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Integrative networks of the complex social-ecological systems

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Abstract

As an integrative platform of ecology, economy, management and complex networks, the complex social-ecological systems networks provide one new perspective on the comprehensive management of ecological and socio-economical processes. Through research of the structures, functions and processes, the four-dimensional conceptual model of the complex social-ecological systems for sustainable development was set up which comprises of natural subsystem, social subsystem, economic subsystem and integrative decision subsystem. The complex social-ecological systems networks were defined as one six-element tuple denoting the comprehensive spatial structure of different kinds of units from ecosystem, social system and economic system. The complex social-ecological systems networks have four sub-networks including biological sub-network, material cycle sub-network, economic sub-network and social sub-network, and some important attributes such as hierarchical, power-low of degree, vulnerability, resilience, dynamics, co-evolution of flow and structure were analyzed. One case study of the Taihu lake basin water pollution and human body health risk network was conducted. Based on the Multimedia Environment Pollutant Assessment System (MEPAS) of US EPA and the risk network, POPs (Persistent Organic Pollutants) exposure and lifetime fatal cancer risk were studied.

Keywords: Complex social-ecological systems; integrative network; process;

1. Introduction

Since the middle of the 20th century, ecology has experienced several development stages including original ecology, classic ecology, ecosystem ecology, sustainable ecology and global change ecology [1].

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In the past few decades, the basic concept of ecology had unceasingly developed. The comprehensive and integrative thinking has inspired the development of related disciplines. Multiple theories and methods, such as control mechanisms of ecosystem processes and structures, observation and trials of dynamic network for ecosystem, multi-level boundaries and multi-scale conversions of ecosystem have made a great progress and provided rich scientific data and methods for human adaptive management. As the key component of earth life support system, ecosystem provides kinds of indispensable services including material products, environment regulation, culture functions and these services construct the base of human society. In the other way, human activities have more and more effects on ecosystem. An important feature of current ecosystem is that human activities have exceeded the natural power in some fields which leads to the ever-increasing changes of the earth environment. The way human activities affect the ecosystem has changed from the pattern and structure to biogeochemical processes, and ultimately the spatiotemporal pattern, structure, functions and ecological processes of ecosystem have been leaded to undergo complex and profound changes.

The integrative research of ecosystem, human activities, natural system and economic system has been the major thinking for the global ecological problems [2]. The bi-directional driving mechanism of economy and ecosystem has become the premise of ecosystem changes and sustainable development. Measuring, simulating and analyzing the coupled human-nature ecosystem, grasping the interaction between human welfare and ecosystem services, studying on the ecosystem services functions changes adaptive management in global changes have been regarded as the pressing matter in the moment.

2. A four-dimensional conceptual model of the social-ecological systems

2.1. Structures, functions and processes

As the complex functional macro-bodies, the social-ecological systems are driven by the interactions between ecosystem and social-economic systems. Vegetation, animals, microbial community and inorganic environment are all elements of the social-ecological systems. The soul of the social-ecological systems is the integrated thinking of natural environment, ecosystem and human society and this accentuate the integrity, composition, integrality, structural stability, functional synchronization and balance between the ecological processes and components changes [3, 4].

The complex social-ecological systems have three major phases including structures, functions and processes. The structures are stable organization forms, coupled modes and orders produced by the interrelations and inter-reactions of the biological, no-living and social-ecological components. The more components the structures have, the more complex the systems are. One of the highlight characteristics of the social-ecological systems is productivity, and the functions of the social-ecological systems denote the ability to provide production and services. A basic principle of the social-ecological systems for sustainable development is that structures support functions and the functions are realized through the processes. The processes include predator/prey cycles, water cycles, fire, microelement cycles, production activities, and the material and economic value flows.

The social-ecological systems processes react to some impact factors which would affect systematic activities and control the factors in turn. The impact factors include resources supplying factor, speed regulation factor, interference factor and biome and human activities factors. In the recent years, the disturbances from human activities increase continually. Kinds of human activities such as land development, forest harvesting, mine cutting, fishing and other recreations caused more disturbances than water and wild fire in nature.

