
</tr>
<tr>
<td>TDG – LM</td>
<td>43.0</td>
<td>53.4</td>
<td></td>
</tr>
<tr>
<td>LM – SMX</td>
<td>295.6</td>
<td>281.3</td>
<td></td>
</tr>
<tr>
<td>SMX – HYK</td>
<td>59.2</td>
<td>60.6</td>
<td></td>
</tr>
<tr>
<td>Below HYK</td>
<td>160.7</td>
<td>155.0</td>
<td></td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>947.3</strong></td>
<td><strong>933.9</strong></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Abbreviations are as follows: LZ, Lanzhou; TDG, Toudaoguai; LM, Longmen; SMX, Sanmenxia; HYK, Huayuankou.

Fig. 2.3 Crop types in the agricultural areas. Irrigation areas are also superimposed on the figure. Irrigated fields cover most of the NCP and are used for double cropping of winter wheat and summer maize, in addition to three large irrigation zones.
More than 90% of total water extracted was used for irrigation in the Yellow River Basin, but a low proportion of this was used in the NCP (Liu and Xia, 2004; Cai, 2006). The irrigation water use was automatically simulated by NICE-DRY, and the average water use in 1987 in main cities in the Yellow River Basin and the NCP (Hebei Department of Water Conservancy, 1987; Yellow River Conservancy Commission, 2002) was input directly into the model. It is evident that the water demand of municipal and industrial sectors has been growing dramatically yearly, in line with the social economic development of the NCP (Guo and Cai, 2000), and this has greatly affected the hydrologic cycle and cone depressions of groundwater occurring around the bigger cities (Nakayama, 2011b; Nakayama et al., 2006).

However, the reuse of irrigation return flow is common in the basin. In the 1990s, the amount of return flow was as much as 35% of the withdrawal in the upper area, 25% in the middle area, but close to 0% in the downstream area (Chen et al., 2003a; Cai and Rosegrant, 2004). There are two large irrigation zones in the upper area: Qingtongxia in Ningxia Hui, and Hetao in Inner Mongolia, (covering areas of 5,228 km² and 11,900 km²), and a large zone in the downstream area: Weisan in Shandong Province, (covering an area of 3,600 km²), where there is a severe impact on the water quality due to salt leaching from the soil, due to the semi-arid climate. The Hetao and Weisan irrigation zones are dominated by cultivated fields, but the Qingtongxia irrigation zone is partially covered by paddy fields (Fig. 2.1). The return flows at Qingtongxia and Hetao are 59% and 25% of withdrawal, whereas that of Weisan is close to 0%, because the river bed is above the level of the plain (Chen et al., 2003a; Cai and Rosegrant, 2004). This information was input into NICE-DRY.

2.4.4 Boundary Conditions and Running the Simulation

A reflecting condition on the hydraulic head was used in the upstream boundaries, under the assumption that there is no inflow from the mountains in the opposite direction (Nakayama and Watanabe, 2004). At the eastern sea boundary (Bohai Sea), a constant head was set at 0 m. The hydraulic head values parallel to the observed ground level were input as initial conditions for the groundwater sub-model. As initial conditions, the ratios of river and aquifer irrigation were set at the same constant values as in section 2.3.2. Digital river networks produced by CAS (1982) from 1:50,000 and 1:100,000 topographic maps covering the basin were used. In the 1,747 river cells (including the Yellow River, the Tao, Datong, Wei, Jing, Beiluo, Wuding, Fen, and Qin tributaries, and the Hai River (Fig. 2.1)), inflows into, or outflows from, the mean elevation of river beds (Yellow River Conservancy Commission, 1987-1988) were dependent on the difference between the hydraulic heads for the groundwater and the river.

The simulation area covered 3,000 km by 1,000 km in Albers (WGS 1984) coordinates, covering almost the entire Yellow River Basin and the NCP. The area was discretized into a grid of 300 × 100 blocks with a grid spacing of 10 km in the horizontal direction, and into 20 layers with a weighting factor of 1.1 (finer in the upper layers and coarser in the lower layers) in the vertical direction (Nakayama and Watanabe, 2008b; Nakayama et al., 2006). The upper layer was set at a depth of 2 m, and the 20th layer was defined as an elevation of -500 m from the sea surface. Simulations were performed with a time step of 6 hours for 2 years, from 1 January 1987 to 31 December 1988, after 6 months of warm-up period until equilibrium. The author first calibrated the simulated values including irrigation water use against previous results in 1987, and then validated the values in 1988. Previously observed data of river discharge (9 points; Yellow River Conservancy Commission, 1987-1988), soil moisture (7 points of the Global Soil Moisture Data Bank; Entin et al., 2000; Robock et al., 2000), and
groundwater level (26 points; China Institute for Geo-Environmental Monitoring, 2003) were also used for verification of the model (Fig. 2.1, Table 2.1), in addition to values published in the literature (Clapp and Hornberger, 1978; Rawls et al., 1982). Furthermore, two irrigation supply scenarios were conducted using the same set of parameters, in order to evaluate how irrigation affects the hydrologic cycle in the basin. The first is the scenario analysis of a conversion from irrigated to an unirrigated run, and the second scenario is from dryland to irrigated fields.

2.5 Results and Discussion

2.5.1 Verification of Hydrologic Cycle

The irrigation water use simulated in 1987 was firstly calibrated against previous results (Cai and Rosegrant, 2004; Liu and Xia, 2004; Yang et al., 2004; Cai, 2006), showing a close agreement with the results of Cai and Rosegrant (2004) ($r^2 = 0.951$, BIAS = -3.0%, RMSE = $2.7 \times 10^9$ m$^3$, RRMSE = 0.45, MSSS = 0.598). The simulated value in 1988 was then validated with previous research (Table 2.3), and this indicated that there was reasonable agreement with each other, and that irrigation water use is higher in: the large irrigation zones (LZ-TDG); along the Wei and Fen rivers (LM-SMX) in the middle area; and in the downstream area (below HYK). The results also show a high correlation between irrigation area and water use: $r^2 = 0.986$ (Chen et al., 2003a) and $r^2 = 0.826$ (Liu and Xia, 2004). The actual ET simulated by NICE-DRY reproduces the general trend of two years reasonably well. In particular, it reproduced the drier condition in 1987, as estimated by integrated AVHRR NDVI data (Sun et al., 2004), and this achievement could support the predictive skill of NICE-DRY (Fig. 2.4). Although there are some discrepancies, particularly for the lowest ET area (EP < 200 mm/year), (mainly because of the banded color figures), the simulated result adequately reproduces the characteristics of a lowest value downstream of the middle area and on the Erdos Plateau (less than 200-300 mm per year except in the irrigated area, where there is desert vegetation and the soil consists mostly of sand), and reproduces the value gradually increasing towards the south-east. The simulated result also indicates that this spatial heterogeneity is related to human intervention and the resultant water stress by spring/winter cultivation in the upper/middle areas (Chen et al., 2003a; Tao et al., 2006), and winter wheat and summer maize cultivations in the middle/downstream (including the Wei and Fen tributaries) and the NCP (Wang et al., 2001b; Liu et al., 2002; Nakayama et al., 2006).

Although the satellite-derived data are effective for understanding the spatial distribution of the actual ET, there are some inefficiencies in terms of the underestimation in sparsely vegetated regions (Inner Mongolia and Shaanxi Province) and the overestimation in densely vegetated or irrigated regions (source area and Henan Province), as suggested by previous research (Sun et al., 2004; Zhou et al., 2007). The simulation overcomes and improves these inefficiencies, mainly due to the inclusion of drought impact within the model.
Table 2.3  Validation of amount of irrigation water use simulated by NICE-DRY with values from previous research.

<table>
<thead>
<tr>
<th>Reachesa</th>
<th>Irrigation water use ($\times 10^9$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above LZ</td>
<td>1.5</td>
</tr>
<tr>
<td>LZ – TDG</td>
<td>6.8</td>
</tr>
<tr>
<td>TDG – LM</td>
<td>1.1</td>
</tr>
<tr>
<td>LM – SMX</td>
<td>10.4</td>
</tr>
<tr>
<td>SMX – HYK</td>
<td>2.0</td>
</tr>
<tr>
<td>Below HYK</td>
<td>8.4</td>
</tr>
<tr>
<td>Sum</td>
<td>30.2</td>
</tr>
</tbody>
</table>

$^a$Abbreviations are as follows: LZ, Lanzhou; TDG, Toudaoguai; LM, Longmen; SMX, Sanmenxia; HYK, Huayuankou.

$^b$Value in parenthesis shows the target year in the simulation and in literature.

Fig. 2.4  Verification of annual-averaged spatial distribution of evapotranspiration in 1987 and 1988: (a) previous research estimated by NDVI; (b) simulated result.
A comparison with a previous study based on the Penman-Monteith method and the crop coefficient (Fang et al., 2006), shows that the model is able to reasonably simulate the spatial distribution of irrigation water use (Fig. 2.5a), not only in reach level (Table 2.3) but also in spatial distribution. Although the model was in general agreement with previous research, the simulated result shows an overestimation around the three large irrigation zones and an underestimation around unirrigated fields, which could be attributed to the improvements facilitated by the model due to the inclusion of the effect of drought impact and water stress.

In a previous simulation, the NICE-AGR was also able to adequately reproduce temporal variations in irrigation water use and the spatial distribution of crop water use in the NCP (Nakayama et al., 2006). This indicates that the water requirement estimated by NICE-DRY is valuable in explaining the general hydrologic cycle, and implies that there may be a greater use of irrigation water in the three large irrigation zones and in the NCP than in other areas (Chen et al., 2003a; Cai and Rosegrant, 2004). Simulated ratios of river to total irrigation (= river + aquifer) show great variation within the basin (Fig. 2.5b); more water is drawn from the river for irrigation in the upper area, and most of the irrigation in the downstream area depends on groundwater, particularly in the NCP (Nakayama et al., 2006). This difference in usage has caused large hydrologic changes in the basin.

![Fig. 2.5 Simulated result of: (a) irrigation water use in 1988; (b) ratios of river to total irrigation (= river + aquifer).](image_url)
The simulated groundwater levels and soil moisture contents were calibrated and validated against observed data (Entin et al., 2000; Robock et al., 2000; China Institute for Geo-Environmental Monitoring, 2003), as shown in Fig. 1 and Table 1. The simulation reproduced the general distribution well (BIAS = -21.2%, RMSE = 5.6 m, RRMSE = -0.468, MSSS = 0.356), but the correlation of groundwater level relative to the surface ($r^2 = 0.401$) was not as good as that of the absolute groundwater level ($r^2 = 0.983$), and the simulated value showed a tendency to overestimate the observed value in the calibration procedure for 1987 (Fig. 2.6a). This disagreement was due to the difference in surface elevation on the point-scale and mesh-scale (scale dependence), and the resolution of the groundwater flow model (changes in elevation from 0 m to 3000 m - 4000 m in the basin). Because the simulated level is the hydraulic head in an aquifer, it can have a larger value than that of the land surface, particularly for a grid cell near, or on, the river. Another reason for the disagreement could be that the irrigation use simulated by the model is underestimated because automatic irrigation which supplied the water requirement for crops in order to satisfy the observed soil moisture, river discharge, groundwater level, LAI, evapotranspiration, and crop coefficient, was theoretically pumped up from the river or the aquifer in the model. In reality, it is possible that farmers use a greater amount of irrigation water, although there is not enough statistical or observed data to support this assumption. The simulated water level in the validation for 1988 decreases rapidly around the source area, indicating that there are many springs in this region (Fig. 2.6b), and is very low in the downstream area (below sea level in some regions) because of the low elevation and overexploitation, as is the case in the NCP (Nakayama, 2011b; Nakayama et al., 2006). The soil moisture is higher in the source area and in the paddy-dominated Qingtongxia Irrigation Zone (data not shown), corresponding closely with the distribution of the groundwater level.

