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Discrete Event Simulation for Exploring Strategies: An Urban Water Management Case

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This paper presents a model structure aimed at offering an overview of the various elements of a strategy and exploring their multidimensional effects through time in an efficient way. It treats a strategy as a set of discrete events planned to achieve a certain strategic goal and develops a new form of causal networks as an interfacing component between decision makers and environment models, e.g., life cycle inventory and material flow models. The causal network receives a strategic plan as input in a discrete manner and then outputs the updated parameter sets to the subsequent environmental models. Accordingly, the potential dynamic evolution of environmental systems caused by various strategies can be stepwise simulated. It enables a way to incorporate discontinuous change in models for environmental strategy analysis, and enhances the interpretability and extendibility of a complex model by its cellular constructs. It is exemplified using an urban water management case in Kunming, a major city in Southwest China. By utilizing the presented method, the case study modeled the cross-scale interdependencies of the urban drainage system and regional water balance systems, and evaluated the effectiveness of various strategies for improving the situation of Dianchi Lake.

1. Introduction

The management of coupled human−environment systems is complex in nature. Urban water management is a typical example. It comprises strategies, policies, and activities for achieving self-sufficiency in water resources, safe drinking-water supply, water pollution control, flood control, and for meeting the urban ecological water demand. Management of such a complex system requires adequate scientific tools.

Methods such as life cycle inventory (LCI) and material flow analysis, for instance, are frequently applied in analyzing and assessing the environmental impacts attributed to the life cycle of a good or service (*1*). Applications in strategy analysis of urban water management also arise (*2*). LCI is usually based on a database and computational models that specify the mass or energy transfer processes in the system being studied (*3*). Deficiencies have been identified in using it for decision support or policy making (*4*−*6*). One is the fact that LCI is currently limited to the mass or energy transfer processes, while the driving forces and boundary condition changes that account for the dynamic development of environmental systems are not well represented in the models. To bridge this gap, a new model is called for that extends the usability of LCI and makes it more accessible for dynamic strategy analysis. Therefore, we present a model structure that aims to facilitate the identification of the multiple elements of a strategy, as well as explore its multidimensional effects through time in an efficient way.

The modeling approach we apply is straightforward. We specify a strategy with a set of decision variables attributed with sequence and time. Strategy variations cause the networked parameter change in the form of a stepwise update of the boundary-conditions of the environmental system in LCI models. Thus, for different strategies we predict their consequences on the entire system at each individual time step assuming a steady state. This is in fact rooted in discrete-event systems theory (DES) (*7*). There has been recent work in the field of industrial ecology using discrete event simulation to conduct LCI and material flow analysis (*8*, *9*). However, in addition to these contributions, this paper provides a structuring approach that matches the purpose of facilitating the search and management of strategies over time. We use distributed cellular constructs such that the extendibility and illustrative power of the model is also enhanced.

The model is applied to a water management case study in Kunming (Yunnan Province, Southwest China), where urban water problems and the eutrophication of Dianchi Lake are significant concerns.

2. Model Structure

The model consists of four components (**A**, **S**, **G**, and **M**), which are the agent component, strategy component, timed causal networks, and the life cycle inventory models, respectively, and two loops (Figure 1). The inner loop (solid line) represents the simulations of model parts (**S**, **G**, **M**), while the outer loop (dashed line) represents organizational learning and strategy adaptation by decision makers. **G** and **M** contain parametric uncertainty items σ_G and σ_M, respectively, so that the model can include probabilistic uncertainty analysis. The variable d_t is a vector of actions at time t defined in a strategy. Each component is illustrated below.

The agent component **A** represents the agents or decision makers and their strategic management assisted by simulations. The basic idea to place **A** in the outer loop of the model structure is to enhance learning and strategy adaptation as an objective for modeling (*10*, *11*). Thus the agents' understandings of the problem and their strategic plans can be improved. In this paper we focus on explaining the inner loop.

The strategy component **S** represents all possible sets of strategies S that can be generated by **A**. A strategy can be defined as a plan of action spanning a certain time range $[t_0,t_e]$ for achieving a specific goal, where t_0 is the starting time and t_e is the ending time of the simulation. It is specified by a set of n different decision variables s_i ($i = 1, \cdots, n$), which are explicitly predefined for the time period of concern.

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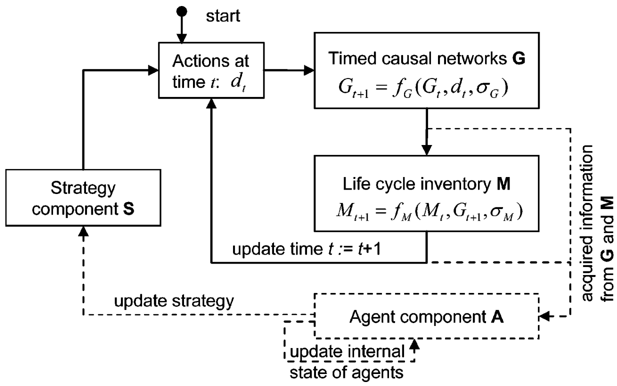


FIGURE 1. Model structure of the discrete event simulation for exploring strategies.

