DISS. ETH NO. 16907

Dong-Bin Huang

A Discrete-Event Dynamic Systems Approach for Environmental Decision-Support

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

DISS. ETH NO. 16907

A Discrete-Event Dynamic Systems Approach for Environmental Decision-Support

A dissertation submitted to the

SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

for the degree of

Doctor of Sciences

presented by

DONG-BIN HUANG

MSc. Hefei University of Technology, China

born December 9th, 1969

citizen of P. R. China

accepted on the recommendation of

Prof. Dr. Roland W. Scholz, examiner
Prof. Dr. Willi Gujer, co-examiner
Dipl. Eng. Roland Schertenleib, co-examiner
Prof. Dr. Hansruedi Siegirst, co-examiner

2006

To the health of mother

Summary

The thesis aims to develop a model structure matching environmental strategic planning and policy research, which facilitates identifying the multiple elements of a strategy and explores the multi-dimensional effects of a strategy through time in an efficient way.

It conceptualizes a strategy as a set of sequential or concurrent 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. 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.

The thesis advances the state-of-the-art method of environmental strategic planning for large-scale, long-term projects with the following originalities: Firstly, it specifies and digitalizes a strategy with decision variables, and makes the multiple elements of a strategy accessible to decision makers. Secondly, it develops a timed causal network for identifying decision variables and modeling the boundary conditions of environmental systems. And thirdly, it develops a distributed representation of material flow diagrams and cellular networks enhancing the interpretability and extendibility of a complex model.

In general, the thesis brings forward a computational policy or strategy experimentation method that incorporates discontinuous changes. It offers also a way to identify the operational attributes of a strategy to be made. The scenario analysis based on the model structure is quantitative and dynamic. The computational method it applied also advances the dynamic material flow analysis, or dynamic life cycle inventory analysis, that may be used as a new tool for the field of industrial ecology. The generality of the model structure merits a wide application in environmental strategic planning and policy research, as well as environmental case studies.

As a result of this improved method, its application in the study of Kunming urban water management provided the following practical significance: (i) it integrates the cross-scale interdependencies of the urban drainage system and the regional water balance system; (ii) it identifies as many as eighteen decision variables for constructing various strategic assumptions on urban water management and simulates the impacts from the present till in the long term; (iii) it provides an holistic overview of the current situation, future limitations, potential solutions attributed with sequence and timing, as well as (iv) a tool for the decision makers to explore strategies for reaching the preferred and attainable future conditions.

The above merits together with its illustrative power of the model structure render it to be potentially very useful in the field of environmental decision-support.

Zusammenfassung

Ziel der Doktorarbeit ist es, eine Modellstruktur zu entwickeln, die an strategische Planung und Forschung angepasst werden kann. Das Modell soll es ermöglichen, die verschiedenen Elemente einer Strategie zu identifizieren und die mehrdimensionalen Effekte einer Strategie im Laufe der Zeit in einer effizienten Weise zu erforschen.

Der Begriff „Strategie" wird als eine Reihe von sequentiellen oder parallelen Ereignissen verstanden, die geplant werden, um ein bestimmtes strategisches Ziel zu erreichen. Die Arbeit entwickelt eine neue Form kausaler Netzwerke als überbrückende Komponente zwischen Entscheidungsträgern und Umwelt-Modellen. Das kausale Netzwerk behandelt den strategischen Plan als diskreten Input und leitet die aktualisierten Parametergruppen als Output an die darauf folgenden Umweltmodelle weiter. Dementsprechend kann die potentielle dynamische Entwicklung der Umweltsysteme, die durch verschiedene Strategien verursacht wird, stufenweise simuliert werden.

Die Arbeit entwickelt die state-of-the-art Methode der strategischen Umweltplanung für langfristige grosse und aufwändige Projekte weiter und zwar mit folgenden neuen Ansätzen: Erstens spezifiziert und digitalisiert sie eine Strategie mit Entscheidungsvariablen und macht dadurch die verschiedenen Elemente einer Strategie den Entscheidungsträgern zugänglich. Zweitens entwickelt sie ein zeitlich abhängiges, kausales Netzwerk für die Identifizierung von Entscheidungsvariablen und um die Randbedingungen der Umweltsysteme zu modellieren. Und drittens entwickelt sie eine verteilte Darstellung der Stoffflussdiagramme und Zellular-Netze, die die Interpretierbarkeit und Ausbaubarkeit eines komplexen Modells zu verbessern.

Grundsätzlich entwickelt die Arbeit eine computergestützte Methode zum Experimentieren mit Strategien, die diskontinuierliche Änderung aufnimmt. Es bietet auch an, Ansätze für vorzunehmende Veränderungen einer Strategie zu identifizieren. Die Szenarienanalyse, die auf der präsentierten Modellstruktur basiert, ist quantitativ und dynamisch. Die angewandte Berechnungsmethode entwickelte die dynamische Stoffflussanalyse und die dynamische Life-Cycle-Inventory Analyse weiter, welche als neue Werkzeuge für das Umfeld der Industrial Ecology genutzt werden können. Die Allgemeinheit der Modelstruktur ermöglicht eine breite Anwendung in der strategischen Umweltplanung und Policy Forschung, sowie bei Umweltfallstudien.

Resultierend aus dieser verbesserten Methode, stellte seine Anwendung in der vorliegenden Studie zur städtischen Wasserwirtschaft in Kunming die erste umfangreiche Strategie Analyse zur Verfügung. Die Fallstudie ist bis jetzt die erste Arbeit die: (i) cross-scale Abhängigkeiten des städtischen Entwässerungs-Systems und des regionalen Wasserhaushaltes integriert, (ii) achtzehn Entscheidungsvariablen für das Konstruieren der verschieden strategischen Annahmen im Hinblick auf das städtische Wassermanagement identifiziert und ihre Auswirkungen von der Gegenwart bis in die ferne Zukunft simuliert; (iii) einen holistischen Überblick über Ist-Zustand, zukünftige Beschränkung, und die möglichen Lösungen in ihre Zeitlichen Sequenzen beschreibt, so wie (iv) ein

Werkzeug für die Entscheidungsträge potenziale Strategien für das Erreichen der bevorzugten aber auch erreichbaren zukünftigen Systemszustände zu erforschen.

Mit den oben genannten Stärken und dem illustrativen Kraft, der Modellstruktur lässt sich eine signifikante Ansatz für die Entscheidungsunterstützung der Umwelt zu anwenden können.

Table of contents

A Discrete-Event Dynamic Systems Approach for 1

Environmental Decision-Support 1

A Discrete-Event Dynamic Systems Approach for Environmental Decision-Support 3

Summary 1

Zusammenfassung 2

Table of contents 4

1 Introduction 8

1.1 Goal of the thesis 8

1.2 Finding the gap 8

1.3 A traditional strength to keep and extend 11

1.4 Concepts and terminologies 11

1.5 An overview of the thesis 13

1.6 References 15

2 Confronting Limitations: New Solutions Required for Urban Water Management in Kunming City 18

Abstract 18

2.1 Introduction 18

2.2 Study area description 20

2.3 Method 22

2.3.1 System analysis 22

2.3.2 Model approach 23

2.3.3 Data acquisition and estimation 25

2.4 Results and discussions 31

2.4.1 Current conditions 31

2.4.2 Sensitivity and uncertainty analysis 32

2.4.3 Technical limitation 34

2.5 Discussion on measures 35

2.6 Conclusions 37

2.7 Acknowledgements 37

2.8 Reference 38

3 Discrete Event Simulation for Exploring Strategies: An Urban Water Management Case 41

Abstract 41

3.1 Introduction 41

3.2 Model Structure 42

3.3 Case Study ... 45
3.3.1 Problem Background ... 45
3.3.2 Application of discrete event simulation to urban water management. ... 45
3.3.3 Interpretation of results from strategy S_1 ... 49
3.3.4 Scenario analysis ... 50
3.3.5 How structure reduces uncertainty ... 51
3.4 Discussion ... 52
3.5 Acknowledgements ... 53
3.6 Surporting Information Available ... 53
3.7 Literature Cited ... 53
3.8 Supporting Information ... 56
3.8.1 More explanations on the background of Kunming case ... 56
3.8.2 Other transitions ... 56
3.8.3 Explanations on the strategic assumption S_1 in Figure 4. ... 58
3.8.4 Results interpretations for Figure 5 and Figure 6. ... 59
3.8.5 Literatures related to supporting information ... 61
4 Facilitating Strategy Exploration Using Discrete Event Systems Simulation for Environmental Planning ... 62
Abstract 62
4.1 Introduction ... 62
4.2 Model approach ... 64
4.2.1 General setting ... 64
4.2.2 Agent component ... 65
4.2.3 Strategy component ... 66
4.2.4 Timed causal network (TCN) ... 66
4.2.5 Object component (environmental system) ... 67
4.2.6 On the process of facilitation ... 68
4.3 Case study ... 68
4.3.1 Background and motivation ... 68
4.3.2 Agent Analysis ... 69
4.3.3 Object component of the case study ... 71
4.3.4 Developing the timed causal network thinking ... 71
4.3.5 Developing the strategy component ... 72
4.3.6 Information generating and interpreting ... 73
4.3.7 Discussions of the case study ... 78
4.4 General discussion ... 80
4.5 Acknowledgements ... 81
4.6 References ... 81
4.7 Appendix ... 85
5 Discussions ... 87
5.1 Nature of the contribution ... 87
5.2 Strategy exploration as an emerging theme for environmental decisions ... 87
5.3 Uncertainty types and improvement by model structure ... 88

5.4 Perspectives on the Kunming urban water management case ... 89
5.5 Reference ... 90

6 Appendix: Assessment Method for Evaluating Existing and Alternative Measures of Urban Water Management ... 91

Abstract 91

6.1 Introduction ... 91
6.2 System Comparison ... 92
6.3 Determination of Wastewater Origins Using Pattern Recognition ... 93
6.4 Determination of Extraneous Water by System Identification ... 96
6.5 Response Analysis for the Complete Urine Separation Scenario ... 97
6.6 Conclusions and Discussions ... 99
6.7 Acknowledgements ... 99
6.8 References ... 100

Acknowledgements ... 101

Curriculum Vitae ... 102

1 Introduction

The status of our environment is in fact the accumulated impacts of natural processes and human interventions in the past. We can assume that by viewing the human intervention as events occurring or enacted in discrete time, the state evolution of environmental systems can be treated as the behavior of a discrete-event dynamic system (Cassandras and Lafortune, 1999; Zeigler, et al., 2000).

1.1 Goal of the thesis

In simple terms, the thesis was initiated with the aim to develop a method for analyzing environmental impacts of various management alternatives. The urban water management in Kunming, a major city in Southwest China, is used as a case study.

The case study has the characteristics of a large-scale, long-term project. Various studies have been conducted on the pollution control of Dianchi lake in the Kunming area (Gray and Li, 1999; Huang, et al., 2006; KIES, 2003; Liu, et al., 2004; Tsinghua-University, et al., 2003; UTL, 2001; YEPO, 1997). No comprehensive strategic planning is available on the urban water management in Kunming and its interdependences with the pollution control of Dianchi Lake. Although previous studies did make efforts to provide solutions or at least strategic suggestions, none of them was based on a well structured, scientific approach and therefore has not adequately offered a clear image of what can be done immediately, and what can be done in the future to achieve the attainable goals. This situation has lead to a call for a shift in the understanding of the problem (Deng, 2006). Politicians have also called for decision support to take a broader and more responsible view (Hu, 2004; Li, 2005).

One of the reasons causing this situation is arguably that a powerful strategic planning tool for a problem of this kind (see Chapter 3, Case Study) has not been available. My view is that even the theoretical foundations for devising such tools have not, up to this point, been adequately established.

So, the major theoretical challenge targeted by this thesis is to identify the multiple elements of a strategy, and to explore the multi-dimensional effects of a strategy through time in an efficient way.

1.2 Finding the gap

Like business decisions which must be made based on the understanding of the specific business mechanisms, environmental decisions must also be grounded in the specific domains of knowledge of the relevant environmental systems. Therefore an environmental model is an indispensable component in supporting environmental decisions (Clark, et al., 2001; Pielke and Conant, 2003). However, the following two gaps are noticeable.

1.2.1 Inadequate model structure in representing driving forces and boundary conditions

An environmental model, by nature, describes the system area or environmental objects, usually a natural or technical part of the overall system of concern, governed by natural laws, *e.g.*, the mass and energy conservation laws. *Driving forces* are the strategies, policies and activities for achieving the multiple needs of human society, and enables the process of social-economic-environmental changes. *Boundary condition* of an environmental system refers to a structure in which the causal mechanisms of the related functionalities of environmental processes are described, as will be explained in Chapter 3.

For example, life cycle inventory (LCI), material flow analysis (MFA), and substance flow analysis (SFA), are a class of environmental models frequently applied in analyzing and assessing the environmental impacts attributed to the life cycle of a good or service (Brunner and Rechberger, 2004; Johnson, et al., 2005; Rebitzer, et al., 2004). Their applications in strategy analysis of urban water management are also reported (Jeppsson and Hellstrom, 2002; Lundie, et al., 2004; Lundin, et al., 2000). These methods, though labeled differently, fall into the same category of process-based input-output analysis. Since LCI is more generally accepted as an environmental assessment method, as a convention, the thesis uses LCI abbreviation to refer all the three methods mentioned above. LCI are usually based on a data base and computational models that specify the mass or energy transfer processes in the system being studied (Curran, 2004). Deficiencies have been identified in using it for decision support or policy making (Burgess and Brennan, 2001; Hertwich, 2005; Werner and Scholz, 2002). One problem lies in 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 represented.

Why is it important to represent the driving forces and boundary condition changes? An event-based view on the dynamics of environmental systems (Figure 1) demonstrates the reason. In accordance with this Figure: (1) the LCI describes the area of the system governed by a natural scientific law - the mass and energy conservation law; (2) The driving forces, i.e., policies, strategies and management events to be enacted, imposes its effects first on the boundary conditions and then on the environmental system.

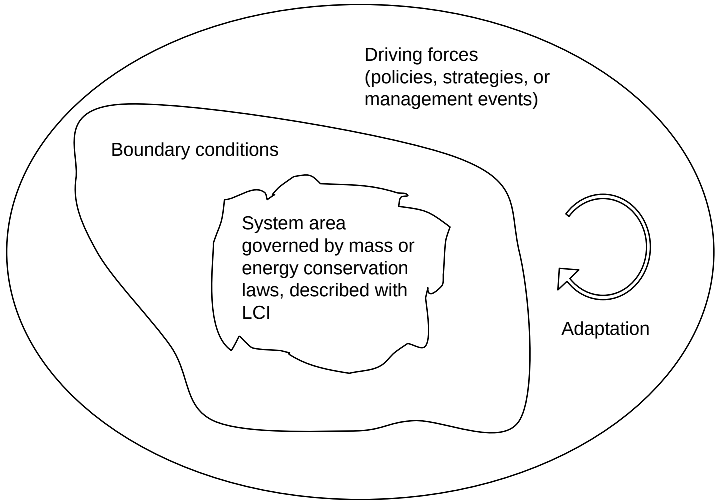


Figure 1. An event-based view on the dynamics of environmental systems

By so seeing, the thesis devises the model structure in such a way that the boundary conditions' model plays two roles: (1) identifying a holistic set of decision variables and making them accessible for decision makers who construct the strategies. Otherwise decisions can be mistaken by overlooking important decision variables, i.e., by inadequate search for alternatives (Nutt, 2004; Nutt, 2005); (2) preprocess a change in policy and strategy to guarantee its cascading effect on other interrelated parameters is computed before being used as an updated boundary condition for the LCI models Otherwise potential impacts can be mistaken by overlooking the cascading parameter changes triggered by a strategy modification.

1.2.2 Limitations of static and continuous dynamic modeling in strategy analysis

At present, most LCI practices are still based on static models. One reason is that some of the decision problems are intrinsically static, and do not need to involve dynamic solutions. For example, activities such as, evaluating a current situation of an environmental system, or to assess a scenario under certain timeless assumptions, only require static models. Nevertheless, when sequence and timing of actions are involved, the static model approach is not more appropriate.

Most present dynamic simulations in environmental modeling define the differential equations on state variables continuously within a time frame. However, in reality, actions and policy interventions on the environmental system occurs in discrete time and in a certain sequence. The elasticity of boundary conditions being modified by the society can not be dealt efficiently with continuous equations.

There is an increasing demand for developing means to model the discrete dynamics of environmental system in the context of policy analysis. The concern is clearly stated in

Morgan, et al., (2005) that "*most people, including most academically trained analysts, are better equipped to analyze incremental rather than revolutionary change. Nonetheless, if a reasonable range of plausible futures is to be crafted in future assessments, participants will have to increase their comfort with employing diverse methods of assessing both smooth and nonlinear trajectories.....*"

1.3 A traditional strength to keep and extend

From the material flow analysis literature, a technique of *material flow diagram* shows its power in providing an explicit overview and solid quantifications on how a system functions (Baccini and Bader, 1996; Brunner and Rechberger, 2004; Schwarzenbach, et al., 1999). It traces the origins, flows, and the fates of a material or substances through enough detailed processes within a system of concern. It is in fact a quantified *process diagram*, with all the *stocks and flows* interactively labeled by simulation. Due to its important role in decision support, the *process diagram* has been put as one of the key elements of an environmental management system, as it can be used to facilitate understanding, enhance communication, and verify the material's disposition (Matthews, et al., 2004). The technique does have its strength in quantifying the flows and visualizing the processes at a system level. Therefore it is meaningful to keep this strength in the new model structure.

However, the multi-level and cross-scale interactions of processes, and the dynamic properties in system configuration responding to management events, call for a more robust representation. Thus, the thesis also develops a technique of *distributed material flow diagrams* (DMF diagram) being generated as the simulation proceeds. The DMF diagrams reflect two aspects of integration (1) vertical integration on different system levels, scales or parts; and (2) horizontal integration on time, *where*, for each time step, a static diagram can be produced. The vertical integration is developed by simply sharing variables between the distributed parts, while the horizontal integration is produced using discrete dynamic simulations.

The benefits of DMF diagram are (1) it represents a large system in distributed cellular mode, and holds power in reusability, extendibility, and interpretability; and (2) it represents a holistic overview on various levels and scales at any sampled time from the simulated dynamic evolution of the systems resulting from different strategic assumptions.

1.4 Concepts and terminologies

Discrete event (dynamic) system (DES) is an established sub-field of system theory and applied mathematics since 1980's (Ho, 2006). The event-based view on the dynamics of environmental systems lays the foundation for the method development. However, the thesis builds upon but is not restricted by the established DES theory and methods. For example, for a discrete event system that has multiple processes or transitions, Petri nets is usually a suitable model approach. However, "*most real world problem will require so large a Petri nets that there does not exist a paper large enough to draw the Petri net diagram*", and therefore it is "*mostly used to illustrate academic examples or small scale real timing problems*" (Ho, 2006). In the modeling part of boundary conditions the thesis utilizes the basic axioms of Petri nets, and clusters the variables and their relations, and decomposes the whole network into a cellular network.

As a preparation, fundamental concepts and terminologies are introduced in Table 1.

Table 1. Concepts and terminologies

Concept	**Definition**
Discrete event system	*Discrete event system* is a *discrete-state*, *event driven* system; its state evolution depends on the occurrence of asynchronous and concurrent discrete *events* over time. Examples of discrete event systems include queuing systems, computer systems, communication systems, manufacturing systems, traffic systems, database systems, software systems, monitor and control of complex systems (Cassandras and Lafortune, 1999).
Event	An *event* defines an occurrence or a process, both of which cause changes from one state to another.
Discrete state	In a *discrete-state* model, the dynamics of the state are the trajectories of stepwise static state evolving over time.
Time driven	If a system state is expected to change as a function of time, then it is called *time driven*, such models are frequently described with differential equations.
Event driven	If a system state including its configuration is expected to change with an occurrence of an event or process, it is called *event driven.*
State	The *state* of a system at time t_0 is the information required at t_0 such that output $y(t)$, for all $t \geq t_0$, is uniquely determined from this information and from input $u(t)$, $t \geq t_0$ (Cassandras and Lafortune, 1999).
Transition	Intuitively, *transition* means change from one to another. In discrete event system theory, a transition refers to an entity that modifies the state of a system. In can be an event, computation step, signal processor, task or job, clause in logic or information processing etc. (Murata, 1989).

1.5 An overview of the thesis

The main body of the thesis contains three chapters. As an initial state analysis, Chapter 2 describes the current conditions assessment (Huang, et al., 2006). This is a logical beginning because a strategy analysis almost always starts with a diagnosis on the current situation, from where the future starts to evolve (Grant, 2005).

Chapter 3 and 4 develop the core of the theory and extend the scope of the case study. The event-based view (see Figure 1) on the dynamics of environmental system lays a conceptual foundation. It is developed into a model structure (Figure 2) illustrated in Chapter 3 and 4 with different focuses. Chapter 3 focuses on the inner loop (single lined in Figure 2) while Chapter 4 focuses on the outer loop (double lined).

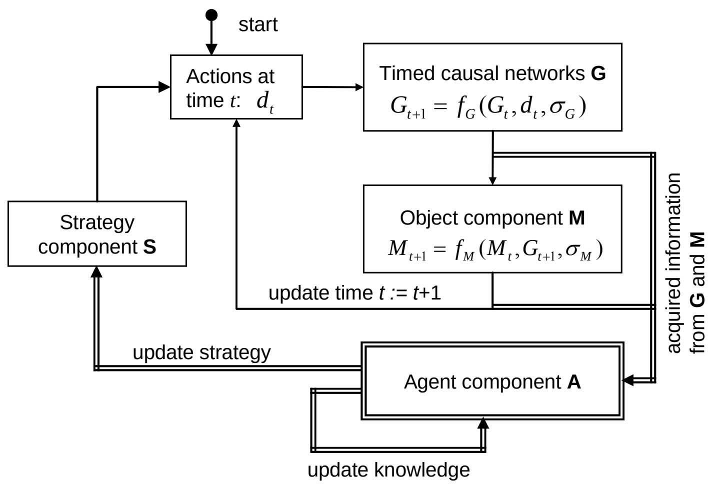


Figure 2. The model structure that implements discrete event dynamics of environmental systems

The conceptual links between the event-based view and the developed model structure are as follows:

The object component **M** is developed to represent the system area governed by mass or energy conservation laws. In the case study application, it consists of two interlinked levels of subsystems described with LCI models: the urban drainage system of Kunming City and the regional water balance system of the Dianchi Lake catchment. The timed causal network, component **G** in the model, is developed for modeling the boundary conditions, where the causal mechanisms that govern the dynamics of the environmental system are represented. The driving forces are described with the strategy component **S** explicitly with decision variables, each of which is well defined within a time horizon appropriately long to attract the concern of decision makers or stakeholders. Lastly, the "adaptation" in Figure 1 is transformed into a process with the agent component **A** in the model, Figure 2.

All together, an overview of the thesis is provided in Table 2.

Table 2. An overview on the research questions, purpose and building blocks

Chapter	Research questions or purpose	Building blocks
2	(1) What are the current conditions of the urban drainage system in Kunming? (2) What is the best condition attainable by conventional urban drainage and wastewater treatment? What does it imply for the future?	- A material flow analysis on the current urban drainage system in Kunming City, including data calibration, sensitivity and uncertainty analysis and scenario analysis. The scenario analysis in this chapter is a static quantitative approach. - The current condition analysis identified the severity of the problem, a BAT (best available technology) scenario analysis indicated the technical limitation to be confronted with, and the scenarios suggested several potential strategic changes to be made.
3	(1) What is the new model structure that assists identifying the multiple elements of a strategy and exploring the multi-dimensional effects of a strategy though time? (2) How the discrete-event dynamic systems simulation is enabled with the life cycle inventory analysis and material flow analysis method for environmental strategic planning?	- A general model structure that enables discrete event dynamic systems simulation for environmental strategic planning. The focus is limited on the simulation modeling part (**S,G,M**). - A method of *timed causal network* (TCN) is developed to identify decision variables and model the causal mechanisms governing the dynamics of the environmental systems. - A distributed material flow diagram technique. - A dynamic quantitative scenario analysis. - A model-based strategy analysis on the urban water management of Kunming City
4	- How to facilitate strategy exploration of a top management team, assumed as a unitary agent, with the proposed model? - How to integrate qualitative and quantitative approaches for environmental strategic planning?	- An upgraded illustration on the model structure, and agent component on the basis of Chapter 3. - Strategy-exploration facilitation is structured and preliminarily implemented with a top management team on water management in Kunming, with the assistance of the model presented. - Integrating hard operation research (OR) method with soft OR method in a general setting.

An additional paper (Huang, et al., 2003) is presented as an appendix chapter of the thesis. This chapter describes a method to determine the origins of the wastewater in Zurich wastewater treatment plant Werdhölzli based on a statistical pattern recognition analysis on the time series of flow measurement. This paper contributes to the thesis in that it provides a background understanding on the urban drainage system in Zurich, and later on is utilized as a reference system for the BAT scenario analysis.

1.6 References

Baccini, P., Bader, H.-P. 1996. *Regionaler Stoffhaushalt Erfassung, Bewertung und Steuerung*. Heidelberg etc.: Spektrum.

Brunner, P. H., Rechberger, H. 2004. *Practical handbook of material flow analysis*. Boca Raton, FL: Lewis Publishers.

Burgess, A. A., Brennan, D. J. 2001. Application of life cycle assessment to chemical processes. *Chemical Engineering Science*, 56(8), 2589-2604.

Cassandras, C. G., Lafortune, S. 1999. *Introduction to discrete event systems*. Boston: Kluwer Academic Publishers.

Clark, J. S., Carpenter, S. R., Barber, M., Collins, S., Dobson, A., Foley, J. A., Lodge, D. M., Pascual, M., Pielke, R., Pizer, W., Pringle, C., Reid, W. V., Rose, K. A., Sala, O., Schlesinger, W. H., Wall, D. H., Wear, D. 2001. Ecological forecasts: An emerging imperative. *Science*, 293(5530), 657-660.

Curran, M. A. 2004. The status of life-cycle assessment as an environmental management tool. *Environmental Progress*, 23(4), 277-283.

Deng, D. R. 2006. *Personal communication*. Kunming: Expert leader of Dianchi Lake Protection Bureau.

Grant, R. M. 2005. *Contemporary strategy analysis* (5th ed.). Malden, Mass.: Blackwell Publishing.

Gray, A. V., Li, W. 1999. Case study on water quality modelling of Dianchi lake, Yunnan Province, South West China. *Water Science and Technology*, 40(2), 35-43.

Hertwich, E. G. 2005. Life cycle approaches to sustainable consumption: A critical review. *Environmental Science & Technology*, 39(13), 4673-4684.

Ho, Y. C. (2006). Personal communication. Harvard University.

Hu, X. (2004). Personal communication. Vice Mayor of Kunming City Government. Kunming.

Huang, D. B., Bader, H.-P., Scheidegger, R., Schertenleib, R., Gujer, W. 2006. Confronting limitations: New solutions required for urban water management in Kunming City. *Journal of Environmental Management*, In press. Online available: doi:10.1016/j.jenvman.2006.05.004

Huang, D. B., Schertenleib, R., Siegrist, H., Larsen, T. A., Gujer, W. (2003). Assessment method for evaluating existing and alternative measures of urban water management. In *the 2nd International Symposium on Ecological Sanitation* (pp. 749-756). Lübeck, Germany: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.

