Impact of water degradation on ecosystem change and adaptation strategy for sustainable development

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Abstract

Environmental pollution is becoming intertwined with degradations of water environment, imbalance of the hydrologic cycle, thermal environment, and contamination. Water stress has intensified water use conflicts between upstream and downstream and between agriculture and municipal/industrial sectors. Here, the process-based National Integrated Catchment-based Eco-hydrology (NICE) model, which includes interactions between surface water, canopy, unsaturated water, aquifer, lake, and rivers, was applied to develop coupled human and natural systems and to assess the impact of water degradation on ecosystem change. Combinations of a numerical model, satellite image, and statistical analysis showed close relationship between water resource and economic growth, which has greatly affected ecosystem degradation and its serious burden on the environment. The author also presented a procedure to visualize the missing role of hydrothermal interactions in atmospheric, land and water areas, which would be effective to recover the sound hydrologic cycle and to create thermally-pleasing environments in an eco-conscious society. The procedure to construct an integrated assessment system for win-win solution would support decision-making on sustainable development and adaptation to climate change and urbanization in global scale.
Keywords: eco-hydrology model, economic growth, ecosystem degradation, hydrologic change, integrated assessment system, sustainable development, visualization, water stress, win-win solution.

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1 Introduction

Human activity has dramatically changed ecosystem dynamics in East Asia. In particular, the change from rural or wilderness to urban or agricultural uses has greatly affected the surrounding ecosystems in the catchments. Environmental pollution is recently becoming intertwined with degradations of water environment, thermal environment, and contamination in urban areas.

In China, hydro-climate is diverse between north and south (Fig. 1) [1–3]. The North China Plain (NCP) is located in the downstream of Yellow River with a semi-arid climate, and has suffered serious water deficit problems due to the fact that it is one of the most important grain cropping areas in China [4–7]. Furthermore, it includes some vast metropolitan areas such as Beijing and Tianjin. This water stress has intensified water use conflicts between the upstream and downstream areas and also between agriculture and municipal/industrial sectors. This region has changed from a water-rich one in the 1950s to a water-poor one currently, reflecting various ecosystem degradations such as the drying-out of the Yellow River, the near closure of the Hai River, and groundwater degradation in the NCP [1, 2, 7, 8]. This has led to the occurrence of large depression cones and land subsidence in urban areas, and the expansion of the area of saline-alkaline land due to seawater intrusion in the coastal zone [1, 4–6]. Some researchers stated that China's environmental pressure already exceeds its carrying capacity of this densely populated land [9].

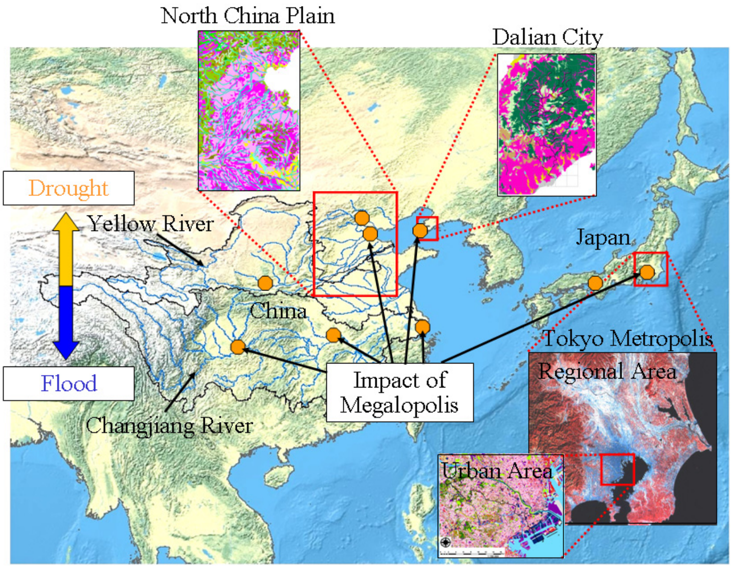


Figure 1: Intertwined environmental pollution in East Asia.

Because Dalian is located at the southern tip of the Liaodong Peninsula, it has inherently little fresh water supply. Most of the city's water necessary for its fast economic growth is drawn at a great distance from there, the Biliu Reservoir at the middle of the river. Since the completion of the dam in 1984, most of the water has been piped to Dalian, and the catchment has changed from water-rich to water-poor, as evidenced by drying out of the downstream river, groundwater fall, and seawater intrusion, all seen in other regions at northern China [2, 7, 10].