![Simulated annual average groundwater level in the basin](image)

Fig. 2.6 Simulated annual average groundwater level in the basin: (a) calibration of simulated value relative to the surface; (b) simulated groundwater level in 1988. In Fig. 2.6a, $r^2$ shows the correlation between observed and simulated values.
2.5.2 Impact of Irrigation on River Discharge and Groundwater Level

The scenario analysis run of a conversion from unirrigated to irrigated land predicted the hydrologic changes (Fig. 2.7). However, the prediction for land without irrigation (solid line) overestimates the observed river discharge (Fig. 2.7 a-c); this effect is more prominent in the middle and downstream areas, as supported by reports that the difference between natural and observed runoff is larger downstream (Ren et al., 2002; Fu et al., 2004; Liu and Zheng, 2004). The difference between simulations with and without irrigation strongly supports previous studies, indicating that the influence of human interventions on river runoff has increased downstream over the last five decades (Chen et al., 2003a; Liu and Xia, 2004; Yang et al., 2004; Cai, 2006; Tang et al., 2007) (Table 2.3), and is also represented by the decline of water renewal times (Liu et al., 2003) and water resource renewability (Xia et al., 2004). Although both $r^2$ and the Nash-Sutcliffe criterion (NS; Nash and Sutcliffe, 1970) have relatively low values across the basin (max: $r^2 = 0.447$, NS = 0.452), the simulated results with irrigation (bold line) reproduce these characteristics well, and the statistics for MV (mean value), SD (standard deviation), and CV (coefficient of variation; CV = SD/MV) generally agree well with the observed values, as also supported by the better reproduction of other components of the hydrologic cycle, such as annual ET (Fig. 2.4) (data not shown in the case without irrigation) and irrigation water use (Fig. 2.5a, Table 2.3). The simulated result with irrigation also reproduces the observed data for a low flow, and sometimes drying-up (Zhang et al., 1990; Yang et al., 1998b; Ren et al., 2002), being attributable to the inclusion of the dynamic wave effect in NICE-DRY, which was not reproducible by other NICE series prior to NICE-DRY. Furthermore, the model improves the reproduction of river discharge in the basin in comparison with previous research (Yang and Musiake, 2003), where the ratio of absolute error to the mean was more than 60% at Huayankou hydrological station, one of the worst such cases on a major river in Asia. The major reason for this disagreement is that NICE-DRY general includes an artificial water regulation, such as reservoirs, water intake, and diversions, in addition to the extreme annual variation in flood seasons (Nakayama and Watanabe, 2008b). The scenario analysis also predicted the groundwater level change and indicates that the effect of groundwater irrigation is predominant in the middle and downstream areas (Fig. 2.7d) where surface water is seriously limited, as shown in Fig. 2.5b and described in section 2.3.2 (Yellow River Conservancy Commission, 2002), mainly because of the intensified water-use conflicts between the upstream and downstream areas, and between agriculture, municipal, and industrial sectors (Brown and Halweil, 1998; Shimada, 2000; Chen et al., 2003b; Nakayama et al., 2006).
Fig. 2.7 Scenario analysis run of the conversion from unirrigated to irrigated land; (a-c) prediction of river discharge in Yellow River mainstream during 1987-1988; (d) groundwater level change. In Fig. 2.7 a-c, circles show observation data; solid line is the simulated result without irrigation effect; bold line is the simulated result with irrigation. \( r^2 \) shows the correlation between the observed and simulated values; NS shows the Nash-Sutcliffe Criterion. MV, mean value; SD, standard deviation; CV, coefficient of variation (= SD/MV).
2.5.3 Relationship between Hydrologic Change and Crop Productivity

The second scenario analysis of a conversion from dryland to irrigated land, assuming that the ratios of river and aquifer irrigation are the same as those described in the above sections, predicted a large decrease in the river discharge and groundwater level, particularly in the middle and downstream areas, where most of the dryland fields are mainly distributed because of the increase in ET (Fig. 2.8). The smaller change in groundwater level in the upper area was largely attributed to its unsuitability for crop production and the higher dependency of irrigation on surface water (Fig. 2.5b), as described previously (Yellow River Conservancy Commission, 2002). The river discharge decreased mainly in the winter through wheat cultivation, but increased slightly at times during the flood season, indicating that the precipitation in irrigated fields can respond quickly to flood drainage. Some of these areas lack fertility, and it is therefore impossible to expect a substantial increase in crop productivity. However, it is important to predict the relationship between the hydrologic cycle and crop productivity because farmers are limited by water availability more than by the fertility of the land and there is a possibility that an increased quantity of water could be available through water transfer in the future, which would greatly affect the change in water renewal times (Liu et al., 2003) and water resource renewability (Xia et al., 2004) in the basin.

Fig. 2.8 Prediction of hydrologic changes on the scenario of a conversion from dryland to irrigated fields: (a) river discharge in the upper-middle area (R–3; Qingtongxia) and the lower area (R–6; Huayuankou) in Table 2.1; (b) change in groundwater level. In Fig. 2.8a, the dotted line indicates the simulated result in Fig. 2.3, and the solid line indicates the prediction that all the agricultural areas will be changed into irrigated fields.
The NDVI in both the irrigated and dryland fields was higher than in natural areas during the grain filling and harvest seasons. Because the TINDVI is linearly related to the dry biomass, the spatial distribution of this value is a good indicator of the rate of crop production. Fig. 2.9 shows the temporal trend of the mean TINDVI during 1982 and 1999 in agricultural fields, calculated by ordinary least-squares regression. Because the original NDVI data in 1994 contained a great deal of noise and low accuracy, this data was omitted from the TINDVI analysis. The spatially heterogeneous TINDVI gradient corresponds well to the regional distribution of water resources. The increasing trend in the TINDVI in irrigated fields is larger at Juancheng (R–8) than at Huayuankou (R–6), because of the higher use of irrigation water (Fig. 2.5a) and a greater amount of evapotranspiration (Fig. 2.4) from the large irrigation zone (Weisan) in the downstream area (Fig. 2.9a). The spatial pattern of the mean TINDVI gradient in agricultural fields shows a generally increasing tendency, particularly in the downstream area and the NCP (Fig. 2.9b). This is caused mainly by an increasing tendency for winter wheat production in the downstream area (USDA, 1994). The decrease in the TINDVI gradient near the Bohai Sea and the Taihang Mountains was due to several effects, including that of groundwater degradation (Shimada, 2000; Chen et al., 2003b; Nakayama et al., 2006), seawater intrusion (Brown and Halweil, 1998; Shimada, 2000; Nakayama, 2011b), and rapid urbanization in the areas surrounding bigger cities (Kondoh and Oyamada, 2000). The slightly decreasing trend, particularly in the source area and middle area, also implies environmental deterioration which is mainly due to human activities, and to damage attributed to rodents and insects, as reported previously (Wang et al., 2001a; Sato et al., 2008; Tang et al., 2008b), in spite of some improvements in land management and conservation measures in the middle area (Yang et al., 1998b; Sun et al., 2004). Generally, these results suggest that the increased use of irrigation water is one of the reasons for the increase in crop production (Chen et al., 2003a; Cai and Rosegrant, 2004; Liu and Xia, 2004; Yang et al., 2004; Cai, 2006). The increased use of irrigation water is also related to the construction of large dams, as reflected clearly in the long-term decrease in discharge (Yang et al., 2004) and the short-term changes in discharge (Fig. 2.7) and groundwater level (Fig. 2.6).
Fig. 2.9  TINDVI over the agricultural fields by NOAA/AVHRR satellite images of agricultural fields; (a) trend of mean TINDVI in the grain filling season at Huayuankou (R–6) and Juancheng (R–8) in Table 2.1; (b) spatial patterns in mean TINDVI gradient (per year) during 1982-1999. The solid line in Fig. 2.9a is a least-square regression line estimated from mean TINDVI (circle). The TINDVI gradient shows a generally increasing tendency, particularly in the downstream area and the NCP.

2.6 Conclusion

This study has addressed the important issue of simulating the rather complex and diverse water system in the highly cultivated Yellow River Basin, including hydrological processes such as river dry-up, groundwater deterioration, agricultural/urban water use, dam/canal effects, and so on. This region is heavily irrigated, and the combination of an increased demand for food with a declining availability of water is creating substantial pressures. The author coupled the NICE series with more complex components such as irrigation, urban water use, and dam/canal systems, in order to simulate the effects of irrigation on the hydrologic cycle in the basin (NICE-DRY). This simulation clarified the relationship between the drying of rivers, groundwater degradation, seawater intrusion, and ecosystem degradation. Scenario analyses of the impact of human intervention on hydrologic changes imply the need for further correct evaluations and appropriate measures against such irrigation.
References

Chinese Academy of Sciences (CAS) (1982) Topographic maps of 1:50,000 and 1:100,000.


Chapter 3

Role of Lake Flood Storage Capability in the Humid Changjiang River Basin
Abstract

China is affected by severe flooding on a near annual basis. This causes considerable economic loss and serious damage to towns and farms, and affects the middle and lower regions of the Changjiang (Yangtze) River in particular. In addition to abnormal weather patterns, previous research concludes that a significant cause of major flood disasters in the basin are caused by human-induced, artificial effects, such as: (i) extreme deforestation and soil erosion in the upper reaches; (ii) shrinking lake water volumes and a restriction of the connection of lakes with the Changjiang River due to lake reclamation which caused a retardation of water in the middle reaches; and (iii) restriction of the channel capacity following construction of a levee.

The research in this chapter focuses on the flood storage capability of the Dongting and Poyang Lakes in the middle region of the river, and simulates the water/heat dynamics for the 1998 large-scale flood, one of the largest floods in the 20th century, over the entire Changjiang River Basin. The previous process-based model was expanded for its application to broader basins (NICE-FLD) in order to evaluate large-scale flooding in the Changjiang River, and used to compare the severe flood-period of 1998 with the usual flood-period of 1987–1988. The model excellently reproduces factors such as the river discharge, soil moisture, evapotranspiration, and groundwater level. In order to evaluate the role of the flood storage capability of the lakes, a back-casting simulation was also conducted by recreating the areas of both lakes in the 1950s, and by then inputting meteorological data from the 1998 severe flood. The simulation shows that the peak flow and groundwater level decrease both around and downstream from the junction, as described qualitatively in previous research. This indicates that by increasing the lake’s storage capacity the peak value of the lake water level is moderated during flood periods and the groundwater level surrounding the lakes is decreased. This result is very important for use in minimizing flood damage, and for making informed decisions relating to sustainable development in the basin.

Keywords: Changjiang River, flood-storage capability, climate change, integrated catchment-based eco-hydrology model, human activity
3.1 Introduction

China is affected by severe flooding on a near-anual basis, causing considerable economic loss and serious damage to towns and farms. Large-scale flood events are concentrated mainly in the lower reaches of the “seven big rivers,” including the Changjiang (Yangtze) River, the Yellow (Huanghe) River, and the Huaihe River (Fig. 3.1). These areas are home to 50% of China’s population and produce 70% of its industrial and agricultural value (Nakayama and Watanabe, 2008b).

The Changjiang River and the Yellow River originate on the Qinghai Tibet Plateau and flow east for about 6,000 km, to the East China Sea. The Changjiang River is located in the humid southern regions of China and is the fourth largest source of water supplying the oceans, after the Amazon, Zaire, and Orinoco Rivers. The Changjiang basin is divided into: the upper region (length: 4300 km, area: 1,000,000 km$^2$) from the headwater to Yichang in Hubei province; the middle region (length: 950 km, area: 680,000 km$^2$) from Yichang to Hukou in Jiangxi province; and the lower region (length: 930 km, area: 120,000 km$^2$) from Hukou to the estuary (Fig. 3.1). The topography of the upper region is hilly with a high riverbed slope. In contrast, the vast plain in the middle and lower regions accounts for more than half the area of flat land in the whole basin, and there is a difference in altitude of only about 40 m from Yichang to the estuary, with a bed slope of 0.002%. Consequently, the Changjiang mainstream section is tidal downstream of Datong, which is 624 km upstream of the estuary.