2.2. A four-dimensional conceptual model of sustainable development

Sustainable development means that the development potential of ecology, culture and economy in the long term in an area should be guaranteed and at the same time every stakeholder should attend the plan and design program. Sustainable development of the social-ecological systems integrates ecological, social and economic values in a whole new word [4]. A four-dimensional conceptual model was proposed in this paper, every dimension corresponding to natural subsystem, social subsystem, economic subsystem and integrative decision subsystem, separately. And the interdependencies of the four subsystems construct the base of sustainable development as fig. 1 depicts.

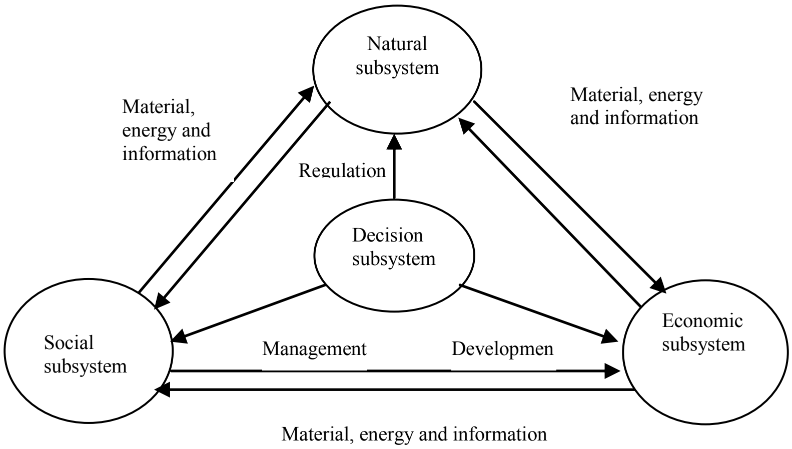

Fig. 1. Four-dimensional conceptual model of sustainable development

- Natural subsystem

Natural subsystem is an organism combined with living and non living individuals. Human, plants, animals and the abiotic environment play different roles in carrying out ecological and geographical functions, changing the processes in ecosystem, and keeping special balances. For example, the species abundance should be stable to sustain ecosystem biodiversity; the population quantity should be large enough to keep breeding and the balance of the food chain; and the land and water resources should be kept at a high level to meet vegetation evaporation, animal generation and human production and life.

- Social subsystem

One of the important targets of the Social subsystem is to study the connections between the spatial structural pattern of ecosystem and society, medicine and psychology. And the influence of the human activities on the social functions of ecosystem is another goal. Some scholars have started to study the natural landscape beauty and the cultivation of close-to-nature ecosystem.

- Economic subsystem

Ecosystem can provide many kinds of productions and services with high economic values for mankind. These productions and services contain industrial and domestic resources, human health level promotion, agricultural pest inhibition and tourism, etc. The goal of the economic subsystem is to compute the economic values and effects of human activities through associating the spatial pattern with the potentiality of productions and services of ecosystem.

- Integrative decision subsystem

Through the flows of material, energy and information the natural subsystem, social subsystem and economic subsystem are correlative with each other. The objectives of the integrative decision subsystem are to design the goals of the relevant areas, develop the integrative decision making theory and methods and formulate the sustainable solutions based on multiple disciplines.

3. Modelling the integrative networks of the complex social-ecological systems

3.1. Basic model

The complex interactions between nature and human society organize the hierarchical networks from cell level to social-ecological systems level. The structures and dynamics of the networks depend on the acquisition, storage and transmission processes of material, energy and information. For example, in one typical biological network many elements transact locally and thereby some new complex properties emerge in middle-scales and macro-scales. Through the interactions and communications among the units and networks, the social-ecological networks keep up evolution unceasingly.