On the other hand, urban heat island has become a serious environmental problem with the expansion of cities and industrial areas in the world [11]. The Japanese governments have taken various measures to mitigate this problem in Tokyo Metropolis (Fig. 1) by rearranging surface layer, reconstructing elderly buildings and urban geometry, applying green-infrastructure system, increasing energy efficiency, and managing traffic/transportation system. Promotion of vaporization by using water-holding pavements would be effective as strategies to mitigate the heat island in combination with use of light-coloured surfaces and vegetated surfaces [12, 13]. Because this heat relaxation in newly symbiotic pavement is closely related to the heat capacity of water and the conductivity of the pavement, it is estimated that groundwater use in almost constant temperature as a heat sink would be very effective for tackling the heat island [14]. On the other hand, the metropolitan area has been troubled with serious damage by an imbalance of hydrologic cycle, for example, flooding and buoyant forces to underground infrastructures after the regulation of groundwater use [15, 16]. Water and thermal pollutions in water area is also becoming serious every year. Nowadays, roles of water resources such as river, lake, sea, and groundwater are thought important for the mitigation of the urban heat island. Watersides are becoming precious as an urban cool-island in addition to open parks and green areas [14]. A policy to promote infiltration into the aquifer is also important to prevent ground degradation as has occurred in the past [16, 17].

The objective of this study is to present a method of combination between numerical model, satellite image, and statistical analysis in order to clarify close relationship between water resource and economic growth, which has greatly affected ecosystem degradation and its serious burden on the environment. The process-based model includes complex sub-systems to simulate hydrological change resulting from human intervention such as drying up of the rivers and groundwater degradation, to evaluate the linkage between urban development and sustainable water resource management in the catchment, and to simulate the effect of urban geometry and anthropogenic exhaustion on the change of water and heat cycles in the megalopolis. The author also presented procedure to visualize intertwined environmental pollution such as missing role of hydrothermal interactions in atmospheric, land and water areas. This procedure to construct integrated assessment system for win-win solution would help to reveal ways of solving the complex nature of the water problems and support decision-making on sustainable development.

2 Methods

2.1 Developing process-based model applicable to urban area

Previously, 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 the variations in phenology based on satellite data [1–3, 7, 13, 16–26] (Fig. 2). NICE has been coupled with complex sub-systems in irrigation, urban water use, stream junction, and dam/canal, in order to develop coupled human and natural systems and to analyze impact of anthropogenic activity on eco-hydrologic change. The unsaturated layer divides canopy into two layers, and soil into three layers in the vertical dimension in the SiB2 (Simple Biosphere model 2) [27]. About the saturated layer, NICE solves three-dimensional groundwater flow for both unconfined and confined aquifers. The hillslope hydrology can be expressed by the two-layer surface run-off model including freezing/thawing processes. NICE connects each sub-model by considering water/heat fluxes: gradient of hydraulic potentials between the deepest unsaturated layer and the groundwater, effective precipitation, and seepage between river and groundwater.

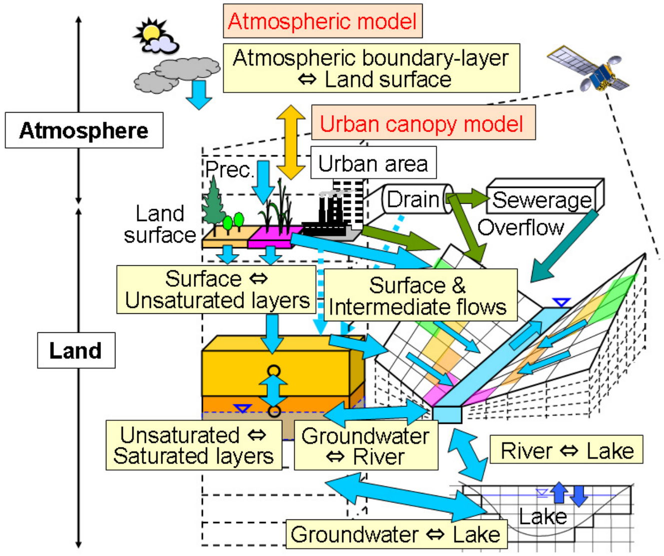


Figure 2: National integrated catchment-based eco-hydrology (NICE) model.

In an agricultural field, NICE is coupled with DSSAT (Decision Support Systems for Agro-technology Transfer) [28], in which automatic irrigation mode supplies crop water requirement for cultivated fields [1, 2, 7] and for paddy fields [3]. The model includes different functions of representative crops (wheat, maize, soybean, and rice, etc.) and simulates automatically dynamic growth processes. Plant growth is based on biomass formulation, which is limited by various reduction factors like light, temperature, water, and nutrient, etc. [1–3, 7]. Most of this water is transferred through many dams (reservoirs) and canals to main cities and cultivated fields of the NCP and the Dalian (Fig. 1). Because there are few available data about discharge control at most of these dams, the constant ratio of inflow to outflow was used at the major dams where there are no available data, which is simpler than the storage–runoff function model [1].

