POLSKA AKADEMIA NAUK

Instytut Badań Systemowych

BADANIA OPERACYJNE I SYSTEMOWE: ŚRODOWISKO NATURALNE, PRZESTRZEŃ, OPTYMALIZACJA

Olgierd Hryniewicz,
Andrzej Straszak,
Jan Studziński
red.

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Środowisko i jego ochrona

CATCHMENT MODELLING UNDER DEEP UNCERTAINTY ON THE PERI-URBAN AREAS

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This paper presents an integrated approach to modelling complex hydro-socio-economic-climatic processes at the catchment scale. The problem's complexity is due not only to its combinatorial nature, but also due to the intrinsic multidimensional spatio-temporal relationships of its variables. Furthermore, there is no explicit solution for such NP-complete combinatorial optimization problem; thus an heuristic optimization technique such as exploratory analysis is used to search for ‘‘good’’ solutions in a finite but huge solution space. In this paper, the approach applied in the BMBF project “Integrated catchment management and risk-based resource allocation in urban and peri-urban areas’’, carried out in the Great Stuttgart Region (GSR) as a common project between the Stuttgart University (USTUTT), Helmholtz Center in Leipzig (UFZ), Potsdam University (UPOT), Polish Academy of Sciences (PAS) and Agricultural University in Szczecin, is to be presented.

1. Introduction

Water managers and decision makers face big challenges when trying to implement Integrated Water Resources Management (IWRM) strategies in the GSR area (BMBF, 2007; Miklewski and Krawczak, 1997; Miklewska, 2006a,b; Miklewski, 2001, 2006, 2007).

Such an implementation unfolds particularly complex in regions that are characterized by a large number of non-complementary societal objectives following the EU Water Initiative (EUWI) objectives (EU, 2007) and the Millennium Development Goals (MDG) (UN, 2007). The task is delicate because of two main reasons:

1) the functioning of the natural system is far from well understood (Lempert et al., 2003; Popper et al., 2005), and
2) the consequences of any decision taken now will affect at last, in one way or another, the environment as well as the well-being of actual and future generations (Sachs, 2005).

Anthropogenic impact inducing global climatic changes will very likely intensify the water cycle in most regions of the world (Houghton et al., 2001; Alley et al., 2007; IPCC, 2008). As a result, weather patterns will become more intense and erratic. This negative development will certainly add a new dimension to the complex task mentioned above.

The problem in IWRM is that the system for which policy options are to be drawn is simply too complex to make definitive predictions on system future behaviour (Popper et al., 2005; Samaniego and Bárdossy, 2007; Kundzewicz, 2007). In other words, the immediate results and future consequences of any policy option (or strategy) adopted by stakeholders are always subject to *"deep" uncertainty*, or "*deep structural uncertainty*" (see Arrow, 1999). Weitzman (2008, 4) argued that "*…structural or deep uncertainty is potentially much more of a driving force than discounting or pure risk*".

Consequently, policies oriented at finding balance between the economy and the environment require innovative decision-making tools that give the society in general, and the stakeholders in particular a broad spectrum of possible actions as well as the risks of failure associated with each of them. Based on this concept, we propose a somewhat novel approach whose main objective is:

> *to develop a Policy Exploration System (PES) that will allow stakeholders to draw up robust and adaptive policy options that work well over a wide range of plausible futures but always fulfilling the EUWI objectives and the MDG goals.*

The description of the dominant processes of the natural system (biotic and non-biotic subsystems) is, of course, based on sound science, significant amounts of data, and societal preferences. Additional scientific and technical (S&T) objectives pursued by this research project are the following:

1) to assist a water manager and the stakeholders to find ways to cope with the systems uncertainty rather than ignoring it,
2) to investigate the behaviour of the system under a wide range of plausible paths to the future – sometimes called scenarios – that may occur under the conditions of a given policy option, and
3) to investigate the adaptation capability of a given policy option subject to climate fluctuations originated by a macro climatic scenario of Intergovernmental Panel on Climate Change, IPCC (Houghton et al., 2001; IPCC, 2008).