Jeppsson, U., Hellstrom, D. 2002. Systems analysis for environmental assessment of urban water and wastewater systems. *Water Science and Technology*, 46(6-7), 121-129.

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. 2005. Contemporary anthropogenic silver cycle: A multilevel analysis. *Environmental Science & Technology*, 39(12), 4655-4665.

KIES. (2003). *Investigation of pollution sources of Dianchi Lake*. Kunming, China: Kunming Institute of Environmental Science.

Li, J. W. (2005). *Talk on the environmental protection issues of Kunming City, Kunming City Congress.*Unpublished manuscript.

Liu, Y., Chen, J. N., Mol, A. P. J. 2004. Evaluation of phosphorus flows in the Dianchi watershed, Southwest of China. *Population and Environment*, 25(6), 637-656.

Lundie, S., Peters, G. M., Beavis, P. C. 2004. Life Cycle Assessment for sustainable metropolitan water systems planning. *Environmental Science & Technology*, 38(13), 3465-3473.

Lundin, M., Bengtsson, M., Molander, S. 2000. Life cycle assessment of wastewater systems: Influence of system boundaries and scale on calculated environmental loads. *Environmental Science & Technology*, 34(1), 180-186.

Matthews, D. H., Christini, G. C., Hendrickson, C. T. 2004. Five elements for organizational decision-making with an environmental management system. *Environmental Science & Technology*, 38(7), 1927-1932.

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. 2005. Learning from the US National Assessment of Climate Change impacts. *Environmental Science & Technology*, 39(23), 9023-9032.

Murata, T. 1989. Petri Nets - Properties, Analysis and Applications. *Proceedings of the Ieee*, 77(4), 541-580.

Nutt, P. C. 2004. Averting decision debacles. *Technological Forecasting and Social Change*, 71(3), 239-265.

Nutt, P. C. 2005. Search during decision making. *European Journal of Operational Research*, 160(3), 851-876.

Pielke, R. A., Conant, R. T. 2003. Best practices in prediction for decision-making: Lessons from the atmospheric and earth sciences. *Ecology*, 84(6), 1351-1358.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B. P., Pennington, D. W. 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30(5), 701-720.

Schwarzenbach, R. C., Scholz, R. W., Heitzer, A., Staubli, B., Grossmann, B. 1999. A regional perspective on contaminated site remediation - Fate of materials and pollutants. *Environmental Science & Technology*, 33(14), 2305-2310.

Tsinghua-University, KIES, KIWM. (2003). *Planning for Round Dianchi Lake Ecological Conservation*: Department of Environmental Science and Technology Tsinghua University, Kunming Institute of Environmental Science, Kunming Institute of Water Management.

UTL. (2001). *Final Report - evaluation of the present situation of remediation measures and elaboration of the proposals for the improvement of Dianchi Lake*. Kunming, China: UTL-Umwelttechnik Leopoldau and Kunming Institute of Environmental Science.

Werner, F., Scholz, R. W. 2002. Ambiguities in decision-oriented life cycle inventories - The role of mental models. *International Journal of Life Cycle Assessment*, 7(6), 330-338.

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

Zeigler, B. P., Praehofer, H., Kim, T. G. 2000. *Theory of modeling and simulation: Integrating discrete event and continuous complex dynamic systems* (Second ed.). San Diego: Academic Press.

2 Confronting Limitations: New Solutions Required for Urban Water Management in Kunming City[1]

Abstract

Despite continuous investment and various efforts to control pollution, urban water environments are worsening in large parts of the developing world. In order to reveal potential constraints and limitations of current practices of urban water management and to stimulate proactive intervention, we conducted a material flow analysis of the urban water system in Kunming City. The results demonstrate that the current efficiency of wastewater treatment is only around 25% and the emission of total phosphorous from the city into its receiving water, Dianchi Lake, is more than 25 times higher than its estimated tolerance. With regard to the crisis of water quantity and quality, the goal of a sustainable urban water environment cannot be attained with the current problem-solving approach in the region due to the technical limitations of the conventional urban drainage and treatment systems. A set of strategies is therefore proposed. The urban drainage system in Zurich is used as a reference for a potential best-available technology for conventional urban water management (BAT) scenario in terms of its low combined frequency of sewer overflow.

Keywords: Eutrophication; Material flow analysis; Scenario planning; Urban water management

2.1 Introduction

Worldwide research activities are undertaken in the field of urban sanitation to find and test alternative solutions such as source control or ecological sanitation (Larsen and Gujer, 1996; Otterpohl et al., 1999; Langergraber and Muellegger, 2005). However, these alternatives are rarely applied in urban areas at present. The construction of water infrastructures using the prevailing end-of-pipe technology is still the first choice in practice. As an example, Kunming City (the capital of Yunnan Province in southwest China), has been trying to improve its urban water environment since the late 1980s. Eutrophication caused by rapid urbanisation and an inadequate urban water infrastructure is currently one of the most intractable water problems in Kunming. It is questionable whether this problem can be

---

[1] This chapter is accepted for publication in the Journal of Environmental Management on 5 May 2006. The authentic journal version is available on www.elsevier.com/locate/jenvman. Authors: Dong-Bin Huang, Hans-Peter Bader, Ruth Scheidegger, Roland Schertenleib, Willi Gujer.

solved by the prevailing end-of-pipe technology. In other words, what are the technical and economic limits of these practices? How can these limits be overcome? Decision makers and planners require this type of knowledge to avoid pitfalls and to help them make better decisions and plans (Clark et al., 2001). Kunming is adjacent to the sixth largest body of fresh water in China, namely Dianchi Lake. Due to the severity of its pollution and its important role in water supply, local climate, flood control and tourism in the region, it has been listed in the "Three Important Lakes Restoration Act in China" (KIES, 2003). The city currently faces a difficult dilemma: whereas on the one hand many efforts have been undertaken to improve the local water environment, the pollution problem is still overwhelming. And on the other hand, the city is growing and its dependence on the lake, though already severely problematic, is also growing.

Despite this dilemma, solutions need to be found to avoid the destruction of Dianchi Lake, especially as similar problems are faced by most of the large lakes in China, such as Taihu, Chaohu and Dongtinghu (SEPA, 2001). There is a strongly held local belief that freshwater lakes, including their ecological and hydrological functions, should not be diminished by the careless interference of human beings (Li, 2005). It is evident from the regular updated planning efforts, institutional reorganisation and the large investment already made that both political planners and the public want to return Dianchi Lake to its historical pristine state.

Gray and Li (1999) reported that if Dianchi Lake is to have the high water quality it had in the 1960s, the annual total phosphorous (TP) inflow through surface water should be less than 60 tons per year. (Although this critical value may depend on the amount of water flowing through the lake, it is reasonable to take this value as a critical requirement for preventing eutrophication of the lake.) This report drew a pessimistic conclusion: "The TP load reduction envisaged as realistic would only stabilises the lake water quality by about the year 2008; unfortunately, interventions could not return the lake to its former pristine condition."

If we take the current ratio of the TP load into Dianchi Lake from the urban drainage system to that from agriculture, namely 55:45 (KIES, 2003) as our reference value for the future, then 27 tons/year of TP load can be budgeted for agricultural sources while the maximum TP input from the city to Dianchi Lake should not exceed 33 tons per year.

Wastewater discharge from urban drainage systems currently accounts for the main nutrient load to Dianchi Lake (KIES, 2003; Liu et al., 2004). Reliable quantifications of the flows of total nitrogen (TN) and TP in urban drainage systems are currently of major concern. The objective of this paper is consequently to answer the following questions:

- What are the current conditions of the urban drainage system in Kunming?
- What is the best condition attainable by conventional urban drainage and wastewater treatment? What does it imply for the future?

2.2 Study area description

Kunming City is situated upstream of Dianchi Lake (Fig. 1). The boundary of the study area is the urban settlement of Kunming City within the catchment area of Dianchi Lake. It is being enlarged as the city develops. Its population has grown eightfold since 1950 and is currently approximately 2.4 million. Large population transfers from rural to urban areas are to be expected for two reasons: (1) the limited arable land and jobs in agriculture; (2) the large economic income gap between urban and rural citizens; the current ratio is 3:1 in Kunming (KMSB, 2003; KPB, 2004). According to KPB (2004), the population within the Dianchi catchment area is expected to reach between 4.5 and 5.6 million.

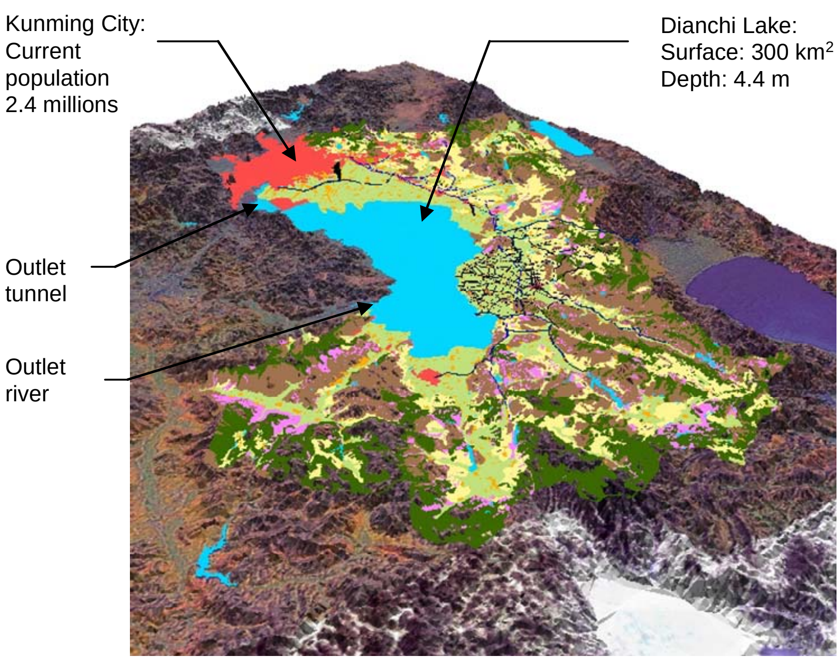


Fig 1. Kunming and Dianchi Lake, geographical position (satellite picture source: ORL/ETHZ, 2002)

Dianchi Lake has a surface area of 300 km^2 and an average depth of only 4.4 meters. The water surface is at 1886.5 m above sea level. The inflow of the lake is mainly from the upstream reservoirs and from rain runoff in the greater Kunming catchment area. Outflow is ultimately discharged into Yangtze River. Urbanisation and lifestyle change has on the one hand supplied citizens with convenient water and sanitation service, but on the other hand has caused severe eutrophication of the lake since 1980s (Liu, Chen et al. 2004).

The reference study area is the catchment of wastewater treatment plant (WWTP) Werdhölzli Zurich, Switzerland. This area is not a focus of this paper, but serves as a guide for the best available technology (BAT) scenario with regards to the conventional urban drainage systems with an overflow frequency as low as 1%. Basic comparison information is listed in table 1. The population in Zurich City has been stabilized since 1950. Its reliable urban water management system has contributed to its clean water environment and the living quality of the city.

Table 1: Basic information on case study areas

	Urban population (millions)	urban area (hectare)	impervious area percentage	connection to water supply	status of urban drainage system
Kunming	2.4	18000	68%	100%	incomplete[a]
WHZH[b]	0.45[c]	5770	43%	100%	complete

[a]: The quantitative value of wastewater collecting rate is to be identified in this study.

[b]: WHZH here denotes for catchment area of wastewater treatment plant (WWTP) Werdhölzli, in Zurich.

[c]: including inhabitants, commuters and travellers, commuters are assumed to stay in the city for an average of 9 hours on every working day (data source on commuters: Statistics Zurich City, 2003).

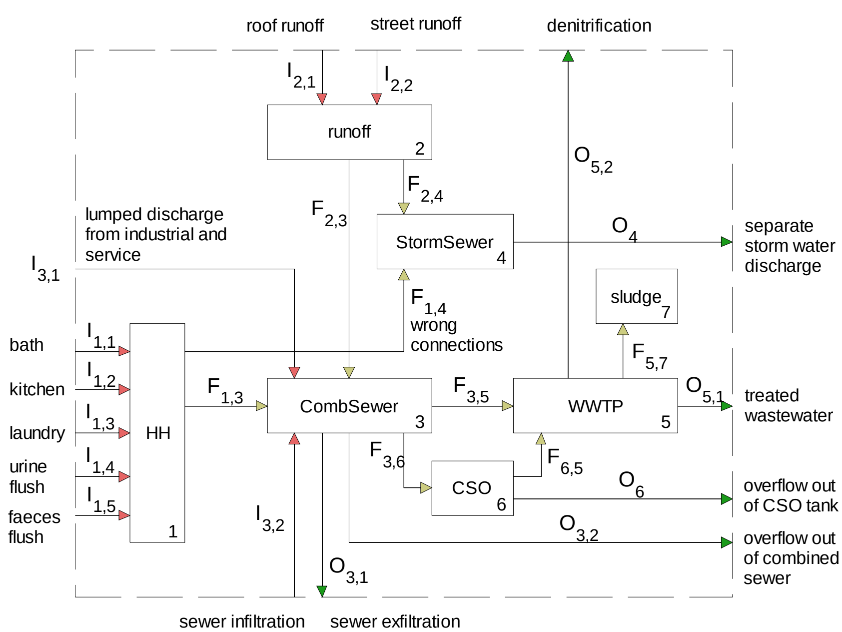


Fig. 2. System description of the urban drainage system. "HH"—household, "StormSewer"—separated storm sewer, "CombSewer"—combined sewer. In the case of Kunming, this is a conceptualisation of the mixed sewers—open canals that are used for conveying wastewater. The CSO detention tank is included in the system for scenario analysis. However, it is currently not a component of the urban drainage system in Kunming. Since separate storm sewers exist only in one residential area of Kunming, only wrong connections from households to storm sewers are considered.

2.3 Method

The method used is a mathematically extended material flow analysis. It describes, quantifies and models the material flows of the system considered (Baccini and Bader, 1996). The method consists of four steps: (1) system analysis, (2) model approach, (3) data acquisition and calibration and (4) simulations including a sensitivity and uncertainty analysis. Studies of material flow analyses in urban water management and related problems can be found in Herrmann and Klaus (1997); Gray and Becker (2002); Jeppsson and Hellstrom (2002); Jönsson (2002); Tangsubkul et al. (2005) and Schmid et al. (2004).

2.3.1 System analysis

The object of the study is defined as the urban drainage system of Kunming City. Its components and flows are described in Fig. 2. The system consists of seven balance volumes (boxes in Fig. 2) and 23 flows (arrows in Fig. 2). The water, TN and TP flows (in a stationary state, with time resolution of 1 year) of the system described are studied.

Balance volumes

(1) Household wastewater (HH): all households connected to the sewage system.

(2) Runoff collection (Runoff): all places with rain runoff from a pool of impervious areas.

(3) Combined sewers (Comb.sewer): containing wastewater from household, industry and service, urban runoff and sewer infiltration flow (for definition, refer Section 3.3.4). In many cases, this volume comprises a mixture of pipes, open canals and covered ditches.

(4) Separate storm sewer system (Storm sewer): storm water runoff collected separately from sanitary sewers. Wrong connections can occur in the case of careless construction and management. This leads to sewage in storm water pipes and vice versa.

(5) WWTPs of the city.

(6) Combined sewer overflow tank (CSO): This is widely implemented as a component of urban drainage systems in Switzerland. In heavy rain events, the CSO acts as temporary storage. The stored overflow of wastewater is later pumped into the WWTP for treatment, and this overflows when the runoff exceeds its operational volume. This is currently not a component in Kunming.

(7) Sludge production from WWTP (Sludge): This is an important sink for pollutants. Whether it goes for incineration, landfill, agricultural reuse or any other disposal is not considered in this paper.

Flows

There are three types of flows described in the defined system, i.e. input flows, internal flows and output flows. Input flows $I_{1,1}$,….,$I_{1,5}$ are the household wastewater flows. The five categories are: "bath", "kitchen", "laundry", "urine flush" and "faeces flush". Separating household wastewater flows into categories allows for consideration of source control strategies (Henze 1997; Larsen and Gujer 2001). Input $I_{2,1}$ and $I_{2,2}$ are the roof and street runoffs respectively. $I_{3,1}$ is the industrial wastewater and $I_{3,2}$ the infiltration water.

$F_{i,j}$ denote the various internal flows, from balance volume *i* to *j*.

Output flows $O_{3,1}$ and $O_{3,2}$ are the sewer ex-filtration and the combined sewer overflow. O_4 is the storm water discharge, $O_{5,1}$ and $O_{5,2}$ are treated wastewater and emission to air respectively, and O_6 the CSO overflow.

2.3.2 Model approach

Thirty variables were used to describe the system, namely seven stock change rates (see below) and 23 flows. There are a total of 90 variables for water (30), nitrogen (30) and phosphorous (30). The equations describing the system behaviour in mathematical terms consist of the seven balance equations and 23 model equations for water and the two substances. According to the current state of system knowledge, a modified input–output model was chosen to adequately describe the current conditions and to assess the possible scenarios of the system. The simulation of current conditions, the sensitivity and uncertainty analysis, the BAT and other scenario analyses were performed using the SIMBOX simulation programme.

Modelling approach for water

Stock change rates. Since the analysis presented here is based on yearly averaged flows, it can be assumed that the stock change rates are zero except for the "sludge" balance volume, which is a sink especially for nutrients.

Conventions. For flow variables, let superscript denote materials or substances, subscript denote the balance volume in question. Let $Itot$ be the total inflow into a certain balance volume, including all input flows and inter-compartment flows that enter into that balance volume.

Input equations.

$$I_1 = P \cdot \begin{bmatrix} p_1 & p_2 & p_3 & p_4 & p_5 \end{bmatrix}^T \cdot 365 \qquad (1)$$

"T" in (1) means the transpose of the vector.

$$I_2 = P \cdot H \cdot A \cdot 10^4 \cdot \begin{bmatrix} r \cdot p_6 \\ (1-r) \cdot p_7 \end{bmatrix} \qquad (2)$$

$$I_{3,1} = P \cdot p_8 \cdot 365 \qquad (3)$$

where P : population of sanitation connected households

$p_{1,\dots,5}$: specific wastewater flows per person and day from bath, kitchen, laundry, urine flush and faeces flush respectively in [l / cap day]

H : rainfall in [mm / year]

A : specific impervious area per capita in [m^2 / cap];

r : fraction of roof area in impervious area

p_6 : net runoff coefficient of roofs

p_7 : net runoff coefficient of streets

p_8 : specific wastewater per person and day from industry in [l / cap day]

The factor 365 transforms daily flows to yearly flows.

Input-output equations

$$F_{1,4} = k_{1,4} \cdot Itot_1 \quad (4)$$

$$F_{2,3} = k_{2,3} \cdot Itot_2 \quad (5)$$

$$F_{6,5} = k_{6,5} \cdot Itot_6 \quad (6)$$

$$O_{3,1} = k_3^{(1)} \cdot Itot_3 \quad (7)$$

$$O_{5,1} = k_5^{(1)} \cdot Itot_5 \quad (8)$$

$$O_{5,2} = k_5^{(2)} \cdot Itot_5 \quad (9)$$

where $k_{i,j}$ is the transfer coefficient from balance volume i to balance volume j. $k_i^{(j)}$ is the transfer coefficient from balance volume V_i to the j-th output of V_i, e.g. $k_3^{(1)}$ is the transfer coefficient of water from V_3 (combined sewer) to its first output flow $O_3(1)$.

$$k_{1,4} = p_9 \cdot p_{10}$$

p_9 : fraction of people living in areas with separated storm sewerage systems

p_{10} : fraction of wrong connections that connect household wastewater to the storm sewer system in separated sewerage areas

$$k_{2,3} = p_{11} + (1 - p_{11}) \cdot p_{12}$$

p_{11} : fraction of impervious area which is by design connected to combined sewer within the whole area

p_{12} : fraction of wrong connections that connect storm water to sanitary sewer systems in separated sewerage areas

Specific equations

Infiltration:

$$I_{3,2} = p_{13} \cdot (F_{1,3} + I_{3,1}) \quad (10)$$

Input into WWTP and CSO:

$$F_{3,5} = \begin{cases} F_{capac} & Itot_3 - F_{2,3} - O_{3,1} \geq F_{capac} \\ Min(F_{capac}, Max(k_{3,5} \cdot (Itot_3 - O_{3,1}), Itot_3 - F_{2,3} - O_{3,1})) & Itot_3 - F_{2,3} - O_{3,1} < F_{capac} \end{cases} \quad (11)$$

$$F_{3,6} = Min(k_{3,6} \cdot (Itot_3 - O_{3,1}), Itot_3 - F_{2,3} - O_{3,1}) \quad (12)$$

where p_{13} is the ratio of infiltration to sanitary wastewater. F_{capac} is the operating capacity of WWTP per year, equivalent to treated wastewater quantity, in [l / year]. The first case in equation (11) describes the situation where the capacity of the WWTP is smaller than $Itot_3 - F_{2,3} - O_{3,1}$, which is the output of wastewater from combined sewer during dry weather conditions. This is the current conditions in Kunming. The second case of equation (11) describes the transfer of wastewater to WWTP if the capacity is higher. The Min/Max condition guarantees that $F_{3,5}$ is continuous as a function of $Itot_3$, $F_{2,3}$, $O_{3,1}$ and F_{capac}.

Note that the transfer coefficients $k_{3,5}$ and $k_{3,6}$ refer to the total input into combined sewer reduced by the ex-filtration: $Itot_3$ - $O_{3,1}$. The Min... condition in equation (12) is responsible that $F_{3,5}$ + $F_{3,6}$ is not greater than the output of combined sewer.

Model approach for N and P

The model approach for nitrogen and phosphorous can easily be set out on the basis of the following principles: The inputs I_1 and $I_{3,1}$ are similarly given as in equations (1) and (3). For the inputs I_2 and $I_{3,2}$ the concentrations are given as parameters. Ideal mixing is assumed in balance volumes V_1, V_2, and V_4. Therefore the flows $F_{1,4}$, and $F_{2,3}$ are related to the total input of their origin balance volumes and the corresponding water flows. For Nitrogen and phosphorous the transfer coefficients of WWTP to treated wastewater, to sludge and to air are given. For the current conditions, ideal mixing in a "combined sewer" is assumed whereas for BAT for the flows $F_{3,6}$, $F_{6,5}$, $O_{3,1}$ and $F_{3,5}$ the transfer coefficients are given.

2.3.3 Data acquisition and estimation

Due to the scarce data in Kunming, we combined available Kunming data, data from literature, and data from reference cases in Zurich to estimate the values of the parameters. The idea of plausible reasoning (Collins and Michalski 1989; Wagman 2003) is helpful in this process.

Data for household wastewater flows

According to Water Supply Zurich (2001) the water consumption pattern in Zurich is approximated as: Bath : Kitchen : Laundry : Urine Flush : Faeces Flush = 7 : 4 : 4 : 4 : 1. For Kunming the similar water consumption pattern is assumed.

The total wastewater quantity from households in Kunming is estimated as follows based on (Yang and Zhang, 2005): 1. the total water production is: 2.4×10^8 m^3 / year; 2. the industrial production (from groundwater) is: 4.8×10^7 m^3 / year; 3. the losses in distribution systems are estimated at 18%; 4. industrial water consumption is 9.0×10^7 m^3 / year, 5. losses, including evaporation through industrial processes, is approximately 20% of industrial water consumption. Based on these data, household wastewater production in Kunming City is approximately 185 l / cap.day, slightly higher than that of the Swiss average of 162 l / cap.day (SVGW 2002). However, the distribution loss in Kunming system is much higher. From the household wastewater and the consumption pattern above, the specific wastewater production pattern (parameter p_1, ..., p_5) listed in table 2 follow.

Data for roof and street runoff

The yearly rainfall in table 2 is the long term average over 30 years. The normal yearly variation is ± 200 mm (Task group urban water planning Kunming, 1990). The impervious area of roofs and streets were obtained by multiplying the urban area of Kunming City 18000 hectare (table 1) with the ratio of impervious area, i.e. 68% (Statistic Yearly Report, Kunming City, 2004). From (Herrmann and Klaus 1997), it can be inferred that the ratio of roof area to street area is 1:1 for European cities. Obviously population density and building density in Kunming is higher. Ratio of roof area to street area is assumed to be approximately as 3:2 in consensus with the local planning institute in Kunming (KIES, 2003).

The runoff coefficients of roofs and streets (p_6 and p_7) are assumed to be the same. However, since Kunming is on a high plateau, has more intense sunshine, and a dry and windy climate, evaporation is expected to be relatively higher. Since Zurich's runoff coefficient for impervious areas is 0.85 (Gujer 1999), runoff coefficient for impervious areas in Kunming is estimated to be 0.75 ± 0.05.

Transfer coefficients

There is currently no CSO tank in Kunming urban drainage systems, hence for simulation of the current conditions: $k_{3,6} = k_{6,5} = 0$. According to (KMSC 2003), approximately 20% of the city's population live in an area where a separated storm sewerage system is used ($p_9 = 0.2$). In this area, the wrong connection rate p_{10} is approximately 1/3. This leads to a wrong connection transfer coefficient $k_{1,4} = p_9 \cdot p_{10} = 0.067$. The fraction of area that is connected to the combined sewer system is 80% ($p_{11} = 0.8$); it is worthwhile to notice that although in this specific case $p_9 + p_{11} = 1$, but it is not always so, because p_9 is a ratio of population, while p_{11} is a ratio of area. The ratio of wrong connections of runoff to sanitary sewer in the area with separated storm sewerage is 1/6 (p_{12}). Hence, the transfer coefficient from runoff to combined sewer $k_{2,3} = p_{11} + (1 - p_{11}) \cdot p_{12} = 0.83$.

For transfer coefficient $k_5^{(1)}$ (WWTP to treated wastewater) and $k_5^{(2)}$ (WWTP to air), we first assume that the evaporation of water in WWTP to the air can be neglected, i.e. $k_5^{(2)}$ is set as 0 for water, then $k_5^{(1)}$ is 1 minus the percentage of dewatered sludge production. Since Kunming is applying mechanical dewatering process without anaerobic sludge digestion, we could assume that dewatered sludge production is between 0.4 – 1 l / cap.day based on empirical data (Herrmann and Klaus 1997; Lenz 2004). Assuming the average total wastewater production is 500 l / cap.day (including admixture of infiltration, industrial wastewater, rain runoff), the transfer coefficient of water from WWTP to sludge is between 0.0008 - 0.002, hence, $k_5^{(1)}$ is between 0.998 – 0.9992. It is nevertheless necessary not to approximate this value to one; the difference is the dewatered sludge production.