The social-ecological systems networks are comprised of kinds of basic units of ecological, social economic systems, and every unit connects directly or indirectly with each other to form complex networks. The complex social-ecological systems networks can be expressed as a six-elements tuple, $ESN=(N,S,E,R,F,L)$. In this expression, N denotes the natural subsystem comprising of u basic natural unit nodes, $N=\{n_1,n_2\cdots,n_u\}$. S denotes the social subsystem comprising of k basic social nodes, $S=\{s_1,s_2,\cdots,s_k\}$. E denotes the economic subsystem including l basic economic nodes, $E=\{e_1,e_2,\cdots,e_l\}$. R denotes the aggregation of q connections, and every connection is the combination of several relevant nodes with a special structure and function, $R=\{r_1,r_2,\cdots,r_q\}$. F denotes the total functional aggregation of all of the basic nodes and connections, $F=\{F_{n_1},F_{n_2},\cdots,F_{n_u};F_{s_1},F_{s_2},\cdots,F_{s_k};F_{e_1},F_{e_2},\cdots F_{e_l};F_{r_1},F_{r_2},\cdots F_{r_q}\}$. F_{n_i} is the functional aggregation of node n_i, F_{s_i} is the functional aggregation of node s_i, F_{e_i} is the functional aggregation of unit e_i, F_{r_i} is the functional aggregation of r_i. L denotes the total flow aggregation of all of the nodes and combined collections. $L=\{L_{n_1},L_{n_2},\cdots,L_{n_u};L_{s_1},L_{s_2},\cdots,L_{s_k};L_{e_1},L_{e_2},\cdots,L_{e_l};L_{r_1},L_{r_2},\cdots,L_{r_q}\}$. L_{n_i} is the flow aggregation of node n_i, L_{s_i} is the flow aggregation of node s_i, L_{e_i} is the flow aggregation of node e_i, L_{r_i} is the flow aggregation of r_i.

The ecological matrix generated from the connections of every two unit nodes can be expressed as $P=\{p_{ij}\}$, where, p_{ij} indicates the connection between unit node i and unit node j which is a Boolean value, 1 meaning connection and 0 meaning non-connection.

Flows in the social-ecological networks include inflows, absorptions and outflows among different unit nodes of material, energy and information, and simultaneously the exchange between the network and the external environment, namely import, export and discharge as depicted in fig. 2. The importance of one connection can be predicted by the flow quantity.

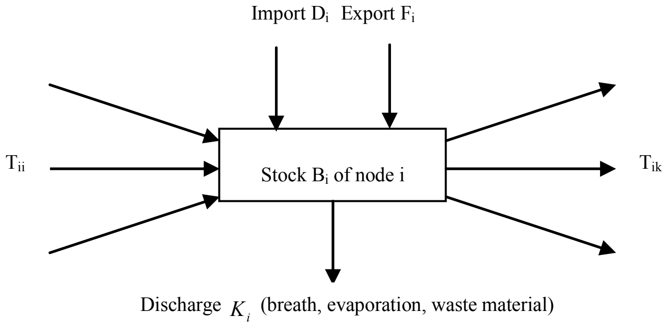

Fig. 2. Flows structure of one unit node

The flows in the networks can be quantified based on the laws of conservation of mass and energy. In the biological processes of the natural subsystem the predation and immigration regulate the inflows but the outflows are depended on preying, death, breath, excretion and emigration [5]. The schematic diagram as shown in fig.2 depicts the flows in one unit node. The static equilibrium can be described as equation (1).

$$D_i + \sum_{j=1}^{n} T_{ji} + B_i = \sum_{k=1}^{m} T_{ik} + F_i + K_i \quad (1)$$

The gradient network is an extractive directed sub-network drawn out of the social-ecological systems networks. The gradient edge is a directed link from node i to the neighbor node on the substrate network which has the largest gradient value in the neighborhood. If node i has the largest value, then the gradient edge is a self-loop. With this perspective we can conclude that the social-ecological systems networks are the substrate network of the gradient network and each node in the gradient network has only one directed edge linking out. In the gradient network, the flow velocity and quantity are deeply influenced by the gradient size. The gradient may come from potential energy difference, value difference, disproportion in distribution or driven power by production and requirement. We can suppose many kinds of flows produced by gradient, such as electric current, heat flow, resource flow, product flow and knowledge flow, etc. The gradient networks structures change dynamically along with the social-ecological networks and the flows behaves changing, too. Based on the gradient network, the flows efficiency and the sensibility [6] to the social-ecological networks congestion can be calculated.