2. Deep uncertainty

Water resource systems are characterized by a complex network of interrelated processes – anthropogenic and naturally induced – whose governing state variables are subject to "deep uncertainty". According to Bankes (1993, 2002), decision makers or analysts confront "deep uncertainty" when they are not able to agree on:

1) the appropriate model to describe the long term evolution of the system's variables,
2) the probability distribution of key variables and parameters of the models and/or
3) how to value the attractiveness of alternative outcomes.

In the past decade there has been a strong tendency to move from optimal towards robust control theory, in various fields such as economics, operation research or engineering, Zhou et al. (1996), Kouvelis and Yu (1997), Ben-Haim

(2006). Interestingly, water resources' planning has not been the focus of such research application so far for a number of reasons.

Currently, the assessment of relevant state variables of a water system (including biotic and non-biotic subsystems) is hampered not only by the non-exhaustive character of the available measurements but also by the insufficient process understanding and their representation within the existing environmental models.

These deficiencies lead to a considerable uncertainty in both the environmental and socio-economic data sets as well as in the predictive power of available models. These shortcomings – which occur even if one is "only" focusing on modelling a single subsystem, e.g. the hydrological cycle – are increased even further when trying to merge submodels to so-called integrated models mainly due to the lack of synergy and feedback effects between the (sub-)systems processes.

The complexity of the relationships among water system's variables and their intrinsic uncertainty (Bogardi and Kundzewicz, 2005; Kundzewicz 2007) has been the main reason why water resources planners (Plate, 2000), environmentalists, and social scientists have oversimplified the interdependencies among the key system variables, or, in some cases, analyzed each sub-system separately. As a result, feedback effects may have been neglected or underestimated.

Therefore, optimal control strategies based on these assumptions tend to be vulnerable to endogenous and/or exogenous changes (e.g. environment) because both the formal system (i.e. the model) and the optimization algorithm employed are mostly not capable of coping with changes.

In most cases, a normative or ad hoc solution is the norm rather than the exception. This simplistic and non-integrative planning approach has led to suboptimal, non-sustainable, and sometimes catastrophic situations around the world. Very well known examples are, for instance: the Aswan Dam Project in Egypt, the large irrigation project built in the Aral See basin in the former USSR, and the river training executed in the Rhine Rivera long the border between Germany and France (Saeijs and Schuyt, 2001; Spoor 1996).

These examples have proven that the conventional methods used in water resources management are not sufficient to ensure a sustainable use of neither the present, nor the future water resources. Instead, current research, points out that an iterative analysis and planning approach with emphasis on the system's uncertainty rather than on deterministic knowledge is the appropriate choice (Bankes, 1993; Kabat and van Schaik, 2003; Pahl-Wostl, 2002; Weitzman, 2008). It is worth noting that this challenge is not restricted to the water sector, but is rather inherent to many other aspects of environmental management (Young, 1998; Embrechts, 2004). Only by continuous interaction with the system, can stakeholders learn more about the behaviour of the system being subject to continuously changing driving forces.

In contrast, robust control theory recognizes the need of incorporating adaptation in both the formal description of the system and in the control strategy (i.e. the policy option). Therefore, the main goal is to seek robust rather optimal strategies. To attain this objective, exploratory algorithms (Jablonowski, 2003) are used within the space of alternative strategies to find those that are insensitive to changes in the system and can maintain their stability and performance. This exploratory technique is question driven. Other forms of exploration techniques can be used to determine which families of potential models and parameters that best describe the available data (Samaniego, 2003; Samaniego and Bárdossy, 2005).

A possible measure of the performance of a given policy option is its inherent risk of failure. Using this measure, among other possibilities, stakeholders will be able to fully address the uncertainty that characterizes a water resource system, and simultaneously, find a robust strategy (i.e. one having a low risk of failure given a large ensemble of realizations evaluated according to several predefined objectives) (Samaniego and Bárdossy, 2007).