Table 2: Upper part: Calibrated data sets for material flow analysis of urban drainage system Kunming, current conditions. Lower part: data sets for BAT scenario

Data sets for simulation of current conditions					
	items	Q litre/cap·day	TN g/cap·day	TP g/cap·day	data source
	grey water	(1)	(2)	(2)	(1) KMWS [a],
p_1	bath	65(±20%)	0.3±10%	0.2±10%	2003
p_2	kitchen	37(±20%)	0.2±10%	0.1±10%	(2)Herrmann,
p_3	laundry	37(±20%)	0.3±10%	0.2±10%	1997.
	black water				
p_4	urine flush	37(±20%)	9.6±10%	1.1±10%	Jönsson, H.
p_5	faeces flush	9(±20%)	1.4±10%	0.55±10%	2003
p_8	industry	80 (±20%)	1.4(±20%)	0.06(±20%)	KIES [b], 2003
	items		TN	TP	data source
C_{roof}	average concentration in roof runoff (mg/l)		0.5 – 2.0	0.1 – 0.4	Boller, 2005
C_{street}	average concentration in street runoff (mg/l)		2.3 ± 0.5	0.28 ± 0.1	Boller, 2005
C_{infil}	average concentration in infiltration (mg/l)		0.02 ± 50%	0.01 ± 50%	estimation
η_c	remove rate		0.56±10%	0.7±10%	KMSC [c], 2003
$k_{5,7}$	N transfer coeff. WWTP to sludge		0.16±10%		KMSC, 2003
$k_5^{(2)}$	P transfer coeff. WWTP to air			0	Gujer, 1999
	items			water	data source
H	rain (mm)			1005±20%	KIES, 2003
A	specific impervious area (m²/cap)			51±20%	KMSC, 2003
r	fraction of roof area in impervious area			0.6 ±10%	KIES, 2003
p_6	runoff coefficient of roof area			0.75±0.1	estimation
p_7	runoff coefficient of street area			0.75±0.1	estimation

p_9	fraction of people living in separated storm sewerage area		0.2±20%		KMSC, 2003
p_{10}	wrong connection rate in separated storm sewerage area		1/3±30%		KMSC, 2003
p_{11}	rate of impervious area connected to combined sewerage system		0.8±20%		KMSC, 2003
p_{12}	wrong connection rate that connect runoff by mistake to combined sewer in designed separated storm sewerage area		1/6±30%		KMSC, 2003
p_{13}	ratio of infiltration to foul wastewater discharge		1±0.3		parameter estimation
$k_5^{(1)}$	transfer coefficient of water to treated wastewater		0.998 – 0.9992		Herrmann 1997 & Lenz, 2004
$k_5^{(2)}$	transfer coefficient of water to air		0		assumption
$k_3^{(1)}$	transfer coefficient water to exfiltration		0		assumption
F_{capac}	average operating volume [b] (l / cap.day)		160(±10%)		KMSC, 2003
Data sets for BAT scenario (based on estimates of Zurich)					
p_{10}	wrong connection rate in separated storm sewerage area		0		assumption
p_{12}	wrong connection rate that connect runoff by mistake to combined sewer in designed separated storm sewerage area		0		assumption
p_{13}	ratio of infiltration to foul wastewater discharge		0.3		assumption
	items		TN	TP	data source
η_c	remove rate		0.62	0.98	ERZ 2003 for TN, Siegrist [d] (2005) for TP
	items	water	TN	TP	data source
$k_{3,5}$	Transfer coeff. combined sewer (cs) -> WWTP	0.9	0.965	0.965	(ERZ 2003)
$k_{3,6}$	Transfer coeff. cs ->CSO	0.095	0.034	0.034	(ERZ 2003)
$k_{6,5}$	Transfer coeff. CSO ->WWTP	0.84	0.84	0.84	(ERZ 2003)

[a]: KMWS – Kunming Water Supply

[b]: KIES – Kunming Institute of Environmental Science

[c]: KMSC – Kunming Municipal Sewerage Co.

[d]: personal communications

[e] :ERZ – Entsorgung und Recycling Zurich

Estimating infiltration and exfiltration water

Infiltration is undesired non-polluted water entering into the sewer system which leads to poor performance of the system (Weiss, Brombach et al. 2002). It includes the flows from ground water infiltration through cracks or open sewers, and also river water that connected to sewers as well. Exfiltration is wastewater that leaks out of sewers into the ground through cracks or unimproved sewer systems. Exfiltration rates are dependent on ground water levels and left uncontrolled harm ground water quality. These two "hidden" flows are usually ignored in planning of urban water management systems.

Kunming is a shallow ground water region. Ground water table ranges from 0.4 to 2.5 meters under ground surface (Song 2005), while depth of sewer pipe being constructed underground ranges from 1 – 8 m (KMSC 2003). This is to say, a large part of sewer system is actually below the water table. Since the ground water level in Kunming is high, the exfiltration can be assumed to be insignificant. Therefore $k_3^{(1)}$ is assumed to be zero.

A direct measurement of the infiltration is not practicable. An estimation based on the dilution of the inflow to WWTP is proposed. For dry weather conditions holds:

$$F_{1,3}^{(s)} + I_{3,1}^{(s)} + I_{3,2}^{(s)} = C_{3,5}^{(s)} \cdot (F_{1,3}^{(w)} + I_{3,1}^{(w)} + I_{3,2}^{(w)}) \qquad (13)$$

$C_{3,5}^{(s)}$ is the dry weather concentration of substance s in the inflow to WWTP.

From equation (13) for N and P and the model equations of section 3.2, the concentrations $C_{3,5}^{(N)}$ and $C_{3,5}^{(P)}$ as a function of the infiltration parameter p_{13} can be calculated. The results are shown in Fig. 3. Comparing these values with measured values for $C_{3,5}^{(N)}$ and $C_{3,5}^{(P)}$ allows an estimation of p_{13}. Unfortunately the sampling scheme for chemical analysis of WWTP in Kunming is basically instant sampling, i.e. an instant wastewater sample for analysing concentrations is usually taken at approximately 9:00 AM. However what is needed is daily average concentration of TN and TP. So we need to adjust the value of 9AM sample to daily average value according to the hourly variation patterns.

After cautiously studying the local measured data and combining expert knowledge, experience of local engineers, we made two operations here: First, for getting the average concentration of TN and TP, we select WWTP No. 2 Kunming whose inflow concentration of TN and TP is not influenced by the recirculation from sludge dewatering processes. The plausibility of taking this WWTP as the representative for the "average" condition for determining sewer infiltration in Kunming is not to be discussed in this paper; (2) Secondly, an empirical ratio C_{9AM}/C_{av} (notes: C_{9AM} - 9 AM concentration; C_{av} - average daily concentration) was obtained by comparing the hourly variation of water consumption in Kunming with that of Zurich City. Data from both cities showed similar patterns in the morning. Therefore it was assumed that the empirical ratio of C_{9AM}/C_{av} of Zurich would be the similar as for Kunming. 10% of uncertainties were assumed. A reliable measurement for such a task would require "flow-proportional sampling" technique.

Based on this scheme we derived a range of average concentration of TN in wastewater in Kunming as: 20 – 28 mg / l; and TP as 3.6 – 4.8 mg / l for dry weather conditions (Table 3). The parameter p_{13} is then estimated as 1 ± 0.3 based on the above analysis, which means that under dry weather conditions the influent to WWTP consists of 50% ± 15% of relatively unpolluted infiltration water.

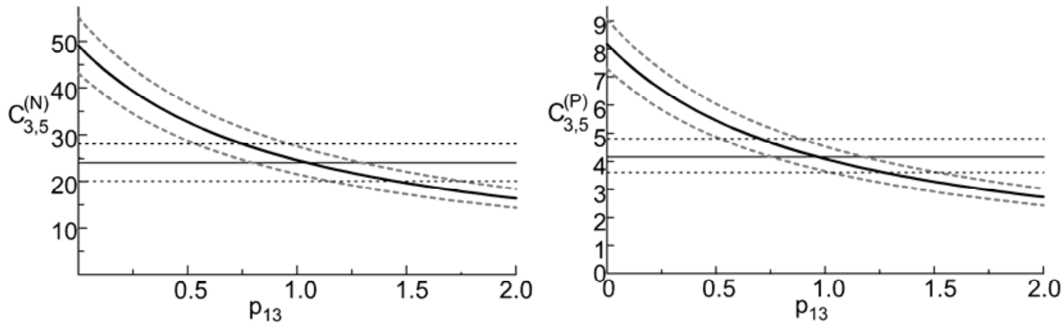


Fig. 3. Calculated concentrations $C_{3,5}^{(N)}$ and $C_{3,5}^{(P)}$ in function of parameter p_{13}. The dashed line indicates the range of uncertainty.

Table 3: Adjust 9 AM sample concentrations into daily average concentrations, in dry weather conditions

	9 AM sample concentration, dry weather	Empirical ratio of C_{9AM} / C_{av}	Calibrated daily average concentration, dry weather
$C_{3,5}$(N)	33±2	1.26 ~ 1.54	20 ~ 28
$C_{3,5}$(P)	3.4±0.2	0.74 ~ 0.90	3.6 ~ 4.8

Capacity of WWTP

According to KMSC (2003), the operational volume of all WWTP in Kunming is measured by ultrasonic water level measurements in a Venturi channel. The current operational volume of all WWTP in Kunming totals 1.4×10^8 m^3 / year with an uncertainty of ± 20%. It is worthy to notice that we are referring to the average operational volume instead of design capacity of WWTP.

Data for specific pollutants emission pattern

Diet plays an important role in the nutrients contained in human waste. Jönsson and Vinneras (2003) studied the relation between food consumption and nutrient emission out of human waste. He showed that unlike India, Africa and other developing countries, the Chinese diet produces more phosphorous and potassium, but less nitrogen in urine compared with that of Europe. The fraction of TN and TP originating from human waste in China is taken from Jönsson and Vinneras (2003) (table 2).

Data on grey water emission is summarized by Herrmann and Klaus (1997). Industrial emissions are measured by local environmental agencies (KIES 2003).

Data for concentrations in rainwater and infiltration

In case of solid waste being well collected and disposed, urban runoff is not a major source of nitrogen and phosphorous. Data collected in Switzerland by Boller (2005) for TN and TP is used in this study, since nutrients in urban runoff are not sensitive quantities for the problems of interest in the system described here. Heavy metals are of more concerns in urban runoff (Boller 1997; Zobrist, Muller et al. 2000).

An average concentration of TN and TP in infiltration is assumed based on the ground water quality data (KIES, 2003) to be: 0.02 mg / l of TN and 0.01 mg / l of TP, both with 50% of uncertainty (table 2).

Data for transfer coefficients of N and P of WWTP

The current average efficiency of TN and TP removal in WWTP Kunming is 56% and 70% respectively (KMSC 2003). Since the transfer coefficient of nitrogen from WWTP to sludge is primarily dependant on the heterotrophic growth of biomass, i.e. less dependent on nitrogen removal processes, it can be assumed to be a constant for WWTP with different nitrogen removal efficiencies. Therefore, it is assumed to be similar to general literature data $k_{5,7}^{(N)} = 0.16$ (Herrmann and Klaus 1997); for TP the transfer coefficient to air $k_5^{(2)}(P) =$ 0.

2.4 Results and discussions

2.4.1 Current conditions

Simulation results for the current conditions of water, TN and TP flows in the urban drainage system of Kunming are illustrated in Fig. 4. The main results for the current status can be summarised as follows:

(1) The efficiency of the current wastewater collecting system (i.e., the ratio of wastewater treated in the WWTPs versus the overall incoming wastewater) in Kunming is less than 30%. As a result, large amounts of wastewater are discharged into receiving waters without treatment.

(2) Sewer infiltration is as high as 100% of the total quantity of sanitary wastewater discharged into the sewer system during dry weather; this is a major problem for the current sewer system in the city.

(3) The emission of TP from the current urban drainage system is more than 20 times higher than the total tolerance level of Dianchi Lake estimated by Gray and Li (1999).

(4) The existing wrong connections alone contribute more than twice the TP tolerance of Dianchi Lake.

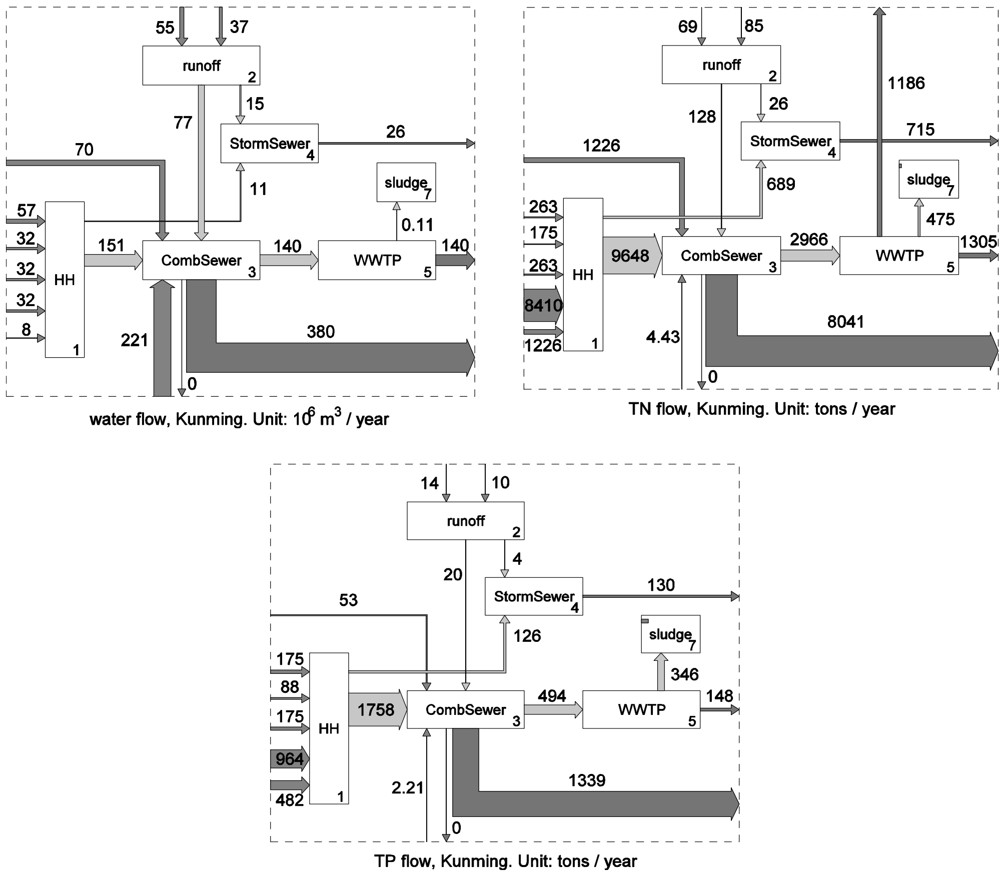


Fig. 4. Current conditions—material flow scheme of water, TN, TP in the urban drainage system of Kunming City. For descriptions about flows, refer to Fig. 2.

Table 4
Results comparison with Liu 2004 and Liu 2005

TP flows (tons / year)	Denotation in model	Liu, 2004	Liu, 2005	This paper
Human waste	$I_4 + I_5$	1601	895	1446 ± 150
Input WWTP	$F_{3,5}$	581	533	488 ± 108
Overflow	$O_{3,2}$	0	233	1339 ± 84
Effluent WWTP	$O_{5,1}$	150	138	148 ± 44
WWTP to sludge	$F_{5,7}$	430	394	346 ± 81

Table 4 compares the TP results of Liu et al. (2004); Liu (2005) and of this paper. As can be seen from the table, previous studies greatly underestimated the overflow load because they overlooked the large amount of sewer infiltration, including both groundwater and river water, entering the sewerage system.

2.4.2 Sensitivity and uncertainty analysis

To identify the most sensitive parameters for the total emission of the whole system, a sensitivity analysis is conducted by altering each of the parameters by 10%. It showed that the most sensitive parameters with respect to the total output to receiving waters are the population in the catchment area, the specific emission per person and day from urine and faeces, the WWTP capacity and the treatment efficiency. The sewer infiltration flow is currently one of the key reasons for reduced wastewater collection and treatment efficiency. However, it must be pointed out that this is only true for the set of parameters used for the current conditions. Other parameters may be more sensitive for other parameter sets.

Uncertainty analysis is a necessary way of estimating the uncertainty of the simulation results. The uncertainty of the parameters in Table 2 was estimated using comparative literature data and plausibility arguments. A log-normal probability distribution was assumed for the parameters of Table 2 with given mean and standard deviation in %. A uniform distribution was assumed for the parameters given by ranges.

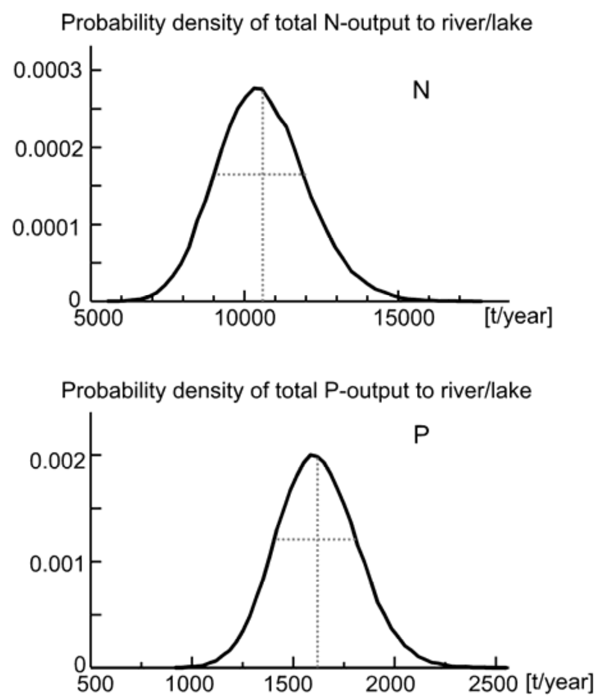


Fig. 5 Uncertainty analysis—probability density of the total output of TN and TP (in tons/year) to receiving water from the current urban drainage system in Kunming in terms of the uncertainties of all parameters involved.

A Monte Carlo simulation with a sample size of 100,000 was applied to calculate the distribution of the flows and stock change rates. Fig. 5 shows the result for the flows of nitrogen and phosphorous to the receiving water. Thus even taking into account the large uncertainties of the data, the phosphorous flow to the receiving water is far beyond the critical load of Dianchi Lake (33 tons/year of TP from the urban drainage system).

2.4.3 Technical limitation

In this analysis, we apply the scenario of BAT to the case of Kunming. It is assumed that Kunming will upgrade its urban drainage system to the standard of Zurich and all WWTPs will use BAT for their wastewater treatment. For the BAT scenario, the operational data of CSO tanks in Zurich are used for calculating the transfer coefficients $k_{3,6}$, $k_{3,5}$, $k_{6,5}$, etc. It is important to note the differences of these transfer coefficients between water and other substances, because the CSO occurs at heavy rain events when wastewater is diluted. The details are listed in Table 2.

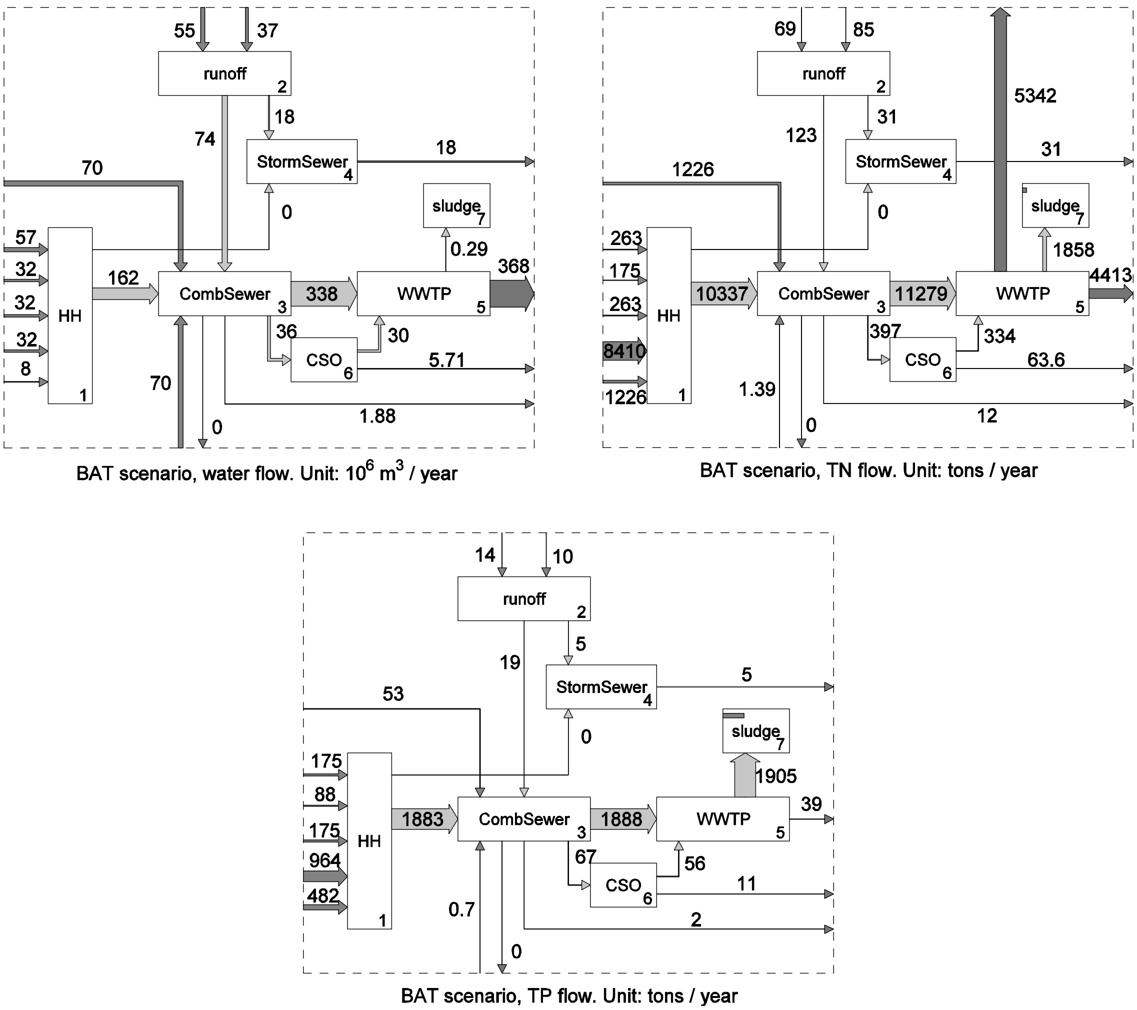


Fig. 6 BAT scenario—material flow scheme of water, TN and TP of the urban drainage system in Kunming for the best-available technology. For descriptions about flows, refer to Fig. 2.

In the BAT scenario, wrong connections are eliminated by properly standardised industrially designed pipes and by sewerage construction management. Sewer infiltration is controlled to a range of approximately 30% of water consumption. Simulation results (Fig. 6) show the emissions from the urban drainage system with the BAT to be about 39 tons/year from WWTP effluent and 11 tons/year from CSO tank overflow. Moreover, 2 tons/year from high-water discharge ($O_{3,2}$ in Fig. 2 for the BAT scenario), and 5 tons from separated storm-water discharge (20% of area connected to separated storm sewerage). Altogether the emission into receiving water is approximately 57 tons/ year, which is about 1.7 times the estimated critical value for the urban drainage system. Therefore, even with a BAT dimensioned for the current population size, the urban drainage system is incapable of removing sufficient phosphorous to remain below the critical load for Dianchi Lake.

2.5 Discussion on measures

The above discussion of the BAT has made it clear that new strategies have to be taken to avert the ecological deterioration of Dianchi Lake. The present serious conditions and the technical limitations of current methods are certainly a surprise for practitioners who are eager to imitate the past "success" stories of conventional urban water management in developed countries. The functionality of many ecosystems could be restored if appropriate action was taken in time (Lubchenco, 1998). In situations like that of Kunming, both immediate as well as long-term actions are necessary. The longer the present situation is allowed to continue, the more difficult it will be to restore the lake.

An analysis based on the model was conducted with selected scenarios, which were designed to identify strategies for overcoming the technical limitations. The relationship between the critical population size within the Dianchi Catchment and selected controllable variables is studied here.

We defined the carrying capacity of the catchment area of Dianchi Lake as the population that Dianchi Lake can tolerate in terms of phosphorous load, denoted as P_{crit}. Then based on the model of section 3.2, neglecting the phosphorous infiltration flow $I_{3,2}^{(P)}$, it follows in the case of BAT for the total output to the receiving waters:

$$\begin{aligned} O^{(P)} &= O_{5,1}^{(P)} + O_{6}^{(P)} + O_{3,2}^{(P)} + O_{4}^{(P)} \\ &= \{1-\eta_c^{(P)} \cdot (k_{3,5}^{(P)} + k_{3,6}^{(P)} \cdot k_{6,5}^{(P)})\} \cdot P_{crit} \cdot (p_1^{(P)} + p_2^{(P)} + p_3^{(P)} + p_4^{(P)} + p_5^{(P)} + p_8^{(P)}) \cdot 365 \\ &\quad + P_{crit} \cdot H \cdot A \cdot \{C_{roof}^{(P)} \cdot r \cdot p_6 + C_{street}^{(P)} \cdot (1-r) \cdot p_7\} \cdot (1 - p_{11} \cdot \eta_c^{(P)} \cdot (k_{3,5}^{(P)} + k_{3,6}^{(P)} \cdot k_{6,5}^{(P)})) \end{aligned} \tag{14}$$

$$\kappa \cdot O^{(P)} \le \tau \tag{15}$$

Where τ is the allowable TP load from the urban drainage system into Dianchi Lake, t / year; κ the percentage of urban water effluent that discharges into the Dianchi Lake. $1-\kappa$ is the percentage of urban water effluent discharged into downstream rivers.

Based on BAT scenario, we introduce a discharge diverting factor κ, which is the fraction of wastewater treated with BAT and discharged into the Dianchi Lake, while $1-\kappa$ be treated and discharged into rivers downstream of Dianchi Lake.

Equation (14, 15) allows a simple quantitative discussion of the possibilities to reduce the discharge of phosphorous into Dianchi Lake. In particular, various scenarios including separated storm sewerage system, urine separation, water saving, and urban discharge diverting, etc. have been evaluated. Table 5 lists the total output of TP into Dianchi Lake in following simple scenarios: (1) BAT with current urban population; (2) BAT with projected urban population of 4.5 millions; (3) 40% of urine separation based on scenario 2; (4) Scenario 3 and 60% of water diverted to rivers downstream of Dianchi Lake. The main results are:

- If all effluent is discharged into Dianchi Lake, the current population in Kunming City has already exceeded the carrying capacity of Dianchi Lake, even in the BAT scenario, see section 4.2;
- Urine separation (reduced specific emission $p_4^{(p)}$ in equation (14)) and water saving is worthy to recommend, if implemented in a feasible way (Starkl and Brunner 2004). 40% of urine separation reduces the total emission into the Dianchi Lake considerably and hence increases the carrying capacity of the catchment area. More than increasing the carrying capacity, the contribution of urine separation will reduce the required size of WWTP due to decreasing of nitrogen removal load, which is the main reason to enlarge WWTP. The separated urine is assumed to be collected and treated appropriately as fertilizer, as is still a traditional agriculture practice in the local rural area;
- In highly populated areas as in Kunming, discharge diversion of the urban drainage system is almost obligatory to stop the eutrophication problem of receiving lakes. Based on the above mentioned scenarios for Dianchi Lake, at 60% diversion of urban drainage discharge, even with an enlarged population, the critical requirement of TP emission from the city can be met. It must be noted that prerequisites for this are (1) the water balance of the Dianchi Lake is maintained, and (2) the diverted discharge should meet the requirements of the downstream rivers;

Table 5
Total emission of TP into Dianchi Lake in various scenarios

Scenario	No of scenario	Total output of TP into Dianchi Lake (tons/year)
Current condition + urine and faeces separation	"1"	410
BAT	"2"	57
BAT + projected future population	"3"	106
"3" + 40% of urine separation	"4"	87
"4" + 60% water diversion	"5"	35

The water balance of the Dianchi Lake must be handled carefully if the water diverting measure is taken. It is nevertheless feasible when (1) a certain amount of clean water is discharged from upstream reservoirs down into the Dianchi Lake and (2) Dianchi Lake itself is also used as one of the water supply sources. This condition could only be enabled when the water quality of Dianchi Lake were already improved to meet the standard of water supply resources.