Decision variables are changeable factors over which decision makers can exercise direct control. They are sometimes also referred to as controllable variables or policy variables (*12*). A formal representation of a strategy S is as follows:

$$S = (\vec{s}_1, \cdots \vec{s}_i, \cdots \vec{s}_n) = \begin{pmatrix} s_{1,t_0} & \cdots & s_{i,t_0} & \cdots & s_{n,t_0} \\ \vdots & & \vdots & & \vdots \\ s_{1,t} & \cdots & s_{i,t} & \cdots & s_{n,t} \\ \vdots & & \vdots & & \vdots \\ s_{1,t_e} & \cdots & s_{i,t_e} & \cdots & s_{n,t_e} \end{pmatrix} = \begin{pmatrix} \vec{d}_{t_0} \\ \vdots \\ \vec{d}_t \\ \vdots \\ \vec{d}_{t_e} \end{pmatrix} \quad (1)$$

Each column in eq 1 represents the state of a predefined decision variable s_i over time and each row is the action set d_t to be enacted at a certain time step t. For each d_t, the model will make a stepwise state update in the subsequent model component.

In the course of strategy exploration, decision variables can be added, removed, or modified according to the understanding of the problem and inquiries. When new decision variables are identified, the subsequent components, **G** and **M**, need to be adjusted so as to include the mechanisms that relate with the new added decision variables. Identifying adequate decision variables is an important procedure, which requires dialogue between decision makers and decision analysts, and with other stakeholders of the related problem.

The timed causal network **G** describes the mechanisms that govern the dynamics of environmental systems, i.e., it models the boundary conditions of the LCI component. It stepwise computes the state updating from $G_t \rightarrow G_{t+1}$ (G_t represents all the state variables encoded in **G** at time t, and all decision variables are a subset of G) resulting from the actions d_t at time t, by a set of state transition functions f_G as follows:

$$G_{t+1} = f_G(G_t, d_t, \sigma_G) \quad (2)$$

G_t includes the complete set of state variables at time t that are specified in **G** and σ_G is the parametric uncertainty in **G**. In principle, it is similar to a timed automaton, for which the initial conditions must also be well defined (*7*). We use the term "timed causal networks" because, first, it describes causal relations, and second, both the strategic actions received and the state variables that are updated by the network are timed information.

Graphically **G** can be represented as a directed acyclic graph model (*13*) that has two types of nodes: a circle representing an abstract entity named "place" and a square representing a "transition" (see Figure 3). Such language is inherited from Petri net theory, which has been adapted and applied in various fields (*7*, *14*, *15*). In **G**, the term "place" refers to a group of state variables that are attributed to that "place". The term "transition" refers to an embedded computation program that describes the causal relations of the variables grouped in its linked "places". **G** is made of a group of distributed cellular networks (*16*), each of which encodes one "transition" and the "places" that it is directly linked with (see Figure 3). Together these networks describe the causal relationships in **G**.

The procedures for generating complex timed causal networks can be described as follows: (1) Identify the "transitions" that constitute the causal model by determining the processes that drive the system. (2) Identify the direct preconditions and consequences associated with each "transition". (3) Identify the variables that are attributes of each "place". (4) Describe the relations and operations, if any, within each "transition".

The LCI model component **M** receives updated output variables G_{t+1} from **G** as parameters, and calculates the updated state M_{t+1} as follows:

$$M_{t+1} = f_M(M_t, G_{t+1}, \sigma_M) \quad (3)$$

where f_M describes the conservation laws of mass and energy of all the included processes, and σ_M is the parametric uncertainty in **M**. M represents all the state variables of flows and stocks in **M**, which can comprise multiple levels of subsystems, e.g., an urban drainage system and a regional water balance system, as will be illustrated in the case study.

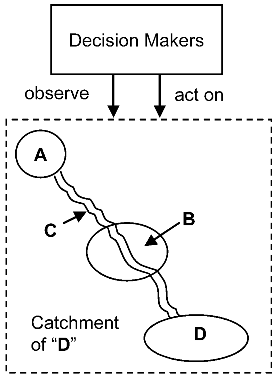
3. Case Study

We illustrate how the proposed model structure can be utilized to explore and to assess the latent effects of various strategies on the urban water management problem in Kunming.

3.1 Problem Background. The urban growth of Kunming has resulted in a water scarcity problem and in the pollution of the receiving water, Dianchi Lake. In Figure 2, panels (1) and (2) present the key background information within the study area, and panel (3) defines the goals, primary objectives, and the decision makers. For greater detail and data records, please refer to previous work (*17*−*19*) and Supporting Information of this paper as well.