Recently, large frequent flooding in the lowland areas of the middle and lower regions of the Changjiang River Basin has hugely affected human lives, the environment, and the agricultural economy. In addition to abnormal weather events, artificial effects, such as extreme deforestation and the reclamation of lakes, which has retarded water in the middle reaches, are considered to be the main cause of such changes (Cheng, 1999; Yin and Li, 2001; Zhao and Fang, 2004; Zhao et al., 2005). From June to September 1998, the area-averaged precipitation total was significantly above the usual in the Changjiang River Basin. The most excessive rainfall occurred during June and July, when area-averaged totals exceeded 300 mm and 220 mm, respectively. Overall, the largest anomalies were observed over the eastern portion of the basin, in the region which includes Nanchang (Fig. 3.1). In this area, a record amount of rainfall totaling 1000 mm fell during June and July 1998, surpassing the previous record of approximately 950 mm set in 1954 (Bell et al., 1999; Zhu et al., 2003), although the flood discharge was less than that of 1954. The entire Changjiang River Basin suffered a tremendous amount of flooding, but the river stage at peak was higher in the middle reaches. A lower discharge in 1998 created a higher river stage, and this suggests a channel aggradation along the lower section of the river in relation to environmental degradation by artificial effects.

The types of degradation related to flood disasters in the Changjiang River Basin due to human intervention are (Yin and Li, 2001): (i) the destruction of vegetation and soil erosion in the upper reaches, along with rapid urbanization (Piao et al., 2003); (ii) the shrinking of lake water volumes and the reduced connection of lakes with the Changjiang River due to reclamation; and (iii) a restriction of the channel capacity following the construction of a levee. With reference to point (ii), the Dongting and Poyang Lakes shrank from respective areas of 4,000 km$^2$ and 5,000 km$^2$ in the 1950s, to 2,600 km$^2$ and 3,200 km$^2$ in the 1990s. Their capability of storing water decreased from 27 to 17 billion m$^3$ and from 32 to 21 m$^3$, respectively (Du et al., 2001; Yin and Li, 2001; Shankman and Liang, 2003; Zhao and Fang, 2004; Peng et al., 2005; Zhao et al., 2005). It is therefore considered that there is an urgent
need to evaluate the water/heat/nutrient transport processes of the whole basin on a spatial scale. These processes will be changed by the operation of the Three Gorges Dam (TGD), which was already built and completed in 2009 (Fig. 3.1). Although the dam scheme will provide flood control, irrigation water, and the generation of hydroelectric power, etc., it is possible that changes in the aquatic environment of the Changjiang estuary and the East China Sea might be brought about by changes in pollutant loads caused by the deposition of large amounts of sediment carried from the dam in the upper region of the Changjiang River Basin and the artificial control of its discharge volume (Kwai-cheong, 1995; Zhang et al., 1999; Chen, 2000; Chen et al., 2001). Although this huge construction project runs in opposition to the current worldwide trend of removing huge dams, it is very important to predict the response of the whole basin to completion of the artificial environmental modifications, as described in the following Chapter 4. It will be further effective to quantify the natural forces that could reduce flood damage in the basin, by using a process-based model that can simulate the dynamics of water, heat, and nutrients over various temporal scales. This would then be related to the effective management of the six flood diversion works along the Changjiang River Basin (Jingjiang, Dongting Lake, Honghu, Wuhan, Poyang Lake, and Huayang). The appropriate development and use of this model would make it possible to establish a management tool that allows sustainable development in the basin.

Fig. 3.1  Location of study area in the Changjiang River Basin. The bold black line shows the border of the basin. Plotted in this figure are the validation data for: river discharge (open circle); soil moisture (open triangle); and groundwater level (green dot). The black dotted-line is the border of the groundwater change study area around both Dongting and Poyang Lakes in Fig. 3.8.
Because there have been few studies using numerical models related to changes in water/heat dynamics resulting from human activity in the entire Changjiang River Basin, and the role of flood storage capability of lakes in addition to irrigations, it is important to quantify the complex phenomena related to water/heat dynamics. The aim of the research presented in this chapter is to simulate the water/heat dynamics for the 1998 large-scale flood in the Changjiang River basin, (one of the largest floods in the 20th century, and the largest flood since 1954). Using the National Integrated Catchment-based Eco-hydrology (NICE) model, the author compares the severe flood-period of 1998 with the usual flood-period of 1987-1988. Furthermore, the author evaluates the role of the flood storage capability of lakes in addition to irrigations in relation to the water/heat budget, and simulates changes in water/heat dynamics resulting from human activity in order to aid decision-making on sustainable development in the basin.

3.2 Regional Overview

The headwaters of the Changjiang River are in the mountains of Tibet, and the river flows in a general eastward direction towards the coast (Fig. 3.1). The upper section of the river and its major tributaries flow through narrow and incised river valleys (Geological Atlas of China, 2002). The downstream section, below the Three-Gorges, is surrounded by broad alluvial valleys that support intensive agriculture and are at the center of China’s rice growing region (Chinese Academy of Sciences, 1988; Liu, 1996; Nakayama and Watanabe, 2008b). The fertile alluvial plains and humid sub-tropical climate of southern China make this region ideal for cultivation, and the Changjiang River drains much of the humid subtropical region of southern China. This region has short, mild winters, hot summers, and a long growing-season. The rainy season typically begins in late spring or early summer, when southerly monsoon winds move warm, humid air masses inland. These air masses encounter cold air from the arid part of central Asia and are lifted along a stationary front causing abundant rainfall. The discharge and water level of the Changjiang River and its major tributaries increase during the late spring and summer months. The most severe floods almost always occur during or following El Nino events which cause more widespread and persistent rains in the region than during non-El Nino years (Shankman et al., 2006).
Fig. 3.2  Flow diagram of NICE-FLD. Bold frames indicate the new developed processes in the NICE-FLD model.
3.3 Methods

3.3.1 Coupling of NICE with Rice Model

The author developed the NICE series of process-based catchment models applicable to natural, agricultural, and urban regions in various catchments and basins (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012). In the agricultural field, NICE is coupled with the Decision Support Systems for Agro-technology Transfer (DSSAT) (Ritchie et al., 1998), in which an automatic irrigation mode supplies the crop water requirements for cultivated fields (Nakayama et al., 2006; Nakayama, 2011a-b) and paddy fields (Nakayama and Watanabe, 2008b). The model includes various functions for representative crops such as wheat, maize, soybean, and rice, and automatically simulates the dynamic growth processes. (Details are described in Chapter 1 and previous related papers.)

Paddy fields are widely distributed in areas along the Changjiang mainstream, and cover about 50% of the area downstream of Wuhan. According to the Vegetation Map of China (1:4,000,000) developed by the Institute of Geographical Science and Natural Resources Research (IGSRR), Chinese Academy of Sciences (CAS) (1982), single cropping of rice was practiced in the following areas: the Sichuan Basin, the upper region of the Hanjiang catchment, and the area along the lower reaches of the Changjiang mainstream; and double cropping was usually practiced in all other regions, including the catchment areas of Dongting and Poyang lakes. Each crop was automatically simulated using the agricultural submodel of the NICE, and details are given in Nakayama et al. (2006).

3.3.2 Modeling of Flood Storage Ability of Dongting and Poyang Lakes (NICE-FLD)

Dongting and Poyang lakes drain into the Changjiang through narrow outlets (Fig. 3.1). In order to evaluate the role of the flood storage capability of lakes it is useful to simultaneously simulate the lake level with the river discharge from channels that connect the mainstream with the two lakes (Fig. 3.2), and to execute this the original NICE was combined with a lake model (Nakayama and Watanabe, 2008a) and a stream junction model, in the same way as the HEC-RAS model (U.S. Army Corps of Engineers, 2006) in NICE-FLD (Nakayama and Watanabe, 2008b). Seepage rates computed for each interface between lake cells and horizontally or vertically adjacent aquifer cells are added to the appropriate elements in the RHS (right-hand side residual) and HCOF (coefficient) matrices in the equation for groundwater flow as follows (McDonald and Harbaugh, 1988; Nakayama and Watanabe, 2005, 2008a):

\[
RHS_{ijk} = RHS_{ijk} - c_m h_{ij}^{n-1} \text{ for } h_a > h_{bot} \text{ in vertical column} \\
= RHS_{ijk} - c_m (h_{ij}^{n-1} - h_{bot}) \text{ for } h_a < h_{bot} \text{ at horizontal interface} \\
= RHS_{ijk} \pm 0 \text{ for } h_a < h_{bot} \text{ at vertical interface} \tag{3.1}
\]

\[
HCOF_{ijk} = HCOF_{ijk} - c_m \text{ for } h_a > h_{bot} \\
= HCOF_{ijk} \pm 0 \text{ for } h_a < h_{bot} \tag{3.2}
\]
where $ijk$ designates the particular matrix term; $m$ denotes a particular cell interface; $c_m$ (m$^2$/s) is the conductance across that interface; $h_{bot}$ (m) is the lakebed elevation; and $n-1$ denotes the previous time step. For a transient simulation of the lake, the lake grid is set surrounded by the aquifer, and the lake level is simulated and updated at each time step, $\Delta t$ (s), by using the water balance Eq. (3.3) (Merritt and Konikow, 2000; Nakayama and Watanabe, 2005, 2008a):

$$h^\text{new}_l = h^\text{old}_l + \Delta t \frac{p - e + rnf - w - q_l + Q_{si} - Q_{so}}{A_s}$$

(3.3)

where $q_l$ (m$^3$/s) is the seepage between the lake and the aquifer expressed by the application of Darcy’s Law; $h^\text{new}_l$ and $h^\text{old}_l$ (m) are the lake levels at the new time step and the previous time step; $p$ (m$^3$/s) is the rate of precipitation on the lake during the time step; $e$ (m$^3$/s) is the rate of evaporation from the lake surface during the time step; $rnf$ (m$^3$/s) is the rate of surface runoff to the lake during the time step; $w$ (m$^3$/s) is the rate of water withdrawal from the lake during the time step (a negative value indicates augmentation); $Q_{si}$ (m$^3$/s) is the rate of inflow from streams during the time step; $Q_{so}$ (m$^3$/s) is the rate of outflow to streams during the time step; and $A_s$ (m$^2$) is the surface area of the lake at the beginning of the time step. After sufficient iterations of the groundwater submodel have been performed for the aquifer heads to converge to a solution, the lake level ($h^\text{new}_l$) is recomputed one more time for each lake using Eq. (3.3).

The above-mentioned $Q_{so}$ (m$^3$/s) is simultaneously solved with the stream junction model in the same way as within the HEC-RAS model (U.S. Army Corps of Engineers, 2006) (Fig. 3.2). This energy-based method solves river discharge across the junction by performing standard step backwater and forewater calculations with the continuity equation and with one-dimensional energy equations. The continuity equation of stream flow considers the flow direction of the junction connecting the mainstream with two lakes (Fig. 3.1). Because most streams have a highly subcritical flow, the influence of the tributary flow angle is often insignificant, and the author therefore did not account for the angle of the junction flows and also assumed that the expansion or contraction loss coefficient was constant (0.3 or 0.1) in previous research (U.S. Army Corps of Engineers, 2006). The conversion from lake storage to lake level is based on the relationship between the average water level and the volume of storage in each lake.

For Dongting Lake, this relationship is given by simple static planar analysis of the increase in the volume and surface area of water according to the increase in the water level, by using a digital elevation model (DEM) of the lake bed with a spatial resolution of 50 m developed by IGSRR based on a topographic map with a scale of 1:25,000 developed by the Nanjing Geology Institute, CAS (1988). This relationship is very similar to the previous result for Dongting Lake (Peng et al., 2005). For Poyang Lake, the relationship is also given by a similar DEM, based on a topographic map developed by the local government of Jiangxi province (1983), and from the same static analysis as that used for Dongting Lake. The simultaneous equations incorporating the continuity equation and energy equations were solved using the Newton method. The author obtained the simulated values of river discharges including junctions, soil moitures, groundwater levels, lake water levels, lake seepages, and other factors by using the NICE-FLD model.
3.4 Input Data and Boundary Conditions for Simulation

3.4.1 Meteorological Forcing Data

Six-hour reanalyzed data for downward short- and long-wave radiation, precipitation, atmospheric pressure, air temperature, air humidity, wind speed at a reference level, FPAR (Fraction of Photosynthetically Active Radiation), and LAI (Leaf Area Index) were input into the model after interpolation of ISLSCP (International Satellite Land Surface Climatology Project) for 1987-1988 and ECMWF (European Centre for Medium-Range Weather Forecasts) for 1998-1999 simulations in inverse proportion to the distance back-calculated in each grid cell. Because the ECMWF precipitation data had the least reliability and underestimated the observed values at the peak time, rain gauge daily precipitation data collected in the Changjian River basin at 4,783 stations for 1987-1988, and 919 stations for 1998-1999, (operated by the China Meteorological Bureau and the Changjiang Water Resources Commission (CWRC)), were also assimilated to create grid data. Because the forcing precipitation data created in this study agrees closely with the GPCC (Bell et al., 1999) during June and July 1998, these data were used in the simulation. Details are described in Nakayama and Watanabe (2008b) and Nakayama and Shankman (2013a).