2.6 Conclusions

Fundamental progress in improving the water environment in developing countries cannot be achieved through incremental advancement with conventional technical approaches. Decision makers and planners face both serious current conditions and the technical limitations of conventional urban drainage and wastewater treatment, as exemplified by the city of Kunming. However, this should neither be taken as a criticism of today's urban drainage concepts nor as an argument for abandoning these concepts. A city without sewerage and a WWTP is difficult to imagine. But to overcome the limitations of these systems and to prevent ecological problems in the future, there is urgent need for measures to improve the performance of today's systems.

With this message, we would argue that the research efforts made to develop household sanitation oriented to source control and its appropriate policy enforcement are still required until an equivalent or better household sanitation service can be supplied than the traditional approach. This should be done despite the fact that a generally accepted alternative system is not yet practical for a city beyond the pilot scale.

We would also argue that solutions must be found in a systematic way. As indicated by the case of Kunming, this will not only involve the improvement of the household sanitation system, sewerage system and wastewater treatment, but also the regional water balance and the water supply system. Such a complexity of solutions requires further studies.

2.7 Acknowledgements

This project is financed through the Swiss NCCR North–South "Partnership on Mitigating Syndromes of Global Change". We thank Dr. Derek E. Chitwood for his valuable remarks and help in improving the language, Dr. Hansruedi Siegrist, Dr. Markus Boller, Dr. Heinrich Bührer and various research partners in Kunming for valuable discussions and inputs, and in particular both the Kunming City government and Zurich City Drainage for their vital data support and cooperation.

2.8 Reference

Baccini, P., Bader, H.-P., 1996. Regionaler Stoffhaushalt Erfassung, Bewertung und Steuerung. Spektrum, Heidelberg, etc.

Boller, M., 1997. Tracking heavy metals reveals sustainability deficits of urban drainage systems. Water Science and Technology 35 (9), 77–87.

Boller, M., 2005. Measurement of Pollutants in Rain Runoff in Swiss Urban Area. Zurich. Swiss Federal Institute of Environmental Science and Technology, Duebendorf, Switzerland.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A., Lodge, D.M., Pascual, M., Pielke, R., Pizer, W., Pringle, C., Reid, W.V., Rose, K.A., Sala, O., Schlesinger, W.H., Wall, D.H., Wear, D., 2001. Ecological forecasts: an emerging imperative. Science 293 (5530), 657–660.

Collins, A., Michalski, R., 1989. The logic of plausible reasoning—a core theory. Cognitive Science 13 (1), 1–49.

ERZ, 2003. Operational data of WWTP Werdho¨ lzli, Zurich, Entsorgung und Recycling Zurich.

Gray, S.R., Becker, N.S.C., 2002. Contaminant flows in urban residential water systems. Urban Water 4 (4), 331–346.

Gray, A.V., Li, W., 1999. Case study on water quality modelling of Dianchi Lake, Yunnan Province, South West China. Water Science and Technology 40 (2), 35–43.

Gujer, W., 1999. Siedlungswasserwirtschaft. Springer, Berlin, etc.

Henze, M., 1997. Waste design for households with respect to water, organics and nutrients. Water Science and Technology 35 (9), 113–120.

Herrmann, T., Klaus, U., 1997. Fluxes of nutrients in urban drainage systems: assessment of sources, pathways and treatment techniques. Water Science and Technology 36 (8–9), 167–172.

Jeppsson, U., Hellstrom, D., 2002. Systems analysis for environmental assessment of urban water and wastewater systems. Water Science and Technology 46 (6–7), 121–129.

Jönsson, H., 2002. Urine separating sewage systems—environmental effects and resource usage. Water Science and Technology 46 (6–7), 333–340.

Jönsson, H., Vinneras, B., 2003. Adapting the nutrient content of urine and faeces in different countries using FAO and Swedish data. “closing the loop”. In: Second International Symposium on Ecological Sanitation, Lübeck, Germany, Deutsche Gesellschaft für Technische Zusammenarbeiten (GTZ) GmbH.

KIES, 2003. Investigation of Pollution Source of Dianchi Lake. Kunming Institute of Environmental Science, Kunming City, China.

KMSB, 2003. Statistical Annual Report, Kunming City, Kunming Statistics Bureau, Kunming City, China.

KMSC, 2003. Operation data of WWTP in Kunming. Kunming Sewerage Co., Kunming City, China.

KMWS, 2003. Personal communication.

KPB, 2004. Planning Outline for a "modern new Kunming". Kunming Planning Bureau and Kunming Institute for Urban Planning, Kunming City, China.

Langergraber, G.,Muellegger, E., 2005. Ecological sanitation—a way to solve global sanitation problems? Environment International 31 (3), 433–444.

Larsen, T.A., Gujer, W., 1996. Separate management of anthropogenic nutrient solutions (human urine). Water Science and Technology 34 (3–4), 87–94.

Larsen, T.A., Gujer, W., 2001. Waste design and source control lead to flexibility in wastewater management. Water Science and Technology 43 (5), 309–317.

Lenz, G., 2004. Qualification of Sewerage Treatment Plant Staff—Basic Terms/Characteristic Data, ATV—DVWK. German Association for Water, Wastewater and Waste, Germany.

Li, J.W., 2005. Talk on the Environmental Protection Issues of Kunming City. Kunming City Congress, Kunming, China.

Liu, Y., 2005. Phosphorus Flows in China: Physical Profiles and Environmental Regulation. Wageningen University, Netherlands.

Liu, Y., Chen, J.N., Mol, A.P.J., 2004. Evaluation of phosphorus flows in the Dianchi watershed, Southwest of China. Population and Environment 25 (6), 637–656.

Lubchenco, J., 1998. Entering the century of the environment: a new social contract for science. Science 279 (5350), 491–497.

Otterpohl, R., Albold, A., Oldenburg, M., 1999. Source control in urban sanitation and waste management: ten systems with reuse of resources. Water Science and Technology 39 (5), 153–160.

Schmid, T., Bader, H.-P., Scheidegger, R., 2004. Food consumption and nutrient flows—nitrogen in Sweden since the 1870s. Journal of Industrial Ecology, in press.

SEPA, 2001, Bulletin of the Chinese environment—state of the art. State Environmental Protection Administration of China, Beijing China, also available on www.sepa.gov.cn.

Siegrist, H., 2005. Personal communication.

Song, X.-L., 2005. Map of Kunming Ground Water Level. Yunnan Institute of Geology, Kunming, China.

Starkl, M., Brunner, N., 2004. Feasibility versus sustainability in urban water management. Journal of Environmental Management 71 (3), 245–260.

Statistisches Jahrbuch der Stadt Zürich, 2004. Hrsg.: Präsidialdepartement der Stadt Zürich,

Statistik Stadt Zürich 2003. Statistik Stadt Zürich, Zürich.

SVGW, 2002. Wasserverbrauch im Haushault Studie des SVGW in Zusammenarbeit mit dem BUWAL, Schweizerischer Verein des Gasund Wasserfaches.

Tangsubkul, N., Moore, S., Waite, T.D., 2005. Incorporating phosphorus management considerations into wastewater management practice. Environmental Science & Policy 8 (1), 1–15.

Task group urban water planning Kunming, 1990. Personal communication.

Wagman, M., 2003. Reasoning Processes in Humans and Computers: Theory and Research in Psychology and Artificial Intelligence. Praeger, Westport, CT.

Weiss, G., Brombach, H., Haller, B., 2002. Infiltration and inflow in combined sewer systems: long-term analysis. Water Science and Technology 45 (7), 11–19.

Yang, W.-P., Zhang, W., 2005. Technical report on water supply system Kunming, Kunming Water Supply.

Zobrist, J., Müller, S.R., Ammann, A., Bucheli, T.D., Mottier, V., Ochs, M., Schoenenberger, R., Eugster, J., Boller, M., 2000. Quality of roof runoff for groundwater infiltration. Water Research 34 (5), 1455–1462.

Zurich Water Supply Authority, 2001. Personal communication.

3 Discrete Event Simulation for Exploring Strategies: An Urban Water Management Case[2]

Abstract

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.

3.1 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 data base and computational models that specify the mass or energy transfer processes in the system being studied (*3*).

[2] This chapter is accepted for publication in the Environmental Science & Technology on 23 October, 2006. The authentic journal version is available on http://pubs.acs.org. Authors: Dong-Bin Huang, Roland W. Scholz, Willi Gujer, Derek E. Chitwood, Peter Loukopoulos, Roland Schertenleib, Hansruedi Siegrist.

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 multi-dimensional 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.

3.2 Model Structure

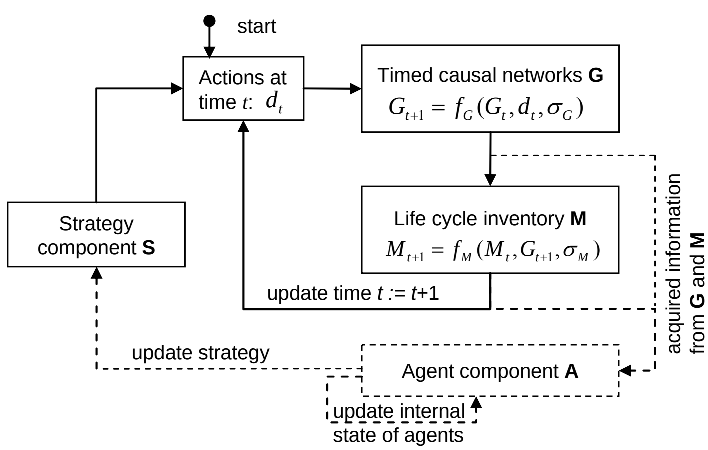


FIGURE 1. Model structure of the discrete event simulation for exploring strategies

The model consists of four components $(\mathbf{A},\mathbf{S},\mathbf{G},\mathbf{M})$, 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 $(\mathbf{S},\mathbf{G},\mathbf{M})$, while the outer loop (dashed line) represents organizational learning and strategy adaptation by decision makers. $\mathbf{G}$ and $\mathbf{M}$ 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 $\mathbf{A}$ represents the agents or decision makers and their strategic management assisted by simulations. The basic idea to place $\mathbf{A}$ 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 $\mathbf{S}$ represents all possible sets of strategies S that can be generated by $\mathbf{A}$. 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. *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:

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

Each column in Equation 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, $\mathbf{G}$ and $\mathbf{M}$, 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 $\mathbf{G}$ 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 $\mathbf{G}$ 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:

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

G_t includes the complete set of state variables at time t that are specified in $\mathbf{G}$ and σ_G is the parametric uncertainty in $\mathbf{G}$. 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, firstly, 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, $\mathbf{G}$ 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 $\mathbf{G}$, 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". $\mathbf{G}$ 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 $\mathbf{G}$.

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 $\mathbf{M}$ receives updated output variables G_{t+1} from $\mathbf{G}$ as parameters, and calculates the updated state M_{t+1} as follows:

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

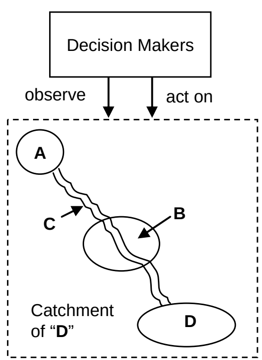
Where f_M describes the conservation laws of mass and energy of all the included processes, and σ_M the parametric uncertainty in $\mathbf{M}$. M represents all the state variables of flows and stocks in **M**, which can comprise multiple levels of subsystems, *e.g.*, an urban drainage system and a regional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

3.3 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.

3.3.1 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 the paper as well.



(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

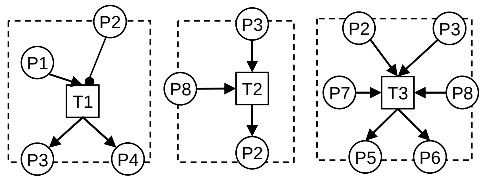
Goals	1) The local environment will support urban growth to a projected population of between 4.4 to 4.9 million people within the Dianchi catchment area 2) Dianchi Lake shall return to healthy condition
Primary Objectives	1) Total phosphorous load to the lake should be smaller than the tolerance value 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

3.3.2 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.



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 2. Annual immigrants 3. Local rural population transferred to urban population 4. Ratio of industrial water consumption to household water consumption as an indicator for industry	*%/a* *p/a* *p/a* -
*P*2	Water resource availability	1. Local water resource availability 2. External water resource availability	*m³/a* *m³/a*
*P*3	Water consumers	1. Total rural population 2. Total urban population 3. Industries in population equivalence of water consumption	*p* *p* *p*
*P*4	Urban area	1. Total impervious area of the city 2. Pollution coefficients in runoff, e.g. for total phosphorous 3. Constructed new impervious area	*hectare* *mg/m³* *hectare*
*P*5	Supplied water	1. Normal quality water supply 2. Excellent quality water supply	*L/p.d* *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 2. Maximum flow of urban rivers 3. Frequency of dry weather flow when minimum flow needs to be enforced by discharging from upstream reservoirs	*m³/s* *m³/s* *%/a*
*P*8	Receiving water	1. TP tolerance in receiving water 2. Suitability as resource for local water supply	*tons/a* -

Note: "-" means no unit, "*p*" for persons, "*L/p.d*" for liters per capita and day, "*m³/s*" for *m³* per second

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

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 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*). Based on 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.

A part 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 to s_3, s_6), technical operations (s_7 to s_{18}), and resource availability (s_4, 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.

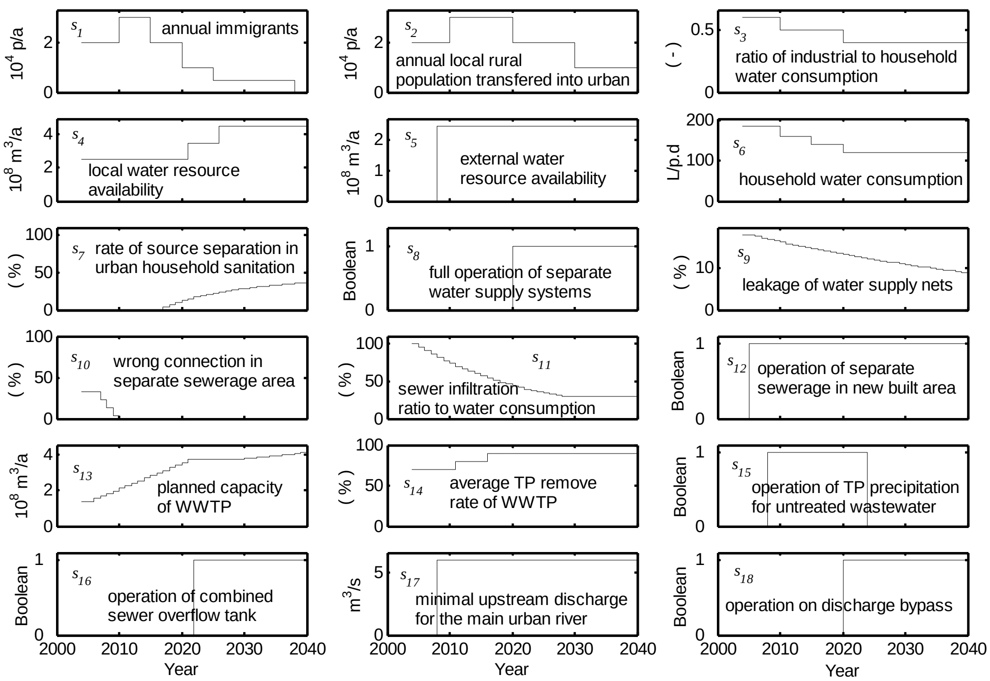


FIGURE 4. Identified decision variables and an example strategy as input for the system

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 (*17*), and the regional water balance was built upon the conceptualization and data source provided in (*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 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.

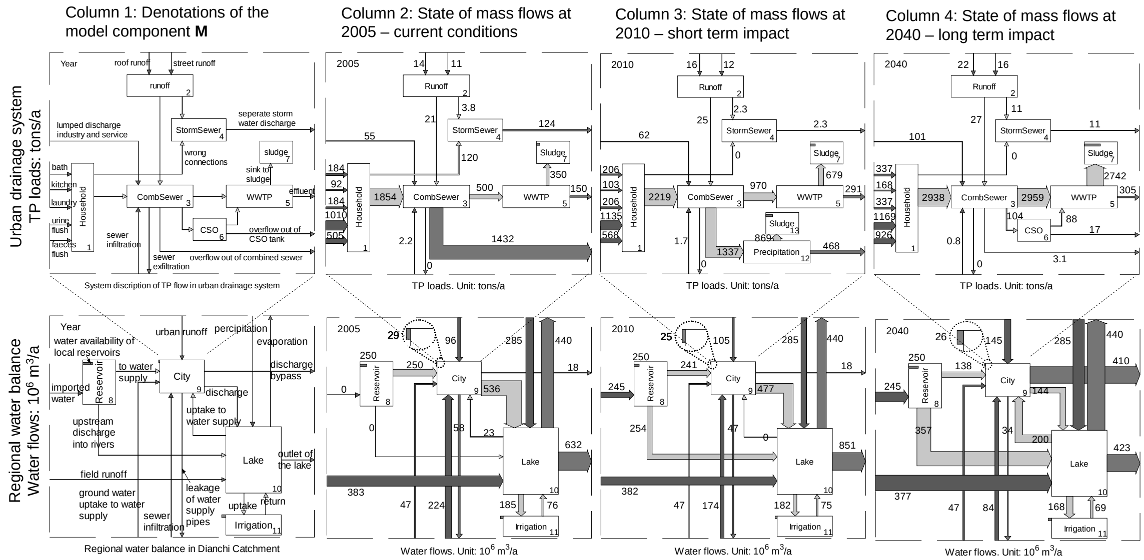


FIGURE 5. Distributed flow diagrams of the TP loads in the urban drainage system and of the water flows in the regional water balance system of Kunming resulting from strategy assumption S_1

3.3.3 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).

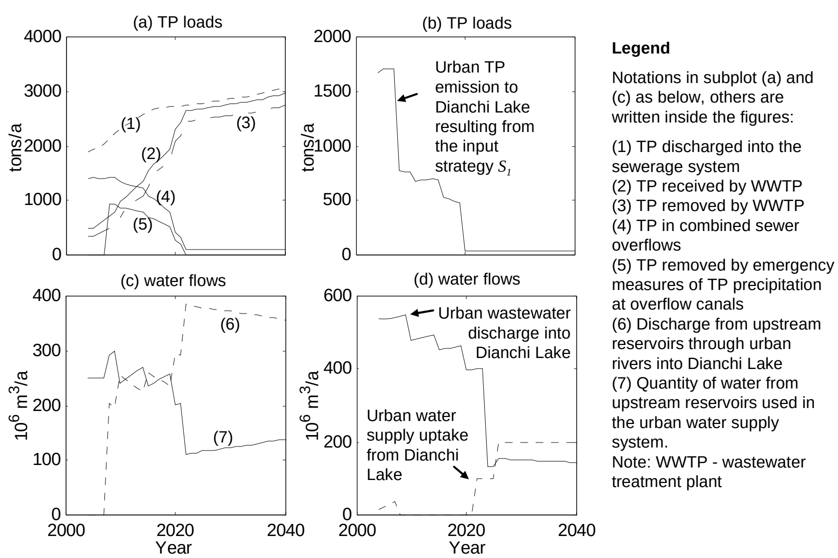


FIGURE 6. Temporal dynamics of sampled variables resulting from strategy S_1

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 on Figure 5 and Figure 6, please refer to the Supporting Information of the paper.

3.3.4 Scenario analysis

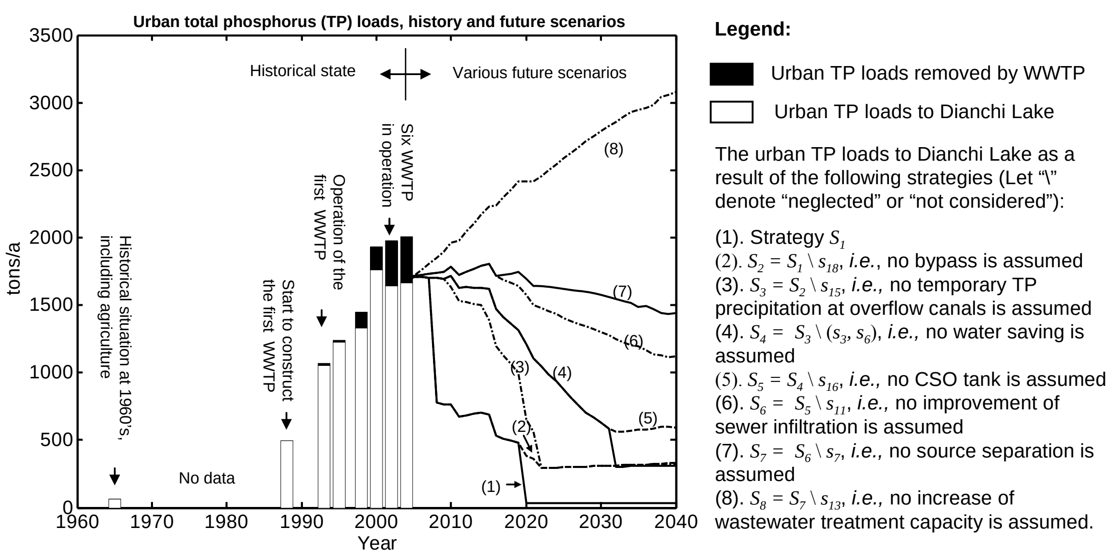


FIGURE 7. The urban TP loads to Dianchi Lake, history and future scenarios

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 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; suggests 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.

3.3.5 How structure reduces uncertainty

Different origins and types of uncertainty requires 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 information 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 understandings on 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 understandings on 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.

3.4 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.

3.5 Acknowledgements

We thank the Swiss National Science Foundation and Swiss Development Agency for their joint funding through the research framework of Swiss NCCR North-South, as well as the Kunming city government and its affiliated institutes for their positive cooperation. We are also indebted to Yu-Chi Ho, Mitchell J. Small, and Peter Reichert for their valuable comments and criticisms, which helped to improve the manuscript. We thank Heinrich Bührer, Hans-Peter Bader, Claudia R. Binder, Peter de Haan, Thomas Köllner, and Timo Smieszek who have offered their help in the processing of the draft. Finally, we thank Franklin M. Fisher for his encouragement in making helpful research.

3.6 Surporting 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.

3.7 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. *Chemical Engineering Science* **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, 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. Softw.* **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 US 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 etc., 1990.

(13) Pearl, J. *Causality: Models, reasoning and inference*; Cambridge University Press, 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, 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 and Environment* **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 Analysis* **1999**, *19*, 33-42.

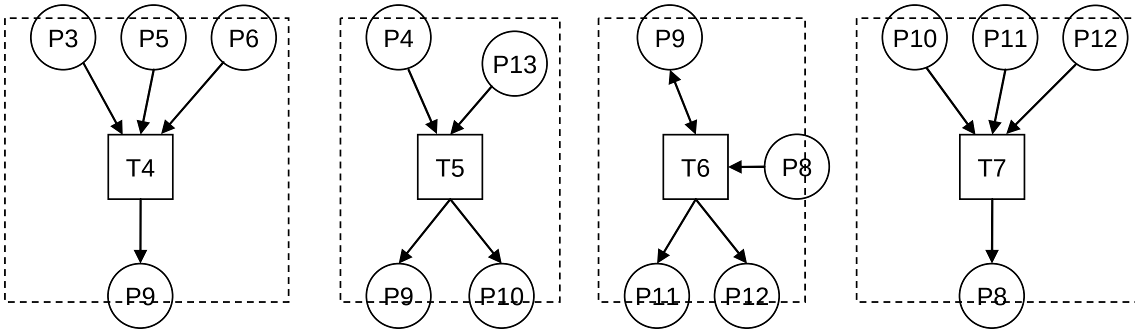
3.8 Supporting Information

3.8.1 More explanations on the background of Kunming case.

The current quality and flows of the rivers passing through Kunming and the water quality in Dianchi Lake are well below acceptable levels. Previous studies suggest that Dianchi Lake is a total phosphorous (TP) limited eutrophic lake (*1*) with a tolerance of 60 tons/a of TP input from all sources of surface water discharge, including both urban drainage and agricultural discharge. However it is estimated that the present TP input from the city alone is already 20 to 30 times higher (*2*). Although interventions to improve the water quality of the lake were initiated in the 1980s, no significant improvement has been achieved. On top of this, the stress on the local water environment, caused by the accelerating urbanization process, continues to increase. While several studies have been conducted in an attempt to find a reasonable solution for this problem, no coherent solution has as yet been found due to the lack of an integrated approach.

Clearly, controlling TP input into Dianchi Lake does not mean that the lake will immediately become clean. The response of the lake's water quality to the reduction of nutrient input level is nonlinear. It will take a long time for the lake to return to its initially clean state even after the nutrient load is controlled (*3*). In the worst case, the changes may even be irreversible (*4*). However, if TP input is not controlled, the chances of restoring Dianchi Lake to a healthy condition are minimal. Therefore, in this study, we restrict ourselves to the primary objectives identified in Figure 2, panel (3). These are controlling TP input from the city into the lake to within 33 tons/a and maintaining the water balance of the lake at adequate levels so as to guarantee that the city grows without permanently damaging Dianchi Lake.

3.8.2 Other transitions



*T*4 – water consumption; *T*5 – urban runoff drainage; *T*6 – wastewater management; *T*7 – pollution control of receiving water

*P*3 – water consumers; *P*4 – urban area; *P*5 – supplied water; *P*6 – water supply infrastructure; *P*8 – receiving water; *P*9 – mixed wastewater; *P*10 – separate sewerage; *P*11 – wastewater infrastructure; *P*12 – wastewater emission; *P*13 – rain

FIGURE A. Other transitions from $T4$ to $T7$

The overall network is in fact an ensemble of the entire cellular networks from $T1$ to $T7$, as displayed in Figure B.