3.2 Application of Discrete Event Simulation to Urban Water Management. The first step of constructing the simulation model was to develop the component **M**, the LCI of the Kunming urban water drainage system and the regional water balance system. The next step was to analyze, using the timed causal network **G**, the driving forces that account for the dynamics of the LCI. In this process the state variables encoded in **G** and their direct relationships were determined. Then, based on the list of state variables from G, we identified the decision variables $s_i \in G$ that are controllable by the agents. The decision variables can be modified to formulate various strategies. Finally, the simulation using these strategies can demonstrate the resulting dynamics of flow volumes and pollutant loads.

Describing the Driving Processes with Timed Causal Networks. We follow the procedures for constructing timed causal networks described in the previous section. By logical analysis, starting from the primary driving force of "urban development", we identified the transitions of an urban water management system as follows: "*T1*", urban development—the city requires vast amounts of water to be readily available; "*T2*", water resource self-sufficiency—the city searches for and attempts to ensure sufficient water resources are available to support its existence; "*T3*", demand management—refers to the construction of water supply systems and the supply of water for use, while at the same time guaranteeing ecological water demand, such as maintaining minimum river flows in dry seasons; "*T4*", water consumption—water



(1) Key objects of the human-environment systems of concern

A: Upstream reservoirs	1) Water availability: 250 million m^3/a + imported water 245 million m^3/a after the year of 2008 2) Water quality: good; drinking water resource
B: Kunming City	1) Urban population: 2.5 million, 0.7 million local rural people to be urbanized 2) Natural growth of population: 0.71% per year on average (Immigration and population transition is the largest driving force of urban growth)
C: Urban rivers	1) Water quantity: nearly no water discharge from upstream reservoirs in non raining period 2) Water quality: heavily polluted with untreated wastewater and wastewater treatment plant effluent
D: Dianchi Lake	1) 300 km^2 water surface; 4.4 meters average depth 2) Water quality: hyper-eutrophic.

(2) General background information of the key objects

Goals	1) The local environment will support urban growth to a projected population of between 4.4 to 4.9 million people within the Dianchi catchment area 2) Dianchi Lake shall return to healthy condition
Primary Objectives	1) Total phosphorous load to the lake should be smaller than the tolerance value 60 tons/a in average (*18*), including from urban drainage 33 tons/a (presently greater than 1500 tons/a) and agriculture drainage 27 tons/a (*17*). 2) The lake should have an appropriate inflow of freshwater to prevent being dried out and to avoid flooding 3) Time and cost effectiveness
Decision Makers	1) For public infrastructure, the city government (CG) makes decisions in consultation with the people; the city congress represents the rights of people 2) The CG has functional departments carrying out their specific roles 3) The CG is also embedded in the provincial and national governments 4) At the household and private business levels, people make their own decisions.

(3) Goals, objectives, and decision makers.

FIGURE 2. General background information of the case study and the defined goals, objectives, and decision makers.

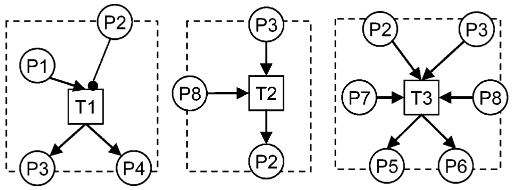
consumers use clean water and produce wastewater; "*T5*", urban runoff drainage—the urban area needs special care with respect to runoff drainage (e.g., storage, usage, discharge) and flood control during periods of rain; "*T6*", wastewater management—the construction of infrastructure systems to collect and treat wastewater to a certain standard before discharging it into the environment, and the proper disposal of "secondary pollutants", such as sludge; "*T7*", pollution control of receiving water—the city guarantees the ecological quality of water systems as a whole so as to sustain the well-being of the area. The cellular network models for three selected "transitions" from the overall urban water management systems are illustrated in Figure 3. Others are supplied in the Supporting Information.

Formulating strategies with decision variables. We defined each action planned in a strategy as an operation on decision variables. An important step is to define the decision variables so that strategic assumptions are made explicit (*20*). On the basis of the timed causal networks, eighteen important decision variables were identified—by sorting out the controllable variables from the complete list of state variables in **G**—and used for constructing strategies (Figure 4). We refer to the information in Figure 4 as the "control panel" upon which communications between decision analysts and decision makers can be based. Let S_1 be the assumed strategy shown in Figure 4. The "control panel" offers coherent decision variables for decision makers to explore alternatives. The presented decision variables in Figure 4 present example strategic assumptions rather than real predictions.

s_1 through s_{18} are the individual decision variables for constructing strategies. By modifying the decision variables, the strategy is revised. In general, there is by definition no fixed value of a decision variable and is up to the decision makers to select (*12*). The purpose of an exploratory model (*21*), such as the one developed here, is to assist decision makers in choosing the decision variable values so that, through computational assisted reasoning, better strategies may be identified.