3.4.2 Vegetation and Geological Properties

The mean elevation of each 10-km grid cell was calculated using the spatial average of a global digital elevation model (DEM; GTOPO30) with a horizontal grid spacing of 30 arc-seconds (approximately 1-km mesh) (U.S. Geological Survey, 1996) throughout the Changjiang River basin (Fig. 3.1). Vegetation class and soil texture were categorized and digitized into 1-km mesh data using the Vegetation and Soil Maps of China (1:4,000,000) (Chinese Academy of Sciences, 1988). These finer-resolution data were more accurate than the ISLSCP data with a resolution of 1° × 1° (Sellers et al., 1996) (Fig. 3.3). Using these refined data, approximately 50 vegetation and soil parameters were calculated in each cell. The major parameters included vegetation cover, green fraction, albedo, surface roughness length and zero displacement height, soil conductivity and soil water potential at saturation, and some parameters of stomatal resistance that relate to environmental factors. Hydrologic parameters of the soil layers, such as saturation water content, lowest water content for crop growth, upper water content after free drainage and saturated water conductivity, were calculated from the input soil texture and soil organic matter by the model itself.
Fig. 3.3  Soil texture from: (a) ISLSCP data with a resolution of 1° × 1°; and (b) categorized and digitized data with 1-km mesh using the Vegetation and Soil Maps of China (1:4,000,000) in this study.

Digital land cover data produced by the Institute of Remote Sensing Applications (IRSA) at the Chinese Academy of Sciences (CAS), based on Landsat TM data from the early 1990s (Liu, 1996), were categorized into 10-km mesh data for the simulation. The vegetation of the mountainous and hilly areas in the upper region of the basin consists of forests, grasses, bushes, and shrubs. Paddy and cultivated fields are widely distributed in the Sichuan Basin, and in the middle and lower reaches of the Changjiang mainstream area. From the 1990s to the 2000s, human activity in the basin led to various types of degradation (Fig. 3.4 and Table 3.1). Deforestation (Yin and Li, 2001), reclamation of lakes (Du et al., 2001; Zhao and Fang, 2004; Zhao et al., 2005), and rapid urbanization (Piao et al., 2003) have also occurred in the last decade, particularly around the lakes in the middle and lower reaches of the basin. Extreme deforestation and rapid urbanization predominate in the upper reaches (Yin and Li, 2001; Piao et al., 2003), and reclamation of lakes and rapid urbanization have also occurred in the middle and lower reaches (Du et al., 2001; Piao et al., 2003; Zhao and Fang, 2004; Zhao et al., 2005), leading to depletion of lake water volumes and a reduction in their connection with the Changjiang River, due to a retardation of water in the basin.
Fig. 3.4  Land cover around the Dongting lake in: (a) 1990s; and (b) 2000s. Land cover changes (shrinking of the lake) are predominant around the dotted-circle area.
Table 3.1  Land cover change in the 1990s and 2000s in the Changjiang River Basin.

<table>
<thead>
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<tbody>
<tr>
<td>Paddy</td>
<td>5.5E+10</td>
<td>5.5E+10</td>
<td>100.5%</td>
<td>1.6E+11</td>
<td>1.6E+11</td>
<td>99.9%</td>
</tr>
<tr>
<td>Farm</td>
<td>1.4E+11</td>
<td>1.5E+11</td>
<td>100.9%</td>
<td>6.1E+10</td>
<td>6.1E+10</td>
<td>100.2%</td>
</tr>
<tr>
<td>Forest</td>
<td>1.5E+11</td>
<td>1.5E+11</td>
<td>99.4%</td>
<td>2.6E+11</td>
<td>2.6E+11</td>
<td>99.9%</td>
</tr>
<tr>
<td>Grassland</td>
<td>6.1E+11</td>
<td>6.1E+11</td>
<td>100.1%</td>
<td>1.8E+11</td>
<td>1.8E+11</td>
<td>100.1%</td>
</tr>
<tr>
<td>River &amp; Lake</td>
<td>1.1E+10</td>
<td>1.1E+10</td>
<td>102.7%</td>
<td>2.3E+10</td>
<td>2.3E+10</td>
<td>100.2%</td>
</tr>
<tr>
<td>Glacier area</td>
<td>1.9E+09</td>
<td>1.9E+09</td>
<td>100.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Urban area</td>
<td>1.9E+09</td>
<td>2.2E+09</td>
<td>115.7%</td>
<td>3.6E+09</td>
<td>3.7E+09</td>
<td>104.0%</td>
</tr>
<tr>
<td>Sandy land</td>
<td>1.4E+10</td>
<td>1.4E+10</td>
<td>100.9%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Others</td>
<td>2.9E+10</td>
<td>2.9E+10</td>
<td>102.0%</td>
<td>1.8E+09</td>
<td>1.8E+09</td>
<td>101.9%</td>
</tr>
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</table>

In this study, using the NICE-FLD the author evaluated the effect of the shrinking volumes of lake water on the hydrologic budget. In the back-casting simulation, both Dongting and Poyang Lakes were recovered to their respective areas during the 1950s (areas; 4,000 km² and 5,000 km²), in accordance with previous research (Du et al., 2001; Yin and Li, 2001; Shankman and Liang, 2003; Zhao and Fang, 2004; Peng et al., 2005; Zhao et al., 2005) and meteorological data of the 1998 severe flood was input. The geological structures of the plateau were ascertained by scanning and digitizing geological material (Geological Atlas of China, 2002), which also included core-sampling data at some points. The geology of the upper region is composed of metamorphic rock, alpine meadows, and sub-alpine soils (Qu et al., 1993; Geological Atlas of China, 2002). The eastern border of the plateau is covered with a brown soil. The plateau has an elevation of 4,000-5,000 m at its highest point, and on the eastern side the elevation falls to 1,500-2,500 m, except in the Sichuan Basin. The dominant rock type in the north of the plateau is of detrital sedimentary material, basic and ultra-basic rocks in the southwest, limestone in the mid-south, and outcrops of granite and detrital sedimentary rocks in the southeast. The soils of the plateau range from brown to yellow to red. The middle and lower reaches of the basin are dominated by paddy soils (Hydrgric Anthrosols) and loose sediments such as yellow earth (Ferralic Cambisol), red earth (Haplic Acrisol), and yellow-brown earth (Haplic Luvisol). The author was able to divide the geological structure into four types with a resolution of 10 km in the horizontal direction and 20 layers in the vertical direction, on the basis of hydraulic conductivity ($K_h$ and $K_v$), the specific storage of porous material ($S_s$) and specific yield ($S_y$), in the same way as Nakayama et al. (2006).
3.4.3 Boundary Conditions and Running the Simulation

The reflecting condition on the hydraulic head in the upper sections of the drainage basin was used with the assumption that there was no inflow from the mountains in the opposite direction (Nakayama and Watanabe, 2004), and at the eastern sea boundary (East China Sea and South China Sea) a constant head was set at 0 m. The hydraulic head values parallel to ground level were input as the initial conditions for the groundwater submodel. The digital river network, produced by the IGSRR (1982) from 1:50,000 and 1:100,000 topographic maps covering the basin was used in this study. In the late 1980s previous research fixed the diversion ratio of water at 0.15 from three openings in the Dongting Lake region, the so-called Jingjiang reach (Songzi, Taiping, and Ouchi), and from the Changjiang River (Fig. 3.1) (Li and Ni, 2001; Dai et al., 2005). In 5,124 river cells, including the Changjiang River, the inflow and outflow from the riverbed was simulated at each time step depending on the difference between the hydraulic heads for groundwater and the river.

The simulation area is 3,000 km wide by 1,000 km long by Albers (WGS 1984) co-ordinates, and covers most of the Changjiang basin. The area was discretized into a grid of 300 \times 100 blocks with a grid spacing of 10 km in the horizontal direction and into 20 layers, with a weighting factor of 1.1 (finer at the upper layers) in the vertical direction. The upper layer was set at a depth of 2 m, and the 20th layer was defined as an elevation of -500 m from the sea surface. Simulations were performed with a time step of 6 hours for 2 years from 1 January 1987 to 31 December 1988 (normal summer flood) and from 1 January 1998 to 31 December 1999 (severe summer flood), after a 1 year warm-up period until equilibrium.

Previous observation data for river discharge (10 points; Changjiang Water Conservancy Committee, 1998–1999), soil moisture (3 points from the Global Soil Moisture Data Bank; Entin et al., 2000; Robock et al., 2000), and groundwater level (25 points; China Institute for Geo-Environmental Monitoring, 2003), were used for calibration and validation of the simulations (Fig. 3.1). Details are described in Nakayama and Watanabe (2008b) and Nakayama and Shankman (2013a).
3.5 Results and Discussion

3.5.1 Hydrologic Changes under different Climate Conditions

The observed discharge during both normal and severe floods in the upstream tributaries and the mainstream of the Changjiang River Basin has been reproduced well in research (Nakayama and Watanabe, 2008b; Nakayama and Shankman, 2013a). The heavy rainfall during the 1998 flood, which surpassed the flood storage ability of the lake resulting in wide-spread floods around the lake and along the lower Changjiang, has also been verified (Shankman and Liang, 2003; Shankman et al., 2006). Fig. 3.5 shows the simulated river discharge of the Changjiang mainstream during 1998-1999, as verified by observed data (Changjiang Water Conservancy Committee, 1998-1999). It is clear that although the flood diversion and inundated area in the 1998 flood were smaller than that of the biggest flood of 1954, the discharge was much greater than that in 1987-1988. The large-scale flood discharge that occurred from June-September in 1998 was 33% greater than the usual annual discharge.

The result of this simulation shows that the effect of land cover changes on river discharge in the Changjian mainstream made between 1990s and 2000s (Fig. 3.4 and Table 3.1), such as deforestation (Yin and Li, 2001), reclamation of lakes and sedimentation (Du et al., 2001; Zhao and Fang, 2004; Zhao et al., 2005), and rapid urbanization (Piao et al., 2003), was less marked than that of the effect of extreme weather and climate events, such as the heavy rainfall in 1998. The forcing precipitation data created from the rain gauge data and ECMWF in this study closely agreed with the GPCC (Bell et al., 1999), and thus the simulation adequately reproduces the peak value of the observed discharge.

Fig. 3.5  Simulation result of 1998 big-flood in the Changjiang mainstream. The circles represent the observation data and the lines represent the simulated results by NICE-FLD. \( r^2 \) and NS are also plotted.
The river discharge around the junction during the usual flood-period from 1987 to 1988 were compared with those from the severe flood-period in 1998 (Fig. 3.6). Poyang Lake plays an important role as a flood storage reserve (Yin and Li, 2001; Shankman and Liang, 2003; Shankman et al., 2006), and as such, a portion of the water resulting from heavy rain in the summer of 1987 flowed from the mainstream into Poyang Lake (negative value) (Fig. 3.6c). This usually occurs during the middle and late summer months. The discharge at the junction and in the downstream section of the mainstream is excellently reproduced by the simulation, in the same way as in previous research (Shankman and Liang, 2003; Shankman et al., 2006). Because an even greater amount of rainfall occurred around the Poyang Lake catchment from June to July in 1998, a greater amount of lake water flowed into the mainstream (Fig. 3.6d). This means that the amount of rain that fell during the 1998 large-scale flood surpassed the flood storage ability of Poyang Lake, resulting in a broader, inundated, area around the lakes and along the mainstream, and also in the serious damage that occurred in the downstream regions.

