



2010 International workshop from the International Congress on Environmental Modeling and Software (iEMSs2010)

The cumulative effects of dam project on river ecosystem based on multi-scale ecological network analysis

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Abstract

The importance of addressing cumulative environmental impact of large development projects on rivers has been increasingly highlighted. Consideration to potential impact pathways may be difficult, however, without appropriate analytical methods. By introducing ecological network model, this paper focuses on the quantification of the cause-effect relationships inherent the cumulative effects of dam construction from a holistic perspective. With Lancang river of Longitudinal Range-Gorge Region (LRGR) as an example, the risk-based interaction instead of the conventional energy or material flow of ecological network model has been created to conceptualize the cumulative effects network model. Based on this model, the network structural and functional analysis were adjusted for the assessment of potential eco-environmental impact within the ecosystem, thus demonstrating how the risk-based ecological network analysis can be used to characterize the holistic cumulative effects of dams on the temporal and spatial scale.

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Keywords: Cumulative Effects; Dam Project; Ecological Network Analysis

1. Introduction

Dam project is regarded as one of the most critical factors contributing to changes of river ecosystem. Eco-environmental impact may arise during all project phases, i.e. construction, river impoundment, and dam operation [1]. The flow manipulations result in physical, chemical, and biological changes to the ecosystems of upstream backwaters, the reservoir body and surroundings, and downstream. Attention has been paid to the eco-environment impact of dam project due to its important role in balancing environmental protection and dam operation, maintaining the river ecosystem health and promoting regional sustainable development. However, the holistic assessment of the cumulative effects incorporating potential impact pathways brought by the dam project in the multi-scale context has not yet been addressed.

Applying ecological network model to ecological risk assessment of river ecosystems, the present study developed the system-oriented model for the assessment of the dam-induced cumulative effects of the river ecosystem, incorporating interactive impact factors of different levels. The risk-based interaction was created to

represent the potential impact intensity from one factor to another, which was then analyzed using the adjusted ecological network analysis (ENA). The established model may provide a useful tool to identify the direct and indirect dam-induced impact and help understand how the river ecosystem reacts to the anthropocentric disturbances from the holistic perspective.

2. Conventional ecological network analysis

2.1 The basis of ecological network model

In light of system ecology, ENA is developed as a systems-oriented modelling technique for examining the structure and flow of materials in ecosystems, which is represented by a network of nodes and connections [2-5]. Interestingly, the Network Analysis (NA), recently reintroduced to societal and economic analysis of urban area, is actually an environmental application of input-output analysis for the interdependence of industries in an economy in the first place [6-8].

ENA places great emphasis on the interactions between nodes rather than the characteristics of individuals, and both direct and indirect effects within the system can be identified and quantified via network structural analysis and functional analysis (i.e., throughflow analysis, utility analysis, control analysis, etc.). In fact, because of its basic assumption about objects connected together as part of a larger system, which is used in several disciplines, the most promising application of network analysis may be as a platform for the integrated eco-environmental impact assessment models to address sustainability issues of human-natural systems [9].

2.2 The application of conventional ENA

The existing applied studies of this systematical method depended greatly on the food webs within natural community (excluding the non-living things) or ecosystem (incorporating the non-livings, e.g. detritus), most of which were concerned with specific aquatic ecosystems, e.g., the Chesapeake Bay [10,11], Northern Benguela [12,13] and Neuse River Estuary [14], with several exceptions though, such as social and economic systems [15,16], water use systems [17], and urban metabolic systems [18]. Often energy- and material-based flows were utilized as the conservative mediators for these studies. In other limited cases, it can be expanded to water flow or energy [18,19]. However, information flows play an important part in ecological network, especially for the combined human-natural systems, and a holistic apprehension of the whole system's behaviours cannot be addressed simply based on the quantitative transactions of energy or material between compartments.

3. Risk-based ecological network model of dam-induced impact

3.1 Risk-based interaction

In order to derive a holistic and quantitative picture of cumulative effects, the impact assessment was focused on how to define the medium (or so called the currency) for the multi-process network model. The exploration into the medium entails a conceptual conversion of ENA (Fig.1). Conventionally, the material or energy flow from compartment i to j (f_{ij}), exogenous input to compartment i (X_i) and medium from compartment j to other compartments (E_j) are affected by the sudden stress due to dam operation and proceed into risk for the ecosystem, the stress can be determined through the change of these material or energy flows. Alternatively, a more direct and succinct fashion developed here defined the environmental stress as risk-based interaction. The changes of risk flow from compartment i to j (rf_{ij}), exogenous input to compartment i (X_i') and medium from compartment j to other compartments (E_j') represent the risk of ecosystem directly, which induce a loss of the asset (biomass, useful energy, etc.) of ecosystem. The existence of a risk flow (a arrow pointing from one node to another, denotes as f_{ij}) means that the donor discharge a risk it produced previously, while the receptor is suffered from the risk it exposed to, while the one in dashed line (denotes as y_i) represent the risk self-elimination due to the self-restoration capacity of most (not all) entities of ecosystem. In order to uniform the different units on a common basis, the non-dimensionalization can be completed using the ratio of the changes associated with the harms of ecosystem to the

background value. The probability can be derived from case analysis. The intensity and the probability (P) together determine the risk flow, which is formulated as:

$$RF = RI \times P_i, \quad RI = \frac{I_t - I_0}{I_0} \tag{1}$$

where, RF stands for risk flow; RI stands for risk intensity; I_t refers to the impact at t moment; I_0 refers to the original value; P_i refers to the probability of the risk.