Some of the decision variables are illustrated in the Supporting Information section except those readily discernible from Figure 4. In general we deal with three categories of decision variables, i.e., consumer dynamics and behavior (s_1–s_3, s_6), technical operations (s_7–s_{18}), and resource availability (s_4 and s_5). A number of Boolean variables are used to represent explicit conditions changes, e.g., s_8 represents the condition of "full operation of separate water supply systems". Other decision variables, e.g., s_{11}, represent incremental changes. Other discrete changes are stepwise, such as s_4, which denotes the local surface water resource available for urban water supply in the Dianchi Lake catchment area. We assume that it will increase stepwise after the year 2020 by taking adequate amounts of water from Dianchi Lake for urban water supply. The prerequisites for this will be that there is sufficient wastewater collection and treatment capacity so that the emission of pollutants into Dianchi Lake is reasonably controlled and that a separate (two pipe, two water quality) water supply system is adopted. Water from upstream reservoirs is used for the potable water supply system, with water from Dianchi Lake being used for non-drinking purposes.

Using Multiple Layers of Subsystems for LCI Models. The LCI model component **M** consists of two subsystems: the urban drainage system and the regional water balance (Figure 5). The system definitions are displayed in Figure 5 column 1 (the urban drainage system was illustrated in ref *17*, and the regional water balance was built upon the conceptualization and data source provided in ref *22*). The urban drainage model and the regional water balance model are linked via shared variables. The need to include both of these systems arises from the relations between water supply, urban drainage, and local water balance, which are the primary



Notations: *P* for place and *T* for transition; " —● " for conditional inhibitor, means the "transition" it links to can be inhibited by defined conditions. When the link is from *P* to *T*, it denotes that *P* is a precondition of transition *T*; and if the link is from *T* to *P*, it denotes that *P* is the direct consequence of transition *T*.

Transitions: *T*1 – urban development; *T*2 – water resource self-sufficiency; *T*3 – demand management

*Logical interpretations for cellular network model T*1 *and T*2:

*T*1 takes population and industrial growth *P*1 and water resource availability *P*2 as preconditions. When water resource availability is insufficient, transition "*T*1" can be inhibited, i.e., the simulation stopped. The direct "consequences" of transition "*T*1" are the changes on water consumers *P*3 and urban area *P*4.

*T*2: water availability contains two decision variables (see below), people can decide whether to take Dianchi Lake as water supply and how much to take depending on the situation, people can also decide whether to import water and how much to import from outside of the catchment. Therefore, logically *P*2 depends on *P*3 and *P*8. The logical interpretations of *T*3 is readily discernible.

List of "places" in timed causal network and their attributed variables

	Name	**State variables** $G \in \mathbf{G}$	**Unit**
*P*1	Population and industrial growth	1. Natural population growth rate	*%/a*
		2. Annual immigrants	*p/a*
		3. Local rural population transferred to urban population	*p/a*
		4. Ratio of industrial water consumption to household water consumption as an indicator for industry	-
*P*2	Water resource availability	1. Local water resource availability	m^3/a
		2. External water resource availability	m^3/a
*P*3	Water consumers	1. Total rural population	*p*
		2. Total urban population	*p*
		3. Industries in population equivalence of water consumption	*p*
*P*4	Urban area	1. Total impervious area of the city	*hectare*
		2. Pollution coefficients in runoff, e.g. for total phosphorous	mg/m^3
		3. Constructed new impervious area	*hectare*
*P*5	Supplied water	1. Normal quality water supply	*L/p.d*
		2. Excellent quality water supply	*L/p.d*
*P*6	Water supply infrastructure	1. Type of water supply system (two alternatives: either one pipe system or two pipe system with two water qualities)	-
		2. Losses from the water distribution net	*%*
*P*7	Ecological water demand	1. Minimum flow of urban rivers	m^3/s
		2. Maximum flow of urban rivers	m^3/s
		3. Frequency of dry weather flow when minimum flow needs to be enforced by discharging from upstream reservoirs	*%/a*
*P*8	Receiving water	1. TP tolerance in receiving water	*tons/a*
		2. Suitability as resource for local water supply	-

Note: "-" means no unit, "*p*" for persons, "*L/p.d*" for liters per capita and day, "m^3/s" for m^3 per second

FIGURE 3. Cellular network models for selected transitions of an urban water management system.

attributes of concern in the system. It is necessary to mention that the amount of water entering Dianchi Lake through groundwater flows remains unknown. Therefore, groundwater flows in the system are not included in this simulation.

3.3 Interpretation of Results from Strategy S_1. The simulation produces the potential impacts of assumed strategy S_1 over time period from year 2004 to 2040, and simultaneously generates two forms of figures. One is the distributed material flow diagrams (Figure 5) which is a plot of the static state of the system at sampled time. The other plot is of the temporal dynamics of sampled state variables over the whole time period (Figure 6).

For example, from the second column of Figure 5, we can observe from the upper figure that the large urban TP emission condition is due to wastewater overflow, wrong connections in the sewer system, and the very limited wastewater collection and treatment capacity available.