The discharge at the junction around Dongting Lake flowed into the mainstream in both 1987-1988 and in 1998 (Fig. 3.6 a-b). Because a higher rainfall occurred around Dongting Lake than that in a usual year, there was no backwater flow at this junction, even during the flood period. The observed discharge and water budget around Dongting Lake was excellently reproduced by the NICE-FLD, in the range of previous research (Li and Ni, 2001; Dai et al., 2005), and the model reproduced the observed values reasonably well, in accordance with the change of the river-lake relationship (Hongfu et al., 2007; Wang et al., 2008), and also the surface water-groundwater interaction (Eltahir and Yeh, 1999; Dai et al., 2010; Gribovszki et al., 2010). In particular, the discharge from Poyang Lake into the Changjiang River and the backflow into the lake depend on the relationship between the flood storage ability of the lake, groundwater seepage, and the hydro-climatic conditions around the lake’s mouth.
Fig. 3.6   Simulation result of river discharge around the junction during both 1987-1988 and 1998-1999: (a) around Dongting Lake during 1987-1988; (b) around Dongting Lake during 1998-1999; (c) around Poyang Lake during 1987; and (d) around Poyang Lake during 1998-1999. Simulated discharges were compared with observed values both at the junctions (R–7; Chenglingji, and R–9; Hukou) and at downstream mainchannels (R–8; Luoshan, and R–10; Datong) in Fig. 3.1. Positive discharge at junction shows the flow from the lakes to the mainstream Changjiang River.
3.5.2 Surface Water – Groundwater Interactions

Using Radium 226 (\(^{226}\text{Ra}\)) specific activity, Dai et al. (2010) evaluated that the groundwater discharge from Dongting Lake to the main channel during the extreme drought event (from September to December 2006) accounted for 22% of the discharge difference between Jianli and Luoshan (or the outlet discharge into the main channel at Chenglingji); indicating a noticeable contribution of groundwater discharge from the lake basin into the main channel. This contribution became even greater when the TGD empounded water from 20 September to 27 October 2006 during the extreme drought, preventing drying out of the river.

Fig. 3.7a shows the distribution of simulated seepage from groundwater to the river and lake along the mid-lower reaches. Positive values indicate groundwater seepage into the river or lake. The ratio of seepage to outlet discharge becomes greater during normal periods than during periods of extreme flood because the groundwater level along the river or lake becomes higher than the surface water level. This result indicates that groundwater seepage into the river and lake could play a more important role along the mid-lower reaches in a normal year than in years with extreme floods (Nakayama and Shankman, 2013b). Such a possibility is also supported by a previous study using a \(^{226}\text{Ra}\) method, revealing its importance in maintaining stream flow in the dry season (Dai et al., 2010). In particular, lake stages change significantly near the mouths of the two lakes and their major tributaries, and this indicates complex river-lake-groundwater interactions.

Fig. 3.7 b-c shows the inter-annual power spectra of river discharge at Yichang and Datong for 1987-1988 (normal and drought) and 1998–1999 (extreme flood). Generally, the spectrum at Yichang (upstream of lake region) follows values of \(S(f)\sim f^{-0.3}\) within time scales from one week to one year, and that at Datong (downstream of lake region) is steeper, with values of \(f^{-0.5}\) up to two months; in accordance with previous studies (Pelletier and Turcotte, 1997; Blender and Fraedrich, 2006). Such variability is due to the lake’s capability of storing water and the delayed release of such water from the extended lakes connected to the main channel (Wang et al., 2008). In particular, this characteristic changes between normal periods and flood periods. Because the backflow from the main channel into Poyang Lake occurs at times during normal periods (Nakayama and Watanabe, 2008b), the water retarded from the discharge outlet into the main channel affects the steeper damping of spectrum in the higher frequency at the junction at Hukou. This mechanism also causes a steeper damping of spectrum at the downstream main channel at Datong, due to the flood storage capability of the lakes, and therefore the behavior of the regime differs in the upper and lower reaches (Nakayama and Watanabe, 2008b). The change is also related to an increase in groundwater seepage as a baseflow during normal periods, as described above.
Fig. 3.7  Surface water to groundwater interactions in the Changjiang River: (a) Simulated seepage from groundwater to river and lake; (b)-(c) Power spectra of river discharge at Yichang and Datong during normal and severe floods.
3.5.3 Evaluation of Flood Storage Ability of Lakes

Observed discharge in the lower Changjiang reaches during normal and severe floods has been excellent reproduced by previous research (Nakayama and Watanabe, 2008b). It has also been verified that the heavy rainfall occurring during the 1998 flood surpassed the flood storage ability of the lake, resulting in wide-spread floods around the lake and along the lower Changjiang (Shankman and Liang, 2003; Shankman et al., 2009). The observed values were reproduced reasonably well by the model, in accordance with both a change in the river-lake relationship (Hongfu et al., 2007; Wang et al., 2008), and the surface water-groundwater interaction (Eltahir and Yeh, 1999; Dai et al., 2010).

We conducted the test simulation by recreating the historical areas of Dongting and Poyang Lakes from the 1950s (4,000 km² and 5,000 km², respectively), and by inputting the meteorological data for the large-scale flood of 1998 (Fig. 3.8). The simulation showed that the river discharges at the junction (and downstream from the junction) decreased due to the water storage effect of Dongting and Poyang Lakes, as qualitatively described by previous research (Du et al., 2001; Yin and Li, 2001; Shankman and Liang, 2003; Zhao and Fang, 2004; Peng et al., 2005; Zhao et al., 2005) (Fig. 3.8a-b). The peak flow, in particular, was reduced by about 5-15% at the junction, indicating that both Dongting and Poyang Lakes have an important flood storage function. It is of interest that the groundwater level decreases greatly around the inlet of major tributaries into both lakes and around the junction of mainstream (Fig. 3.8c). This indicates that the increase in the lakes’ storage capacity moderates the peak value of the lake water level during the flood periods and decreases the groundwater level surrounding the lakes. The NICE-FLD suggests that it would be very effective if the past areas of the lakes were recovered as much as possible, to prevent large-scale floods such as that of 1998, from the view point of the return period in the hydrologic cycle.
Fig. 3.8  Simulation result of hydrologic change by recovering the areas of Dongting and Poyang Lakes to that of the 1950s (4,000 km² and 5,000 km²): (a) river discharge downstream of Dongting Lake (R–8; Luoshan); (b) river discharge downstream of Poyang Lake (R–10; Datong); and (c) change of groundwater level around both lakes. The circles in Fig. 3.8 a-b represent observation data and the lines represent the simulated results from 1998-1999 (the same as in Fig. 3.6b and 3.6d). The bold line represents results using a simulation of the lakes when recovered to an area of the 1950s. The plotted area in Fig. 3.8c is described in Fig. 3.1, and the black and pink lines represent the lakeshores in 1990s and 1950s.

3.6 Conclusion

The NICE model was coupled with the lake and junction models (NICE-FLD) in order to evaluate the river-lake-groundwater relationship and the role of the flood storage capability of the lake area in the Changjiang River Basin. Using this simulation we compared the severe flood-period of 1998 with the usual flood-period of 1987-1988. NICE showed the previously-unrevealed role of surface water-groundwater interactions and lateral subsurface flows, which have not been considered important in previous research on continental scales, when assuming stationarity. Furthermore, the author conducted a back-casting simulation by recovering the lake water volume of the 1950s and by inputting meteorological data of the 1998 severe flood, in order to evaluate the role of the flood storage capability of the lakes in relation to the water/heat budgets.
References


Chapter 4

Relation between Uneven Water Resources, Withdrawal, and Ecosystem Degradation in the Changjiang and Yellow River Basins
Abstract

The hydro-climate differs vastly between northern and southern China, and this led to an imbalance in environmental resources related to an increased demand for food and declining water availability. The Three Gorges Dam (TGD) was designed to diminish flooding and the South-to-North Water Transfer Project (SNWTP) has been planned to enable the transfer of water from the Changjiang River basin to the Yellow and Hai Rivers. However, these projects will not necessarily solve all problems associated with water availability within the basins, and there is an urgent need for the development of a sophisticated eco-hydrological model to evaluate the optimum amount of transferred water, and the socio-economic and environmental consequences from such endeavors/projects.

In this chapter, a process-based National Integrated Catchment-based Eco-hydrology (NICE) model was modified and coupled with complex irrigation, stream junction, reservoir operation, and water transfer subsystems, for the development of a coupled human and natural systems model, and to evaluate the causes and effects of uneven water resources. The model clarified the impact of irrigation on eco-hydrological processes, and predicted the hydrologic change after operation of the TGD and SNWTP, to estimate whether there would be a reduction in problems associated with water stress, crop productivity, and ecosystem degradation. The result also revealed the missing roles of surface water-groundwater interactions and lateral subsurface flow, previously considered to be not as important in previous studies that assumed stationarity on continental scales. The heterogeneous pattern of the Time-Integrated Normalized Difference Vegetation Index (TINDVI) gradient in agricultural fields helped to estimate uneven crop yield and its relation to water availability.

This integrated approach not only has a role in re-considering these complex processes from the view point of the hydrologic and biogeochemical cycles, but also to clarify how substantial pressures from complex issues can be overcome by effective trans-boundary solutions.

Keywords: crop yield, eco-hydrology model, extremes, TINDVI, water withdrawal
4.1 Introduction

The Changjiang and Yellow Rivers originate on the Qinghai Tibet Plateau and flow eastwards for about 6,000 km to the East China Sea (Fig. 4.1). Both rivers represent 50%-60% of all the water discharge from Chinese rivers to the western Pacific Ocean, and up to 80% of the sediment load. In China, the hydro-climate differs between the north and south. The upper section of the Changjiang River Basin in the humid south flows through narrow and incised river valleys, whereas the downstream section is surrounded by broad alluvial valleys supporting intensive rice growth. Deforestation and land reclamation have induced serious soil erosion and an increase of floods in this river basin, and in particular there is a shrinkage of the flood storage capability around lakes (Zhao et al., 2005; Nakayama and Watanabe, 2008b; Nakayama and Shankman, 2013).

Although the Three Gorges Dam (TGD) provides flood control, changes in the aquatic environment of the estuary and the East China Sea will eventually occur from changes in pollutant loads caused by the deposition of large amounts of sediment carried from the upper region in the dam and the artificial control of discharge volume (Yang et al., 2006). From the time of its operation there have been increasing problems with flood occurrence in the downstream area of the Changjiang river associated with the TGD, and such issues were not considered when originally justifying the dam’s construction (Shankman and Liang, 2003; Zhao et al., 2005; Nakayama and Watanabe, 2008b; Nakayama and Shankman, 2013).

![Crop types in agricultural areas of the Changjiang and Yellow River Basins in China.](image)

Irrigation areas are overshaded in the figure. The black dotted square represents the border of the simulation area containing a grid of 300 × 200 blocks of Albers (WGS 1984) co-ordinates. Black dotted line is the border of the North China Plain (NCP), which includes the downstream area of the Yellow River.
In contrast, the Yellow River is located in the semi-arid north and is well known for its high suspended sediments concentration, frequent floods, unique channel characteristics in the lower reach (the river bed is raised above the land outside its banks), and limited water resources (Nakayama, 2011b). The North China Plain (NCP) (Fig. 4.1) is a giant alluvial plain formed by deposition from the Yellow, Hai, and Luan Rivers and their tributaries, and is one of China’s most important grain cropping areas (because of its large area of approximately $1.36 \times 10^5$ km$^2$ and population of around 112 million). Many palaeochannels from different stages form the various geomorphologic features (Chen, 1996). Over the past half century, the groundwater has lowered dramatically owing to both drought and over-pumping, and in areas this has been accompanied by the expansion of saline-alkaline land (Brown and Halweil, 1998; Liu and Xia, 2004; Nakayama, 2011a; Nakayama et al., 2006). Since the completion of a large-scale irrigation project in 1969, over-withdrawal of water in the Yellow River has resulted in noticeable river drying occurring on an increasingly frequent timescale (Fu et al., 2004). The combination of an increased demand for food and a declining availability of water are creating substantial pressures for this heavily irrigated area (Brown and Halweil, 1998; Fu et al., 2004; Yang et al., 2004a; Nakayama, 2011b).

