Appropriate Modelling in DSSs for River Basin Management

Yueping Xu

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Yueping Xu and **Martijn J. Booij**

Water Engineering and Management, Faculty of Engineering, University of Twente, Enschede, the Netherlands (email: y.p.xu@ctw.utwente.nl; m.j.booij@ctw.utwente.nl)

Abstract: There is increasing interest in the development of decision support systems (DSSs) for river basin management. Moreover, new ideas and techniques such as sustainability, adaptive management, Geographic Information System, Remote Sensing and participations of new stakeholders have stimulated their development. A DSS often encompasses a number of sub-models, such as models for flood risk, ecology, tourism, recreation and navigation. These models are fundamental in supporting the whole decision-making process. However, often complicated and sophisticated models are used which are difficult to understand and operate for decision-makers. Moreover, these models may be not necessary for some specific-purpose DSSs, such as those for preliminary planning purposes. The aim of this paper is therefore to find appropriate models by applying a proposed appropriateness framework. An appropriate system is defined as 'a system which can produce outputs enabling decision makers to distinguish different river management actions under uncertainty according to the current problem'. The proposed framework is applied to a sub-model of a DSS — a flood risk model to illustrate the idea of appropriateness. The results show that the framework proposed is applicable. It helps distinguish the management actions and find the appropriate models for the DSSs.

Keywords: decision support system; flood risk model; appropriate modelling; Latin Hypercube Simulation; Morris' method

1. INTRODUCTION

There is increasing interest in the development of decision support systems (DSSs) for river basin management. Moreover , new ideas and techniques like sustainability, adaptive management, Geographic Information System (GIS), Remote Sensing (RS) and participations of new stakeholders have stimulated their development [Smits et al. 2000]. A DSS for river basin management often encompasses a number of sub-models, such as models for flood risk, ecology, tourism, recreation and navigation. These models are fundamental in supporting the whole decision-making process. However, often complicated and sophisticated models are used which are difficult to understand and operate for decision-makers. Moreover, these models may be not necessary for some specific-purpose DSSs, such as those for preliminary planning purposes. In case of data insufficiency, simple models could be preferable if they can satisfy the requirements from the decision makers, e.g., with respect to accuracy.

In the field of river basin management, uncertainty studies have been an essential part to support the decision making. In case a ranking of the river management actions based on particular decision variables is required, uncertainty will be one of the main obstacles. In order to make a sound decision, uncertainty reduction is often the first solution the analysts can provide.

An appropriateness framework is proposed in this paper. An appropriate system is defined as 'a system which can produce outputs enabling decision makers to distinguish different river management actions under uncertainty according to the current problem'. The framework employs uncertainty analysis to analyze the appropriateness of models used in the DSSs. As an example, a sub-model of a DSS — a flood risk model will be used to illustrate the use of the proposed approach.

2. APPROPRIATENESS FRAMEWORK

Figure 1 shows the general appropriateness framework proposed in this paper. This framework is used to find appropriate models in the DSSs with an aim to distinguish (rank) the river management actions. According to this figure, there are three important aspects (after inputs and quantitative modelling) involved in this framework. They are uncertainty analysis, appropriateness analysis and model improvements through uncertainty reduction respectively.

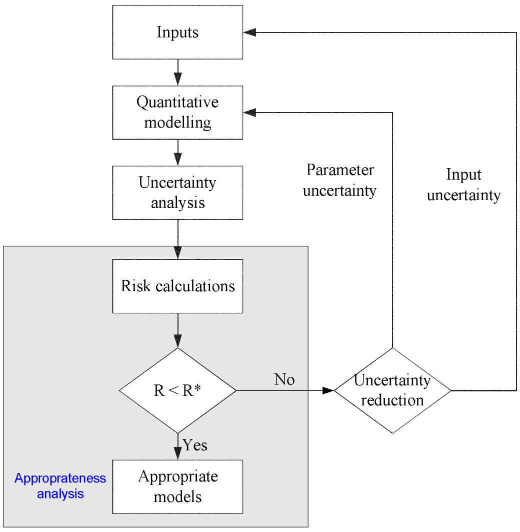

Figure 1: An appropriateness framework (R is the calculated risk and R* is the acceptable risk)