In this aspect, the proposed research project goes beyond current state-of-the-art in integrated models (e.g. those used in EU-funded research projects such as RIVERTWIN), in which the emphasis was more to understand the function of the system rather than to explore the possible policy alternatives that can be used by the stakeholders. In this sense, this project is a logical step forward from the lessons learned in the last decade of intensive modeling efforts.

3. Exploratory analysis

In catchment modelling we face NP-complete combinatorial optimization problems. Practically, this means that no algorithm can solve the problem in polynomial time. A combinatorial problem that is solvable in Non-Polynomial time, i.e. *a problem that cannot be solved to optimality because the search for an optimum requires prohibitive amounts of time* (van Laarhoven and Aarts, 1987).

Now we present the idea of exploratory analysis (Fig. 1).

The dynamics of our model (holistic analysis) is described by:

$$\dot{x}_i^t = f\left(x, v, \alpha, t\right) + \eta_i^t, \qquad y_i^t = g\left(x, \alpha, t\right) + \varepsilon_i^t, \tag{1}$$

where:

x – state variables,

inputs: $v_i^t = \left\{M_i^t, G_i^t, U_i^t \ldots\right\}$,

M_i^t climatic,

G_i^t physiographical,

U_i^t economic;

outputs: $y_i^t = \left\{K_{il}^t, L_{il}^t, T_{ijl}^t, Q_{il}^t, \ldots\right\}$,

K_{il}^t capital,

L_{il}^{t} employment,

T_{ijl}^{t} transportation goods,

Q_{il}^{t} discharge.

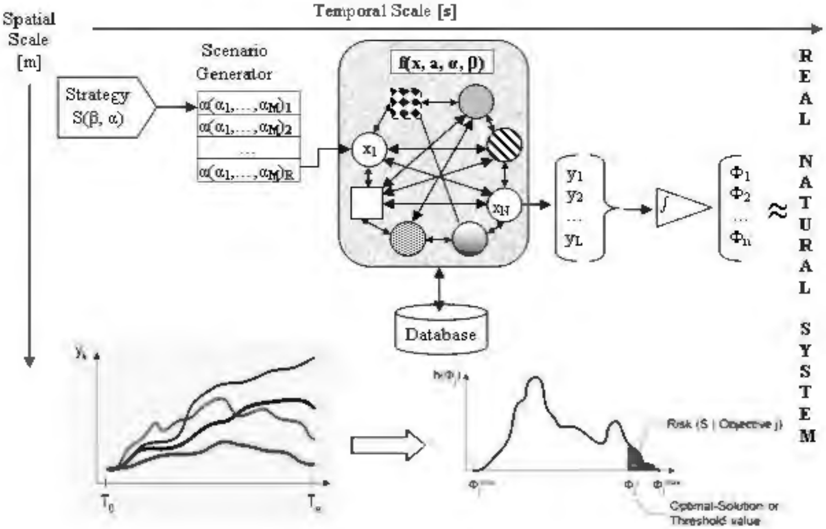

Fig. 1. Exploratory analysis (BMBF project, 2007)

We denote model calibration by $\min_{\hat{\alpha}} \left\| y - g(x, \alpha, t) \right\|$.

Integrated model is described as:

$$x_l = f_l\left(x_1, \ldots, x_{l-1}, x_{l+1}, \ldots, x_G\right) \quad l = 1, \ldots, N, \tag{2}$$

We have to maximize/minimize

$$\Phi\left(x\right) = \Phi\left(\phi_1(x), \ldots, \phi_n(x)\right), \tag{3}$$

subject to:

$\mathrm{G}_{\mathrm{i}}^{\mathrm{t}}\left(\mathrm{x}, \beta_{\mathrm{s}}\right) \geq 0 \quad i = 1, \ldots, I \quad t = t_0, \ldots, t_e$,

$\mathrm{F}\ \left(\mathrm{x}, \mathrm{v}, \hat{\alpha}, \alpha, \beta_{\mathrm{s}}\right) = 0$ ($x^* \rightarrow$ - a Pareto-optimal solution,

$\beta_s \rightarrow$ - parameter of the strategy *S*).