In previous research the author evaluated the general characteristics of the eco-hydrological process in the entire Changjiang and Yellow River Basins and in extensions of separate basins, to evaluate the optimum amount of potentially-transferable water, and the associated socio-economic and environmental consequences, by constructing the basic structure of the model with different functions of representative crops (wheat, maize, soybean, and rice) (Nakayama, 2012c). At present, China is accelerating its huge project to drive water from the Changjiang to the Yellow and Hai Rivers (South-to-North Water Transfer Project; SNWTP) (Yang and Zehnder, 2001; Li et al., 2007). Although it has been estimated that the TGD and the SNWTP will remove the geographical and socio-economic imbalances as much as possible (Yang and Zehnder, 2001; Li et al., 2007), there is an urgent need to clarify the relations of the two extremes of drought and flood which are affected by human activity. The development of a process-based model is therefore necessary to present an integrated approach for the appropriate management of water resources and to achieve sustainable development on a regional scale.

In this study the process-based National Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012) was coupled with complex sub-systems in irrigation, stream junction, reservoir operation, and water transfer, to evaluate the cause and effect of uneven water resources in the entire Changjiang and Yellow River Basins. The model includes the different growth processes of representative crops and predicts the hydrologic changes after operation of the TGD and SNWTP, to estimate whether critical problems related to water stress, crop productivity, and ecosystem degradation would diminish in the basins. NICE also evaluates the missing role of surface water-groundwater interactions and lateral subsurface flow, which has previously been considered to be unimportant when assuming stationarity in previous research on a continental scale (Milly et al., 2008). Furthermore, Time-Integrated NDVI (TINDVI) was analyzed using satellite NDVI images in NOAA/AVHRR (Advanced Very High Resolution Radiometer), and by ascertaining heterogeneous patterns of the TINDVI gradient in agricultural fields, an uneven crop yield, and its relation to water availability was estimated for both surface and groundwater. The integrated approach explored in this chapter not only assists in the re-consideration of complex processes from the view point of the hydrologic and
biogeochemical cycles, but also in clarifying how substantial pressures from complicated issues can be overcome by effective trans-boundary solutions.

4.2 Materials and Methods

4.2.1 Development of the Coupled Human and Natural System

The process-based National Integrated Catchment-based Eco-hydrology (NICE) model includes surface-unsaturated-saturated water processes, and assimilates land-surface hydrothermal processes describing phenology with satellite data (Fig. 4.2) (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012). The unsaturated layer divides the canopy into two layers in the vertical dimension using the SiB2 (Simple Biosphere model 2), and the soil into three layers (Sellers et al., 1996). For the saturated layer, NICE solves three-dimensional groundwater flow for both unconfined and confined aquifers. Hillslope hydrology, including freezing/thawing processes, can be expressed using the two-layer surface runoff model. NICE connects each sub-model by considering: the water/heat fluxes; the gradient of hydraulic potentials between the deepest unsaturated layer and the groundwater; effective precipitation; and seepage between river and groundwater (Nakayama and Watanabe, 2004). NICE is coupled with DSSAT (Decision Support Systems for Agro-technology Transfer) (Ritchie et al., 1998) in an agricultural field to include the different functions of representative crops (wheat, maize, soybean, and rice) (Nakayama et al., 2006). The model automatically simulates dynamic growth processes and biomass formulation by inputting: previous point data for each crop type (Wang et al., 2001; Liu et al., 2002; Tao et al., 2006), the spatial distribution of crop types (Chinese Academy of Sciences, 1988; Fang et al., 2006), and the irrigation area (Liu, 1996), (in which the automatic irrigation mode supplies the crop water requirement, assuming that average available water in the top layer falls below soil moisture at field capacity for cultivated fields (Nakayama, 2011a, 2011b; Nakayama et al., 2006) and that water level is maintained in the irrigation schedule of the irrigated water depth for paddy fields) (Nakayama and Watanabe, 2008b). NICE is also combined with lake and stream junction models (Nakayama and Shankman, 2013; Nakayama and Watanabe, 2008b) to evaluate the role of the flood storage capability of Dongting and Poyang lakes, which drain into the Changjiang through narrow outlets (Fig. 4.1). This energy-based method addresses river discharge across the junction by performing standard step backwater and forewater calculations with continuity and energy equations.
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Fig. 4.2  National Integrated Catchment-based Eco-hydrology (NICE) model. NICE is coupled with DSSAT for agricultural fields, to improve the hydrologic cycle and evaluate the relation between uneven crop yield and water availability.

4.2.2 Model Input Data and Satellite Analysis

Six-hour reanalyzed data of downward radiation, precipitation, atmospheric pressure, air temperature, air humidity, wind speed, FPAR (Fraction of Photosynthetically Active Radiation), and LAI (Leaf Area Index) were input into the model after interpolation of ECMWF (European Centre for Medium-Range Weather Forecasts), in an inverse proportion to the distance back-calculated in each grid. Because the ECMWF precipitation had the least reliability and underestimated observed peak values, rain gauge daily precipitation collected at 4,271 meteorological stations were used to correct the ECMWF value. Mean elevation was calculated using a global digital elevation model (DEM; GTOPO30) (U.S. Geological Survey, 1996). Digital land cover data were categorized into forests, grasses, bushes, and shrubs cover mountainous and hilly areas in the upper regions; paddy fields widely distributed along the Changjiang mainstream and cultivated fields mainly along the Yellow River (Fig. 4.1). Vegetation class and soil texture were categorized and digitized using the Vegetation and Soil Maps of China (1:4,000,000) (Chinese Academy of Sciences, 1988). Geological structures were divided into four types on the basis of hydraulic conductivity, the specific storage of porous material, and specific yield, by scanning and digitizing the geological material (Geological Atlas of China, 2002) and core-sampling data.
After downloading original data from WebPaNDA (2008), the NDVI was calculated from NOAA/AVHRR satellite data collected over East Asia between 1982 and 1999. TINDVI was calculated from satellite NDVI images with a resolution of 6 km, using the nearest-neighbor method. This value is defined as the area under a curve described by NDVI with time, because dry biomass is linearly related to TINDVI and crop growth rate related to NDVI (Yang et al., 1998). These values agree well with observed values from previous field experiments (Nakayama et al., 2006), showing that simulated dry biomass has a linear relationship to TINDVI with a high correlation ($r$^2 is greater than 0.950) (Nakayama, 2011b). The result also implies that maximum growth rate generally occurs when the NDVI reaches a plateau stage. This relation is useful for estimating the potential rate of primary production in the basin. These input data are adequate for estimating eco-hydrological process on a scale of hundreds to thousands of kilometers in this study. Details are described in Nakayama (2012c) and Nakayama and Shankman (2013b).

### 4.2.3 Model Modification for TGD and SNWTP

Water level of the TGD is maintained between 145 m (flood season) and 175 m (normal season) above sea level (a.s.l.), depending on optimal flood-control water-level schemes, on the condition that spill discharge is limited to less than 55,000 m$^3$/s to minimize flood risk in the downstream area, and is larger than 35,000 m$^3$/s for navigational benefits (Liu et al., 2008). The author modified the NICE using a one-dimensional water budget with the operation of the reservoir, by applying the relation between water level and storage volume to estimate the released discharge (Fig. 4.2). The model showed that the estimated discharge of the reservoir during a flood event in late summer did not greatly change after the dam’s construction, which implies the dam’s inability to make a substantial effect on discharge during severe floods (Shankman and Liang, 2003). For the prediction of hydrologic changes in normal floods, the author input monthly discharge changes (Yang et al., 2006; Li et al., 2007; Dai et al., 2010; Yi et al., 2010) directly in the model. The model shows that after filling the TGD due to increased evaporation and water usage, the flood water level would become less extreme, and the range at which the water level increases would be dampened downstream (Yi et al., 2010).

The middle route of the SNWTP diverts water from the Danjiangkou Dam upstream from the Hanjiang River to northern China (Fig. 4.1). Therefore, the author also modified the NICE to directly input the water transfer schemes of $9.5 \times 10^9$ m$^3$ and $13.0 \times 10^9$ m$^3$ per year into the model, by considering monthly runoff (Li et al., 2007).

### 4.2.4 Boundary Conditions and Running the Simulation

In the upstream boundaries a reflecting condition on the hydraulic head was used, assuming that there is no inflow from the mountains in the opposite direction (Chen et al., 2005; Nakayama, 2011b; Nakayama and Watanabe, 2008b). At the eastern sea boundary, a constant head was set at 0 m. In river grids (decided by the digital river network from 1:50,000 and 1:100,000 topographic maps), inflows and outflows from riverbeds were simulated at each time step, depending on the difference in the hydraulic heads for ground and river water.

The simulation area is 3,000 km wide by 2,000 km long in the Albers co-ordinates (WGS 1984), and covers most of the Changjiang and Yellow River basins as referred to in Chapters 2 and 3 (Fig. 4.1). This area is discretized into a grid of $300 \times 200$ blocks with a grid spacing
imbalance in environmental resources related to an increased demand for food and declining

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of 10 km in the horizontal direction and into 20 layers with a weighting factor of 1.1 (finer at
the upper layers) in the vertical direction. The upper layer is set at a depth of 2 m, and the
20th layer is defined as an elevation of -500 m from the sea surface. Simulations were
performed with a time step of $\Delta t = 6$ hours for 1987-1988 and 1998-1999 after a 1 year
warm-up period, until equilibrium. Previous observed data of river discharge (Changjiang
Committee, 1987, 1988), soil moisture (Entin et al., 2000; Robock et al., 2000), and
groundwater level (China Institute for Geo-Environmental Monitoring, 2003) were used for
calibration and validation, in addition to values published in literature (Clapp and Hornberger,
1978; Rawls et al., 1982) as in the author’s previous research on the Changjiang (Nakayama
and Watanabe, 2008b; Nakayama and Shankman, 2013a-b) and Yellow Rivers (Nakayama,
2011a-b).

4.3 Results and Discussion

4.3.1 Drought Caused by Over-Irrigation in the Downstream Area of the Yellow River

After verification of hydrologic variables (Nakayama, 2011a-b; Nakayama and Watanabe,
2008b; Nakayama et al., 2006), the effect of over-irrigation on the decrease in river discharge
in the downstream area of the Yellow River is shown (Fig. 4.3). Because the model includes
the irrigation procedure and dynamic wave effect (Nakayama and Watanabe, 2004), it
excellently reproduces the observed discharge for a low flow with a high correlation, and at
times for river dry-up (Yellow River Conservancy Committee, 1987, 1988) (Fig. 4.3b). It
reproduces particularly well the withdrawal of water for agricultural purposes; being more
than 90% of the total water withdrawn downstream (Cai, 2006). The result shows that there is
no clearly observed decrease in the amount of discharge between upstream and downstream
areas, except for the decrease between Pt. C and Pt. D, which is attributed to predominant
evaporation occurring on the area of Loess Plateau expansion between Pt. A and Pt. B, and
also to over-withdrawal and the unique channel characteristics where the river bed lies above
the surrounding land in the area downstream. The model also indicates that the peak discharge
is higher downstream than upstream because of the amount of drainage water produced
during the rainy season, which is a characteristic of semi-arid regions. Furthermore, the
spatial distribution of river irrigation (Fig. 4.3a) is reproduced reasonably well by the model,
not only in reach level but in spatial distribution, as validated by a comparison with a previous
study based on the Penman-Monteith method and the crop coefficient (Nakayama, 2011b;
Nakayama et al., 2006). At a downstream point at Lijin (Pt. D; 37.52 °N, 118.30 °E), the river
discharge dries out during spring, mainly because a large amount of the water is used for the
irrigation of winter wheat. The result also supports the result of the author’s previous research,
which showed that the effect of groundwater irrigation is predominant downstream
(Nakayama, 2011b), mainly because of water-use conflicts that are intensifying between
upstream and downstream areas, and between various sectors such as agricultural, municipal,
and industrial (Brown and Halweil, 1998; Nakayama, 2011a-b; Nakayama et al., 2006). These
results show the smaller change in the hydrologic cycle is largely attributable to its
unsuitability for crop production and the higher dependence of water irrigation.
Fig. 4.3  Decrease in discharge of the Yellow River caused by over-irrigation: (a) simulated result of river irrigation in 1987; (b) river discharge from middle to downstream areas of the river. In Fig. 4.3a, the area colored in white represents the region without irrigation. In Fig. 4.3b, the solid line represents the simulated result with irrigation, and the circle represents the observed value. The right axis shows the temporal change in average precipitation. $r^2$ shows the correlation between observed and simulated values, and NS shows the Nash-Sutcliffe Criterion.