NICE was also coupled with the UCM (urban canopy model) to include the effect of hydrothermal cycle at various pavements, and with the RAMS (Regional Atmospheric Modeling System) [29] to include the hydrothermal interaction in the urban area [13, 17, 26]. Downward short- and long-wave radiation, precipitation, atmospheric pressure, air temperature, air humidity, and wind speed simulated by the atmospheric model are input into the UCM, whereas momentum, sensible, latent, and long-wave flux simulated by the UCM are input into the atmospheric model at each time step. This procedure means that the feedback process about water and heat transfers between atmospheric region and land surface are implicitly included in the simulation process.

2.2 Model input data and statistical analysis of decoupling indicator

Six-hour re-analyzed data were input into the model after interpolation of ECMWF (European Centre for Medium-Range Weather Forecasts) in 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 meteorological stations were used to correct the ECMWF value [1, 25]. For a multi-scaled model in the Tokyo area, hourly observation data from AMeDAS (Automated Meteorological Data Acquisition System) data [30] were assimilated with the model. At the lateral boundaries of regional area, some meteorological data are input to the model from the ECMWF (European Centre for Medium-Range Weather Forecasts) with a resolution of 1°x 1° and from the MSM (Meso Scale Model) with a resolution of 10km x 10km [31]. Mean elevation was calculated by using a global digital elevation model (DEM; GTOPO30) [32]. Digital land cover data were categorized such as forests, grasses, bushes, shrubs, paddy fields, and cultivated fields. About 50 vegetation and soil parameters were calculated on the basis of vegetation class and soil maps [33, 34]. The 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 [16, 35] and core-sampling data. Artificial augmentation of waterworks and sewerage systems, and anthropogenic sensible, latent, and sewage heats generated by buildings and factories were input into the model [16, 17, 26].

The OECD developed procedures to decouple environmental pressures from economic growth [36]. Decoupling can be either absolute or relative. Absolute decoupling occurs when the environmental variable is stable or decreasing while the economic driving force is growing. Relative decoupling occurs when the environmental variable is growing, but not as quickly as the economic variable. A decoupling indicator is calculated from the ratio of the pressure to the driving force at the end to the value at the start of a given time period. In this study, the decoupling indicator procedure was applied to identify impacts of driving force like social activities and its pressure like water consumption and economic growth on the environment in urban area. There are various indicators of driving force, such as population, standard of living, and urbanization, in addition to the GDP. The main objective of this study is to evaluate the linkage between urban development, water resource management, and environmental degradation. Because the study area such as Dalian is a highly industrialized city in China, it is preferable to use the GDP as a typical driving force as a first step. In an analysis of the impact of water abstraction from the Biliu River on the environmental degradation in the catchment, the pressure is the NDVI as an index of environmental degradation and the driving force is water supply from the Biliu River. Details are described in [25].

2.3 Boundary conditions and running the simulation

At the upstream boundaries, reflecting condition on hydraulic head was used assuming that there is no inflow from the mountains in the opposite direction [18]. Time-series of tidal level was input as a variable head at the sea boundary [1, 7, 16, 25]. Vertical geological structures were divided into 10–20 layers with a weighting factor of 1.1 (finer at the upper layers) by using sample database. The hydraulic head values parallel to the ground level were input as the initial conditions. In river grids decided by digital river network, inflows or outflows from the riverbeds were simulated at each time step depending on the difference in the hydraulic heads of groundwater and river.

The simulation area is 530 km wide by 840 km long in the NCP, and 60 km wide by 110 km long in the Dalian [1, 7, 25] (Fig. 1). In the Tokyo area, the simulation was conducted with multi-scaled levels in horizontally regional area (260 km wide by 260 km long with a grid spacing of 2 km covering Kanto region) nesting with one way to urban area (36 km wide by 26 km long with 200 m grid covering the Kawasaki City) [16, 17, 26]. These areas were discretized with a grid spacing of 200 m–5 km in the horizontal direction. The NICE simulation was conducted on a NEC SX-8 supercomputer. The first 6 months were used as a warm-up period until equilibrium water levels were reached, and parameters were estimated by a comparison of simulated steady-state value with that published in previous literatures. A time step of the simulation was changed from Δt = 1.5 sec to 1 h depending on spatial scale and the sub-model. Simulations were validated against various hydrothermal observed variables such as river discharge, soil moisture, groundwater level, air temperature, surface temperature, and heat-flux budget, etc.