The lower figure in column 4 represents an overview of a long-term vision of regional water balance. By this time two separate water supply systems of two different qualities will be completed throughout the urban area. Water uptake from upstream reservoirs will only be distributed for drinking and cooking purposes, while water for other usages will be supplied from Dianchi Lake. A large percentage of the urban drainage discharge (410 million m^3/a) will be diverted through a bypass tunnel to rivers downstream of Dianchi Lake. Only limited discharge will be allowed to enter Dianchi Lake for the purpose of keeping the TP input from the city below the level of 33 tons/a. In such a setting, Dianchi Lake will receive more water discharged from the upstream reservoirs. The regional water balance can be maintained without requiring extra water resource imports, i.e., the water-import project to be in operation by the year 2008 will be enough to support the development of Kunming City and the water balance of Dianchi Lake for the future.

For more interpretations of Figures 5 and 6, please refer to the Supporting Information of this paper.

3.4 Scenario Analysis. A scenario describes a hypothetical future state of a system and provides information on its development (*23*). The development from the current state to a future state can vary widely depending on the strategies chosen. When the comparisons of scenarios are received and deliberated upon by the decision makers (*24*), better strategies may be identified. For example, Figure 7 illustrates

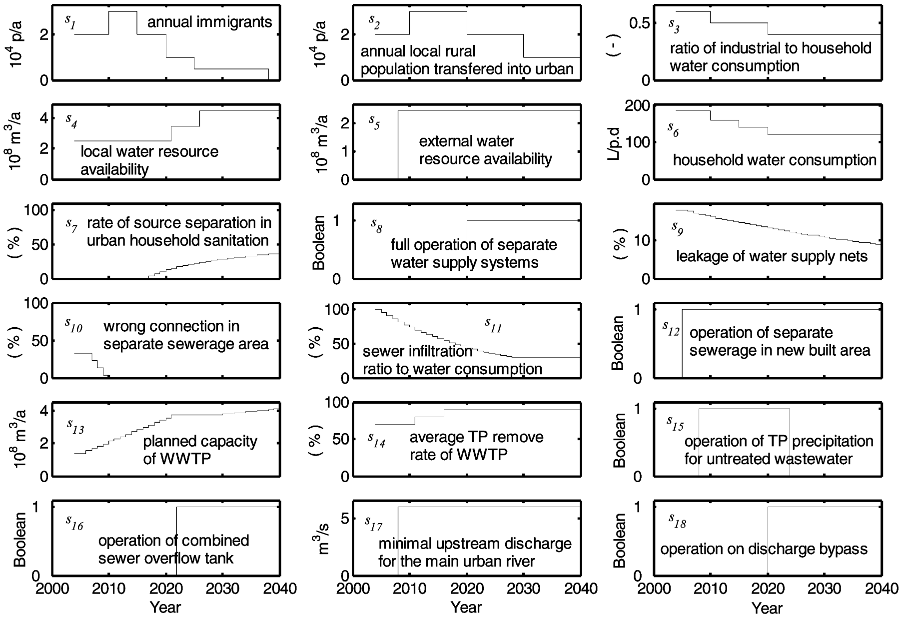


FIGURE 4. Identified decision variables and an example strategy as input for the system.