The relationships among the ecological processes and social economic processes happen with the flows of material and energy [7]. The flows flow through different areas, industries and consumption sections and produce movements, transitions and conversions. The flows can be classified into different kinds in different environment. For example, the resource flows can be marked transverse or longitudinal. The former produces spatial displacement driven by geospatial potential energy and the latter morphological, functional and valuable transformation driven by value potential energy in the aboriginality, processing, consumption and abandonment sections. Resources can also be classified into explicit and implicit kinds. When one kind of resource is used in an explicit way, another accompanying implicit resource may be used in the processes. For example, water resource is an special kind of material in the iron products supply chain.

By means of the food matrix, the accompanying flows matrix of the social-ecological systems networks can be set up. In the accompanying flows matrix each coefficient is calculated through one inflow quantity dividing the total inflow quantity. The accompanying flows matrix can be depicted by equation (2).

$$G = \{g_{ij}\} \tag{2}$$

Where, g_{ij} denotes the coefficient of the flow into i node from j node.

$$g_{ij} = \frac{T_{ji}}{T_{in_i}} \tag{3}$$

$$T_{in_i} = D_i + \sum_{j=1}^{n} T_{ji} \tag{4}$$

Through the accompanying flow matrix of the social-ecological systems networks, we can identify the significance of the flows for the nodes. Also we can analysis the direct and indirect effects of one node on another node.

According to the biological networks theory of Ulanowicz [8], the flow transition matrix of social-ecological systems networks can be designed to analysis the transmission of material and energy among nodes.

$$G_m = \{g_{ij}^m\} \tag{5}$$

g_{ij}^m denotes the flow quantity from node i to node j passing through m road sections. With G_1 , G_2 ,…, G_m , we can find the whole paths through which the flows transmitting. The flow transition matrix depicts the quantitative relationship of the flows among nodes, and further the reliance and contribution degree.

3.2. Sub-networks of the complex social-ecological systems networks

In the complex social-ecological systems networks, biological sub-network, material cycle sub-network, economic sub-network and social sub-network are intertwined.

- Biological sub-network

The biological network was proposed to explain the interactions among different species [9]. A typical biological network is a food chain in which a mutual beneficial symbiotic relationship existing among nodes. The interactions sustain the biodiversity and robustness of the whole system and further motivate small networks constructing bigger networks. Three important properties can be extracted from the biological sub-network. The first is the connectional diversity. The mass of species in the biological system have links to a small subsection which lead to degree disequilibrium of nodes in the network. The second is nesting. Some special species only have connections with a subset of the whole species and hence some small networks may be nested in a bigger network. The third is vulnerability and asymmetry. For example, one kind of plant would depend on one special animal strongly, but it is very different in return. So the biological sub-network is established neither on the random organization nor on the isolated organization, but on the key species.

- Material cycle sub-network

Biological, physical and geochemical processes of water cycle, energy cycle, nutrient cycle and carbon cycle are included in the material cycle sub-network [10]. Based on the material cycle sub-network the influences of human activities on the processes can be measured. Water cycle plays the leading role in the whole ecosystem. Water cycle comprises of atmospheric precipitation, surface and groundwater runoff, sink of runoff, outflow of the watershed, and the soil moisture returning process to atmosphere through surface soil and plant leaves. Carbon cycle is a new study area which contains sequestration, conversion and release processes. Through modeling the processes the material cycle can be related to the environment factors.

In a watershed the water cycle, carbon cycle and nutrient cycle are mutually interdependent. As for the forest vegetation, the forest canopy, litter, root zone, and the physiology and ecology of forest ecosystem in a watershed would influence the spatiotemporal process of precipitation, runoff ingredient, potential evaporation and the water balance.