4.3.2 Impact of TGD and SNWTP on the Downstream area of the Changjiang River

The river discharge around lake regions along the Changjiang River are very sensitive, and fluctuate depending on the hydro-climatic conditions around the junction, which are closely related to the flood storage capability of the lakes (Nakayama and Watanabe, 2008b). The flood risk around Poyang Lake decreases moderately with a decrease in the controlled discharge from the TGD from July to September. However, if the controlled discharge is equal to 40,000 m$^3$/s, the model predicted that water released by the TGD could increase the lake water level and flood occurrence during May to June, regardless of the amount of controlled discharge, in exchange for the benefit of a flood decrease during the summer flood season (in the same way as in previous research (Shankman and Liang, 2003) (Fig. 4.4a). Results show that the discharge and water level that occurred during the severe 1998 flood would not alter greatly unless there was a limitation of the spill discharge by the dam, as suggested by Shankman and Liang (2003). The simulated results also show that after 22 years of the TGD being operational, the flood risk around the lake could be further accelerated through a constant increase in the water level of about 1-2 m, if hydrologic changes cause
downstream channel aggradation by sediment deposition (Yang et al., 2006; Chen et al., 2008; Xu and Milliman, 2009), although sediment deposition in the lake may not greatly affect hydrologic changes over a long-term period (Dai et al., 2005; de Leeuw et al., 2009). This result indicates that it is important to manage not only the flood discharge but also the sediment load in the whole basin during the operation of the TGD and the SNWTP, in addition to permanently removing some of the levees and opening some of the others during severe floods. Though the effect of the SNWTP will not be so remarkable as that of the TGD, the hydrologic changes would occur in spring and early summer around the lake region, in accordance with the water-supply period of rice planting (U.S. Department of Agriculture, 1994), and the probability of a water shortage would be high, in particular around the Hanjiang River catchment, due to its sensitivity to climate change (Li et al., 2007). The groundwater seepage to lakes may play an important role along the mid-lower reaches in a normal year (Fig. 4.4b), and this supposition is supported by previous research which indicated that groundwater seepage to lakes in this area is involved in about 30% of the hydrologic budget, by maintaining stream flow in the drought season (Dai et al., 2010). In particular, the average level around the inlet of major tributaries into the lake would change greatly, and around the junction of the mainstream area, after the TGD and SNWTP are operational, which highlights the complex river-lake-groundwater interactions in this area.

![Figure 4.4](image)

**Fig. 4.4** Impact of the TGD and SNWTP on hydrologic changes around Poyang Lake: (a) lake water level during severe flood event; and (b) difference between the average groundwater level before and after construction. In Fig. 4.4a, the spill discharge of the TGD was changed in consideration of navigational benefits and flood risk downstream. In Fig. 4.4b, the SNWTP scenario uses a water transfer scheme of $13.0 \times 10^9$ m$^3$ per year.
4.3.3 Effect of Channel Morphology and Sediment Deposition on Hydrologic Change

Hydrologic changes in the lower Changjiang River and in Poyang Lake significantly affect channel morphology and lake sediment deposition (Table 4.1). The model predicted the hydrologic changes for a period 22 years after completion of the TGP, attributed to channel aggradation (Li et al., 2004; Yang et al., 2006; Chen et al., 2008; Shankman et al., 2009; Xu and Milliman, 2009) (Fig. 4.5). Simulated results show a stage increase of 1 m - 2 m and a higher flood risk around the lake, assuming channel aggradation after the completion of the TGD. Sediment deposition in the lake is offset by substantial sand mining, and is therefore not likely to promote a risk of floods (Xiang et al., 2002; Dai et al., 2005; de Leeuw et al., 2009) (Fig. 4.5a). It is anticipated that the flood risk associated with hydrologic changes would increase during May and June in addition to the summer floods, in the same way as suggested in other studies (Shankman and Liang, 2003; Shankman et al., 2009). This change is closely related to the complicated hydrologic cycle at the mouth of the lake (Fig. 4.5b). This result indicates that it is important not only to manage the flood discharge, but also the sediment loads throughout the entire basin during operation of the TGD. The back-casting simulation also implies that by recovering the lake water volume to that of the 1950s, the floodwater storage capability is further increased, if the long-term effects of channel morphology and lake sediment deposition are included in the simulation (Nakayama and Watanabe, 2008b).

![Fig. 4.5](image-url) Sensitivity of predicted hydrologic change for the effects of channel morphology and lake sediment deposition in the long-term simulation: (a) lake water level; and (b) river discharge. In Fig. 4.5b, the bold line represents the simulated discharge at junction R–9; Hukou, and the solid line represents the downstream main-channel (R–10; Datong).
Extensive sand mining in Poyang Lake began in 2001 after dredging on the lower Changjiang River was prohibited (Wu et al., 2007; de Leeuw et al., 2009). Fig. 4.6 shows the impact of sand mining on the Poyang Lake region during a severe flood, 22 years after completion of the TGD. The simulated result of dredging at the mouth of Poyang Lake (deepening of the channel by 59 cm per year; Table 4.1) shows that the flood risk would increase greatly during spring and summer because of the closer interaction between the Changjiang River and the lake. Using this scenario, the model predicts that the annual averaged lake stage would increase by a few meters or more, and that the river stage at the lake mouth would also increase by about 10 cm assuming a width extension at the lake’s mouth, although the level would decrease somewhat during September and November because of the sudden decrease in discharge and the lake stage during operation of the TGD (Shankman and Liang, 2003) (Fig. 4.4a). In an alternative scenario, the model predicts that if a diversion towards the lake which is currently disconnected from the mainstream was increased by only a few centimeters at the lake, it would be more effective at reducing the flood risk than the intensive dredging along the junction channel, which proves qualitatively the validity of the previous research (de Leeuw et al., 2009).

![Fig. 4.6 Impact of sand mining on Poyang lake region during severe flood at 22 years after completion of the TGD, using multiple scenarios: intensive dredging at the lake's mouth (bed digging); width extension at the lake's mouth; and a diversion towards the lake that is currently disconnected from the mainstream.](image-url)
### Table 4.1  Channel morphology and lake sediment deposition around Poyang Lake.

<table>
<thead>
<tr>
<th>Source</th>
<th>Place</th>
<th>Period/Condition</th>
<th>Sediment deposition&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average deposition rates (mm/year)</th>
<th>Volume (10&lt;sup&gt;6&lt;/sup&gt; m&lt;sup&gt;3&lt;/sup&gt;/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiang et al., 2002</td>
<td>Poyang Lake</td>
<td>1960–1990</td>
<td></td>
<td>2.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Dai et al., 2005</td>
<td>Poyang Lake</td>
<td>1956–2003</td>
<td></td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>de Leeuw et al., 2009</td>
<td>Poyang Lake</td>
<td>After TGD (2003–)</td>
<td></td>
<td>2.5</td>
<td>10.3</td>
</tr>
<tr>
<td>de Leeuw et al., 2009</td>
<td>Junction channel</td>
<td>Intensive dredging (2003–)</td>
<td></td>
<td>-590.0</td>
<td>-236.0</td>
</tr>
<tr>
<td>de Leeuw et al., 2009</td>
<td>Poyang Lake</td>
<td>Diversion towards lakes (2003–)</td>
<td></td>
<td>-50.2</td>
<td>-200.8</td>
</tr>
<tr>
<td>Dai et al., 2005</td>
<td>Chenglingji - Hukou</td>
<td>1956–2003</td>
<td></td>
<td></td>
<td>36.1</td>
</tr>
<tr>
<td>Chen et al., 2008</td>
<td>Yichang - Datong</td>
<td>1953–2000</td>
<td></td>
<td></td>
<td>115.6</td>
</tr>
<tr>
<td>Xu and Milliman, 2009</td>
<td>Yichang - Datong</td>
<td>1950–2000</td>
<td></td>
<td></td>
<td>48.0</td>
</tr>
<tr>
<td>Chen et al., 2008</td>
<td>Yichang - Datong</td>
<td>2003–2005</td>
<td></td>
<td></td>
<td>-99.1</td>
</tr>
<tr>
<td>Xu and Milliman, 2009</td>
<td>Yichang - Datong</td>
<td>2001–2006</td>
<td></td>
<td></td>
<td>-50.0</td>
</tr>
<tr>
<td>Li et al., 2004</td>
<td>Wuhan - Jiujiang</td>
<td>22 years after TGD</td>
<td></td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>Li et al., 2004</td>
<td>Jiujiang - Hukou</td>
<td>22 years after TGD</td>
<td></td>
<td></td>
<td>70.4</td>
</tr>
<tr>
<td>Li et al., 2004</td>
<td>Hukou - Datong</td>
<td>22 years after TGD</td>
<td></td>
<td></td>
<td>47.7</td>
</tr>
<tr>
<td>Yang et al., 2006</td>
<td>Below Yichang</td>
<td>2010–2030</td>
<td></td>
<td></td>
<td>-83.0</td>
</tr>
<tr>
<td>Yang et al., 2006</td>
<td>Below Yichang</td>
<td>2030–2060</td>
<td></td>
<td></td>
<td>-44.0</td>
</tr>
<tr>
<td>Yang et al., 2006</td>
<td>Below Yichang</td>
<td>2060–2110</td>
<td></td>
<td></td>
<td>14.0</td>
</tr>
</tbody>
</table>

<sup>a</sup>Positive values represent accumulation, and negative values represent erosion.
4.3.4 Effect of Irrigation and Reclamation on Ecosystem Change in Continental Scale

After the verification procedure (Nakayama, 2011b; Nakayama and Watanabe, 2008b), the model simulated the effect of irrigation on evapotranspiration for each crop in the Changjiang and Yellow River Basins, as in the author’s previous research (Nakayama, 2012c). Irrigation during the winter-wheat growing period causes a greater increase in evapotranspiration than that during the summer-maize growing period in the rotation between winter wheat and summer maize in the downstream of Yellow River because more water is withdrawn during the winter-wheat period, due to the small amount of rainfall in the north. In particular, most of the irrigation water is withdrawn from aquifers in the NCP because of the extremely limited amount of surface water (Nakayama, 2011b; Nakayama et al., 2006). In the south, water for irrigation is usually extracted from the river to fill the paddy fields to a ponding water depth (Nakayama and Watanabe, 2008b; Nakayama and Shankman, 2013), which causes a greater increase in evapotranspiration during the drier season. Based on the previous research mentioned above, the model also simulated both the confined and unconfined groundwater levels in both the Changjiang and Yellow River basins. The unconfined level decreases rapidly around the source area and on the Qinghai Tibet Plateau (Fig. 4.7a), which feeds many sources of spring water in these regions. The model also shows a very low value in the downstream area, attributed not only to overexploitation but to the low elevation (Fig. 4.7b), particularly on the NCP (Nakayama, 2011a-b; Nakayama et al., 2006). This result indicates that the hydrologic cycle, including the groundwater level, is not only highly related to the topography but also to the use of irrigation water.
Fig. 4.7  Impact of irrigation on hydrologic change on a continental scale: (a) simulated results of annual-averaged unconfined groundwater level (a.s.l.) in the Changjiang and Yellow River Basins; (b) topographical contour calculated using GTOPO30. In Fig. 4.7a and 4.7b, the black square represents the border of the simulation area in Albers co-ordinates, in the same way as that in Fig. 4.1.
Chapter 4  Relation between Uneven Water Resources, Withdrawal, and Ecosystem Degradation in the Changjiang and Yellow River Basins