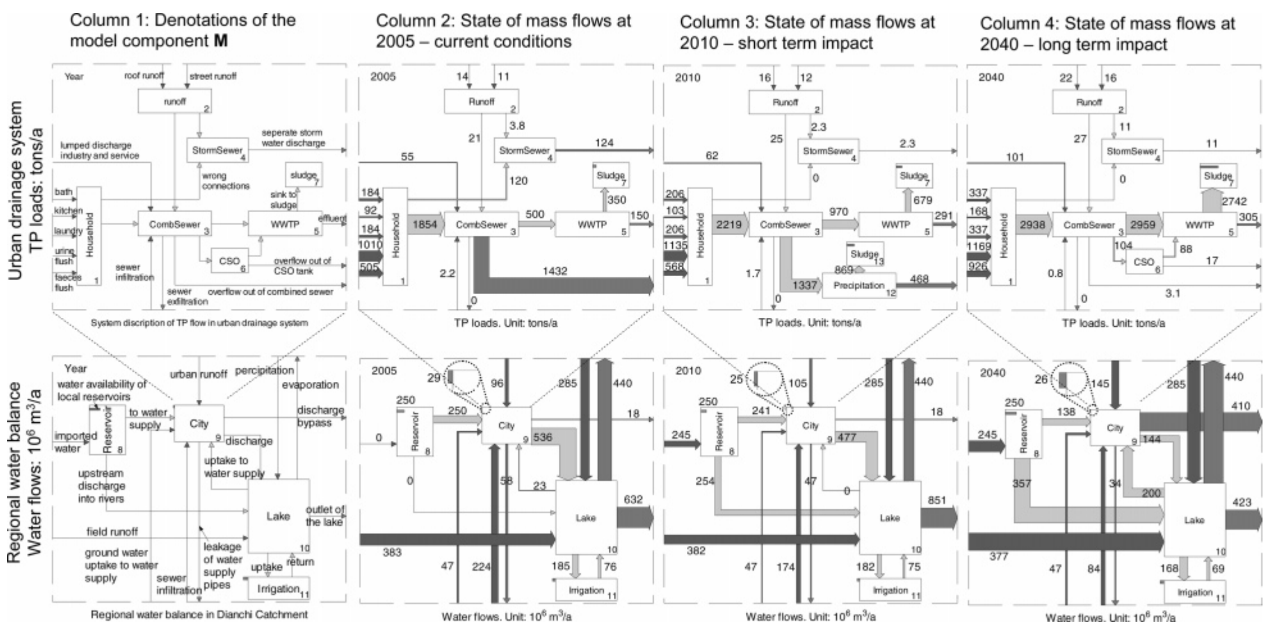


FIGURE 5. Distributed flow diagrams of the TP loads in the urban drainage system and of the water flows in the regional water balance system of Kunming resulting from strategy assumption S_1.

the effect of neglecting some of the decision variables, such as s_3, s_6, s_7, s_{11}, s_{13}, s_{15}, s_{16}, and s_{18}.

By comparing curves (1) and (2), we clearly see that without an adequate volume of wastewater being transferred to rivers below Dianchi Lake through a discharge bypass it would not be possible to limit the TP load entering Dianchi Lake within the budgeted level of 33 tons/a in the future. The intersection of curves (2) and (3) indicates that the quantities of TP reaching Dianchi Lake are significant if temporary TP precipitation at overflow canals is not used. The difference between curves (3) and (4) indicates the importance of water saving, in households as well as in industry. By comparing curves (4) and (5), the limited effect of CSO tanks (combined sewer overflow tanks for temporary overflow storage) in the context of applying S_1 is evident; suggesting that it only makes sense to implement CSO tanks after sufficient wastewater collection and treatment capacity are available in Kunming. The difference between curves (5) and (6) indicates the importance of controlling unwanted sewer infiltration. The comparison between curves (7) and (6) provides an indication of the potential benefit of source separation for human urine from domestic wastewater, provided feasible techniques are available in the future. Finally, curve (8) indicates the important role of increasing wastewater collection efficiency and treatment capacity.

The historical trajectory of the urban TP loads together with the large range of possible future trends in Figure 7 indicates the ineffectiveness of the historical interventions and the urgency for improving the strategy from now on.

3.5 How Structure Reduces Uncertainty. Different origins and types of uncertainty require different methods and means to cope (*25*, *26*). We distinguish between parametric and model structure uncertainty. Parametric uncertainty can be reduced by data quality improvement if a well-structured adequate model is given. Once a well-defined model structure is available, it is advisable to first perform quantitative scenario analysis for exploring combinations of decision variables as strategies. This offers directly relevant informa-

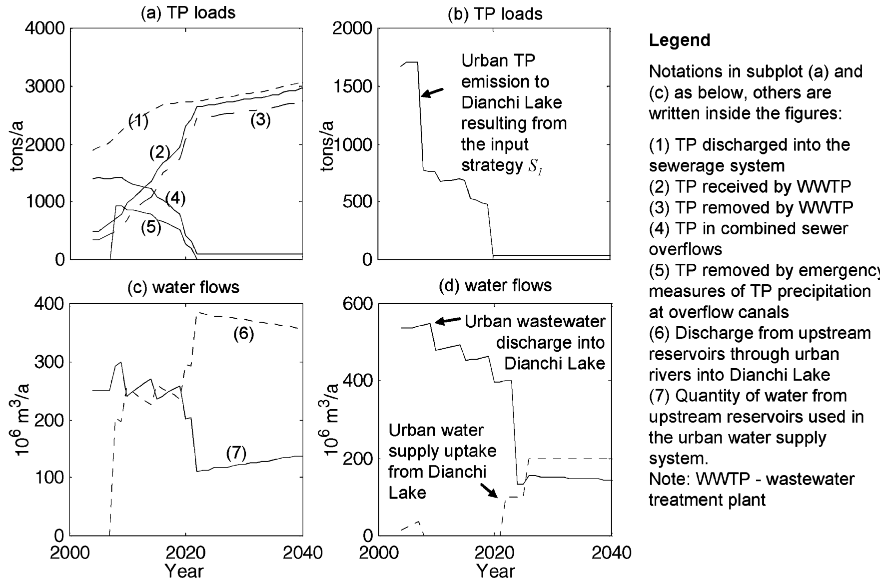


FIGURE 6. Temporal dynamics of sampled variables resulting from strategy S_1.