In order to adjust ENA to the ecological impact assessment, the risk flow (RF) is intended to indicate the true intensity of the risk which transfers from one compartment to another, incorporating risk intensity and the probability of the risk. In this sense, RF is not energy- or mass- based interaction but an information flow, rationally negative and basically undesirable for nature.

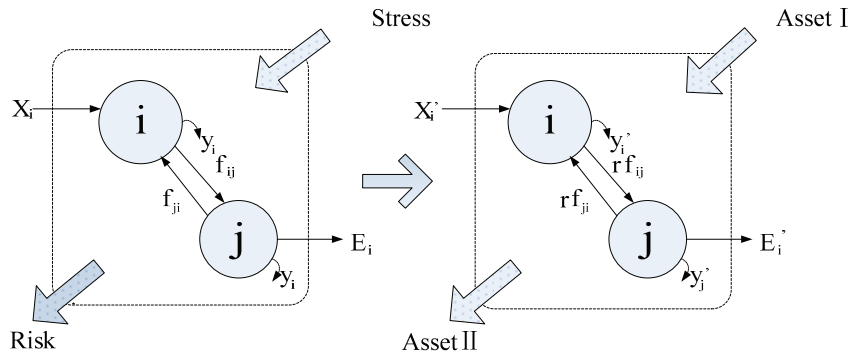


Fig. 1 Conceptual conversion of ENA for ecological risk assessment

3.2 The conceptual model for dam-induced cumulative effects

Large dam projects may induce cumulative effects on the natural environment at various scales and of different orders. A holistic consideration and management of ecosystem functional components based on the ecological impact analysis and case study incorporating all the disturbed elements (direct or indirect ones) is therefore essential. Taking Lancang River of LRGR for example, we identify the impact pathways, including impact sources, factors and destinations of different levels, within the disturbed river ecosystem. The relationships between compartments are clarified and the cumulative effects network model is established based on this model (Fig. 2). Dam construction serves as triggering issue at level 1; Hydrology, water quality and sediment are three impact sources at level 2; Climate, habitat, channel change and hydraulics are four first impact factors at level 3; Aquatic fauna, aquatic flora, terrestrial fauna and terrestrial flora are four second factors at level 4; Biological react is at level 5 associated with the feedback effects; Degradation of ecosystem and loss of biodiversity and biocomplexity are at the final level as the impact destinations or ultimate outputs. The indices inside each compartment are the representative measurement parameters for quantifying the risk flows.

