Research framework of integrated simulation on bilateral interaction between water cycle and socio-economic development

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Abstract. The mechanism of bilateral interaction between natural water cycle evolution and socio-economic development has been obscured in current research due to the complexity of the hydrological process and the socio-economic system. The coupling of economic model CGE (Computable General Equilibrium) and distributed hydrological model WEP (Water and Energy transfer Processes) provides a model-based tool for research on response and feedback of water cycle and social development, as well as economic prospects under the constraint of water resources. On one hand, water policies, such as water use limitation and water price adjustment under different levels of socio-economic development, are to be evaluated by CGE model as assumed conditions and corresponding results of water demand could be put into WEP model to simulate corresponding response during the whole process of water cycle. On the other hand, variation of available water resources quantity under different scenarios simulated by WEP model may provide proper limitation for water demand in CGE model, and corresponding change of economic factors could indicate the influence of water resources constraints on socio-economic development. The research is believed to be helpful for better understanding of bilateral interaction between water and society.

1. Introduction

The mechanism and characteristics of the water cycle has been one of the most essential problems in the field of hydrological research. With rapid socio-economic development, the evolution of the water cycle is becoming increasingly complex due to ever expanding human activities. Solar radiation and gravity are primary driving forces for a natural water system with little human influence, but it has been disturbed to a large extent by water supply and drainage. Dualistic characteristics of hydrological processes have attracted more and more attention in water resources research. Hydrological interactions between human society and the nature system are considered to be the key issue of water resources assessment and management under the changing environment especially for countries facing water scarcity [1].

In view of the high impacts of socio-economic water use on the natural water cycle, hydrological researchers turn to integrated simulation of natural hydrological processes and water-using processes. The theory of dualistic water cycles was proposed and distributed hydrological model developed on the basis of a natural-artificial water cycle [2]. However, the quantity and process of water demand is not yet well regarded by the current dualistic hydrological model in which water use is considered simply by sectoral quotas and total quantity control. The mechanism of bilateral interaction between natural water cycle evolution and socio-economic development has not been clearly illuminated due to complexity of the hydrological process and the socio-economic system. As a fact of vital relation between water consumption and socio-economic development, elements of water and socio-economic system should be taken into consideration, including water resources distribution and industrial structure.

2. Methodology

To discover the coordinated variation of water demand to socio-economic development, the CGE (Computable General Equilibrium) model is recommended, which is able to explain every aspect of the socio-economic system and provide the quantity and the price of all factors in the market, such as labor, land and capital, by quantitative description of the input-output relationship among each account in SAM (Social Accounting Matrix) on the basis of Walras general equilibrium theory [3]. Water resources as one of those factors could also be appropriately considered. Regional water demand of each sector and effects of water resources constraint could be predicted. Meanwhile, WEP model, short for Water and Energy transfer Processes, can well reflect the change of runoff and convergence under different conditions of land surface and water use by simulation of the whole water cycle process based on physical mechanism, in which the spatial varieties inside specific region are fully considered, such as hydrological processes, input variables, boundary conditions and geometric basin characteristics. The quantity of available water resources and corresponding hydrological processes driven by natural factors and human activities play an intermediate role in the connection of human society and the water system. The integration of the economic model CGE and the distributed hydrological model WEP as a model-based tool would be helpful for better understandings on interactive relationships between hydrological evolution and socio-economic development [4], by quantitative analysis of the water consumption and hydrological process variations under preset scenarios.

2.1. Economic model CGE

The CGE model originated in Walras' general equilibrium theory for research on complicated causality in socio-economic system, and has been widely used in policy analysis [5-9]. Different sectors, commodities and production factors are involved in the CGE model. It describes intricate interdependence of production activities and trading behaviors through simultaneous mathematical equations defining the behavior of the different actors. The CGE model is able to indicate the direct and indirect impacts of different sectoral policies in the socio-economic system with chain reactions under various disturbances, by providing the quantity and the price of all factors in the market by numerical simulation of the input-output relationship among each account in the social accounting matrix. It follows the SAM disaggregation for comprehensive actions in socio-economic system. Production activities in CGE are examined according to profits maximization. Consumption behaviors are decided on the basis of utility maximization. There are several essential constraints for overall systems to be satisfied in the model. The modelling approaches and functions in the CGE model are referred to in [3].