2.1 Uncertainty analysis

From a modeler's point of view, there are three types of uncertainty: uncertainty in model quantities, uncertainty about model form and uncertainty about the completeness/adequacy of the model [Van Asselt 2000]. In this paper, only the uncertainties in model quantities are considered. Uncertain model quantities include model inputs and parameters. The uncertainty caused by the model form and model completeness has not been studied although it is known to be important [Cardwell and Ellis 1996; Perrin et al. 2001].

To investigate the effects of uncertainty on the decision variables, many uncertainty analysis methods are available, for example the first order method, Monte Carlo Simulation, Fourier Amplitude Sensitivity Test (FAST), and Response Surface Methods [Morgan and Henrion 1990]. They can be used to study how the uncertainty in the inputs and parameters are propagated into the model outputs (decision variables in the DSSs). Here one of the Monte Carlo Simulation methods, namely Latin Hypercube Simulation (LHS) method, will be used.

2.2 Appropriateness analysis

As introduced in Section 1, the appropriateness is defined under the concept of decision making under uncertainty. The appropriateness is quantified by a criterion, defined as the risk of making a wrong decision (*R*). The risk is the product of the mean difference (*D*) of the model outputs resulting from each combination of management actions and the probability of making a wrong decision (*P*) for each combination of management actions. This criterion can be used to determine whether the models in the DSSs are appropriate or not after uncertainty analysis. The mathematical equation of the risk is

$$R = D * P \qquad (1)$$

Here the probability of making a wrong decision (*P*) is the probability that one measure outperforms another measure based on particular decision variables. According to the definition, there is one risk value for each of the $k\ (k-1)/2$ combinations of management actions. k is the number of management actions. So R can be regarded as a set of risk value.

Assume that the decision makers' acceptable risk is R^*, then the models are determined to be appropriate if all members of the risk set R are smaller than R^*, that is

$$R < R^* \qquad (2)$$

for all combinations of management actions.
Else, the models are determined to be inappropriate.

2.3 Model improvements through uncertainty reduction

If the models are determined as inappropriate, they need to be improved in order to reduce the risk by reducing the uncertainty in the model outputs. There are several techniques available for reducing the uncertainty, for example by obtaining more measurement data. In this paper, reducing uncertainty in the model outputs is completed by reducing uncertainty in the inputs and parameters in the models, as indicated in Figure 1.

In order to reduce the uncertainty, a screening sensitivity analysis method, named the Morris' method [Morris 1991] will be used. This method is used to investigate the importance of all inputs and parameters in the models. The most important inputs and parameters will be identified by the Morris' method and uncertainty will be reduced in those quantities. The most important inputs and parameters are those that contribute most to the uncertainty in the final model outputs. In this way, the most efficient reduction of uncertainty in the model outputs can be achieved.

The models will be improved until the uncertainty in the model outputs is tolerable to the decision makers according to the acceptable risk. Alternatively the efforts (costs and time) to reduce the uncertainty are not worthwhile compared to the amount of uncertainty reduced or it is impossible to reduce the uncertainty because of the nature of the uncertainty.

3. CASE STUDY

A sub-model of a developed DSS for the Dutch Meuse River — a flood risk model — is used to apply the appropriateness framework introduced in Section 2. This sub-model calculates the net present value (*NPV*) for different river management actions. The *NPV* is used as a decision variable to determine the appropriateness of models in the DSS.

There are several components in this flood risk model, namely a flood frequency model, a hydraulic model, an inundation model, and a risk model.

The primary objective of the flood frequency model is to relate the magnitude of extreme events (flood flows) to their frequency of occurrence through the use of probability distributions. In this analysis, the Gumbel Extreme Value distribution is used.