This holistic problem is a nonlinear, "NP-complete" discrete combinatorial problem.

It is assumed that $\mathrm{F}\ (\cdot)$ and $\hat{\alpha}$ are unique. The question arises: if both sets are not unique, how robust is x^*? This question is open.

For our problem we set objectives as follows -

O_1 - to maximize the average time of concentration of the overland flow for a given rainfall intensity within each subcatchment (in the area under study, GSR, Fig. 2),
O_2 - to minimize the landscape fragmentation caused by the urban fabric.

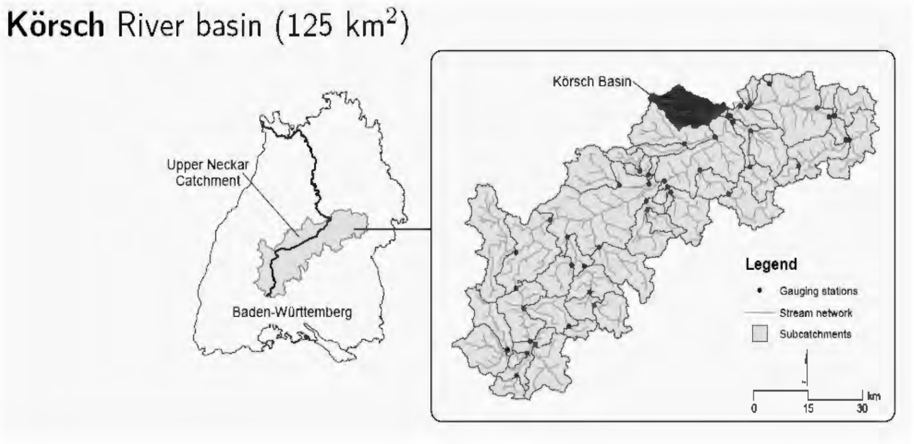

Fig. 2. Study area (BMBF project, 2007)

Definition of objective No. 1:

$$\Phi_1 = \left(\prod_i \frac{t_c(T_2, i)}{t_c(T_0, i)} \right)^{\frac{1}{z}}, \tag{4}$$

$$t_c(i) = \sum_{P_i} k(s_i, l_i, \eta_i, \boldsymbol{\alpha}) \tag{5}$$

where:
Φ_1 = geometric mean of the cell-wise relative increment of t_c,
$t_c(i)$ = time of concentration from every grid cell i to outlet along path P_i,
s_i, l_i = slope and length of cell i,
η_i = surface roughness (i.e. land cover type) cell i,
$\boldsymbol{\alpha}$ = empirical parameters (e.g. Kirpich's equation),
z = number cells within the basin,
T_0 = base time of the simulation = 1993,
T_1 = beginning time of the simulation = 1994, T_2 = ending time of the simulation = 2025.

Fig. 3 presents the solutions for the objective No. 1.