3 Result and discussion

3.1 Water resources degradation due to human intervention

NICE simulates the change in the groundwater level over the previous half century in the NCP (Fig. 3). The model reproduced excellently the observed groundwater levels [5] during the same period and showed that the water table has decreased year by year, because the simulation includes the process of irrigation, industry, and domestic water uses. In particular, the model reproduces better cone depressions around the bigger cities (Cangzhou, Hengshui, Baoding, etc.) owing to excessive groundwater use in the urban area [1, 7]. Hydraulic gradients are steeper around the Taihang and Yanshan Mountains, and are relatively flat in the plain area. Because the groundwater level is higher in the mountainous areas, groundwater constantly flows into the plain, and the mountainous area plays an important role as a recharge region. Generally, the groundwater level is drawn down from March to June–July mainly as a result of winter wheat production, and then starts to recover as the rainy season starts. The simulated groundwater levels reproduce actual levels very accurately in both the mountainous and plain areas.

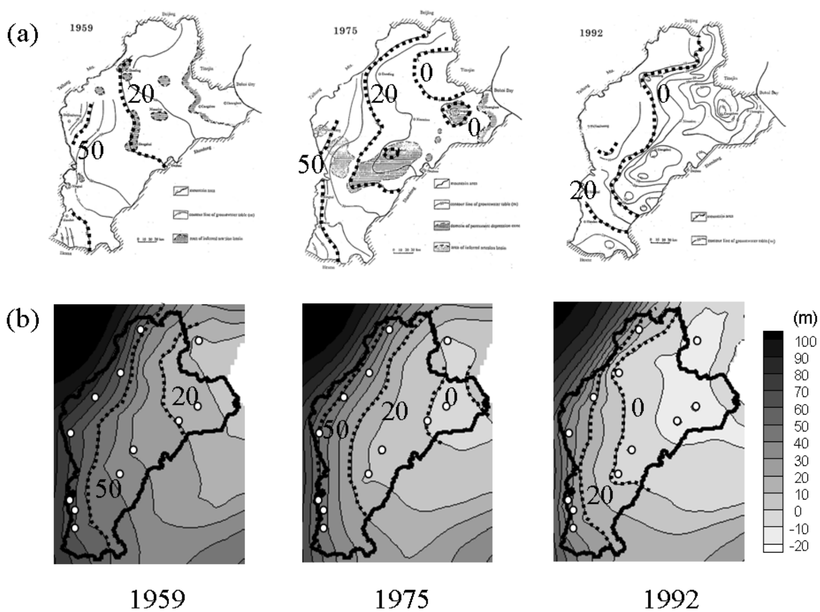
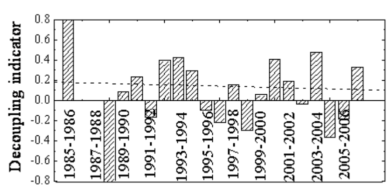


Figure 3: Groundwater degradation in the NCP from 1959 to 1992. (a) observed value [5], and (b) simulated result with irrigation and urban water uses. Dotted lines show the groundwater levels 0 m, 20 m, and 50 m above sea level. In the Fig.3b, circles show the main cities with predominant water use.

3.2 Vegetation degradation affected by economic growth

The economy has grown faster than water consumption in the Dalian city, which shows a pronounced relative decoupling between economic growth and environmental pressure in Dalian during 1992–2007 [25] (Fig. 4). The consumption of water derived from the Biliu River shows a relative decoupling from the GDP of the urban area of Dalian (Fig. 4a). The decoupling indicator values declined, were unstable, and were negative twice in 8 years (1998–1999 and 2004–2005), although the Dalian government has increased the water price several times to control water consumption. The value dropped from 0.43 in 1993–1994 to –0.37 in 1998–1999, became positive at 0.33 again in 2003–2004, and then declined again. These trends show that the environmental pressure of water consumption has increased with economic growth in the urban area, although relative decoupling predominated, especially when the decoupling indicator value was negative. The impact of water withdrawal from the Biliu Reservoir on environmental degradation of NDVI downstream is shown in Fig. 4c. The decoupling indicator value gradually decreased from 0.75 (relative decoupling) in 1988–1989 to –0.25 (no decoupling) in 2006–2007 although the periods of 1985-1988 take irregular values due to the start of dam operation and incorrect data. This shows increasing environmental degradation with increasing abstraction of water from the Biliu River. These results indicate that the environmental degradation in the Biliu River catchment will grow more serious with economic growth in the coming years.