- Economic sub-network

The economic network has been studied from two perspectives. One comes from the economics and sociology and the other come from the complex systems in physics and computer science [11, 12]. In the economic network, nodes represent the different individual agents which can be firms, banks, or even countries, and the links between the nodes represent their mutual interactions, ownership, R&D alliances, or credit-debt relationships. Different agents have different behaviors and strategic under the same conditions. These interactions can be analyzed through the network dynamics which are bounded in space and time and change with the environment. The economic network is formed or devolve based on the addition or deletion of either the agents or the links.

- Social sub-network

The psychology and social behavior dynamics of organization and population now are research hotspots. Alessandro put forward a new question for us that how to predict human activities based on the complex techno-social systems networks [13]. Arising from public opinion, the propagation of knowledge, diseases and the formation of social organization can all be studied based on the social network. The mobile telephone proxy network, air line network and Blog network are all effective tools to analysis human activities and communications.

In the social-ecological systems networks, the ecological restoration, ecological conservation, adaptive management, ecological services and the laws and regulations are all relevant to human activities. The thinking and behavior tendencies of all kinds of organizations and population have important significance for the sustainability of ecosystem. In the past few years, approaches to human interactions and mobility have mostly relied on census and survey data which were often incomplete and/or limited to a specific context. Insights into the nature of the interlinks between people and technology and the dissolution of boundaries between the cyber world and our real-world social activities have upgraded our accessibility to data, leading to “reality-mining,” which has been defined as the collection of machine-sensed environmental data that are related to human social behavior.

3.3. Properties and characteristics of the complex social-ecological systems networks

- Hierarchical

An important property of the social-ecological systems networks is the hierarchy. Natural, economic and social systems sub-networks all have hierarchies. Firstly, the living system has eight hierarchies including cell, tissue, organ, system, individual, population and community, ecosystem and biosphere. Secondly, the economic system is hierarchical, too. Hierarchy is a basic concept of economy. According to the organization level, the economic system can be divided into individual economic system, house economic system, business economic system, industry economic system, regional economic system, country economic system and global economic system. Thirdly, the social system is a combined system with multi-hierarchical structures of material and thinking in which many factors intercommunicating, interacting, and performing special functions.

- Scale-free and clustering

The scale-free property has just been discovered in the past five years, and thus not much work has been done in modelling or analyzing such networks from the algorithmic or data mining perspective. Many real-world graphs have been shown to be scale-free vertex degrees following power law distributions, vertices tend to cluster, and the average length of all shortest paths is small.

In the social-ecological systems networks, a common phenomenon is that there are close connections among the unit nodes in a sub-system or natural, social and economic nodes in a special areas which bring about one by one factions in the network. For one faction, the inner connections among nodes are close but the external connections are loose.

- Robustness, vulnerability and resilience

With the evolutions of the natural and social economic network, much clay of feet was overcome and the adaptability to the environment was enhanced. The social-ecological systems networks have many merits. Robustness means much resistance to the hazards. In the real world, many networks are scale-free in which hub nodes leading to vulnerabilities. When confronted with ecological hazards or an economic crisis, the vulnerabilities will pervade along the social-ecological systems networks. The dynamics of the vulnerabilities depend on the balance between the mobility of flows and the local extinction.

Resilience is currently defined in the literature as the capacity of a system to absorb disturbance and re-organize while undergoing change but still retain essentially the same function, structure, identity and feedbacks The resilience approach emphasizes non-linear dynamics, thresholds, uncertainty and surprise, how periods of gradual change interplay with periods of rapid change and how such dynamics interact across spatiotemporal scales. The resilience of the social-ecological systems networks is a new research area.

- Spatiotemporal dynamics

The additive and delivering effects of natural and human disturbances on the social-ecological systems networks perform obviously at different time and place. For example, one watershed ecosystem can be divided into upstream, midstream and downstream, and it can also be divided into forest, grassland and desert, or countryside and town, and the watershed unit can be very different in different scale according to different rules. Driven by the climatic changes, human production and living, the whole ecosystem networks change dynamically [14].