The mean TINDVI gradients from 1982 to 1999 in various field crops (wheat, maize, and rice), at four stations, were compared with the trends of crop yields in the previous research of Tao et al. (2006) (reprint from Nakayama, 2012c) (Fig. 4.8a). The correlation of both values is relatively good \( (r^2 = 0.986) \) and the TINDVI gradient has a linear relation to the yield trend. The spatial pattern of the mean TINDVI gradient in agricultural fields shows a generally increasing tendency, particularly in the downstream area of the Yellow River and on the NCP (Fig. 4.8b), which is closely related to factors such as: the increasing tendency of winter-wheat production downstream (USDA, 1994); the increase in irrigation water use (Yang et al., 2004a) and chemical fertilizer; changes in crop varieties; improvements in technology such as agricultural machines; and other agronomic changes. However, it shows a generally decreasing tendency, particularly in the mid-lower reaches and around the lakes in the Changjiang River. This is mainly attributed to an increase in lake reclamation, levee construction, and the resultant relative decrease in rice productivity in the lower reaches (USDA, 1994; Shankman and Liang, 2003; Zhao et al., 2005; Nakayama and Watanabe, 2008b). The decrease in the TINDVI gradient near the Bohai Sea, the East China Sea, and the Taihang Mountains is due to several effects, including that of groundwater degradation, seawater intrusion, and rapid urbanization in the areas surrounding bigger cities (Brown and Halweil, 1998). Generally, these results suggest that an increase in irrigation water use is one of the reasons for the increase in crop production (Yang et al., 2004a).

Fig. 4.8  TINDVI over the agricultural fields by NOAA/AVHRR satellite images in the agricultural fields: (a) Comparison of TINDVI with trend in observed yields at 4 stations (Pt.I: Changsha, Pt.II: Hefei, Pt.III: Zhengzhou, Pt.IV: Tianshui); (b) Spatial patterns in mean TINDVI gradient (per year) during 1982-1999. In Fig. 4.8b, the black square line represents the border of the simulation area in Albers co-ordinates in the same way as in Fig. 4.1.
4.4 Conclusion

In this chapter the process-based NICE model was coupled with complex sub-systems in irrigation, stream junction, reservoir operation, and water transfer, to evaluate the cause and effect of uneven water resources in the entire Changjiang and Yellow River Basins. The model included different growth processes of representative crops (wheat, maize, soybean, and rice), and predicted the hydrologic change after operation of the TGD and the SNWTP, to estimate whether critical issues related to water stress, crop productivity, and ecosystem degradation would diminish in the basins. Of considerable importance is that NICE highlighted the missing roles of surface water-groundwater interactions and lateral subsurface flow, which have usually not been considered as important when assuming stationarity in previous research on a continental scale. Furthermore, the heterogeneous pattern of the TINDVI gradient in agricultural fields helped to estimate an uneven crop yield and its relation to water availability. This integrated approach will assist in any re-consideration of the complex environmental processes within the region from the view point of hydrologic and biogeochemical cycles, and will also help to clarify how the substantial pressures of complicated problems can be overcome by effective trans-boundary solutions.

References

Chapter 4  Relation between Uneven Water Resources, Withdrawal, and Ecosystem Degradation in the Changjiang and Yellow River Basins


Abstract
The hydro-climate differs vastly between northern and southern China, and this led to an imbalance in environmental resources related to an increased demand for food and declining water availability. The Three Gorges Dam (TGD) was designed to diminish flooding and the South-to-North Water Transfer Project (SNWTP) has been planned to enable the transfer of water from the Changjiang River basin to the Yellow and Hai Rivers. However, these projects will not necessarily solve all problems associated with water availability within the basins, and there is an urgent need for the development of a sophisticated eco-hydrological model to evaluate the optimum amount of transferred water, and the socio-economic and environmental consequences from such endeavors/projects.

In this chapter, a process-based National Integrated Catchment-based Eco-hydrology (NICE) model was modified and coupled with complex irrigation, stream junction, reservoir operation, and water transfer subsystems, for the development of a coupled human and natural systems model, and to evaluate the causes and effects of uneven water resources. The model clarified the impact of irrigation on eco-hydrological processes, and predicted the hydrologic change after operation of the TGD and SNWTP, to estimate whether there would be a reduction in problems associated with water stress, crop productivity, and ecosystem degradation. The result also revealed the missing roles of surface water-groundwater interactions and lateral subsurface flow, previously considered to be not as important in previous studies that assumed stationarity on continental scales. The heterogeneous pattern of the Time-Integrated Normalized Difference Vegetation Index (TINDVI) gradient in agricultural fields helped to estimate uneven crop yield and its relation to water availability. This integrated approach not only has a role in reconsidering these complex processes from the viewpoint of the hydrologic and biogeochemical cycles, but also to clarify how substantial pressures from complex issues can be overcome by effective trans-boundary solutions.

Keywords: crop yield, eco-hydrology model, extremes, TINDVI, water withdrawal
Chapter 5

Final Conclusions and Future Work
5.1 Final Conclusions

In a previous work the author developed the National Integrated Catchment-based Eco-hydrology (NICE) model, which is a 3-D, grid-based eco-hydrology model that includes interactions between surface water, canopies, unsaturated water, aquifers, lakes, and rivers (Nakayama, 2008a-c, 2009a, 2010a, 2011a-d, 2012a-d, 2013a; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a-b; Nakayama and Watanabe, 2004, 2006a-b, 2008a-c; Nakayama et al., 2006, 2007, 2010, 2012) (Fig. 1.2). In this monograph (Part IV), NICE was enhanced to couple human and natural systems and to evaluate the impact of anthropogenic activity on eco-hydrologic change and the response of river-lake-groundwater interactions in the extremes of the Changjiang and Yellow River basins, in order to assist with decision-making processes for the Three-Gorges Dam (TGD) and the South-to-North Water Transfer Project (SNWTP).

In Chapter 2, NICE was coupled with more complex components such as irrigation, urban water use, and dam/canal systems, in order to simulate the effects of irrigation on the hydrologic cycle in the highly cultivated Yellow River basin (NICE-DRY). The model clarified the relationship between the drying of rivers, groundwater degradation, seawater intrusion, and ecosystem degradation. Scenario analyses of the impact of human intervention on hydrologic changes imply the need for further correct estimation and appropriate measures against such irrigation (Nakayama, 2011a-b; Nakayama et al., 2006, 2010).

In Chapter 3, the NICE model was coupled to the lake and junction models (NICE-FLD) in order to evaluate the river-lake-groundwater relationship and the role of the flood storage capability around lakes in the Changjiang River basin. The model highlighted the missing role of surface water-groundwater interactions and lateral subsurface flow, which have not usually been considered to be so important when assuming stationarity in previous research on continental scales. Furthermore, the model predicted hydrologic change by recovering the volume of lake water to that of the 1950s, and by inputting meteorological data of the 1998 severe flood, in order to evaluate the role of flood storage capability in lakes in relation to water/heat budgets (Nakayama and Shankman, 2013a; Nakayama and Watanabe, 2008b).

In Chapter 4, the NICE model was coupled with complex sub-systems in irrigation, stream junction, reservoir operation, and water transfer, to evaluate the cause and effect of the uneven water resources in both the Changjiang and the Yellow River basins. The model predicted hydrologic change after operation of the TGD and SNWTP, to estimate whether critical issues involving water stress, crop productivity, and ecosystem degradation would diminish in the basins. Furthermore, the heterogeneous pattern of the TINDVI gradient in agricultural fields helped to estimate an uneven crop yield and its relation to water availability (Nakayama, 2012c; Nakayama and Shankman, 2013b).

These above results are crucial for clarifying the effect of human activity on ecosystem degradation caused by water-heat-mass cycle changes on a continental scale. This integrated approach will have assist in any re-consideration that is made of the complex environmental processes from the view point of hydrologic and biogeochemical cycles, and also to clarify how the substantial pressures from complex problems can be overcome by effective trans-boundary solutions.
5.2 Future Work

This monograph indicates that an effective management of water resources is powerful in environmental decision-making and adaptation strategies. The result also strongly suggests the need for trans-boundary and -authority solutions to ensure sustainable development under sound socio-economic conditions in order to contribute to national and global securities.

The author has also so far researched the mutual interaction and feedback of hydro-geomorphology and vegetation dynamics in an ecosystem to further explain the positive feedback between geomorphology and eco-hydrology on irregular slopes and in heterogeneous vegetation (Nakayama, 2008a-b, 2012b, 2013a). After improving this process-based NICE model to include new feedback and down-scaling processes from a regional to a local simulation with finer resolution, the author then attempted to extract the impact of hydrologic change, sedimentation, and nutrient availability, on the complex pattern of alder invasion, and vice versa (Fig. 5.1). The model also predicted the effectiveness of river restoration in conservation plans for the recovery of a native ecosystem, which showed the importance of the process-based model in assessing these ecosystem dynamics. The author further attempted to re-evaluate the ecosystem by extending it with the metabolic theory of ecology (Brown et al., 2004) from the perspective of a meta-ecosystem, by considering the multi-scaled aspects between global-regional-micro (genetic) levels. In addition, the author assessed the impact of water-heat-material cycle changes attributed to human activities on the ecosystem function, and the limiting factors which are accompanied by changes in ecosystem function (Fig. 5.2).

![Diagram of NICE model](image)

**Fig. 5.1** Down-scaling and feedback process in the extension of NICE.
Fig. 5.2  Up-scaling and down-scaling in terrestrial/aquatic ecosystems.
Previous research has suggested that variations and uncertainties in the biogeochemical cycle in terrestrial ecosystems are relatively larger than those in the atmosphere and ocean, and that the terrestrial biosphere sequesters most of the available carbon (Cole et al., 2007). Recently, however, studies have started to reconsider the importance of inland waters including rivers, lakes, and groundwater (Cole et al., 2007; Battin et al., 2009). In particular, inland waters may play a role in the transport, mineralization, and sequestration of carbon, the process of which is complicated by surface-groundwater interactions around wetland and riparian areas; water movement in these areas drives carbon storage and flux.

NICE has so far been based on the rectangular coordinate system of the Albers projection (WGS 1984) or UTM projection, on scales of 1 km-1,000 km. When the model is applied to broader scales, an error increases at the corner of the projection and at the polar zone, and it is necessary to include the curvature of the earth and any distortion through map projection (Fig. 5.3). NICE is therefore now expanding to include an up-scaling process through transformation of the coordinate system from rectangular to longitude-latitude, which is applicable on global scale by the application of a map factor and non-uniform grid. The further improved simulation system will play an important role in the evaluation of spatio-temporal hot spots on a regional scale (Frei et al., 2012), and of boundless biogeochemical cycles on a global scale (Cole et al., 2007; Battin et al., 2009) (Fig. 5.4). Assimilation of NICE with image analysis including remote sensing, satellite data, and aerial images, will be based on quantification through spatio-temporally high-resolution imaging. In addition, the identification of hot spots within hydrological and biogeochemical cycles through a down-scaling process needs to be achieved through assimilation with ground-truth networking systems. This system will also help to contribute to an improvement of the tipping-point early warning system for sustainable development under the constraint of global security and environmental degradation.

The author intends to report this research in a succeeding monograph (Part V) in the near future.

![Fig. 5.3 Coordinate transformation for up-scaling of terrestrial/aquatic ecosystems.](image)
Fig. 5.4 NICE coupled with a biogeochemical model for evaluation of the boundless biogeochemical cycle.

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Appendix

Publications and Presentations
Publications and Presentations

Original Papers and Reviews:


Books:

Conference Reports:


Nakayama, T. (2012) Toward early-warning integrated system by meta-ecosystem analysis in mire, session number S49.10, Eco Summit 2012, Columbus, Ohio, USA, 30 September – 5 October.

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