(a)



(b)

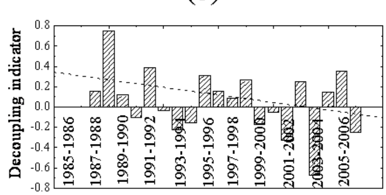


Figure 4: Annual trends of decoupling indicators between; (a) water consumption and GDP in the urban area of Dalian city, and (b) NDVI and water consumption. Dashed-lines are least-square regression lines estimated from annual decoupling indicators (bars).

3.3 Effective management of water resources to reduce urban heat island

The author predicted the hydrothermal changes in the symbiotic urban scenarios (Fig. 5) [17, 26]. The predicted surface temperature on the scenario of water-holding pavement shows a drastic decrease in the entire Kawasaki City (Fig. 5b). In particular, the business district beside the sea, where the urban heat island is predominant mainly due to the paved surface and the greater anthropogenic heat sources, has an effective cooling on this scenario. The predicted groundwater level change in August is interesting in contrast to the simulated temperature (Fig. 5c). In the simulation on the scenario of water-holding pavement, all the necessary water to fill the water-holding pavement was automatically simulated by considering the difference between precipitation and evaporation, and withdrawn from the underneath groundwater in the NICE, which means that the pavement was always saturated. The groundwater level would decrease drastically at the commercial and industrial areas beside the sea and at the inland residential area, in exchange for a drastic cooling in the corresponding and the surrounding areas. The increase in recharge rate and the consequent increase in groundwater level on the scenario of a natural zone and green area are also effective to promote the groundwater resources in the urban area covered by impermeable pavement [16, 26]. The predicted temperature and groundwater

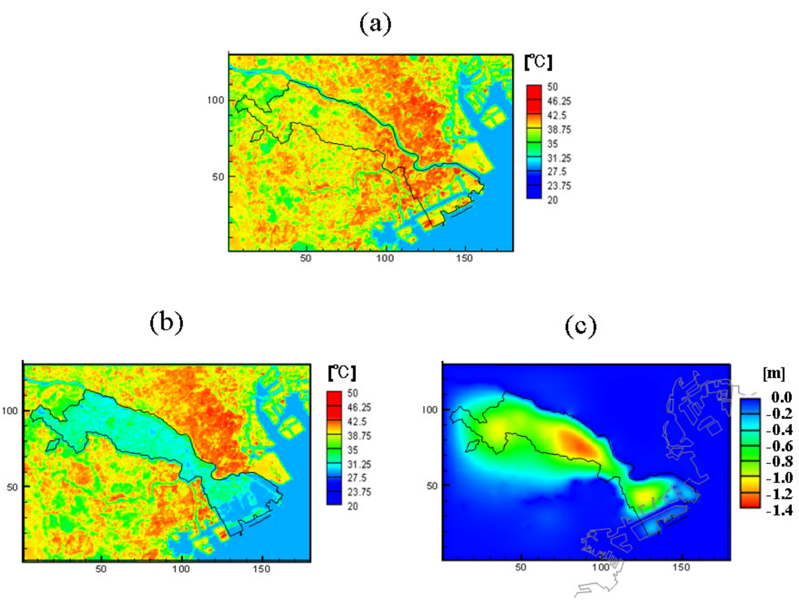


Figure 5: Prediction of hydrothermal changes at 5 August 2006; (a) present surface temperature, (b-c) predictions of surface temperature and groundwater level change after water-holding pavement.

level are greatly affected not only at the business district in the Kawasaki area but also at the Tokyo metropolitan area in the northern side of this study area. This result is very important from the political point of view, which indicates that we have to estimate more precisely the arrangement of symbiotic urban scenario in the study area together with the neighbouring administrations.

4 Conclusions and future works

An integrated approach, including process-based model (Fig. 2) in this study showed close relationship between water resource, economic growth, and ecosystem degradation in the environment. Though water resources are vital for human activity, its overexploitation causes the serious hydrologic change such as drying out river, groundwater fall, and seawater intrusion, etc. (Fig. 3). It also causes various ecosystem degradations and serious burden on the environment (Fig. 4). However, effective management of water resource is also powerful for decision-making and adaptation strategy for sustainable development. This paper indicated a possibility to recover sound hydrologic cycle and to create thermally-pleasing environments simultaneously (Fig. 5). These results indicate effective management of water resource is powerful for achieving win-win solution about hydrothermal pollutions in eco-conscious society.

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