- Evolution of the structures and flows

In the situation of global climatic changes, the structures and processes come up with special changes in different spatiotemporal scales which bring about the co-evolution, even sharp phase changes [15]. In the social-ecological systems networks, the evolution processes are related not only to the natural changes but also to human factors. Landscaping, project planning, forest cut and regeneration, agriculture and industrial restructuring are all important driven factors.

- Integration management

As an integrative platform of development, exploitation and protection for the social and ecological systems, the complex social-ecological systems networks are confronted with many management problems [16]. The burning issues of integration management include spatiotemporal scales of network, ability to providing material and services, and the balance of short term and long term benefits.

When we design the social-ecological networks, several solutions to the dimensions and patterns can be candidates. For example, the ecological system network has four physical properties including total network area, ecosystem quality, network density and conductivity, which all can be used in the spatial integrative management strategies.

4. Case study: water pollution and human body health risk modelling in Taihu lake basin

4.1. Taihu lake basin water pollution

Taihu lake basin is one of the most developed and populous areas in China located in the Yangtze River Delta including parts of Jiangsu, Zhejiang, Anhui, and Shanghai provinces. Taihu lake basin is a typical plain drainage area with 36.9 thousand km^2 and the whole length is 120 thousand km. In 2009 the total population in Taihu lake basin is 51,760,000 accounting for 3.8% of the national population; and the total GDP is 3,636.4 billion RMB accounting for 11% of the national GDP.

With the economic and social development, the water quality of the Tai lake rivers system was polluted seriously in recent years and the nutritional status changed quickly. According to the monitoring report in 2009, of all of the river system 7.6% was in Ⅳ grade, 18.5% was in Ⅴ grade and 73.9% was inferior to Ⅴ grade. The direct driven powers of environmental pollution come from the emission of organic substance, N and P including the pollutants of industries, agriculture and human life. The indirectly driven powers involve continued population growth, fast-developing economy and land-use change [17, 18].

4.2. A framework of the complex social-ecological systems networks in Taihu lake basin

A framework of the complex social-ecological systems networks in Taihu lake basin was conducted as fig. 3. In the networks, four kinds of nodes organize four sub-networks embedded in each other. In every sub-network, there is one kind of dominant nodes, and one node may belong to another sub-network at the same time. Material cycle sub-network consists of different material nodes denoting the relevant materials like toxic substances. Transfer sub-network is composed of kinds of medium nodes including air, water, particulate matter and food. Economic sub-network refers to factories, banks and other organizations. Social sub-network indicates the relation chains among peoples. The transmissions of materials, energy and information in the network would lead to complex unconceivable outcomes.

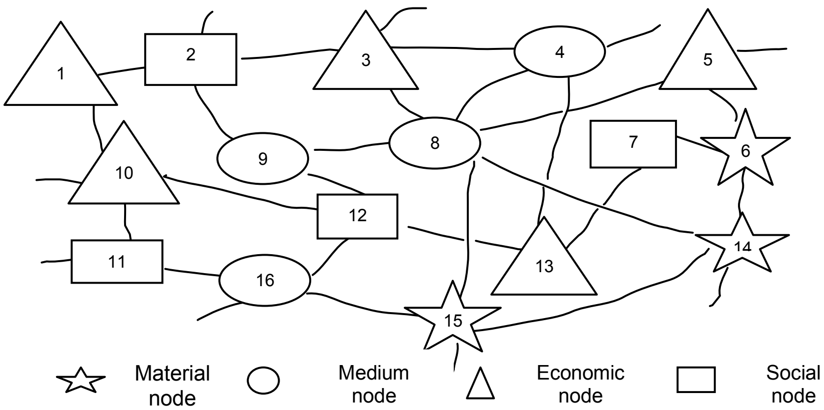

Fig. 3. A framework of the complex social-ecological systems networks in Taihu lake basin

4.3. Water pollution and human body health risk Modelling

POPs (Persistent Organic Pollutants) usually exists in water body, soil, sediment and atmosphere with low consistency. POPs has some special properties such as refractory, lipotropic, semi-volatile, long distance migration and highly toxic and so it would produce chronic toxicity to immunity, nerve and reproductive system of human body in kinds of transfer and transformation processes. The exposure mediums of POPs include air, water, particulate matter and food. A relationship model between Taihu lake basin water pollution and human health in the multi-medium environment was proposed depicted as fig. 4 [19].