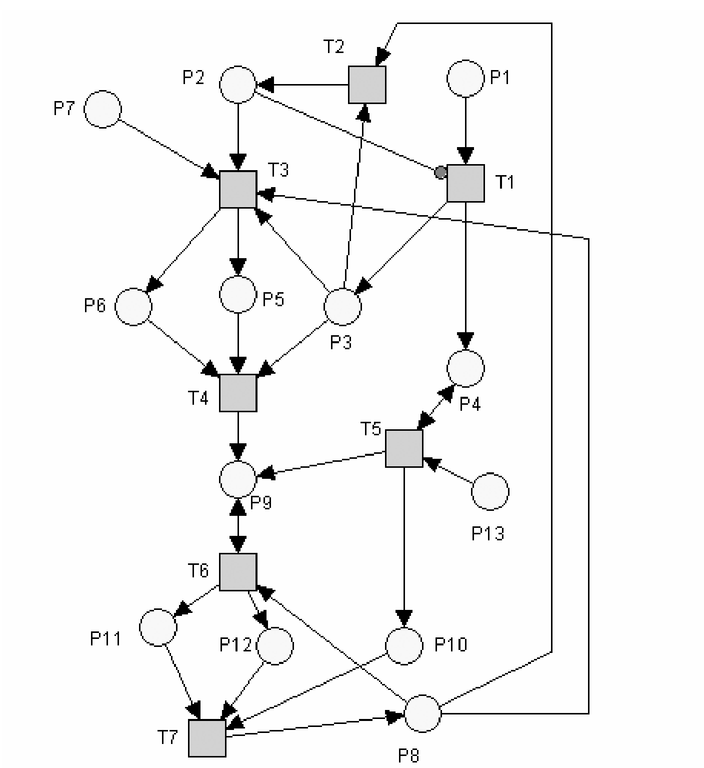


FIGURE B. The overall network is the ensemble of all the cellular networks

3.8.3 Explanations on the strategic assumption S_1 in Figure 4.

s_4 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.

s_7 assumes that by 2016, with technical improvements and effective policy enactment, an acceptable source separation, urban household sanitation system will be available. It also assumes that it will achieve approximately 40% urine separation in urban household sanitation by 2040. s_8 assumes that Kunming will implement a two pipe, two water quality water supply system to mitigate the conflict between urban water demand and regional water balance demand caused by the polluted conditions of the Dianchi Lake and to address the increasing concern of safe drinking water supply.

s_{10} assumes that the current wrong connections (where sewerage lines are connected to stormwater drains) in Kunming's separate sewerage system will be corrected by connecting them to the sanitary sewerage system within a five-year period. s_{11} assumes that sewer infiltration will be reduced at a rate of 5% per year until the 30% target is met. s_{13} assumes that the city will increase wastewater treatment capacity incrementally so that 90% of the city's wastewater, including rain runoff, can be handled.

s_{14} assumes that due to the large volume of untreated wastewater currently discharged directly into Dianchi Lake and the long time required to increase wastewater collection and treatment capacity, chemical precipitation of TP will be used as an emergency measure for temporary control of phosphorous levels in overflow canals entering Dianchi Lake. It is assumed that TP precipitation will be initiated in 2008 and will cease in 2023. During this time it is expected that precipitation will achieve an average of 65% TP removal efficiency. One could also assume that TP precipitation reactors are reconstructed as combined sewer overflow (CSO) tanks after the cessation of TP precipitation in overflow canals. s_{16} assumes that CSO tanks will be in use after sufficient wastewater collection and wastewater treatment plant (WWTP) capacity has been built and after the river precipitation discontinued. s_{18} assumes that a partial bypass of urban drainage will be enabled in 2020 after sufficient WWTP capacity becomes available and Dianchi Lake is used as a local water resource for urban water supply.

3.8.4 Results interpretations for Figure 5 and Figure 6.

Distributed flow diagrams. The presented DES modeling approach produces static material flow diagrams (*5,6*) (see Figure 5) at all levels at any time with one run of simulation. Figure 5 offers an overview of the changes of flow variables and of the configuration of physical environment systems resulting from the example strategy S_1. Column 1 identifies the definitions of both the urban TP loads and the regional water balance values. Columns 2 to 4 are TP flows (upper row) for the urban drainage system and water flows (lower row) for regional water balance for the years 2005 (as an overview of the current conditions), 2010 (as a vision of the short term impacts of S_1) and 2040 (as a vision of the long term impacts of S_1).

As can be seen from Figure 5 column 2, according to the model, the urban drainage system in Kunming presently emits large amounts of TP into Dianchi Lake. Overflows including unconnected wastewater account for 1432 tons/a TP loads, and wrong connections account for 120 tons/a. Effluent from city's wastewater treatment plant accounts for another 150 tons/a. Clearly, the capacity and efficiency of the current sewerage system and the treatment plants does not meet the requirements for protecting Dianchi Lake.

An overview of the current state of regional water balance in Kunming is shown in column 2, lower figure. The urban river receives effectively no water from upstream reservoirs because all available supply is used for the urban water system. A small amount of water (23 million m^3/a on average) is taken from the heavily polluted Dianchi Lake in order to meet the water shortage in the city. This amount can be even greater in years of low rainfall. The average discharge from the city to Dianchi Lake amounts to 536 million m^3/a, of which more than 70% is not treated. On average, 632 million m^3/a of water (only surface water induced flows; groundwater flows are not considered) are discharged through the outlet of Dianchi Lake.

An overview of a short-term vision of the urban TP loads resulting from strategy S_1 is depicted in Figure 5, column 3. Despite the incremental increases in canalization and WWTP capacity, TP loads through sewer overflow will still be high at 1337 tons/a in the year 2010. As part of S_1 described in Figure 4, an emergency measure involving the use of chemical phosphorous precipitation in overflow canals conveying the wastewater to Dianchi

Lake will be put into operation. Chemical precipitation of phosphorous will be needed for approximately 15 years according to this strategy. The intervention correcting the wrong connections in the separate sewerage system will result in reduced TP loads from the storm drainage system, which will only account for 2 tons/a of TP. However, as a result of increased wastewater collection and treatment, the quantity of TP released from WWTP will also increase from 150 to 291 tons/a at this time point.

Column 3, lower figure, provides an overview of a short-term vision of regional water balance. A water-import project accounting for 245 million m^3/a will be in operation in 2008 and, as a result, the viability of urban rivers will be guaranteed. Water-saving plans will also be enacted and will lead to reduced water demand from upstream reservoirs resulting in a decrease from 250 to 241 million m^3/a by the year 2010, despite the assumed population increase. No water will be taken from Dianchi Lake for urban water supply at this stage.

In column 4, the upper figure illustrates the overview of a long-term vision of the TP load in the urban drainage system. The temporary chemical precipitation of phosphorous in rivers flowing into Dianchi Lake will no longer be in operation. Meanwhile, the sewerage system will be able to receive and convey 90% of urban wastewater to the WWTP. (The water quantities in the urban drainage system are not shown in Figure 5). In all, the WWTP will receive 96% of the TP loads from the city. (Note: the difference between the 90% water collection rate and 96% TP collection rate is due to dilution by rain runoff). The combined sewer overflow tank (CSO) will also be in operation. By adding the wastewater captured by the CSO tanks, the overall collecting rate of the urban drainage system will be 99% for wastewater and 98% for TP.

Dynamic plot. Using the dynamic data record plotted in Figure 6, the impact of the example strategy S_1 on the various flow quantities of major concern can be evaluated. Only a few key flow variables are illustrated below.

The subfigure (a) indicates that, according to strategic assumption S_1, it will take approximately another 20 years to reach the required capacity and efficiency of wastewater collection and treatment. Before this, the overflow of untreated wastewater will be responsible for vast amounts of TP input into the lake. Such a situation should be controlled as soon as possible to prevent further difficulties being confronted in the future due to TP accumulation in the lake. The emergency measure of chemical precipitation for phosphorous removal at overflow canals entering Dianchi Lake is able to temporarily improve the situation. In subfigure (b), the effect of strategy S_1 is evident from the declining levels of TP emissions into Dianchi Lake. The first steep decline results from the implementation of the emergency TP precipitation measure. The last steep decline is due to urban drainage discharge being diverted through a bypass tunnel.

As seen in subfigure (c), water inflow from upstream reservoirs to Dianchi Lake will increase as a result of the strategy. At the same time, the uptake from upstream reservoirs to the city's water supply will decrease despite the population reaching about 4.6 million. The decreasing discharge of wastewater from the city into the lake, subfigure (d), is due to water-saving actions being adopted by households and industry, as well as the action of reducing sewer infiltration. After 2023, the main reduction will be achieved by the discharge bypass. Regarding the water uptake from Dianchi Lake to the urban water supply system, it can be seen that before the water resource import project, a small amount is required. According to the model, after 2020 when the water discharge into Danchi Lake is reasonably controlled and the two separate water supply systems have been implemented, Dianchi Lake will be used as a water supply resource for non-drinking water.

3.8.5 Literatures related to supporting information

(1) UTL "Final Report - evaluation of the present situation of remediation measures and elaboration of the proposals for the improvement of Dianchi Lake," UTL-Umwelttechnik Leopoldau and Kunming Institute of Environmental Science, 2001.

(2) 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*

(3) Janse, J. H.; Vanliere, L. PCLAKE - a modeling tool for the evaluation of lake restoration scenarios. *Water Sci. Technol.* **1995**, *31*, 371-374.

(4) Carpenter, S. R.; Ludwig, D.; Brock, W. A. Management of eutrophication for lakes subject to potentially irreversible change. *Ecol. Appl.* **1999**, *9*, 751-771.

(5) Baccini, P.; Bader, H.-P. *Regionaler Stoffhaushalt Erfassung, Bewertung und Steuerung*; Spektrum: Heidelberg etc., 1996.

(6) Brunner, P. H.; Rechberger, H. *Practical handbook of material flow analysis*; Lewis Publishers: Boca Raton, FL, 2004.

4 Facilitating Strategy Exploration Using Discrete Event Systems Simulation for Environmental Planning[3]

Abstract

This paper proposes a model approach simulating cause-effect relations between strategies and their environmental impacts, in order to assist the strategy adaptation of decision makers or agents. The model is in essence a type of discrete event system (DES). The model consists of an agent component, a strategy component, an environmental object model and a timed causal network. The latter models the interface between the strategy component and the object model. A case study on the long-term water management of a big Chinese city presents insights on how strategy exploration can be facilitated with the model. The case study shows how the effectiveness of strategies in coupled human-environment systems can be explored. Strengths of the approach lie in its interpretability and extendibility and the illustrative visualization of results, which make the modeling accessible to the agents.

Key words: OR in strategic planning, environmental planning, discrete event simulation, causality

4.1 Introduction

Significance and complexity often coexist in environmental strategic planning (Odum, 1993; Stern, 2005; Vitousek, et al., 1997). It often involves multiple objectives and activities, which are formulated or performed by a number of organizations. It also frequently requires coping with system variables that are linked with or embedded in various distributed systems, levels and scales. Sometimes some of these variables and their interrelations are hidden or hardly observable (Forrester, 1992; Holland, 1998). These characteristics potentially lead to a type of ill-defined problem, in which the essence of the problem and the complex mixture of interdependencies within the system are difficult to describe and unable to be solved independently of one another (Mingers and Rosenhead, 2004; Mitroff and Emshoff, 1979; Rosenhead, 1996). This particularly holds true in issues such as sustainable development involving coupled human-environment systems (Scholz, et al., 2006; Scholz, et al., 2000). The difficulties escalate with our myopia in learning (Levinthal and March, 1993), short-term orientation in acting (Laverty, 1996), and multiple perspectives on one reality

[3] This chapter is submitted to the European Journal of Operational Research on 20 November 2006. Authors: Roland W. Scholz, Dong-Bin Huang.

(Stauffacher, et al., 2006), as well as with the variation in subjective judgments, which is not amenable to exact description, analytical or otherwise (Whitesides and Ismagilov, 1999).

Efforts in facilitating strategy exploration can be instrumental in directing transitions towards sustainable development (Daily and Walker, 2000; Dietz, et al., 2003). We argue that facilitation is a type of decision support activity that takes a more initiative stance. This differs from the understanding of decision support as a mere information service. Facilitation does not stop at the point when information is produced, but also targets making sense of the information with the participation of stakeholders (agents hereafter) and making changes occur. This paper endeavors to facilitate strategy exploration by supporting decision makers to understand what actions to take and what effects these actions will cause by means of modeling in an open, interactive discourse. For this purpose, we construct a model structure incorporating strategies and their cause-effect relations on environmental objects, and enhance learning with the involvement of decision makers.

The presented model structure has roots in the fields of system dynamics and strategic choice approaches, both of which have been greatly applied in facilitating group decisions (Andersen and Richardson, 1997; Ngwenyama, et al., 1996; Shaw, et al., 2004; Vennix, 1999). The strategic choice approach has evolved as a method for supporting strategic planning and management in organizations. It consists of four complementary activities known as *shaping*, *designing*, *comparing* and *choosing* (Friend and Hickling, 2005). This approach brings together a range of mainly graphical problem-structuring tools to facilitate a group of decision-makers to work progressively towards a set of agreed action commitments (Franco, et al., 2004; Phahlamohlaka and Friend, 2004). However, simulation as a powerful and necessary information processor is somewhat lacking in such approaches. It is assumed that the strength of this approach can be enhanced by putting discrete event simulations into use in relation with the frame for strategy exploration facilitation (Robinson, 2001).

It deserves to be mentioned that this paper focuses on one-agent facilitation, which includes a facilitator (a person or a team), an agent such as a person or an organization that represents a homogeneous unit, and a difficult situation requiring qualified facilitation. In multi agent-facilitation, the agents generally have conflicting interests or compete for resources. In this scenario, the task of the facilitator includes mediating conflicts, preventing lock-in situations, and demonstrating synergies for building necessary coalitions that are required for the facilitation process (Scholz and Tietje, 2002).

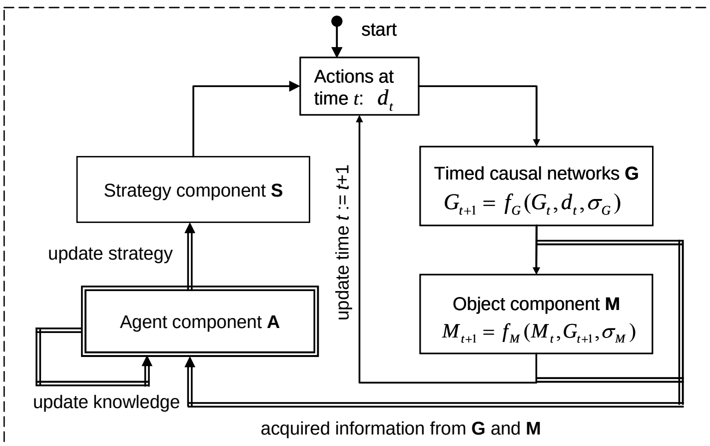
In the following chapters, we first present the model structure that permits the investigation of the multiple elements of a strategy and of the temporal dynamics of multi-dimensional effects of various strategies. The model structure also represents the knowledge in an illustrative way to facilitate learning and knowledge transfer for the decision maker.

We then illustrate the approach with an empirical study of facilitating a governmental top-management-group in exploring strategies for the water management in Kunming, China. By assumption, we treat the group as a unitary agent, temporarily neglecting the potential conflicts in interests and competition for resources, such as project investments. Finally, issues on how to facilitate and structure the interaction of multi-agent settings are discussed.

4.2 Model approach

4.2.1 General setting

The model consists of a tuple $(\mathbf{A},\mathbf{S},\mathbf{G},\mathbf{M})$ (Fig. 1), where $\mathbf{A}$ represents the agent component, $\mathbf{S}$ the strategy component, $\mathbf{G}$ the timed causal network, and $\mathbf{M}$ the environmental systems model (Huang, Scholz, et al., 2006). The inner loop (solid single line) represents the simulation loop of the environmental system. The outer loop (solid double line) represents the strategy making and updating process of the decision makers assisted by the simulation. These two loops function in two different time frames. The inner loop proceeds with predefined computational time steps. The outer loop usually proceeds in real time and in a certain organizational context. The functional procedures of the general setting are explained in Fig. 1.



Step 1: Initialize, requires initial state of **G** and **M**, and a set of strategic plans **S** to evaluate;

Step 2: **G** model reads the strategic plan at every discrete simulation time step, and gets a set of actions d_t at time t, and updates the state in **G**;

Step 3: **M** model takes the updated state variables in **G** as new boundary conditions, and updates the state in **M**;

Step 4: Inner loop is the simulation part. Update time, repeat steps *2* and *4* until the end time point of the planning horizon;

Step 5: Outer loop is the facilitation process. After simulation, the agent component **A** acquires information from **G** and **M**, where impacts of various strategies have been simulated; and updates the agent's knowledge and strategic plans for further evaluation;

Step 6: Renew the strategic plan, repeat steps 1 through step 5 until a satisfactory solution is found, allowing the possibility for future adaptation.

Fig. 1. General setting and procedures

4.2.2 Agent component

The agent component **A** is coupled in the general setting as a complementary construct to the object component as the source of strategies and the converter of information to strategies that change the world, i.e. the object component (Forrester, 1992; Starbuck, 1983). In principal, it represents the learning and strategy adaptation of the agent.

Conceptual model of the agent component

In general, the agent component $\mathbf{A} = \{\tilde{A}, K, I, U, C\}$ represents the included agents, what knowledge they have, what information they acquire and how they evaluate a strategy (by utility functions) under certain social constraints.

$\tilde{A}$ is the set of agents, $\tilde{A} = \{A_1, \cdots, A_i, \cdots, A_m\}, m \geq 1$. $K_i \in K = \{K_1, \cdots, K_i, \cdots, K_m\}$ denotes the knowledge that agent A_i holds on his/her environment including the causality about actions and their impacts on the environmental system. $I = \{I_1, \cdots, I_i, \cdots, I_m\}$ represents the information uptake, *i.e.*, the information sampled over time for each agent. A common way to represent the evaluative structure, goals or preferences is to postulate utility functions, $U = \{U_1, \cdots, U_i, \cdots, U_m\}$. A utility function assigns real numbers to evaluate outcomes resulting from various alternatives (Yates, 1990). Finally, C represents the social constraints or social context imposing an impact on the learning and action of the agents (Chalmeau and Gallo, 1993; Richards, 2001; Tennenholtz, 1999). Pfeffer and Salancik (2003) stated that one important role of management is to adjust and alter the social context surrounding the agents or to adjust the agents to the social context in a way that synergies of cooperation can be improved and unnecessary conflicts avoided.

Making sense of information feedback with the agent component

A model and its generated information can hardly be useful if it does not make sense to the agents. The ultimate purpose of simulation is to learn things about the world by performing computational experiments, whose outcomes are useful in constructing credible arguments (Bankes, et al., 2002; Lempert, 2002). However, the generated information and the model *per se* are often so complex that they require meaningful interpretation for the agent. Misperception of the feedback information can result in strategy failures (Lane, 1999; Langley and Morecroft, 2004; Moxnes, 2004; Sterman, 1989). Neglecting the subjective information of the agent can also paralyze the facilitation process. In line with Hammer (1990), we argue that the principle for the agent component is "not to automate" in the context of coupled human-environment systems, but rather to engage a learning and strategy adaptation process. With this process the produced knowledge as well as the subjective knowledge of the agents is interpreted, and the understandings of the agents and their strategic plans can be improved (Boland, et al., 2001; Starbuck and Mezias, 1996; Weick, et al., 2005) .

4.2.3 Strategy component

Individual and organizational decision makers must develop strategies to attain their goals. From a management perspective, strategies answer two basic questions, *i.e.*: "Where to go?" - and "How to get there?" (Eisenhardt, 1999). From a decision theory perspective, a strategy defines what to do for any situation an agent can be in. We specify a strategy with a set of decision variables s_i ($i = 1,...,n$), which are explicitly predefined for the time period $[t_0,\ t_e]$ of interest where t_0 is the starting time and t_e is the ending time of the simulation. 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 (Morgan, et al., 1990). So, each strategy includes a set of parallel activities which are specified with decision variables that perform at different points of time.

The strategy component $\mathbf{S}$ can be perceived as a control panel that allows visual demonstration of all the decision variables accessible for the decision maker. Each agent A_i has a set of strategies $S(A_i) = \{S_{i,1},...,S_{i,j},...,S_{i,N}\}$ at his or her disposal. A combination of strategies from all involved agents is a strategy bundle. Finding appropriate strategy bundles, which provide solutions that become acceptable for all players, is the art of multi-agent facilitation.

Furthermore, in real world decisions strategies are time related. Thus, the k-th decision variable of agent A_i's j-th strategy $S_{i,j}$ describes what the agent plans to do with regard to this specific decision variable $s^t_{i,j,k}$ at time $t \in [t_0, t_e]$. Therefore,

$$S_{i,j} = ((s^{t_0}_{i,j,1},...,s^{t_0}_{i,j,k},...,s^{t_0}_{i,j,n}),...,(s^{t}_{i,j,1},...,s^{t}_{i,j,k},...,s^{t}_{i,j,n}),...,(s^{t_e}_{i,j,1},...,s^{t_e}_{i,j,k},...,s^{t_e}_{i,j,n})) \quad \text{(Eq. 1)}$$

Thus, the agents are facilitated to formulate strategies in terms of decision variables, which are linked to an environmental object model through a causal network illustrated below.

4.2.4 Timed causal network (TCN)

The TCN models the mechanisms that govern the dynamics of the environmental system and transforms the strategies into updated conditions or parameters of the object component model $\mathbf{M}$. Decision variables are identified with the aid of $\mathbf{G}$ for constructing strategies. They are the controllable state variables in $\mathbf{G}$. In accordance to the procedures described in

Fig. 1, the TCN computes the stepwise state updating from $G_t \rightarrow G_{t+1}$ resulting from the actions d_t at time t, by using a set of state transition functions f_G:

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

$$d_t = (s_1^t, \ldots, s_k^t, \ldots, s_n^t) \quad \text{(Eq. 3)}$$

G_t represents the state variables of $\mathbf{G}$ at time t. σ_G denotes all the parametric uncertainties in $\mathbf{G}$. In principle, this is similar to a timed automaton, whose the initial conditions must also be well defined (Cassandras and Lafortune, 1999). We use the term timed causal network because first, $\mathbf{G}$ describes causal relations, and second, both the actions it receives and the state variables it updates are timed information.

$\mathbf{G}$ is represented by a specific graphic model that has two types of nodes: "place", represented by a circle and "transition" by a square (see Fig. 2). Such language is inherited from Petri net theory (Barad, 2003). In $\mathbf{G}$, 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". $\mathbf{G}$ is made of a group of distributed cellular networks (Ferber, 1999), each of which represents one "transition" and the "places" that it is directly linked with (see Fig. 2). Together these networks describe the causal relationships in the entire $\mathbf{G}$.

The steps for generating complex timed causal networks can be as follows: (1) Identify the relevant "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".

4.2.5 Object component (environmental system)

The agent to be facilitated usually confronts problems with the external world or with other concrete objects, *e.g.*, an area development, an infrastructure system, a river, a lake, or the combination of these objects. We identify this part of the model as the object component $\mathbf{M}$. It models the performance of the objects of concern under various actions. $\mathbf{M}$ receives updated inputs, *i.e.*, output variables G_{t+1} from $\mathbf{G}$ as parameters, and calculates the updated state M_{t+1} as following:

$$M_{t+1} = f_M(M_t, G_{t+1}, \sigma_M) \quad \text{(Eq. 4)}$$

where M_t represents the set of all state variables at time t in the component $\mathbf{M}$, which can comprise multiple levels of subsystems, *e.g.*, an urban drainage system and a regional water balance system, as will be illustrated later on. f_M describes the laws and mechanisms in the object of study, *e.g.*, in our case application of water resource planning and pollution control. It describes the conservation of mass laws of all the included processes. σ_M denotes all the parametric uncertainties in $\mathbf{M}$.

4.2.6 On the process of facilitation

A facilitation process should be sense-making; that is, making sense of the information and of the perspectives taken by both the facilitator and the agents (Boland and Tenkasi, 1995; Monk, 1998). This requires well defined and commonly shared knowledge representations to make any identified evidence of process improvement simple and clear (Pednault, 2000; Pfeffer and Sutton, 2006). The relationship between the facilitator (who is the expert of modeling) and the practitioners (who are the experts of the case) should be equal so that a process of mutual learning can take place. In multi-agent settings, the agents usually have "*differing perspectives, partially conflicting interests, significant intangibles*" and "*perplexing uncertainties*" (Rosenhead, 2006, 759). Thus, facilitation requires mediation of the conflicts between the involved agents. In general, a minimum level of cooperative interests is necessary. A prerequisite of multi-agent facilitation is that the utility functions of all participating agents become specified and transparent, at least to the facilitator. Coalition formation in the game-theoretical sense and negotiation analysis (Raiffa and Richardson, 2002) can thus be applied to coordinate strategies between agents in a joint view on the object level.

4.3 Case study

We now apply the method to facilitate strategy exploration in a water management case in Kunming City, China. The case study focuses on how the agents can benefit from the presented method and gain insight into constructing, evaluating, and modifying strategies in a complex case. In the following, we illustrate the problem, the agent, and the information produced for facilitating strategy exploration.

4.3.1 Background and motivation

Kunming is located in the Dianchi Valley. It is the largest city in Yunnan province in southwest China. It currently has a population of 2.5 million people and is undergoing rapid urbanization. According to local planning authorities, the city agglomeration will eventually have a population of 4.4 to 4.9 million distributed among four areas surrounding Dianchi Lake. The lake is the sixth largest freshwater lake in China with an average surface area of 300 km^2 and an average depth of 4.4 meters. Since the 1980s, the lake has been heavily polluted by an overload of nitrogen and phosphorous from domestic wastewater discharges (KIES, 2003) causing a bloom of blue-green algae and hyacinths. Urban growth and pollution are limiting the water resource availability for the city's water supply. A water import project conveying 245 million m^3/a water into Dianchi Valley has been initiated and will be in operation in 2008.

The first wastewater treatment plant was constructed in Kunming in 1988. Since that time several more wastewater treatment plants have been constructed and other measures taken to reduce the pollution load entering Dianchi Lake. However, all these measures have not kept up with the rate of growth of the city. The urban total phosphorus (TP) load alone to Dianchi Lake in 2003 was around 27 times higher than the lake's TP tolerance level of 60 tons/a. (Gray and Li, 1999; Huang, Bader, et al., 2006). Attempts to reduce pollution have been greatly outweighed by the increase in pollution produced by the city. Compounding conditions include: increasing future stress caused by increased population and industry, technical limitations for removing pollutants from waste streams and financial constraints.

4.3.2 Agent Analysis

The institutional and economic foundations of China are rapidly transforming in the context of ongoing political and economic reform policies. The same holds true for water management. The agents (*e.g.*, institutions, politicians, managers) act within an organizational setting, where the subordinate level agents have a certain amount of autonomy while the top-management agents play a dominant role in strategy making. The transient organizational dynamics and the centralized decision making structure suggests that strategy exploration facilitation should be initially focused on the top management group (tmg-agent hereafter, treated in this paper as a unitary agent consisting of a small group of at large eight top-managers coordinated by a higher-level government leader). Therefore, at this stage $\tilde{A} = \{A_1\}$ is considered. Following this, the next step can move on to multi-agent strategy exploration facilitation, where the focus comes down to the operational level, and the conflicts of interest, objectives, and competition for resources including positional bargaining (Fisher, et al., 1999) need to be considered.

Initially, the situation was that the tmg-agent did not have well-defined information regarding the system. This probably was because little attention had been directed to information systems for supporting diagnosis and analysis of the case from an integrated perspective. Thus, a comprehensive understanding, long-term envisioning, and interventions to deal with the water management problem were still missing. Furthermore, the local expert leader has called for a major change in understanding of the issue and for science-based guidelines for strategic planning (Deng, 2006).

The tmg-agent had the following general aspirations: (a) the urban population will increase to 4.4 to 4.9 million people within Dianchi Valley in the next 20 or 30 years; (b) the city shall have enough safe water available for urban water supply; (c) the local water system, including the urban river and the lake shall be maintained so that it is constantly in a healthy condition.

We assumed that the tmg-agent, A_1, has a utility function U_1 and a set of strategies $S(A_1)$. Each strategy $S_1,...,S_j,...,S_N$ is specified with a set of decision variables, each defines what to do regarding the specific controllable variable in the next 40 years.

During construction of a utility function, the aforementioned three goal variables — urban population, safety of urban water supply, and the quality state of the rivers and Dianchi Lake — were all relevant. It was also agreed upon that Dianchi Lake is the life-supporting system of city and that the lake water quality is a symbol of the city. Thus, the dominant focal variable among the three goal variables was the quality state of Dianchi Lake.