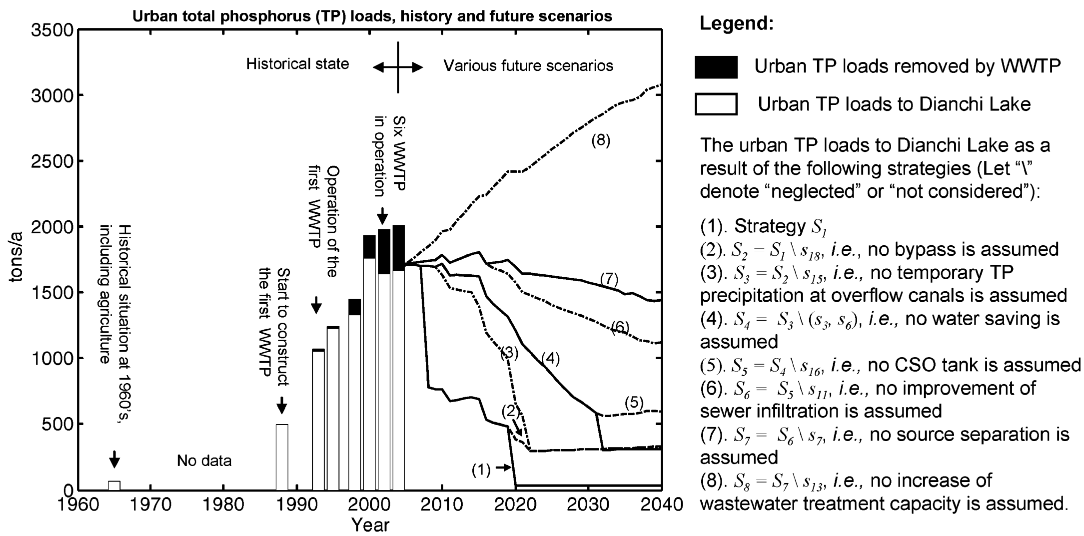


FIGURE 7. Urban TP loads to Dianchi Lake, history and future scenarios.

tion for strategy search and simplifies further probabilistic inquiries based on a limited number of plausible strategies, e.g., when using Monte Carlo simulations.

Model structure uncertainty is at least as important as parametric uncertainty. An improved model structure usually reflects improved understanding of the mechanisms of the system under study. Changes in the boundary conditions and the inside structure of a model can sometimes, if not always, be much more sensitive than parametric uncertainty. For example, the structure of the object model (LCI) indicates that neglecting the interdependencies of substructures of a model can cause significant model uncertainty. The structure of the timed causal network indicates that neglecting certain decision variables and their relations, represented by "places" and "transitions", can also induce considerable uncertainties.

Figure 7 shows the sensitivity of some strategy variations. The future trends of urban TP loads to Dianchi Lake range, but are not strictly limited to, between curve 1 and curve 8. The range depends greatly on what decisions are made and what actions are taken to shape the boundary conditions for the future. To reduce this type of uncertainty, it is almost imperative to provide understanding of the nature of the problem and the complex mixture of interdependencies in the systems. The improved model structure meets this need. As a further step, when a certain variable is considered to stochastically affect one or more variables, the technique of Bayesian networks can also be incorporated.

4. Discussion

This paper demonstrates that actions planned as part of a strategy can be treated as discrete events for simulation models, and that changes in environmental systems can then be viewed in terms of event-driven dynamics. The added value of the introduced model structure is that it offers an integrated overview of various strategies and their multidimensional effects on the environment through time in an efficient way. This efficiency can be seen in the following ways. First, the decision variables, as basic elements of a strategy, are made accessible to decision makers. Second, as a preprocessing model for subsequent environmental models, the timed causal network describes the boundary conditions of the environmental system in response to strategy changes. This offers a robust way in modeling the discontinuity of changes. Third, the distributed cellular representation enhances the interpretability and extensibility of the complex models.

It is worth noting that there are gaps remaining in the case application. On the one hand, we have not yet quantitatively modeled the uncertainties induced by data quality and time resolution. For instance, seasonal and yearly variations are not considered. On the other hand, a description would be helpful on how decision makers could utilize the simulation to improve their performance in solving the water problem in the case study area. These issues need to be further studied. It should also be noted that after controlling the urban TP emissions entering Dianchi Lake, TP loads from agriculture, nitrogen, biodiversity, and the resilience of the lake are all further concerns. Nevertheless, finding solutions will be an important collective task for both scientists and stakeholders. Up to now, the results of the case study have provided much helpful information which could not be efficiently acquired before. These results, if well represented and interpreted, will assist decision makers to apply an adaptive strategy which can stepwise lead to a wanted future.

In general, the proposed approach is designed as a flexible and extendable tool to construct, analyze, evaluate, and modify strategies, so that these complex environmental issues can be coped with better.

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Supporting Information Available

More explanations of the background of Kunming case; other transitions; explanations of the strategic assumption S_1 in Figure 4; results interpretations for Figures 5 and 6. This material is available free of charge via the Internet at http://pubs.acs.org. The computation codes are available by e-mail from the author.