The hydraulic model calculates water levels in the river channel for different flood flows. Stepwise steady non-uniform flow simulation is used for this purpose [Van Rijn 1994]. Assume there are no lateral flows.

The inundation model is employed to calculate the inundation depths in the flood plains. The inundation depths are the differences between water levels and land heights.

The objective of the risk model is to calculate the *NPV* value for each management action. The net present value (*NPV*) is defined as the sum of expected annual damage [Shaw 1994], costs of management actions, and benefits from sand and gravel extractions [Van Leussen et al. 2000]. Here only the direct damage is considered (for example no damage to the ecological value) [De Blois 1996]. For floods of different probabilities, corresponding value of flood damage can be calculated. The economic damage in the floodplains is determined by the inundation depth, land use type and the number of units of that land use type. The damage is given in monetary values per unit (in euros). The expected annual damage is the expected annual value of these damages.

Three management actions are formulated in this paper to investigate how they affect the *NPV* value. They are:

- The base situation (M_1).
- Deepening the summer bed by 1 meter (M_2).
- Spatial planning, for example relocation of valuable capital from the floodplains to higher land (M_3).

4. RESULTS

4.1 Uncertainty analysis: the *NPV* value

As stated before, only uncertainty in the inputs and parameters will be considered. In this case study, there are a total of 112 inputs and parameters in the models. A sample size of 100 will be selected in LHS simulation.

The two parameters in the flood frequency model are assumed to be normally distributed. For the hydraulic parameters, a questionnaire has been employed to investigate how uncertain these parameters are. The distributions of all the other inputs and parameters are arbitrarily set uniform in shape, because there are insufficient data available to infer any particular type of distribution for these inputs and parameters. Ranges of variability have been selected either according to the information available, or in absence of such information, assuming 20% of uncertainty is involved in the inputs and parameters (nominal value ±20%).

The uncertainties in the inputs and parameters are propagated into the model outputs, here *NPV* in million euros. The fitted normal distributions for three management actions are shown in Figure 2 (x-axis is the natural logarithm (LN) of the *NPV* value). This figure shows that large areas of overlap exist among the model outputs, which make it difficult to rank these three management actions.

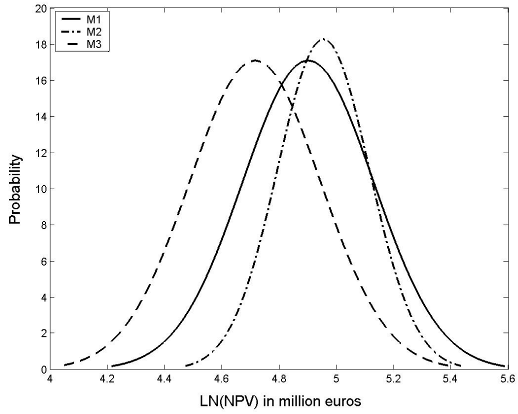

Figure 2: Fitted normal distributions for model outputs from three management actions

4.2 Appropriateness analysis: risk calculation

Table 1, Table 2 and Table 3 present the mean differences, the probabilities of making a wrong decision and the risks of making a wrong decision ('Case 0', bold numbers in three tables) for each combination of management actions.

Table 1 and Table 2 show that, as expected, small mean differences correspond to large probabilities of making a wrong decision. This means the mean differences and the probabilities have counteracting effects on each other. The risks are actually combined effects of both aspects.

Commonly the acceptable risk is determined by decision makers. However, in this case study a value of six million euros is chosen for a preliminary analysis. The appropriateness of the models is judged based on this acceptable risk. The bold numbers in Table 3 indicate that the models used in this case are inappropriate because one of the risks calculated (6.60 million euros) is higher than the acceptable risk.

4.4 Uncertainty reduction: model improvements

As described in Section 4.3, the models are judged as inappropriate because of the failure of satisfying the acceptable risk defined.