The "quality state of Dianchi Lake" is by nature a complex phenomenon, which can be evaluated by different criteria in different contexts. According to (KIES, 2003): (1) the current outstanding quality problem of Dianchi Lake is eutrophication due to overloaded input of nutrient elements, *e.g.*, nitrogen and phosphorous(2) Dianchi Lake is a phosphorous limited eutrophication lake, that is to say, controlling phosphorous load was a prerequisite though not sufficient for restoring the lake; (3) most phosphorous loads have come from urban discharge, and (4) the problem needs to be controlled as soon as possible (Huang, Bader, et al., 2006). Thus, we simplified the utility as a function of urban TP load and time for evaluating the achievement of an urban water management strategy S_j.

Let TP_0 denote the goal of urban TP load. 33 tons/a have been suggested as ideal goal (Huang, Bader, et al., 2006) and 33 to 100 tons/a as an acceptable range. $TP_u(S_j,t)$ denotes the urban TP load to the lake at time t under strategy S_j. In a first step, the construction of a simple utility function, which can be taken as a first device for evaluating the efficacy of a strategy, is needed. The time period $[t_0,t']$, $t' < t_e$ has been used for the evaluation period of the strategy. A reasonable utility function for evaluating strategy S_j, which has been discussed by tmg-agent, accounts for the integral difference between $TP(S_j,t)$ and TP_0, *i.e.*

$$U(S_j) = \int_{t_0}^{t'} (TP_0 - TP(S_j,t))dt \qquad \text{(Eq. 5)}$$

However, this utility function only reflects the average effect of a strategy and does not incorporate the course of the TP inflow with time, in particular the state at a certain point of time t. Therefore, its derivative is introduced, *i.e.*

$$U'(S_j, t) = TP_0 - TP(S_j, t) \qquad \text{(Eq. 6)}$$

In the following, we consider Equation 5, which allowed for a robust evaluation of the strategies that have been considered. Naturally, a weighted mixture of the utility functions of Equation 5 and 6 could also be taken. It is worth noting that in the multi-agent case, when agents require an integration of different aspects such as cost, social impacts or other environmental parameters for an overall evaluation, the above utility functions can be extended to a multi-criteria utility setting (Loukopoulos and Scholz, 2004).

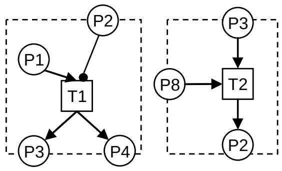
4.3.3 Object component of the case study

The object component $\mathbf{M}$ has been built with two interrelated levels of systems. One level describes the urban drainage system. There are three flows considered: water (Q), total nitrogen (TN), and total phosphorous (TP). Another level describes the regional water balance system. This object model consists of thirteen compartments, *e.g.*, reservoir, river, lake, households, sewer and so on.

The structure of the object component changes over time as strategic interventions are enacted (see Fig. 3). The state variables $M \in \mathbf{M}$ include all stocks and flows inside the systems. The model component $\mathbf{G}$ describes the causal relations of parameters in response to the changes in decision variables over time. These included the decision variables of immigrants and the local urbanization rate, which would trigger the overall urban population change as well as the changes in urban area. The updated parameters in $\mathbf{G}$, then, are the changing boundary conditions for the object components $\mathbf{M}$. The notations and flow variables in $\mathbf{M}$ refer to Appendix A.

4.3.4 Developing the timed causal network thinking

Before TCN ($\mathbf{G}$ in symbol) was introduced, two problems in implementing the dynamic simulation of the object component were faced. First, if one exogenous strategic change or action is made, the object component computes the networked flow quantities but may overlook the connected changes of parameters applied. Second, there is a need to guide the identification of decision variables based on an understanding of the causal mechanisms, and not merely discussions and intuition. Third, the sequence and timing of the events need to be considered. Therefore, a TCN was introduced. The method was detailed in (Huang, Scholz, et al., 2006). $\mathbf{G}$ was constructed to link the strategies into updated parameter changes of the object component model $\mathbf{M}$. Eighteen decision variables (see Appendix B) were identified with the assist of model **G**. Examples of transitions were: $T1$ urban development (the city requires vast amounts of water to be readily available) and $T2$ water resource self-sufficiency (the city searches for and attempts to ensure sufficient water resources in order to support its existence). Each transition has been described with a cellular network model; thus, the timed causal network is actually an ensemble of the cellular network. Fig. 2 illustrates transitions $T1$ and $T2$.



Notations: P for "place", 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: T1 – urban development; T2 – water resource self-sufficiency;

T1

```
IF T1 is NOT inhibited, THEN
   Update urban population
   Update rural population
   Update urban area size
   Update industrial size in PE*
ELSE
   DO NOTHING
END

*: PE denotes population
equivalent in terms of water
consumption.
```

T2

```
IF water availability limited, THEN
   Inhibit urbanization
   IF urbanization is still an incentive for economic growth,
      THEN
      DO
      either increase the capacity of local water resource
      or reduce water consumption
      or import external water resource if feasible
      Update water availability
   END
ELSE inhibitor released
END
```

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

	Name	State variables $G \in \mathbf{G}$	Unit
P1	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	-
P2	water resource availability	1. Local water resource availability	*m³/a*
		2. External water resource availability	*m³/a*
		3. Inhibitor	-
P3	water consumers	1. Total rural population	*p*
		2. Total urban population	*p*
		3. Industries in population equivalence of water consumption	*p*
P4	urban area	1. Total impervious area of the city	*hectare*
		2. Pollution coefficients in runoff, e.g. for total phosphorous	*mg/m³*
		3. Constructed new impervious area	*hectare*
P8	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

Fig. 2. Timed causal networks

4.3.5 Developing the strategy component

To assist the agent in accessing all decision variables explicitly, we plotted all the relevant decision variables that were generated and identified in the discourse with the tmg-agent in the strategy component and linked them explicitly with **G**. Thus the tmg-agent could formulate strategies, which permitted the quantitative assessment of the impacts on the object component by simulation.

For instance, the development of strategic assumptions related to water supply could be assisted with the sampled six decision variables as seen in Fig. 3. Of course, combinations of decision variable changes have only been allowed if they are compatible with the object level. When a described condition for a change at a certain time has not been met, the model pointed out the error by predefined constraints. This also helped the agents to remember all the rules and conditions while making strategic assumptions to be evaluated with simulation.

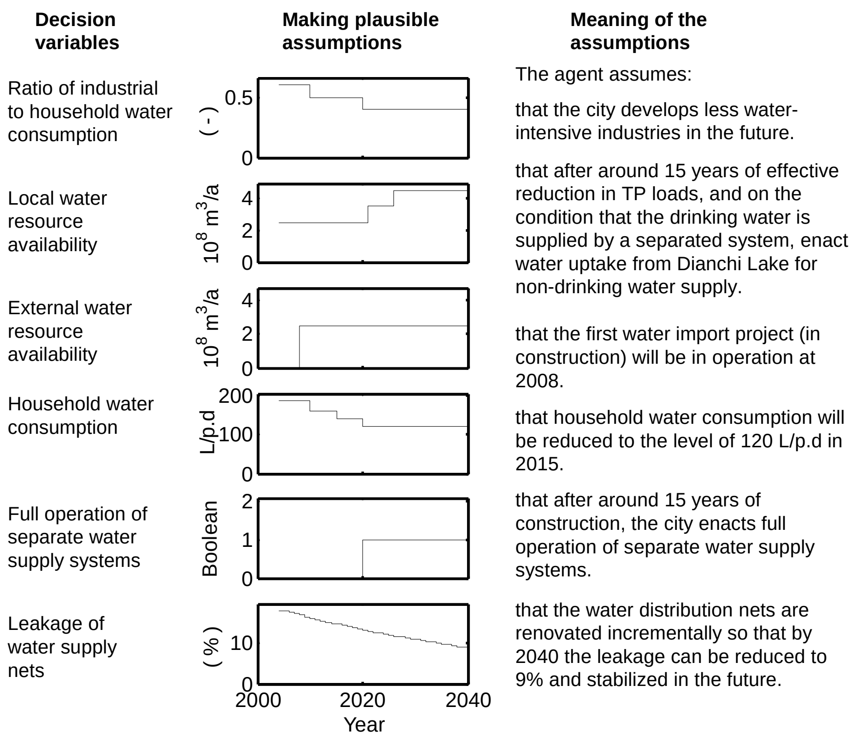
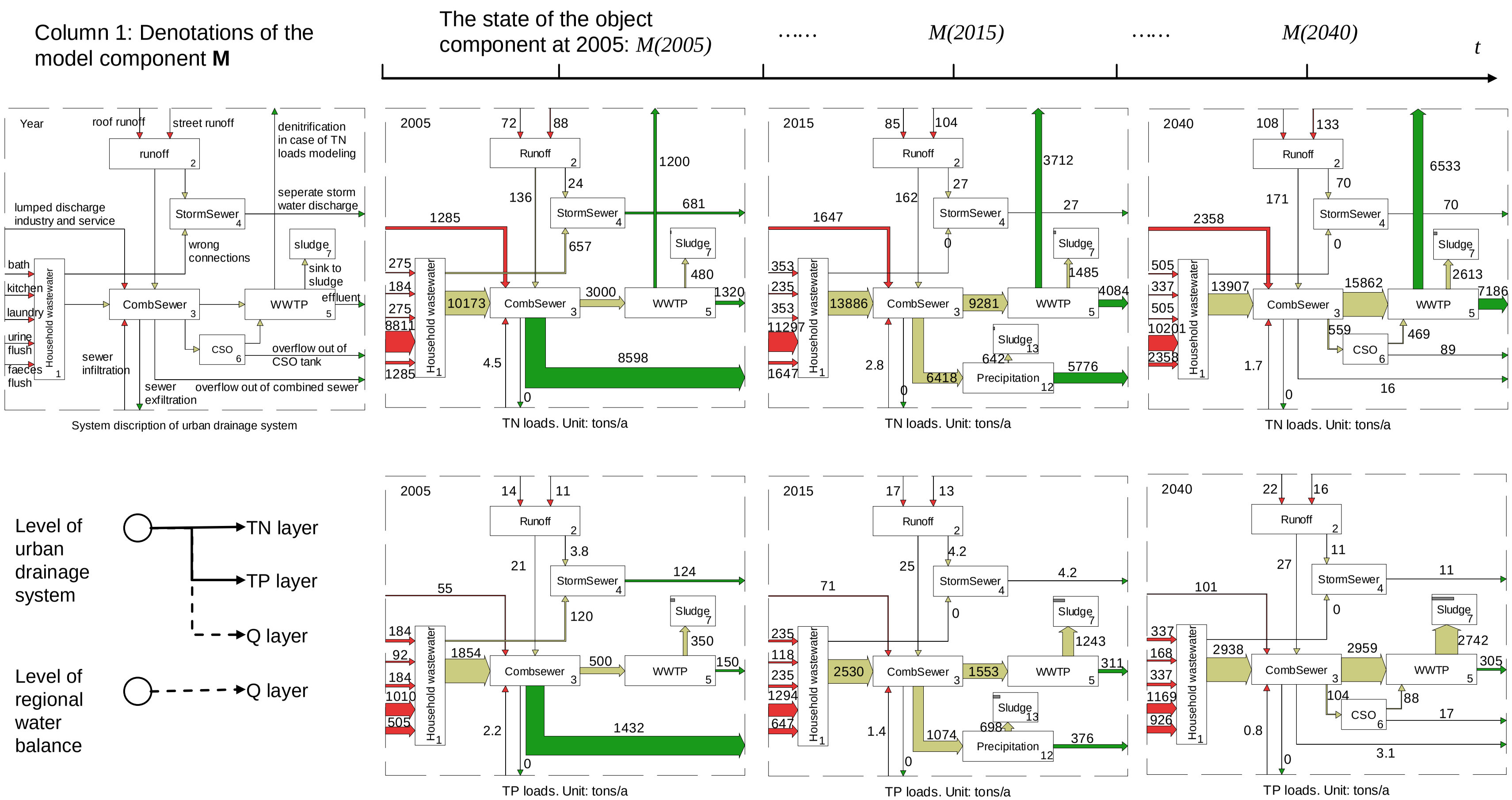


Fig. 3. Example decision variables for making strategic assumptions

4.3.6 Information generating and interpreting

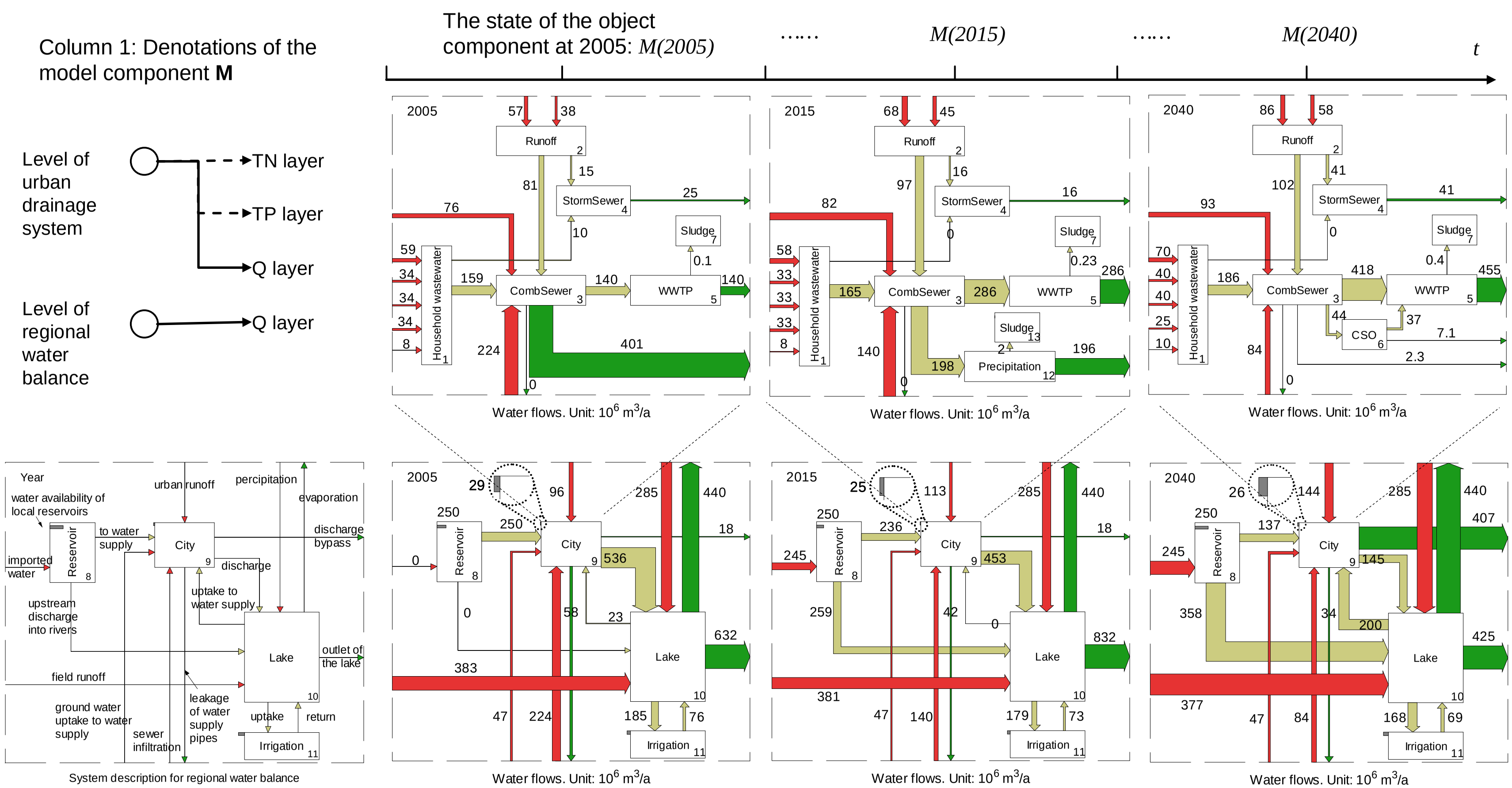
In the discourse of joint information generating and interpreting between the facilitator and the agent, the discussion on visualized outcomes played a major role. Strategy exploration included: (1) the initial state analysis of the environmental objects represented in Fig. 4 (see column $M(2005)$), (2) a discrete description of the state transitions and interdependencies (Fig. 4, indicating *e.g.*, the state transition $M(2005) \rightarrow M(2015) \rightarrow M(2040)$), (3) the temporal dynamics of concerned state variables (Fig. 5), and (4) the evaluation utility curve (Fig. 6).

Fig. 4 consists of distributed material flow diagrams (DMF). They display the interrelations of quantities and the configuration of systems in an explicit form. One important benefit is that representation and visualization is a powerful means for demonstrating both the interdependencies of the object systems and the effects caused by activities in terms of decision variables. For example, the interdependencies of object components such as the upstream reservoir, the city, and the lake at the regional water balance level are traceable in Fig. 4-2. The understanding of the causes of interdependencies among activities is also assisted by such representations. Another benefit of this type of visualization is that the tmg-agent obtains insight into the multi-dimensional effects over time of each strategy. Moreover, flexibility and extendibility are allowed by a distributed modeling approach.



Note: Arrows denote flows or loads numbered with quantities, an arrow's thickness is proportional to its denoted quantity; each box is labeled with a number in the bottom-right corner; a horizontal bar in the upper-left corner denotes a positive quantity of stock, inside means positive stock (e.g., compartment 7), outside denotes a negative quantity of stock (e.g., compartment 9 in Fig. 4-2). "CombSewer" denotes combined sewer. In locations where canalization is not completed and open canals are still used to convey wastewater, these open canals are accounted for in "CombSewer". "CSO" signifies combined sewer overflow tank for temporary overflow storage. "Precipitation" (in Column 3, compartment 12) refers to chemical precipitation for temporary TP removal at the overflow canals flowing to Dianchi Lake.
WWTP – wastewater treatment plant; TP – total phosphorous; TN – total nitrogen; Q – water flows.

Fig. 4 – 1. Distributed flow diagrams of the TN and TP loads in the urban drainage system of Kunming resulting from strategy assumption S_1.



Note: A section of the upper-left corner of compartment 9 (City) is zoomed in upon, displaying the water loss through industry. As a consistency check tool for verifying the computation, the sum of inputs, outputs and stocks of each compartment should be balanced with an error of ±1. The error is due to transforming real numbers into integers. Plotted numbers that are smaller than 10 are displayed to one decimal point, otherwise as an integer).

Fig. 4– 2. Distributed flow diagrams of water quantities in both the models of urban drainage system and also the regional water balance system of Kunming resulting from strategy assumption S_1.

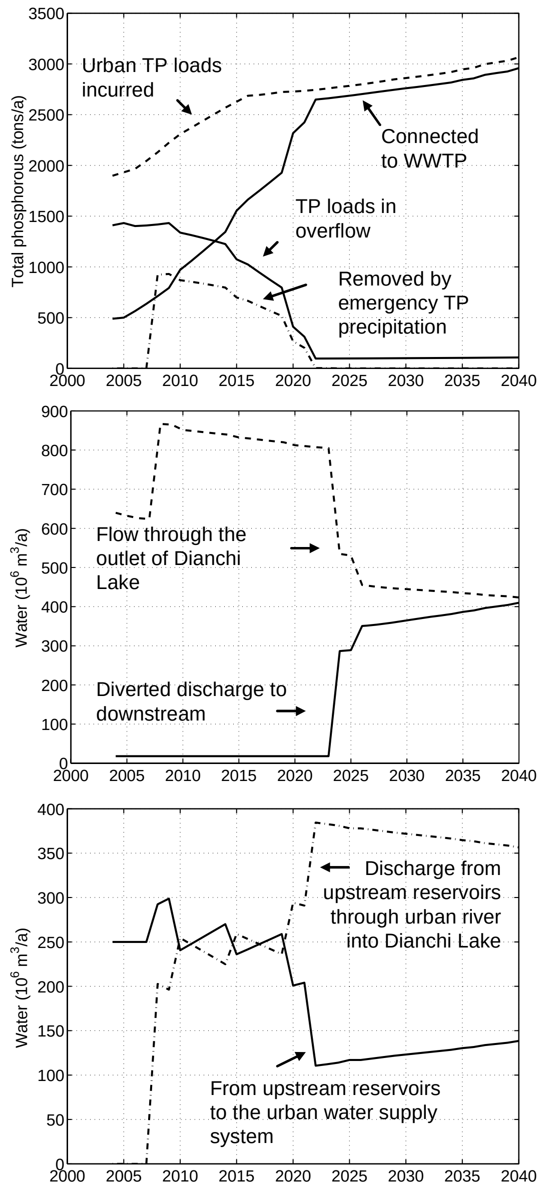
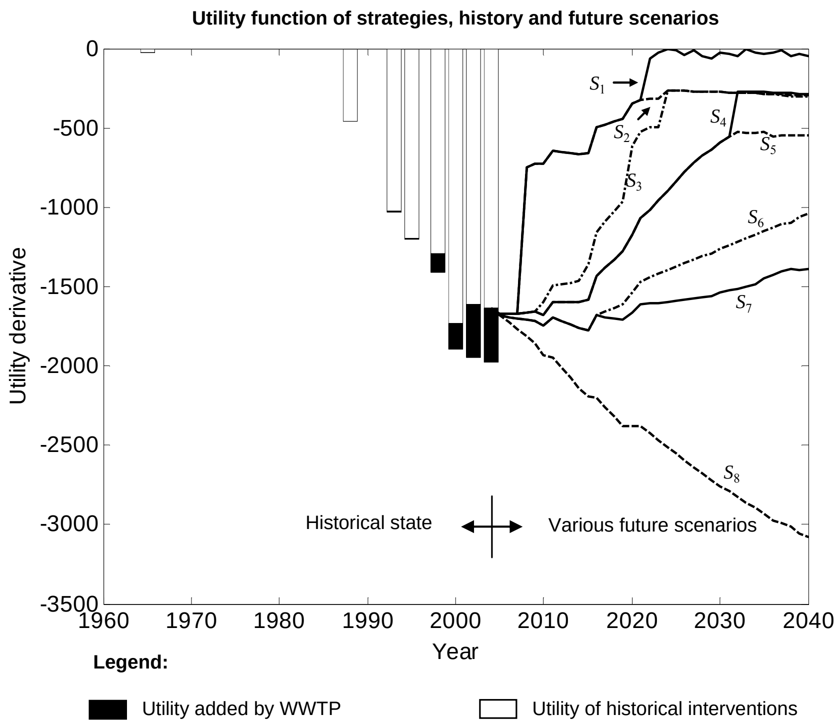


Fig. 5. The dynamics responding to a defined strategy

Information on the temporal dynamics of variables provided insightful knowledge to the agent regarding the cause and effect of strategies. Fig. 5 demonstrates the temporal dynamics of some sampled variables as a result of a defined strategy S_1. For example, the curve of TP loads connected to WWTP is a mixed effect of "correcting wrong connections of sewers", "reducing sewer infiltration", "reducing water consumption in household and industry", "increasing capacity of WWTP", "increasing urban population", "source separation at household sanitation", and so on. Clearly, the temporal dynamics differ when the strategy changes.

Finally, we applied the utility function of Equation 5 to evaluate strategies. It is impossible to make exhaustive variations on strategies. In the following only some differential scenarios based on S_1 are illustrated (Fig. 6).



The utility of historical interventions and future scenarios as a result of the following strategies (Let "\" denote "neglected" or "not considered", "*S*" for a strategy, "*s*" for a decision variable):

strategy S_1
$S_2 = S_1 \setminus s_{18}$, *i.e.*, no bypass is assumed
$S_3 = S_2 \setminus s_{15}$, *i.e.*, no temporary TP precipitation at overflow canals is assumed
$S_4 = S_3 \setminus (s_3, s_6)$, *i.e.*, no water saving is assumed
$S_5 = S_4 \setminus s_{16}$, *i.e.*, no CSO tank is assumed
$S_6 = S_5 \setminus s_{11}$, *i.e.*, no improvement of sewer infiltration is assumed
$S_7 = S_6 \setminus s_7$, *i.e.*, no source separation is assumed
$S_8 = S_7 \setminus s_{13}$, *i.e.*, no increase of wastewater treatment capacity is assumed

Fig. 6. The dynamic utility of strategies - history and future scenarios

4.3.7 Discussions of the case study

The facilitation of strategy exploration in the Kunming water management case is ongoing. Four challenges deserve to be noticed: The first is the willingness of the tmg-agent to participate. The matter of trust and mutual confidence is as important (Earle and Siegrist, 2006) as the building of realistic expectations about the outcomes. In this context the cultural constraints are important (Doney, et al., 1998). The second is the language gap between the theory-equipped facilitator and the practice-equipped tmg-agent. An important help in this respect is a proper visualization of the modeling and the results. This provides a platform for communication and interpretation (van Wijk, 2006). The third is the acceptance of the data and the variables included in the model and of the decision variables by both the agent and the facilitator. The fourth challenge, also the most delicate one, is the agent's acceptance of the validity of a model despite its reductive nature, which is a simplified and idealized representation of the whole reality. For example in the presented case, the financial and the political situation are excluded. This fourth challenge has to do with realistic expectations in decision support tools and procedures. We countered this challenge by pointing out the need for an integrated regional and urban level water system (see Appendix A) and by keeping the flexibility and extendibility of the model with respect to new requirements.

Despite the above challenges, some helpful conclusions can nevertheless be drawn. For example, in Fig. 6, a comparison of the curves labeled S_1 and S_2 makes clear 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 TP_0 in the future. The intersection of curves of S_2 and S_3 indicates that the quantities of TP reaching Dianchi Lake can be significant if temporary TP precipitation at overflow canals is not to be used. The difference between curves of S_3 and S_4 indicates the importance of water saving, in households as well as in industry. By comparing curves of S_4 and S_5, the limited effect of CSO tanks in the context of applying S_1 became evident (see Fig. 4-1, upper right DMF) suggesting that it would only make sense to implement CSO tanks in Kunming after sufficient wastewater collection and treatment capacity would be available, even if CSO tanks become economically acceptable in the future. The difference between curves of S_5 and S_6 indicated the importance of controlling unwanted sewer infiltration. The comparison between curves S_7 and S_6 provided an indication of the potential benefit of source separation for human urine from domestic wastewater, provided there are feasible techniques available in the future. Finally, curve S_8 indicated the important role of increasing wastewater collection efficiency and treatment capacity.

So far, the generated information and interpretations are based on the one agent setting. As different agents (*e.g.*, different departments of the city) are operationally responsible for the realization of effective changes on various decision variables, it became clear that there are potential conflicts of interests. For instance, an agent who is responsible for importing water may tend to oppose water saving actions and the renovation of the water supply system. Theoretically, a forthcoming step can upgrade this simplified one agent setting to multi-agent strategy exploration facilitation.

4.4 General discussion

The model structure presented contributes to strategic decision support. It aims at linking the strength of both (i) systems dynamics and discrete event systems (DES) theory, which are strongly related to the "hard OR (functionalistic, positivist) paradigm" (Robinson, 2001; Sterman, 2001), and (ii) strategic choice or problem structuring approaches, which are rather soft (qualitative) OR methods (Friend and Hickling, 2005; Rosenhead, 2006). The method exhibits some characteristics of both "hard" and "soft" OR approaches. With respect to the "hard" approaches, these characteristics include, for instance, the intensive data demand, the systems based analysis, the idea that mathematical quantitative analysis and modeling help to improve the real world, and the issue that solutions are tested in terms of efficiency and effectiveness. The necessity to include "hard" characteristics is highlighted by the fact that a shared (but negotiated) single objective (*i.e.*, the TP load) had to be taken in a first step due to the necessity of complexity reduction. Characteristics of the DES method that are stronger related to "soft" OR approaches are, for example, that no optimal solution is targeted but rather, only better and sufficient solutions are targeted, that there are strong simplifications and complexity reductions, that models are used to construct and interrogate different perceptions of the real world, and that the knowledge of the agent was a key issue of the analysis. By combining characteristics of "soft" and "hard" OR approaches, the proposed approach goes beyond the traditional system dynamics and hard OR methods but also beyond problem structuring methods (Kotiadis and Mingers, 2006).