Literature Cited

(1) Johnson, J.; Jirikowic, J.; Bertram, M.; Van Beers, D.; Gordon, R. B.; Henderson, K.; Klee, R. J.; Lanzano, T.; Lifset, R.; Oetjen, L.; Graedel, T. E. Contemporary anthropogenic silver cycle: A multilevel analysis. *Environ. Sci. Technol.* **2005**, *39*, 4655−4665.

(2) Lundie, S.; Peters, G. M.; Beavis, P. C. Life Cycle Assessment for sustainable metropolitan water systems planning. *Environ. Sci. Technol.* **2004**, *38*, 3465−3473.

(3) Curran, M. A. The status of life-cycle assessment as an environmental management tool. *Environ. Prog.* **2004**, *23*, 277−283.

(4) Burgess, A. A.; Brennan, D. J. Application of life cycle assessment to chemical processes. *Chem. Eng. Sci.* **2001**, *56*, 2589−2604.

(5) Werner, F.; Scholz, R. W. Ambiguities in decision-oriented life cycle inventories - The role of mental models. *Int. J. Life Cycle Assess.* **2002**, *7*, 330−338.

(6) Hertwich, E. G. Life cycle approaches to sustainable consumption: A critical review. *Environ. Sci. Technol.* **2005**, *39*, 4673−4684.

(7) Cassandras, C. G.; Lafortune, S. *Introduction to Discrete Event Systems*; Kluwer Academic Publishers: Boston, MA, 1999.

(8) Rios, P.; Stuart, J. A.; Grant, E. Plastics disassembly versus bulk recycling: Engineering design for end-of-life electronics resource recovery. *Environ. Sci. Technol.* **2003**, *37*, 5463−5470.

(9) Wohlgemuth, V.; Page, B.; Kreutzer, W. Combining discrete event simulation and material flow analysis in a component-based approach to industrial environmental protection. *Environ. Modell. Software* **2006**, *21*, 1607−1617.

(10) McDaniels, T. L.; Gregory, R. Learning as an objective within a structured risk management decision process. *Environ. Sci. Technol.* **2004**, *38*, 1921−1926.

(11) Morgan, M. G.; Cantor, R.; Clark, W. C.; Fisher, A.; Jacoby, H. D.; Janetos, A. C.; Kinzig, A. P.; Melillo, J.; Street, R. B.; Wilbanks, T. J. Learning from the U.S. National Assessment of Climate Change impacts. *Environ. Sci. Technol.* **2005**, *39*, 9023−9032.

(12) Morgan, M. G.; Henrion, M.; Small, M. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*; Cambridge University Press: Cambridge, 1990.

(13) Pearl, J. *Causality: Models, Reasoning and Inference*; Cambridge University Press: Cambridge, 2001.

(14) Barad, M. An introduction to Petri nets. *Int. J. Gen. Syst.* **2003**, *32*, 565−582.

(15) Sowa, J. F. *Knowledge representation: Logical, Philosophical, and Computational Foundations*; Brooks/Cole: Pacific Grove, CA, 2000.

(16) Ferber, J. *Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence*; Addison-Wesley: Harlow, 1999.

(17) Huang, D. B.; Bader, H.-P.; Scheidegger, R.; Schertenleib, R.; Gujer, W. Confronting limitations: New solutions required for urban water management in Kunming City. *J. Environ. Manage.* **2006**, In press. Online available: doi:10.1016/j.jenvman.2006.05.004.

(18) Gray, A. V.; Li, W. Case study on water quality modelling of Dianchi lake, Yunnan Province, South West China. *Water Sci. Technol.* **1999**, *40*, 35−43.

(19) Liu, Y.; Chen, J. N.; Mol, A. P. J. Evaluation of phosphorus flows in the Dianchi watershed, Southwest of China. *Population Environ.* **2004**, *25*, 637−656.

(20) Mitroff, I.; Emshoff, J. R.; Kilmann, R. H. Assumptional analysis - methodology for strategic problem-solving. *Manage. Sci.* **1979**, *25*, 583−593.

(21) Bankes, S. Exploratory modeling for policy analysis. *Oper. Res.* **1993**, *41*, 435−449.

(22) YEPO. *General plan of water resource in Dianchi Catchment - first phase report*; Yunnan Institute of Environmental Science, and Montogomery Watson, World Bank Yunnan Environment Project Office: Kunming, 1997.

(23) Scholz, R. W.; Tietje, O. *Embedded Case Study Methods: Integrating Quantitative and Qualitative Knowledge*; Sage: London, 2002.

(24) Stern, P. C. Deliberative methods for understanding environmental systems. *BioScience* **2005**, *55*, 976−982.

(25) Kahneman, D.; Tversky, A. Variants of uncertainty. *Cognition* **1982**, *11*, 143−157.

(26) Casman, E. A.; Morgan, M. G.; Dowlatabadi, H. Mixed levels of uncertainty in complex policy models. *Risk Anal.* **1999**, *19*, 33−42.

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