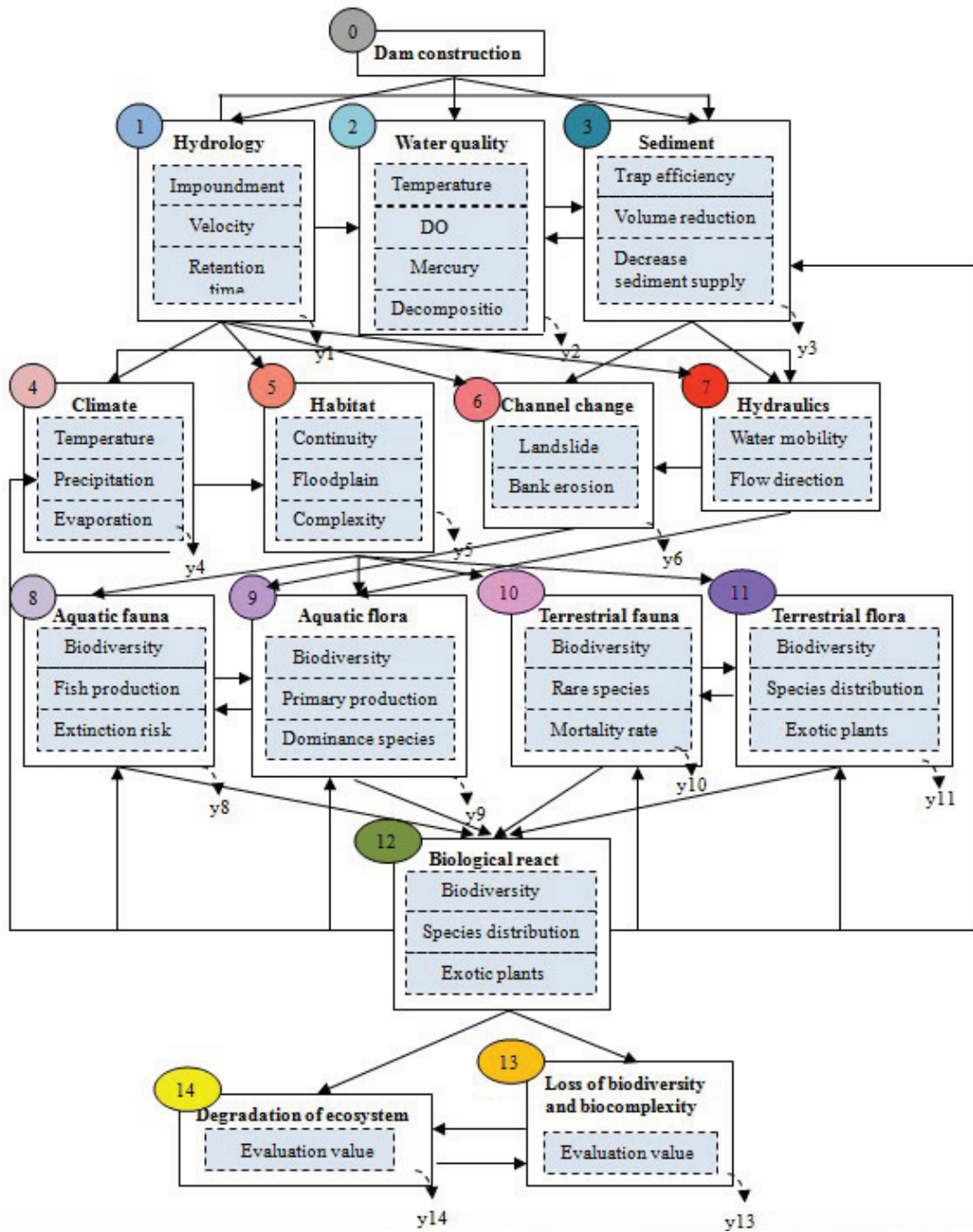


Fig.2 Ecological risk network model (ERNM) during dam operation.

4. Holistic analysis of the dam-induced cumulative effects

4.1 The structural analysis

The structure of ecological network model can be depicted in digraph, which represents the relationship between compartments. The digraph of the established cumulative effects network model (CENM) shows 15 compartments

within the system and 40 flows between them, and also 12 risk self-eliminations. The risk flow can be directed from a high level to a low level (up-down flow), and a feedback from a low level to a high level (down-up flow) or transfer between compartments at the same level. In the CENM of Lancang River, the up-down flows constitute the biggest part of the interactions of whole system, while the down-up flows and parallel flows make up only a small part.

4.2 The functional analysis

- Throughflow analysis

Throughflow analysis depicts the functional relationship between compartments, giving a whole picture of the quantitative network model. By using the adjusted ENA just proposed, the cumulative effects of the whole system are quantified. *RF* represents the inherent risk information, while the total throughflow of *RF* within the system serves as an indicator for the quantification of the holistic impact condition. Different from the conventional ENA, total throughflow of *RF* indicates the holistic intensity of possible hazards or damages. That means, the more frequent or stronger the hazards or damages are, the higher the total throughflow will be derived.

- Utility analysis

From the network structure that we have just derived, we can analyze the mutual relationships between all elements of the network. Conventionally, in the network utility analysis, net direct interactions represent the direct mutualism, while the net indirect interactions stand for the indirect mutualism [5].

Here the mutualism index is adjusted as the risk efficiency indicating the proceeding convenience of cumulative effects, which may be informative for how easily and quickly a potential impact be produced. Positive/negative signs of mutualism index are capable of identifying the relationships between different compartments or the synergism of the whole system in both direct and indirect ways.

- Control analysis

Patten introduced a Network Environ Analysis based measure of control or dominance [2]. This measure is based on the ratio of integral flow from compartment *j* to *i* to the integral flow from *i* to *j*, which implies the control of one component over another.

As the adaptive interpretation here, control analysis for CENM represents the distribution of control among all the compartments, indicating which compartments affect the risk flow of the whole ecosystem most, and which seems less important for the holistic scale. The adaptive control analysis can be utilized to determine the key factors and processes controlling the holistic system, and apply the scenario analysis to these factors and processes. The measurement of ecological impact threshold should also be based on the adaptive control analysis.

5. Conclusion

A risk-based ENA for cumulative effects of dam project is introduced, based on which, the cumulative effects network model (CENM) for dam-induced cumulative effects is established, presenting the impact transfer, accumulation and (biological) feedback of different levels. A conceptual conversion of the conventional ENA and some adjustments of structural and functional analysis were made to further interpret the risk issue of cumulative effects assessment. The conceptual system of the model was perfected based on risk-based ecological network, though more data are needed for a quantitative assessment of the concerned river system.

Acknowledgements

This study was supported by the Program for New Century Excellent Talents in University (NCET-09-0226), National High Technology Research and Development Program of China (No., 2009AA06A419), Key Program of National Natural Science Foundation (No., 50939001), National Natural Science Foundation of China (Nos., 40701023, 40901269, 40871056), National Key Technologies R&D Program (No., 2007BAC28B03), and State Key Basic Research and Development Plan of China (973 Plan, No., 2005CB-724204).

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