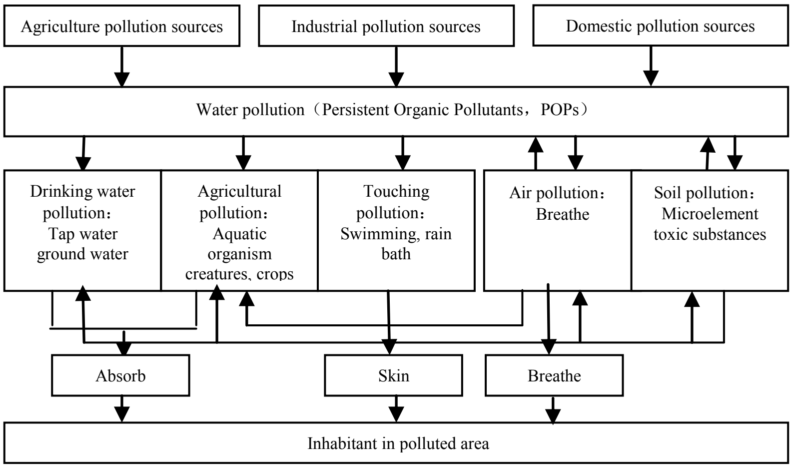

Fig. 4. Water pollution and human body health risk modelling in Taihu lake basin

The relationship between POPs and the major illnesses incidence rate can be predicted. According to the network of Taihu lake basin ecosystem and human health risk and MEPAS of EPA, the Personal exposure of POPs is modeled [20] in equation (6).

$$ADI_{ijk} = C_i \times [\frac{C_j}{C_i}] \times [\frac{CR_{jk}}{BW}] \times \frac{EF \times ED}{AT} \tag{6}$$

where

ADI_{ijk} denotes daily exposure to unit human body mass through the jth medium of the ith POPs, mg/kgd;

C_i denotes POPs quantity in the ith medium, mg/kg;

CR_{jk} denotes daily exposure to human body through the kth way of the jth medium, mg/kgd;

BW denotes human body mass, kg;

ED denotes exposure years, a;

EF denotes exposure frequency, d/a;

AT denotes total exposure time, d.

Human major illnesses risk in lifetime is modelled as equation (7).

$$R_{tkki} = HE_t D_{kki} DF_{ri} \tag{7}$$

where

R_{tkki} denotes the total risk produced through path kk and the radiant quantity i in lifetime;

HE_t denotes risk-health conversion factor in lifetime;

D_{kki} denotes suction volume from radiant quantity i through path kk ;

DF_{ri} denotes conversion factor of radiant quantity i through food, soil and water.

5. Conclusion

As an integrative platform of ecology, economy, management and complex networks, the complex social-ecological systems networks provide one new perspective on the comprehensive management of ecological and socio-economical processes. Through research of the structures, functions and processes, one four-dimensional conceptual model of the complex social-ecological systems for sustainable development was set up which comprises of natural subsystem, social subsystem, economic subsystem and integrative decision subsystem. The complex social-ecological systems networks platform was defined as one six-element tuple denoting the comprehensive spatial structure of different kinds of units from ecological, social and economic systems. As one case study, the relationship between Taihu lake basin water pollution and human body health risk was studied based on the Multimedia Environment Pollutant Assessment System (MEPAS) of US EPA.

At the same time, new problems arise from the complex social-ecological systems networks. Infrastructure establishing and dispatching, mathematic modeling, large scale ecological, social and economic data collecting and analyzing are all challenges. As for the management decision problems of the complex social-ecological systems networks, we can start from two perspectives. One is the micro perspective where the incentive mechanisms can be used to predict the dynamic results of the networks structures and the manners of the nodes agents. The other is the macro perspective where the game theory is a popular tool. Adding, deleting and weight changing of the connections among nodes can be treated as the results of competition and cooperation of different agents.

Acknowledgements

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