The TCN is represented in distributed cellular modes and therefore enhances the extendibility and interpretability of a complex model. It also allows for (i) constructing a strategy with decision variables so that a strategy can be digitalized, (ii) identifying decision variables with the assistance of TCN so that identifying the elements of a strategy are based on causal mechanisms and not only on discussions and intuition, and (iii) linking the strategic change of agents with object components (the environmental system in this paper) through the TCN so that cascading changes of boundary conditions of an environmental system are coherently transformed.

At the current stage it is still an open question as to whether modeling the agents' thinking and learning (Fig. 1, double lines) can be successfully done. Prerequisites for doing this are that the agents' knowledge can be modeled with decision variables and that the updating of knowledge as well as the acquisition of information can be appropriately recorded over a longer time period. We think that most learning takes place in interactive discourses between the facilitator, the agent(s), and the DES simulations. Based on recent psychological research, simple heuristic approaches in the frame of bounded rationality

(Brandstatter, et al., 2006; Scholz, 1987; Selten, 1998; Todd and Gigerenzer, 2003) seem appropriate for describing agent learning. In any case, the agent component will require further in-depth study both from the theoretical and the practical point of view.

Future studies on the case can also be deepened by providing a detailed iterative validation process (*e.g.* of the data utilized) with the participation of the agent. Multi-agent strategy exploration and facilitation are also called for when conflicts of interest and competition for resources, such as financial investments in multiple projects, need to be considered. In such circumstances, the social constraints will also be important to study. A more detailed time resolution of input data can also be accommodated with the model.

In general, as demonstrated by the case study, the model generates useful and well-structured knowledge on the cause-effect relations of strategies for the agent. This knowledge would ordinarily be difficult for the agent to acquire. The presented model structure has a potential strength in integrating both qualitative and quantitative approaches for environmental strategic planning.

4.5 Acknowledgements

We thank the Swiss National Science Foundation and Swiss Development Agency for their joint funding through the research framework of Swiss NCCR North-South, as well as the Kunming city government for positive cooperation. We thank Derek E. Chitwood, Peter Loukopoulos for precious comments and corrections, as well as the valuable pre-reviews offered by Kiyotada Hayashi, Dieter Genske, Thomas Köllner, Timo Smieszek, and Alexander Walter.

4.6 References

Andersen, D. F., Richardson, G. P. 1997. Scripts for group model building. *System Dynamics Review*, 13(2), 107-129.

Bankes, S., Lempert, R., Popper, S. 2002. Making computational social science effective - Epistemology, methodology, and technology. *Social Science Computer Review*, 20(4), 377-388.

Barad, M. 2003. An introduction to Petri nets. *International Journal of General Systems*, 32(6), 565-582.

Boland, R. J., Singh, J., Salipante, P., Aram, J. D., Fay, S. Y., Kanawattanachai, P. 2001. Knowledge representations and knowledge transfer. *Academy of Management Journal*, 44(2), 393-417.

Boland, R. J., Tenkasi, R. V. 1995. Perspective making and perspective-taking in communities of knowing. *Organization Science*, 6(4), 350-372.

Brandstatter, E., Gigerenzer, G., Hertwig, R. 2006. The priority heuristic: Making choices without trade-offs. *Psychological Review*, 113(2), 409-432.

Cassandras, C. G., Lafortune, S. 1999. *Introduction to discrete event systems*. Boston: Kluwer Academic Publishers.

Chalmeau, R., Gallo, A. 1993. Social constraints determine what is learned in the chimpanzee. *Behavioural Processes*, 28(3), 173-179.

Daily, G. C., Walker, B. H. 2000. Seeking the great transition. *Nature*, 403(6767), 243-245.

Deng, D. R. 2006. *Personal communication*. Kunming: Expert leader of Dianchi Lake Protection Bureau.

Dietz, T., Ostrom, E., Stern, P. C. 2003. The struggle to govern the commons. *Science*, 302(5652), 1907-1912.

Doney, P. M., Cannon, J. P., Mullen, M. R. 1998. Understanding the influence of national culture on the development of trust. *Academy of Management Review*, 23(3), 601-620.

Earle, T. C., Siegrist, M. 2006. Morality information, performance information, and the distinction between trust and confidence. *Journal of Applied Social Psychology*, 36(2), 383-416.

Eisenhardt, K. M. 1999. Strategy as strategic decision making. *Sloan Management Review*, 40(3), 65-72.

Ferber, J. 1999. *Multi-agent systems: An introduction to distributed artificial intelligence*. Harlow: Addison-Wesley.

Fisher, R., Ury, W., Patton, B. M. 1999. *Getting to yes: Negotiating an agreement without giving in* (2nd ed.). London: Random House.

Forrester, J. W. 1992. Policies, decisions and information-sources for modeling. *European Journal of Operational Research*, 59(1), 42-63.

Franco, L. A., Cushman, M., Rosenhead, J. 2004. Project review and learning in the construction industry: Embedding a problem structuring method within a partnership context. *European Journal of Operational Research*, 152(3), 586-601.

Friend, J., Hickling, A. 2005. *Planning under pressure - the strategic choice approach* (3rd ed.). Oxford: Elsevier.

Gray, A. V., Li, W. 1999. Case study on water quality modelling of Dianchi lake, Yunnan Province, South West China. *Water Science and Technology*, 40(2), 35-43.

Hammer, M. 1990. Reengineering Work - Dont Automate, Obliterate. *Harvard Business Review*, 68(4), 104-112.

Holland, J. H. 1998. *Emergence: from chaos to order*. Reading, Mass.: Addison-Wesley.

Huang, D. B., Bader, H.-P., Scheidegger, R., Schertenleib, R., Gujer, W. 2006. Confronting limitations: New solutions required for urban water management in Kunming City. *Journal of Environmental Management*, In press. Online available: doi:10.1016/j.jenvman.2006.05.004

Huang, D. B., Scholz, R. W., Gujer, W., Chitwood, D. E., Loukopoulos, P., Schertenleib, R., Siegrist, H. 2006. Discrete event simulation for exploring strategies: An urban water management case. *Environmental Science & Technology*, In press.

KIES. (2003). *Investigation of pollution sources of Dianchi Lake.* Kunming, China: Kunming Institute of Environmental Science.

Kotiadis, K., Mingers, J. 2006. Combining PSMs with hard OR methods: the philosophical and practical challenges. *Journal of the Operational Research Society*, 57(7), 856-867.

Lane, D. C. 1999. Social theory and system dynamics practice. *European Journal of Operational Research*, 113(3), 501-527.

Langley, P. A., Morecroft, J. D. W. 2004. Performance and learning in a simulation of oil industry dynamics. *European Journal of Operational Research*, 155(3), 715-732.

Laverty, K. J. 1996. Economic "short-termism": The debate, the unresolved issues, and the implications for management practice and research. *Academy of Management Review*, 21(3), 825-860.

Lempert, R. J. 2002. A new decision sciences for complex systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99, 7309-7313.

Levinthal, D. A., March, J. G. 1993. The myopia of learning. *Strategic Management Journal*, 14, 95-112.

Loukopoulos, P., Scholz, R. W. 2004. Sustainable future urban mobility: using 'area development negotiations' for scenario assessment and participatory strategic planning. *Environment and Planning A*, 36(12), 2203-2226.

Mingers, J., Rosenhead, J. 2004. Problem structuring methods in action. *European Journal of Operational Research*, 152(3), 530-554.

Mitroff, I. I., Emshoff, J. R. 1979. On strategic assumption-making: A dialectical approach to policy and planning. *The Academy of Management Review*, 4(1), 1-12.

Monk, A. 1998. Cyclic interaction: a unitary approach to intention, action and the environment. *Cognition*, 68(2), 95-110.

Morgan, M. G., Henrion, M., Small, M. 1990. *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis.* Cambridge etc.: Cambridge University Press.

Moxnes, E. 2004. Misperceptions of basic dynamics: the case of renewable resource management. *System Dynamics Review*, 20(2), 139-162.

Ngwenyama, O. K., Bryson, N., Mobolurin, A. 1996. Supporting facilitation in group support systems: Techniques for analyzing consensus relevant data. *Decision Support Systems*, 16(2), 155-168.

Odum, E. P. 1993. *Ecology and our endangered life-support systems* (Second ed.). Sunderland, Massachusetts: Sinauer.

Pednault, E. P. D. 2000. Representation is everything - Issues of representation pose many questions and challenges that must be solved before implementation. *Communications of the Acm*, 43(8), 80-83.

Pfeffer, J., Salancik, G. R. 2003. *The external control of organizations: a resource dependence perspective* (Reissued 2003 ed.). Stanford, Calif.: Stanford Business Books.

Pfeffer, J., Sutton, R. I. 2006. Evidence-based management. *Harvard Business Review*, 84(1), 62-74.

Phahlamohlaka, J., Friend, J. 2004. Community planning for rural education in South Africa. *European Journal of Operational Research*, 152(3), 684-695.

Raiffa, H., Richardson, J. 2002. *Negotiation analysis: the science and art of collaborative decision making*. Cambridge, MA: Belknap Press of Harvard University Press.

Richards, D. 2001. Coordination and shared mental models. *American Journal of Political Science*, 45(2), 259-276.

Robinson, S. 2001. Soft with a hard centre: discrete-event simulation in facilitation. *Journal of the Operational Research Society*, 52(8), 905-915.

Rosenhead, J. 1996. What's the problem? An introduction to problem structuring methods. *Interfaces*, 26(6), 117-131.

Rosenhead, J. 2006. Past, present and future of problem structuring methods. *Journal of the Operational Research Society*, 57(7), 759-765.

Scholz, R. W. 1987. *Cognitive strategies in stochastic thinking*. Dordrecht: Reidel.

Scholz, R. W., Lang, D. J., Wiek, A., Walter, A. I., Stauffacher, M. 2006. Transdisciplinary case studies as a means of sustainability learning: Historical framework and theory. *International Journal of Sustainability in Higher Education*, 7(3), 226-251.

Scholz, R. W., Mieg, H. A., Oswald, J. E. 2000. Transdisciplinarity in groundwater management - Towards mutual learning of science and society. *Water Air and Soil Pollution*, 123(1-4), 477-487.

Scholz, R. W., Tietje, O. 2002. *Embedded case study methods: Integrating quantitative and qualitative knowledge*. London: Sage.

Selten, R. 1998. Features of experimentally observed bounded rationality. *European Economic Review*, 42(3-5), 413-436.

Shaw, D., Westcombe, M., Hodgkin, J., Montibeller, G. 2004. Problem structuring methods for large group interventions. *Journal of the Operational Research Society*, 55(5), 453-463.

Starbuck, W. H. 1983. Organizations as action generators. *American Sociological Review*, 48(1), 91-102.

Starbuck, W. H., Mezias, J. M. 1996. Opening Pandora's box: Studying the accuracy of managers' perceptions. *Journal of Organizational Behavior*, 17(2), 99-117.

Stauffacher, M., Walter, A. I., Lang, D. J., Wiek, A., Scholz, R. W. 2006. Learning to research environmental problems from a functional socio-cultural constructivism perspective: The transdisciplinary case study approach. *International Journal of Sustainability in Higher Education*, 7(3), 252-275.

Sterman, J. D. 1989. Modeling Managerial Behavior - Misperceptions of Feedback in a Dynamic Decision-Making Experiment. *Management Science*, 35(3), 321-339.

Sterman, J. D. 2001. System dynamics modeling: Tools for learning in a complex world. *California Management Review*, 43(4), 8-25.

Stern, P. C. 2005. Deliberative methods for understanding environmental systems. *BioScience*, 55(11), 976-982.

Tennenholtz, M. 1999. On social constraints for rational agents. *Computational Intelligence*, 15(4), 367-383.

Todd, P. M., Gigerenzer, G. 2003. Bounding rationality to the world. *Journal of Economic Psychology*, 24(2), 143-165.

van Wijk, J. J. 2006. Views on visualization. *Ieee Transactions on Visualization and Computer Graphics*, 12(4), 421-432.

Vennix, J. A. M. 1999. Group model-building: tackling messy problems. *System Dynamics Review*, 15(4), 379-401.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., Melillo, J. M. 1997. Human domination of Earth's ecosystems. *Science*, 277(5325), 494-499.

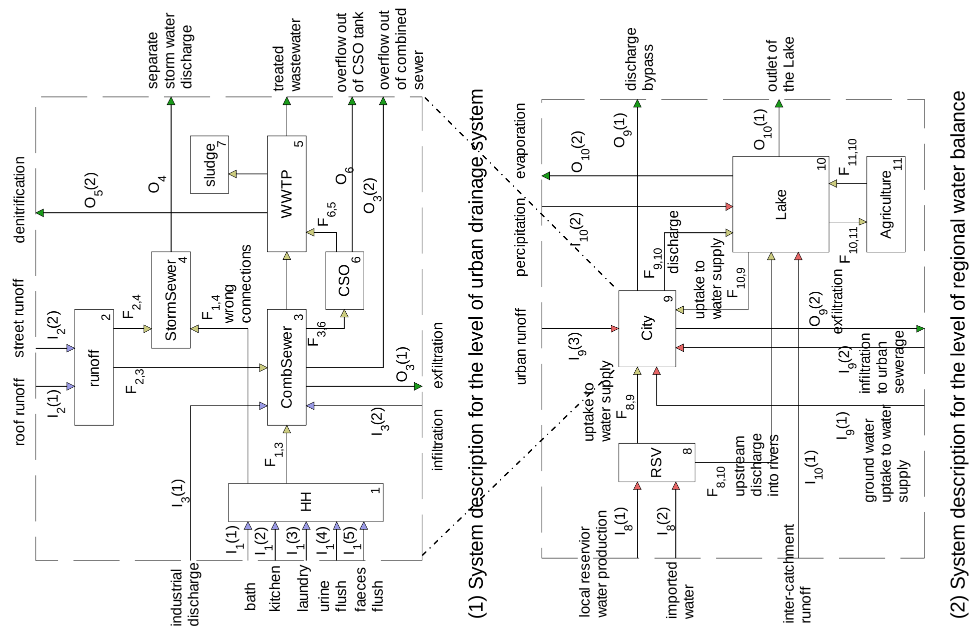
Weick, K. E., Sutcliffe, K. M., Obstfeld, D. 2005. Organizing and the process of sensemaking. *Organization Science*, 16(4), 409-421.

Whitesides, G. M., Ismagilov, R. F. 1999. Complexity in chemistry. *Science*, 284(5411), 89-92.

Yates, J. F. 1990. *Judgment and decision making*. Englewood Cliffs, N.J. etc.: Prentice Hall.

4.7 Appendix

Appendix A: Descriptions of the object component of environmental systems



Appendix B: The list of decision variables for the case study

	meaning	unit	variation range
s_1	annual immigrants	10^4 p/a	[0 3]
s_2	annual local rural population transferred into urban	10^4 p/a	[0 3]
s_3	ratio of industrial to household water consumption	-	[0.6 0.4]
s_4	average local surface water resource availability	10^8 m^3/a	[2.5 5.5]
s_5	imported external water resource availability	10^8 m^3/a	(0, 2.45, or more iff * necessary)
s_6	household water consumption	L/p.d	[200 120]
s_7	rate of source separation in urban household sanitation	%	[0 100]
s_8	full operation of separate water supply system	Boolean	(0, 1)
s_9	leakage of water supply nets	%	[30 5]
s_{10}	wrong connections in separate sewerage area	%	[30 0]
s_{11}	sewer infiltration ratio to water consumption	-	[1 0.3]
s_{12}	operation of separate sewerage in new built area	Boolean	(0, 1)
s_{13}	rate of wastewater treatment to the total wastewater	%	≤90%
s_{14}	average TP remove rate of WWTP	%	[60 95]
s_{15}	temporary enacting of TP precipitation at overflow canals	Boolean	(0, 1)
s_{16}	enacting of combined sewer overflow tank to meet the standard** of yearly 1% of overflow frequency	Boolean	(0, 1)
s_{17}	minimal upstream discharge to the urban river	m^3/s	6 if available
s_{18}	enacting the discharge bypass project	Boolean	(0, 1)

*: iff - if and only if; **: a benchmark standard of the urban drainage system assumed in Huang and Bader et al. (2006)

5 Discussions

5.1 Nature of the contribution

The nature of the thesis' contribution lies in its conceptualization and structuring of the model that match the purpose of facilitating management strategies exploration.

The thesis advances the state-of-the-art of environmental strategic planning for large-scale, long-term projects with the following originalities. (1) It specifies and digitalizes a strategy with decision variables, and makes the multiple elements of a strategy accessible to decision makers. (2) It develops a timed causal network for identifying decision variables and modeling the boundary conditions of environmental systems. (3) It develops a distributed representation of material flow diagrams and cellular networks enhancing the interpretability and extendibility of a complex model.

As a result of this improved method, its application in the study of Kunming urban water management provided the first comprehensive strategy analysis on that case. The case study is so far the first effort that: (i) integrates the cross-scale interdependencies of the urban drainage system and the regional water balance system; (ii) identifies as many as eighteen decision variables for constructing various strategic assumptions on urban water management and simulates the impacts from the present till in the long term; (iii) provides an holistic overview of the current situation, future limitations, potential solutions attributed with sequence and timing, as well as a tool for the decision makers to explore strategies for reaching the preferred and attainable future conditions. Several interactions with the local planners and decision makers have indicated good acceptance and potential implementation of the approach.

In general, the thesis brings forwards a computational policy and strategy experimentation method that incorporates discontinuous and non-incremental changes. It offers also a way to identify the source of changes to be made. The scenario analysis it applies is explicit, quantitative and dynamic. The computation method it applied also advances the dynamic material flow analysis and the dynamic life cycle inventory analysis, which may be embedded as a new tool for the field of industrial ecology.

5.2 Strategy exploration as an emerging theme for environmental decisions

In many similar cases, the task of improving environmental conditions is confronting technical limitations, limited natural tolerance, as well as increasing pressure from society. Such problems cannot be simply be expected to be solved by exploiting the available management routines or "old certainties", some of which can even be destructive in the long run (March, 1991; March, 2006). Thus exploring new possible solutions is becoming one central concern (Huang, et al., 2006).

The goal of strategy exploration is to identify the strategic paths towards preferred and attainable futures. A new solution or strategy does not confine itself to technical breakthroughs, but also frequently emerges by adjusting the combination of available technologies, altering the boundary conditions and the social context. It is hardly possible that a strategy with multiple actions for a large scale environmental system can be directly experimented in reality. Some elements of a strategy may be tested at a pilot scale, but to enact all these elements together in reality is to actually implement the strategy. It is learning-by-doing, if learning does happen after doing. In principle learning-by-doing is not a problem, except when it is used as an excuse for strategy failures, or even worse, for encouraging reckless strategic decisions. Such practices can be very costly and sometimes destructive. This causes a certain degree of difficulty and dysfunction in the environmental decision making activities, as the case study implies. Therefore, strategy exploration equipped with simulation models, but not just rely on automated simulation, may help direct the future trend of environmental decision-support.

The central task of strategy exploration is twofold: explore the multiple elements of a strategy and explore the multi-dimensional effects of a strategy through time that is relevant and long enough for the strategies to be made. These are in fact two fundamental behaviors that make strategic adaptation happen. Although various methods (see chapter 4) have been tackling the relevant issues, there is much more work that remains to be accomplished in the strategy exploration, which might emerge as a subfield of strategic management, both from the theoretical and empirical points of view.

5.3 Uncertainty types and improvement by model structure

One of the recognized distinctions in uncertainty types or sources is between *aleatory* (dependent on some uncertain contingency) and *epistemic uncertainty* (Oberkampf, et al., 2004). *Aleatory uncertainty* is the inherent variation associated with the system under consideration, and is most commonly represented with probability distributions within an established range or assumed range. *Epistemic uncertainty* derives from some level of inadequate understanding of the system under study, lack of knowledge or well-defined model structure. While this classification is agreeable, it is not readily tangible. Casman, et al., (1999) noted in this way: "*These two sources of uncertainty ... "aleatory" and "epistemic." While we have no disagreement with this classification, we avoid the use of the terms simply because we and many others have difficulty remembering what they mean, and which is which!*"

However, based on this classification, I assume that uncertainty is a mixture of two types in a general form, i.e., (σ, Σ). One type is the uncertainty on numbers or quantities, amenable to probability representation, denoted as σ; while the other is the uncertainty on mechanisms or interrelations, not amenable to probabilistic representation, denoted as Σ. This type of uncertainty can be improved by model structure, because model structure reflects the mechanisms or interrelations on the system of study. "*Uncertainty about model structure may become as, or more important than, uncertainty about parameter values*" (Casman, et al., 1999).

The inclusion of σ_M and σ_G in the model structure provides the model with a capacity of accommodating probabilistic uncertainty analysis regarding the parametric, input data's as well as the initial condition's uncertainty. The uncertainty analysis conducted in chapter 2 belongs to this type. On top of that, the thesis also attributes timing to each event. Therefore uncertainty on the firing of an event can also be analyzed.

The uncertainty type Σ is overwhelming and urgent to be improved in the case problem under study, despite the fact that data quality is also of significant concern. Improvement on data quality is a long term persistent effort need the enhancement of measuring infrastructure, monitoring plan and data management. Understandings on the nature of the problem and the complex mixture of interdependencies in the systems must be provided to meet this type of information gap that hinders the process of problem solving (Stern, 2005).

Once a well defined model structure is available, it is recommendable to first implement a quantitative scenario analysis by simulating with finite combinations of decision variables as strategies to be explored; this offers directly relevant information for strategy search and simplifies the further probabilistic inquiries, if necessary, only on a limited number of plausible strategies.

5.4 Perspectives on the Kunming urban water management case

The findings and the method applied in the Kunming urban water management case has drawn good attentions of the local planners, and are considered to be incorporated in the long term planning of city's water resource planning and Dianchi Lake pollution control (Deng, 2006; Xu, 2006).

Beyond all the discussions on the case detailed in chapter 2 to 4, there are another three fundamental perspectives to be addressed.

(1) A bottoms-up information auditing is called for to enhance the reliability of decision basis, i.e., the information and models used. This includes auditing both the data quality, by means of data calibration and measuring campaigns; and auditing the structured information

quality, such as model structure, planning tools that are in use. More need to be gained on: what has been wrong, what is not yet known and needs to be known, and what should be known better.

(2) A well-structured mechanism is called for to enhance the local capacity in model-based (i.e., science-based) strategic planning.

(3) Research on the interdependencies of environmental objects and the coordination on activities of the multiple agents need to be furthered, so that complex environmental issues of the kind can be better coped with.

5.5 Reference

Casman, E. A., Morgan, M. G., Dowlatabadi, H. 1999. Mixed levels of uncertainty in complex policy models. *Risk Analysis*, 19(1), 33-42.

Davis, R. 1998. What are intelligence? And why? 1996 AAAI Presidential address. *Ai Magazine*, 19(1), 91-110.

Deng, D. R. 2006. *Personal communication.* Kunming: Expert leader of Dianchi Lake Protection Bureau.

Huang, D. B., Bader, H.-P., Scheidegger, R., Schertenleib, R., Gujer, W. 2006. Confronting limitations: New solutions required for urban water management in Kunming City. *Journal of Environmental Management*, In press. Online available: doi:10.1016/j.jenvman.2006.05.004

March, J. G. 1991. Exploration and exploitation in organizational learning. *Organization Science*, 2(1), 71-87.

March, J. G. 2006. Rationality, foolishness, and adaptive intelligence. *Strategic Management Journal*, 27(3), 201-214.

Oberkampf, W. L., Helton, J. C., Joslyn, C. A., Wojtkiewicz, S. F., Ferson, S. 2004. Challenge problems: uncertainty in system response given uncertain parameters. *Reliability Engineering & System Safety*, 85(1-3), 11-19.

Stern, P. C. 2005. Deliberative methods for understanding environmental systems. *BioScience*, 55(11), 976-982.

Xu, X. M. (2006). Personal communication. Kunming Institute of Environmental Science.

6 Appendix: Assessment Method for Evaluating Existing and Alternative Measures of Urban Water Management[4]

Abstract

Development of appropriate and sustainable sanitation options are required to face the problem of inadequate sewer systems in developing countries. High population densities and eutrophication problems of freshwater make source control a necessary alternative. To support decision-makers in assessing sewer system and source control, we developed a method to determine the origins of the wastewater and its property changes if source control measures are applied. The prototype of the method is based on a case study conducted in Zurich, which will later be adapted to a case study in Kunming, China. Analysis of uncertainty has been included in the method, as data quality will affect decision-making. Responses of wastewater amount, NH_4-N, TKN, and TP load, as well as concentration after urine separation, are simulated to study further treatment strategies of the new wastewater. The following methods were used: statistical pattern recognition, sensitivity analysis and system identification.

Keywords

Pattern recognition, sewer infiltration, extraneous or parasite water (Fremdwasser in German), urine separation, wastewater

6.1 Introduction

Rapid urbanisation and a booming real estate in developing regions cause important changes in life style and pose a significant threat to freshwater resources. Although urban water management planning applying 'end of pipe' solutions still prevail, they repeatedly proved to be financially unfeasible to solve these problems in time. Poor information and data availability have considerably hindered efficient water pollution control practices.

In 1999, only 7% of the Chinese urban population were connected to wastewater treatment facilities. According to government plans, 45% of the urban wastewater should be treated by 2005. In the next five to ten years, investments in urban wastewater treatment facilities in

---

[4] This chapter is published as a peer-reviewed paper in Proceedings of the 2nd International Symposium on Ecological Sanitation (pp. 749-756). Lübeck, Germany: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Authors: Huang, D. B., Schertenleib, R., Siegrist, H., Larsen, T. A., Gujer, W. (2003). Available at www.gtz.de/ecosan.

China will amount to tens of billions of U.S. dollars (People's Daily, 30/11/2001). The wastewater load estimates are often based on drinking water consumption, which accounts for only about 30-60% of the total wastewater load, depending on the existing hydrological situation and drainage system. Extraneous water ("Fremdwasser" in German, sometimes the term for "parasite water" is also used to refer to "Fremdwasser") from groundwater infiltration, connected streams and rainwater runoff may add another 40 – 70% to the wastewater load if urban drainage is based on combined sewers. In extreme cases, it can amount to more than 70% and result in an insufficient capacity of existing or planned sewers and wastewater treatment plants if extraneous water and rainwater are not correctly taken into consideration in the design phase.

Construction of separate sewer systems to gradually replace combined sewers is regarded as the solution to the problem of combined sewer overflow. However, this is not always the most appropriate option, as it involves financing difficulties and also the risk of untreated rainwater draining directly into receiving waters. This is especially the case in regions with high population densities. In less developed areas with poor solid waste management practices, rain runoff can greatly contribute to the pollution load of receiving waters.

An assessment method for evaluating urban water management in rapidly growing developing countries is required to assist decision-makers, scientists and engineers in improving urban water management and water pollution control practices. The aim is to conduct an impartial study on the current measures and other alternatives, as well as to assess their suitability in different areas and under different conditions. The reason for initiating the study in Zurich was to first develop a method on the basis of good data quality, and to supply a "modern" urban drainage model for further assessment of its suitability in developing countries.