Environment and resources can be incorporated into the model to reflect corresponding responses of economic factors, as a result of preset decisions on resource allocation principle and income distribution mechanism, considering the balancing requirement and feedback system of environment, resources and economic activities [10]. For the research of economic impacts of water policy and water constraint under various situations, the key problem is how to embody water resources in the model to realize the dynamic estimation of water supply and demand. There are two major types of methods incorporating water resources into the traditional CGE model. One is to build relationships between water resources and correlative accounts that already exist in SAM structure by subdivision of those accounts according to the diverse characteristics associated with water supply and demand. Functional expressions and new equations are usually added and relationships between water use and economic departments are defined in terms of input and output benefits, which is easy to be achieved particularly for the circumstance lack of enough data required by SAM. The other way is to transform the social accounting matrix by embedding water resources in the model. The factors of water resources are introduced into the new version of SAM as one of its basic factors. The price and demand of water could be calculated as an endogenous variable. It's essential for the model to illustrate domestic and productive water uses and corresponding economic variations under different scenarios [11].

2.2. Hydrologic model WEP

The WEP model [12] was designed using Physically-Based Spatially Distributed (PBSD) models and Soil Vegetation Atmosphere Transfer (SVAT) models for references. It has demonstrated powerful capability for integrated hydrological simulation under changing environment in Japan and China. There are several technological advantages in the model: (1) organic combination of physically-based hydrologic simulation and energy balance in water cycle, (2) fine description on spatially uneven distribution of underlying surface on small scale by the mosaic method, and (3) self-adaptive operation of different runoff generation methodologies by simultaneously numerical simulation of surface runoff and groundwater on basis of topography and soil characteristics and precipitation features. The modelling structure and corresponding approaches adopted in the WEP model are referred to in [13].

Refinement of simulation grids on micro-scale and physically-based numeric calculation of hydrological components in the WEP model brings tremendous computational work which prevents its application in large basins. Besides, the hydrological processes of artificial branch of the water cycle are not well considered in the original model structure. The WEP-L model is developed on the basis of the theory of the dualistic water cycle by significant improvements of the WEP model [13]. The WEP-L model takes the subdivisions of contour bands intersecting small sub-watersheds as basic calculation units to realize the balance between proper computational work and satisfactory representation of underlying surface. The subdivisions in the model are coded according to the Pfafstetter rule. The vegetation and land use types in the WEP-L model are grouped into three classifications including irrigated fields, non-irrigated farmland, and other land cover to reflect the impacts of artificial irrigation on the water cycle. Moreover, artificial interferences on hydrologic processes by water dispatching of reservoirs, as well as water use and drainage, are simulated by newly the developed water allocation and regulation model (WARM). The WARM model is coupled with the WEP-L model for integrated simulation of the water cycle, in which the processes and distributions of water use and drainage are interpolated by statistics data. Besides, the quantities and processes of snow melting are calculated by improved snow melt module on the basis of temperature-index approach.

The improved WEP model is able to accomplish water cycle simulation and general water resources assessment for preset conditions with and without water use, and fully illustrate water cycle components including both of surface runoff and groundwater. In addition, hydrological variations under a changing environment can be carried out by updating meteorological data or land covers.

2.3. Coupling of CGE and WEP

Along with the rapid socio-economic development and the constant advance of industrialization and urbanization, water scarcity has become a bottleneck which restricts sustainable economy especially for arid regions. Traditional hydrological research focusing on natural water cycle has encountered great challenges derived from the influence of the increasingly powerful artificial water cycle concerning whole procedure from water in-taking and water consumption to water drainage. The hydrological model's incapability on water use simulation and prediction is amplified when dealing with the response and feedback between human system and water system, while the CGE model gives a chance for people to understand the relationship of socio-economic development and corresponding water demand. The integration of the quantitative economic model CGE and distributed hydrological model WEP opens up a new possibility to study the evolution mechanism of coupled socio-economic and water system on basis of dualistic water cycle.