Table 1: The mean differences (million euros)

Management actions compared	Case 0	Case 1	Case 2
M_2 & M_1	**5.61**	6.88	6.93
M_1 & M_3	**23.27**	22.31	22.83
M_2 & M_3	**28.88**	29.19	29.76

Table 2: The probabilities of making a wrong decision

Management actions compared	Case 0	Case 1	Case 2
M_2 & M_1	**0.42**	0.41	0.39
M_1 & M_3	**0.28**	0.24	0.22
M_2 & M_3	**0.20**	0.17	0.12

Table 3: The risks of making a wrong decision (million euros)

Management actions compared	Case 0	Case 1	Case 2
M_2 & M_1	**2.38**	2.85	2.70
M_1 & M_3	**6.60**	5.38	5.10
M_2 & M_3	**5.69**	4.97	3.58

The Morris' method identified that the most important inputs and parameters in the flood risk model are river slope, bed level coefficients, depths of the summer bed and Nikuradse coefficients in the flood plains. They are all parameters in the hydraulic model. The Morris' method also concluded that all the parameters in the hydraulic model appear to be more important than the parameters in the flood frequency model and the parameters in the damage functions of the risk model. These parameters contribute more to the uncertainty in the model outputs than the others. Therefore the idea is to try to reduce the uncertainty in the parameters from the hydraulic model.

In this paper, the modelers are not interested in how the uncertainties are reduced although it is important. To investigate how the uncertainty reduction in the most important inputs and parameters affects the risks, two cases are considered based on different assumptions (for illustration only):

- Case 1: assume a reduction of uncertainty in river slope, bed level coefficients, depths of the summer bed and Nikuradse coefficients in the flood plains
- Case 2: assume deterministic parameters in the hydraulic model

In order to study the effects of uncertainty reduction, the original system without improvement is represented here as 'Case 0'.

The calculated mean differences, the probabilities of making a wrong decision and the risks of making a wrong decision after uncertainty reduction are again shown in Table 1, Table 2 and Table 3 respectively.

Most of the mean differences in Table 1 show an increase of value except the combination for M_1 and M_3. For this combination, the mean difference first decreases and then increases. The increase of the mean difference shows an indication of more easily distinguishing the management actions. The unstable change of the mean differences maybe a result of the non-linearity of the models and insufficient simulation runs (random). The effects of non-linearity and simulation runs have not been investigated in this paper. The probabilities of making a wrong decision presented in Table 2 show a decrease of value because of the reduction of uncertainties, in turn, helping reduce the value of risks calculated.

For both cases, the risks calculated are smaller than the predefined acceptable risk of six million euros. Based on this, it is concluded that, under both cases the models used in the DSS are appropriate.

5. CONCLUSIONS

In the case study presented in this paper, the high uncertainty in the model outputs produced indistinguishable situations for some combinations of management actions. This is often the case for DSSs in general. The models were determined to be inappropriate by comparing the value of risk of making a wrong decision for each combination of management actions with the acceptable risk. After improving the models by reducing the uncertainty in the most important inputs and parameters, the models became appropriate. The analysis in this section gives a good idea of how the proposed appropriate framework worked in this case study.

A key point in this paper is the definition of the criterion that is used to determine the appropriateness of models used in the DSS. This criterion, defined as the risk of making a wrong decision for each combination of management actions, combines two interesting aspects. These aspects are the mean difference for each combination of management actions and the probability of making a wrong decision. They are both important for the risks of making a wrong decision and have counteracting effects on each other. The criterion is proved to be a reasonable one for analyzing the appropriateness of models used in this DSS.

Due to the non-linearity of the models and the random of the simulation, one of the mean differences showed an unstable change when the uncertainty in inputs and parameters was reduced. This can be partly solved by increasing the runs of the LHS simulations or by calculating the confidence intervals of the risks. Else this situation could be an obstacle in finding the appropriate models and results in more efforts necessary in reducing the uncertainty.

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