The city of Kunming, at Yunnan China, numbers 2.4 million inhabitants and 6 operating WWTPs, with a total capacity of 555,000 m^3/d. How efficient are these WWTPs, and how much capacity is still required if that region continues to follow the 'end of pipe' solution? What happens if source control is implemented? The following describes:

- A method to quantify the origins of the wastewater using statistical pattern recognition;
- The simulation of wastewater load and concentration dynamics after applying the urine separation concept.

6.2 System Comparison

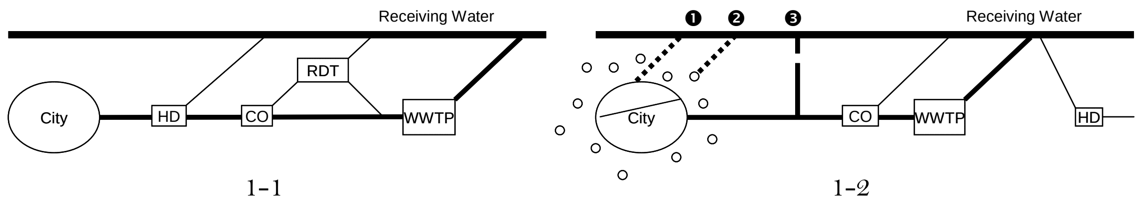


Fig. 1. System comparison: on the left, the urban drainage system in Zurich, on the right, a system in a developing country. ❶ Illustrates city districts not connected to WWTP; ❷ Shows small villages scattered outside the city, mainly without water sanitation facilities;❸ Small streams inside the city of some developing countries used as open sewers and conveying wastewater to WWTP. These are likely to be replaced by sewers requiring important investments in pipe construction. HD: Flood discharge; CO: Canal overflow; RDT: Rainwater detention tank.

Gujer (1999) described the system in Zurich (Fig. 1-1) during different precipitation intensities. A typical system in developing countries is illustrated in Fig. 1-2, with sections of the city not connected to the WWTP, and villages, mainly without sanitation facilities, scattered outside the city. The load from these sections is directly conveyed to receiving waters. Streams or small rivers are sometimes also used as open wastewater canals, thereby greatly increasing the volume of extraneous water and reducing the efficiency of WWTP. Canal overflow occurs frequently during dry and raining days. Street flooding also takes place regularly after heavy and extreme precipitation; the floodwater discharge is not designed ahead of the canal overflow but sometimes at the end of the receiving water.

According to the 1989 Swiss annual statistics report, the wastewater discharged into the treatment plant originates from households (25%), industry (20%), precipitation (15%), and from extraneous water (40%). Extraneous water is currently decreasing due to sewer monitoring and maintenance. However, the volume of rainwater increases, since less untreated rainwater is allowed to be discharged directly into freshwater (Gujer, 1999).

6.3 Determination of Wastewater Origins Using Pattern Recognition

The method applies two simple classification criteria to extract the dry weather flow from the mixed wastewater flow signals (Fig. 2).

$$Q_{in} = Q_{in,dry} + Q_R = (Q_{WW} + Q_F) + Q_R \qquad \text{(Equ. 1)}$$

$$Q_{WW} = (1 - r_{lost}) \cdot Q_{DW} \qquad \text{(Equ. 2)}$$

Consequently: $Q_F = Q_{in,dry} - (1 - r_{lost}) \cdot Q_{DW}$ (Equ. 3)

where: Q_{in} = total wastewater inflow; $Q_{in,dry}$ = dry weather flow; Q_R = rainwater flow.

Q_F = extraneous water flow; Q_{DW} = water supply quantity into distribution system; r_{lost} = lost fraction of water supply. The water recorded as water consumption, which is not conveyed to the sewer, is regarded as "lost"; Q_{WW} = the wastewater conveyed to the sewer after consumption.

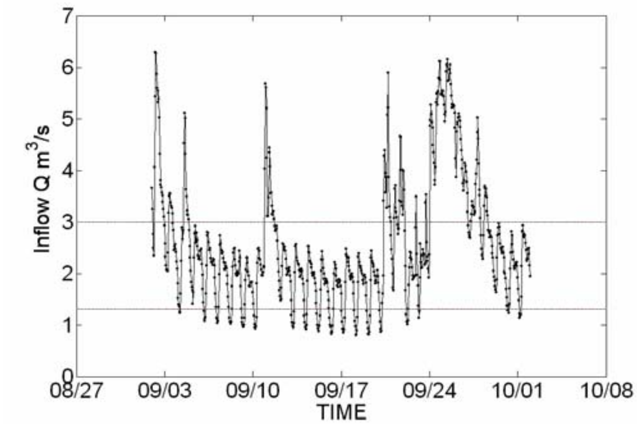


Fig. 2. Time series of wastewater inflow rate into WWTP Werdhölzli. Dry weather flow is classified according to the following criteria: (1) $Q_{min}<1.3$ m³/s, and (2) $Q_{max}<3$ m³/s. A full year dataset was used, however, only one month is illustrated here.

The dry weather flow $Q_{in,dry}$ can be determined on the basis of datasets of WWTP inflow and meteorological data records. However, this involves two difficulties: (1) if the region is quite large and if the rain gauges are not evenly distributed throughout the region, (2) water from the rainwater detention basin (RDT) is not always pumped to the WWTP on meteorologically rainy days. To counteract these difficulties, the method of statistical pattern recognition is applied.

We have established two straightforward criteria for determining dry weather flow derived from the signals in Fig. 2. If the maximum daily flow exceeds 3 m³/s, or the minimum daily flow is greater than 1.3 m³/s, these days are filtered out as days with rainwater runoff in the sewer. Since weekday flows behave differently from those of weekends, we automatically separate weekday, Saturday and Sunday flows and then generate a statistic week flow dynamics. Fig. 3 illustrates the distribution before and after filtering out the rainwater according to the aforementioned classifier. Classification method and its uncertainties can be estimated, but are not addressed in this paper.

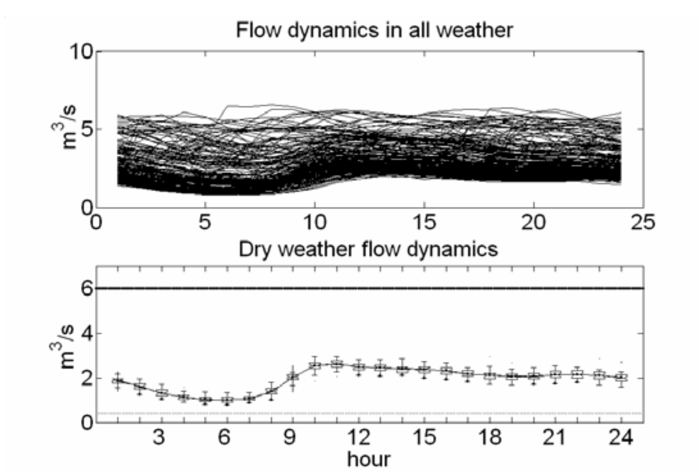


Fig. 3. Flow dynamics before and after classification.

Distributions after classification reveal a similar to normal distribution. Median and average values fit almost exactly (Fig 3). Therefore, calculation of total annual dry weather wastewater quantity, based on the statistical average flow dynamics, is fairly accurate.

By combining the weekdays with Saturdays and Sundays, we have formulated a statistical time-variant-curve (Fig. 4). Note the flow rate difference between weekdays and weekend. By summarising the total weekly wastewater quantity, we obtain $Q_{dry,week}$ (weekly total dry weather flow). Consequently, we obtain $Q_{dry,year} = 5.98 \cdot 10^7$ m^3 / a, (total dry weather flow in 2002).

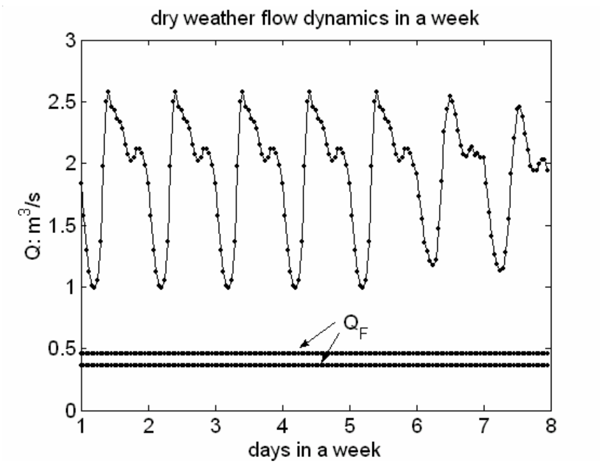


Fig. 4. Statistical dry weather week flow dynamics in WWTP Werdhölzli and estimated extraneous water.

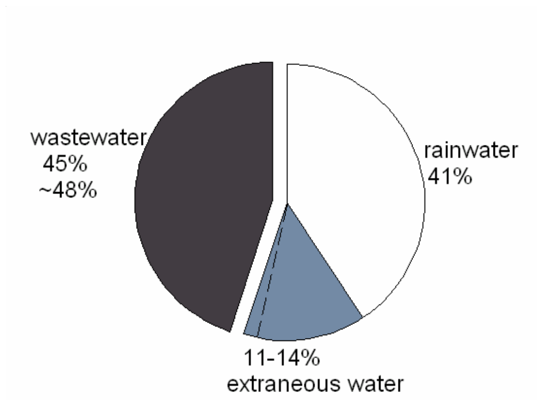


Fig. 5. Origins of wastewater to WWTP Werdhölzli.

We used the statistics on the total water consumption of different communities in the catchment area and statistics of inhabitants in every community connected to the WWTP Werdhölzli. The estimated water consumption in the catchment area amounts to $Q_{DW} = 5.33 \cdot 10^7$ m^3 / a, with 9% loss due to leakage (5%) and quenching water and possible measuring errors (4%) (Zurich Water Supply, 2001). Based on this information, the extraneous water flow into the WWTP Werdhölzli is estimated at 0.36 m^3/s (Fig. 4). We assume that gardening and other water consumption activities, which are not conveyed to the sewer after consumption, account for up to 6%. Therefore, the loss ranges between 9% and 15%. The extraneous water conveyed to the WWTP is then estimated at 0.36 – 0.46 m^3/s, which accounts for 11 – 14% of the total wastewater inflow (Fig. 5) and for 25 – 30% dry weather flow.

Extraneous water is not always constant, especially after precipitation, as revealed by the exponential recession after rainy periods illustrated in Fig. 2. Dynamic extraneous water flow can be simulated by the theory of linear reservoir (Gujer and Krebs, 1997).

The data obtained from the City of Zurich is of good quality. In order to render the methods developed here widely accessible, we conducted a sensitivity and uncertainty analysis. It reveals the importance of data quality for scientists and decision-makers. Sensitivity of Q_F in relation to the three model parameters is predicted as: 0.019 m^3/s for a 1% change of $Q_{in,dry}$, -0.015 m^3/s for a 1% change of Q_{DW} and 0.017 m^3/s for a 1% change of r_{lost}. These numbers indicate that a systematic measurement error of 1% of either $Q_{in,dry}$, Q_{DW} or r_{lost} would change the resulting Q_F by approximately 5%.

Since measurement errors for the three parameters are independent, we can use the Gaussian error propagation law in its simplest form:

$$\sigma_y = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial y}{\partial p_i}\cdot\sigma_{p_i}\right)^2} \quad \text{(Equ. 4)}$$

with σ_y = standard error of prediction y, σ_{pi} = standard error of parameter p_i

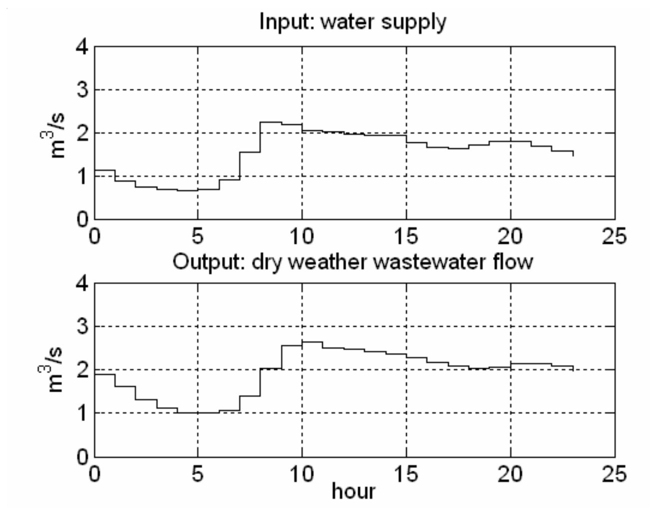


Fig. 6. Daily variation curve of water consumption and dry weather wastewater flow of the catchment area.

For Zurich data, the standard errors for the three parameters are estimated at less than 5%, and result in a standard error of the predicted amount of parasite water of $\sigma_{QF} \leq 0.12$ m^3/s. The prediction method introduced here is obviously quite sensitive to data quality. In developing countries, where measurement errors can possibly be greater than 15%, this error will exceed 0.36 m^3/s, thereby rendering the results practically irrelevant, as the 95% confidence interval of Q_F becomes 0 – 1 m^3/s. Decisions based on poor data quality become highly questionable. Therefore, the methods to be developed must deal with possible data uncertainties. It is also important to enhance data management awareness in developing countries.

6.4 Determination of Extraneous Water by System Identification

$Q_{in,dry}$, obtained through the method of statistical pattern recognition, is now used as the output of the system, and the water supply signals as the input. We used the original water consumption signal of 2002 (hourly data record) for the entire city of Zurich (Bolli, M., 2003). Like with the method in the previous chapter, we also filtered out the weekends and extreme outliers and obtained a daily time-variant-curve distribution on weekdays. Based on this curve, we calculated the hourly factor f_h curve of water consumption. Since the city of

Zurich has the highest population (90%, not including commuters) in the catchment area of WWTP Werdhölzli, the f_h curve can be approximated to that of the entire catchment area. The dynamic curve of water consumption is obtained by multiplying f_h with the average water consumption of the entire catchment area.

Extraneous water Q_F is regarded here as a system parameter. The following simple model neglected the fact that the extremes of the flow rate in the sewer are slightly dampened during residence time of the wastewater in the sewer system:

$$\frac{Q_{\max,DW} - Q_{leak}}{Q_{\min,DW} - Q_{leak}} = \frac{Q_{\max,WW} - Q_F}{Q_{\min,WW} - Q_F} \qquad \text{(Equ. 5)}$$

where $Q_{\max,DW}$ and $Q_{\min,DW}$ stand for maximum and minimum daily drinking water delivery to the distribution system; Q_{leak} for leaks from the water distribution system; $Q_{\max,WW}$ and $Q_{\min,WW}$ for maximum and minimum dry weather flow in the sewer system (Fig. 6).

If no leaks are assumed (Q_{leak} = 0), then Q_F = 0.33 m^3/s. By assuming a loss of 5% drinking water due to leaks, which is typical for Zurich, then Q_F = 0.4 m^3/s. This compares favourably with the previously estimated 0.36 to 0.46 m^3/s.

In developing countries, leaks from distribution systems are generally very high due to lower investments and poor maintenance. It is therefore crucial to consider this aspect if this method is applied in developing countries.

6.5 Response Analysis for the Complete Urine Separation Scenario

How will the properties of urban wastewater change after source control measures, such as urine separation with No-Mix toilets, are implemented? After applying urine separation in the entire catchment area, the “response” is defined here as the change of the following variables: dry weather flow Q, NH_4-N, total Kjeldahl nitrogen (TKN) and total phosphorus (TP).

Since the city of Zurich is service-oriented (trade, financing, tourisms, and other services), the source of ammonium to the WWTP can actually be assumed to originate only from urine. According to an investigation conducted by the WWTP Werdhölzli (Antener, 2002), the living population in the catchment area of WWTP Werdhölzli totals 393,000, commuters to the area are estimated at 100,000 persons/day. By assuming that the commuters spend about 8 hours a day in the area, the specific daily ammonium load per person amounts to:

$$L_{NH4} = NH_{daily,tot} / (inhabitants + 1/3 \cdot commuters) = 7.4 \text{ gNH}_4\text{-N / PE / d}$$

PE stands for population equivalent. The dry weather load of ammonium $NH_{daily,tot}$ = $3.15 \cdot 10^6$ g /d is based on analytical data of the first half of 2002. L_{NH4} values for urine higher than 7.4 g N/PE/d have been reported in medical literature. However, the population sample (age structure, sex, etc.) of a city the size of Zurich is entirely different from the typical sample in the medical literature (adult male), which explains the lower value obtained here.

Pöpel (1993) reports that 88% of TKN and $L_{TP,U}$ = 0.8 g P/PE/d in domestic wastewater originate from urine. With the observed ratio of TKN/NH_4-N = 1.6 in the wastewater of Zurich, the specific nutrient loads in urine become:

$L_{TKN,U} = 7.4 \cdot 1.6 \cdot 0.88 = 10.4$ g N/PE/d; $L_{NH4,U} = 7.4$ g N/PE/d; $L_{TP,U} = 0.8$ g P/PE/d

These values will now be used to compare wastewater composition before and after separation of urine in no-mix toilets.

A complete urine separation in Zurich could remove annually $1.62 \cdot 10^9$ g of the TKN load and $1.25 \cdot 10^8$ g of the TP load. After urine separation, the TKN, NH4-N and TP loads will amount to $2.9 \cdot 10^8$ gN/a, 0 gN/a (excluding the load conveyed by rain), and $2.26 \cdot 10^8$ gP/a respectively. From a resource point of view, the nitrogen could meet the commercial

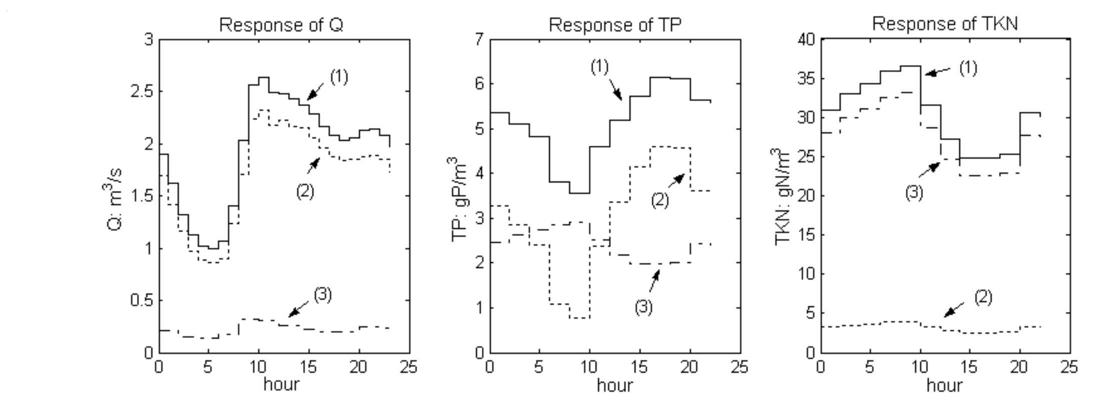


Fig. 7. Variation of wastewater flow, pollution load before and after urine separation (dry weather).
(1): without urine separation; (2): with complete urine separation; (3): urine flush load

fertiliser demand of 186,000 Swiss, and the phosphorus the demand of 83,000 Swiss citizens. The specific commercial fertiliser consumption of N in Switzerland amounts to 8.7 kg_N/PE/a, and of P to 1.5 kg_P/PE/a (Lienert, 2003).

Information on a 2-hour urine and urine flushing quantity is obtained from the NH_4-N time-variant-curve measurements after primary treatment in the WWTP Werdhölzli (with 2-hour time resolution and flow proportional sampling). The dynamic variation of TKN, TP and the inflow rate to the WWTP before and after applying urine separation are simulated (Fig. 7). How the wastewater treatment process should respond to this change can be studied on the basis of the information supplied. However, further measurements on load variation should be conducted. Qualitatively speaking, nitrification and denitrification may become unnecessary. Biological phosphorus removal would probably improve due to removal of substrate competition from the denitrification process. Use of chemicals for phosphorus precipitation and sludge production could also decrease significantly.

In existing conventional sanitation systems, urine separation measures can generally be implemented step by step and whenever feasible. Information on the number of inhabitants connected to conventional systems, and those linked to urine separation, will also allow to assess the wastewater properties after implementing the measures stepwise in some areas.

6.6 Conclusions and Discussions

The prototype of a method to assess the existing and alternative measures of urban water management has been developed and is ready to be adapted to further case studies in Kunming, China. This method will be refined and its function extended further depending on stakeholder requirements. Statistical pattern recognition and system identification are used to determine wastewater origin. The results obtained, including the uncertainty analysis in the case study of Zurich, reveal that the method is reliable and that the current volumetric composition of wastewater conveyed to the WWTP Werdhölzli in Zurich originates from: rainwater (41%), wastewater (45 – 48%) and extraneous water ("Fremdwasser") (11 – 14% accounting for 25 – 30% of dry weather flow). This shows that quite a large amount of extraneous water is still conveyed to the WWTP even in a well-maintained urban sewer system.

The water flow peak reduction in no-mix toilets in Zurich is estimated at around 0.32 m^3/s, which is a minor reduction in sewer runoff. However, urine separation can efficiently remove $1.62 \cdot 10^9$ g of the TKN load, $1.15 \cdot 10^9$ g of the NH_4-N load and $1.25 \cdot 10^8$ g of the TP load per year from the source within the catchment area of WWTP Werdhölzli, Zurich. The simulation results of dynamic variation of Q_{in}, TP, NH_4-N, and TKN, both as load and concentration, reveal how the urban wastewater will respond after urine separation measures are adopted. After urine separation in Zurich, the concentration of NH_4-N will be very small, the TKN concentration will vary between 2.6 and 4.4 gN/m^3, TP concentration will vary between 0.85 and 4.8 gP/m^3. Further studies will indicate how to deal with the "new" wastewater.

6.7 Acknowledgements

This research forms part of the Novaquatis project and NCCR North-South and is financed by SDC and SNSF. Cooperation and data support from the WWTP Werdhölzli and Water Supply Zurich are also highly appreciated.

6.8 References

AWEL, Wasserverbrauch Statistik Kanton Zürich, 1999.

Antener, M., Investigation of populations in the catchment area of WWTP Werdhölzli, 2002, unpublished document.

Bolli, M., Stündliche Werte des Wasserverbrauchs 2002 in Zürich, E-Mail 2003.

Gujer, W., Siedlungswasserwirtschaft, Springer Verlag 1999, pp. 79-81.

Gujer, W., Krebs, P., Siedlungsentwässerung, Skript zur Vorlesung Siedlungsentwässerung an der ETHZ, 1997.

Larsen, T.A., W. Gujer (1996) Separate management of anthropogenic nutrient solutions (human urine). Water Science and Technology 34(3-4): 87-94.

Lienert, J., Haller, M., Berner, A., Stauffacher, M., Larsen, T. A. 2003. How farmers in Switzerland perceive fertilizers from recycled anthropogenic nutrients (urine). Water Science and Technology 48(1): 47-56.

Wehrli, M., Hofmann, A., Zuflussmessungen und Betriebsdaten der WWTP Werdhölzli, 2002.

www.novaquatis.eawag.ch; www.nccr-north-south.unibe.ch

Acknowledgements

I am grateful to the Swiss National Science Foundation and Swiss Development Agency for their joint funding through the research framework of Swiss NCCR North-South, as well as SANDEC / EAWAG.

My project manager, Mr. Roland Schertenleib and Prof. Dr. Hansruedi Siegrist initiated the project and have accompanied the entire process with precious help and discussions.

Prof. Dr. Willi Gujer and Prof. Dr. Roland W. Scholz primarily advised me on the two phases of the thesis, and built together an excellent interdisciplinary support for the thesis, one (Willi) from the angle of urban water management engineering, another (Roland, W.) from the angle of decision sciences.

Dr. Hans-Peter Bader added significant value on chapter 2 from the angle of material flow analysis.

I gained so much that I started to feel guilty for my advisors who have pointed me to the right direction, supplied me with the platform on which I can start to explore the frontier of science, while as an unfair return, I might have disappointed them once in a while with my stubbornness, and my past ineptness in cooperating at the presence of interest's and cultural discrepancies. I am seriously indebt to those who have educated me, supported my PhD thesis in one phase or the other.

Additionally, I thank Prof. Dr. Peter Reichert, Dr. Heinrich Bührer, Dr. Tove A. Larsen, Dr. Thomas Wagner, Dr. Ulrich Zimmerman, Dr. Rudolf Dannecker, Dr. Jaques P. Feiner, Prof. Dr. Claudia R. Binder, Ms. Ruth Scheidegger, Dr. Christian Fux, Dr. Max Maurer, Dr. Edi Medilanski, Dr. Steffan Schweizer, Dr. Christoph Ort, Marc Neumann, Mariska Ronteltap, Dr. Joerg Rieckermann, Dr. Thomas Köllner, Dr. Peter de Haan, Timo Smieszek, Alexander Walter, Dr. Peter Loukopoulos, Dr. Ralf Hansmann, Dr. Joachim Sell and Prof. Dr. Hannes Flühler for their great help in various activities within the thesis. Kunming City Congress, Kunming University of Science & Technology, Kunming Foreign Affairs Office, Dianchi Lake Protection Bureau, Kunming Institute of Environmental Science, Yunnan Institute of Environmental Science, Kunming Sewerage Co, Kunming Water Supply Co., Zurich Urban Drainage, Zurich Water Supply, have offered encouragingly positive cooperation.

For some external help, I am also very grateful that Dr. Yu-Chi Ho (Professor of applied mathematics and system engineering, Harvard), Dr. Mitchell J. Small (Professor of Engineering and Public Policy, Carnegie Mellon), Dr. Franklin M. Fisher (Professor of Microeconomics, MIT) offered their precious time in reading the chapter 3 and gave excellent inputs in improving the method presented. My friend Dr. Derek E. Chitwood and his wife Amy Chitwood must have been disturbed quite often by my urging to correct the language whenever I wrote. Derek's writing style and sharp criticism has been a medicine for my writing.

Last but not least, my wife Chun has been a big support for me in time, patience, and discussions. My lovely family, colleagues of both institutes, and friends is a treasure of life.

Curriculum Vitae

Dong-Bin Huang

Msc. Heifei University of Technology, China

Lecturer, Kunming University of Science & Technology

1969	Born in Anhui, China
1986	High middle school No.1, Feixi, Anhui Province
1986-1988	Study on Environmental Biology, Biology Department, Anhui University
1989-1993	Trainee, process engineer, production manager, Baogong Brewery Co., Hefei, China
1994-1997	Study on Water Resource and Hydrology, Civil Engineering Department, Hefei University of Technology, China Degree: Master of Science
1997-1998	Teaching Assistant, Environmental Engineering Department, Kunming University of Science & Technology
1999-2000	Swiss Federal Scholarship, visiting scholar, Engineering Department of EAWAG, Dübendorf
2000-2002	Lecturer, Environmental Science & Engineering Department, Kunming University of Science & Technology, China
2002-2006	PhD study, ETH Zurich, a PhD program within Swiss NCCR North-South. Thesis: "A discrete-event dynamic systems approach for environmental decision-support"

Contact

Swiss Federal Institute of Technology (ETH Zurich)

Institute for Environmental Decisions (IED)

Natural and Social Science Interface (NSSI)

ETH Zentrum

Universitätstrasse 22, CHN J73.1

8092 Zurich, Switzerland

dongbin_huang@yahoo.com