On one hand, water policies, including water use limitation and water price adjustment, are evaluated by CGE as preset scenarios under different levels of socio-economic development. Sectoral water demand of concerned regions, according with either current situation or planning upgrading and readjustment of industrial structure, will be calculated to meet the principle of general equilibrium in the CGE model. Moreover, the spatial distribution of water use for each sector will be available by multi-area and dynamic improvement of traditional CGE. As multi-area and dynamic CGE model for research unit is usually hard to achieve due to shortage of data, water resources rational allocation model ROWAS (Rules-driven Object-oriented simulation model for Water resources System) is eligible for downscaling the global results of CGE model to a reasonable distribution and corresponding process of water use [14]. The ROWAS model translates complex water system to quantitative framework by mathematical description based on generalization of hierarchical network of the water system. The water sources in the ROWAS model consist of surface water, groundwater and recycled wastewater, while the water users include agriculture, industry, services, urban and rural domestic water, off-stream eco-environment, hydropower, shipping and inner-river ecological water. The confluence and conversion of different water sources are considered to describe water balance of water supply. Subsequently, the results of water use could be input into the WEP model for the simulation of water resources responses with consideration of artificial water cycle. Comprehensive analysis of water use in the socio-economic system and its impacts on regional water resources conditions, including evolution of hydrological processes and water flux transported, will be carried out for the reference of decision-making. The mechanism of interactions between the water system and the socio-economic system would be a rational conclusion by means of coupling the CGE and the WEP model.

On the other hand, variability of available water resources under climate change and land use adjustment may cause enormous impacts on socio-economic development. It's predicted that available water resources will decrease by half by 2050. The distributed hydrological model WEP possesses powerful capabilities on hydrological simulation based on physical mechanism, by which variation of available water resources under different conditions could be well simulated. The results of the WEP model about distribution and evolution rule of regional water resources may provide proper constraints for water demand in the CGE, which is intended to indicate the influence of water resources on socio-economic development especially for changing environment in the future.

3. Scenarios

Different policy orientations of national and regional programming may be tested by coupled CGE and WEP. The reform of water price, such as raising industrial water price and public subsidies for irrigation water, could be treated as an exogenous variable of the CGE model so that the water demand of different sectors is endogenously calculated in terms of general equilibrium theory. Within this context, the response of hydrological process on preset water price policy would be simulated by the WEP and the reasonability and consequence of water policy can be assessed. While the water policy is aimed at water use control, the water price and industrial structure would be endogenous variables. In addition, virtual water trade is also an appreciable subject for water-stressed countries. In China, regime of the most stringent water management has been carried out for each province and main river basin. Application of the coupled CGE and WEP would provide valuable information for decision-makers to evaluate and improve water policy.

Global warming has already drawn much attention of the international communities as an inevitable fact. The Intergovernmental Panel on Climate Change (IPCC for short) has released five assessment reports on global climate change. Scientists studied the possibility of various circumstances on greenhouse gas emission and proposed several scenarios of global climate change denoted by precipitation and temperature on the basis of ensemble forecast. More research on downscaling the global climate change to certain regions has also been accomplished. The impacts of global warming on regional water resources and the corresponding ripple effects on socio-economic development would be an interesting theme of research by the coupling of CGE and WEP. Besides, land use planning is also a probable element worth studying as a vital factor for the both hydrological cycle and the socio-economic system.

4. Conclusions

For the purpose of reasonable simulation on the whole water cycle of natural-artificial dualistic characteristic, the integration of the economic model CGE and the distributed hydrological model WEP is proposed. The coupled model would be a powerful tool to simulate the response of hydrological processes in water system under different socio-economic policies, as well as the feedback of water constraints to socio-economic development of human system. Water demand for each sector of the socio-economic system in the CGE model serves as a key element by which an artificial branch of global water cycle in the WEP model is driven, and the natural water cycle is greatly changed. Water demand in the CGE could be considered by either simply building relationships between water resources and correlative accounts that already exist in SAM structure, or adding the water resources account into SAM of traditional CGE model as an essential factor. Although there are a number of problems to implement this framework, including insufficient data for multi-area and dynamic CGE model, different scales of temporal and spatial water cycle in CGE and WEP, parameter sensitivity and uncertainty, and inconclusive scenes under changing environment, the coupling of the CGE and WEP provides an idea for inspection of the global water cycle and examination of water management. The intensive study, of coupled model and interdisciplinary research involving hydrology and socioeconomics, exhibits a great potential for the overall interpretation of the water cycle which would be helpful for better understanding on bilateral interaction between water system and socio-economic system.

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