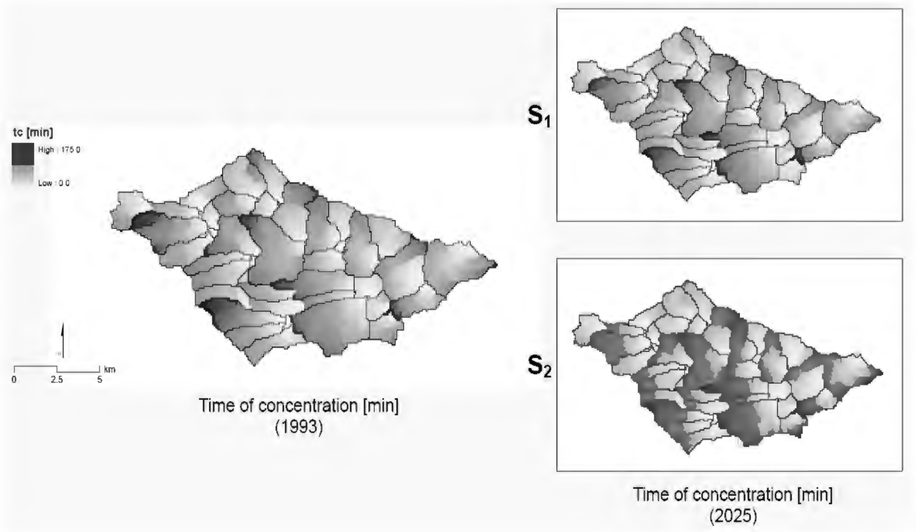

Fig. 3. Solutions for objective No. 1, (BMBF project, 2007)

$$\max O_1 \equiv \max(\Phi_1) \;\Rightarrow\; \Phi_1(S_1) > \Phi_1(S_2),$$

Definition of objective No. 2:

$$\Phi_2 = \frac{\overline{x}}{n},\ \min(O_2) \equiv \max \Phi_2 \Rightarrow \Phi_2(S_2) \gg \Phi_2(S_1),$$

where: Φ_2 = fragmentation index, $\overline{x}$ = average number of cells within an urban cluster, n = the total number of urban clusters (Fig. 4).

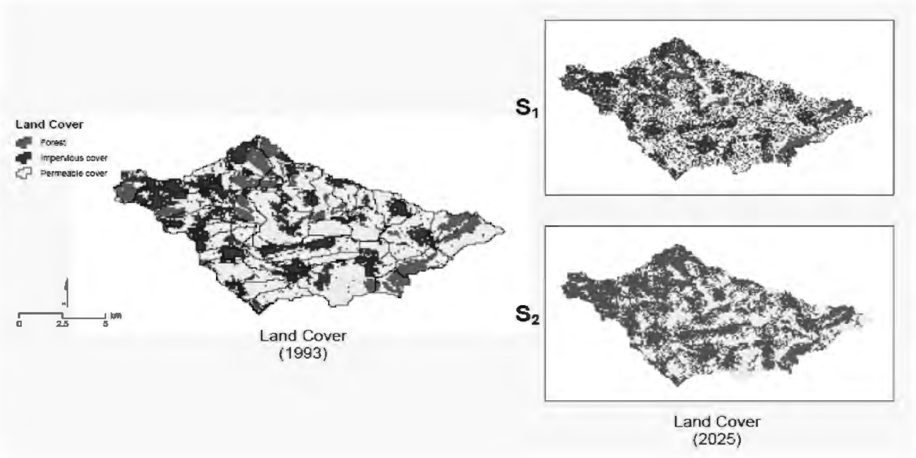

Figure 4. Solutions for objective No. 2, (BMBF project, 2007)

4. Conclusions

On the basis ongoing research project BMBF we conclude:

- Exploratory modelling techniques enable Water Managers to find some of the worst case scenarios for in which their policies fail completely. Hence, it may help to generate contingency plans and to find potential triggers.
- Robust decision making aims to confront stakeholders with several strategic options and the risk of failure that is associated with these options.

More research is still required to investigate the consequences of using different kinds of models (conceptual or physically based ones) with different levels of complexity on robust risk-based decision making.

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BADANIA OPERACYJNE I SYSTEMOWE: ŚRODOWISKO NATURALNE, PRZESTRZEŃ, OPTYMALIZACJA

Książka składa się z artykułów przedstawiających wyniki prac z dziedziny badań operacyjnych i systemowych, poświęconych środowisku naturalnemu i zarządzaniu nim, zwłaszcza w zakresie ochrony atmosfery, globalnego ocieplenia i walki z nim, jakości i zaopatrzenia w wodę. Tematyka ta jest rozszerzona o aspekty przestrzenne, regionalne i samorządowe, a także planowanie i funkcjonowanie infrastruktury. Tom zamykają prace metodyczne, dostarczające technik, będących podstawą prezentowanych zastosowań.

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