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Decision making under uncertainty in a decision support system for the Red River

Inge A.T. de Kort, Martijn J. Booij*

Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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Abstract

Decision support systems (DSSs) are increasingly being used in water management for the evaluation of impacts of policy measures under different scenarios. The exact impacts generally are unknown and surrounded with considerable uncertainties. It may therefore be difficult to make a selection of measures relevant for a particular water management problem. In order to support policy makers to make a strategic selection between different measures in a DSS while taking uncertainty into account, a methodology for the ranking of measures has been developed. The methodology has been applied to a pilot DSS for flood control in the Red River basin in Vietnam and China. The decision variable is the total flood damage and possible flood reducing measures are dike heightening, reforestation and the construction of a retention basin. The methodology consists of a Monte Carlo uncertainty analysis employing Latin Hypercube Sampling and a ranking procedure based on the significance of the difference between output distributions for different measures. The mean flood damage in the base situation is about 2.2 billion US$ for the year 1996 with a standard deviation due to parameter uncertainty of about 1 billion US$. Selected applications of the measures reforestation, dike heightening and the construction of a retention basin reduce the flood damage by about 5, 55 and 300 million US$, respectively. The construction of a retention basin significantly reduces flood damage in the Red River basin, while dike heightening and reforestation reduce flood damage, but not significantly.

Keywords: Decision support system; Water management; Flood damage; Uncertainty; Ranking methodology; Appropriate scale; Red River

1. Introduction

Decision support systems (DSSs) are increasingly being used in water management for the evaluation of impacts of policy measures under different scenarios. For example, AQUATOOL is a generic DSS including modelling capabilities as basin simulation and optimization modules, an aquifer flow modelling module and modules for risk assessment (Andreu et al., 1996). WATERSHEDSS (WATER, Soil and Hydro-Environmental Decision Support System) is composed of an expert system-like interface that links predetermined linear paths to a solution endpoint, an extensive educational component accessible throughout the interface by hypertext links, forms linked to databases and a link into the model environment (Osmond et al., 1997). RAMCo (Rapid Assessment Module for Coastal-Zone Management) combines a geographical information system with a dynamic system model for (bio)physical and socio-economic coastal-zone interactions (de Kok et al., 2001). The mDSS tool is a decision support system for water resources management and is designed to integrate environmental models with multiple-criteria evaluation procedures (Mysiak et al., 2005). A common drawback of policy analysis, impact evaluation or knowledge management based on these systems is the uncertainty present in each component of the system and hence in the results based on these systems (see e.g. Reichert and Borsuk, 2005). In impact evaluations, exact impacts generally are unknown and surrounded with considerable uncertainties. These uncertainties stem from

* Corresponding author. Tel.: +31 53 4892564; fax: +31 53 4895377.
E-mail address: m.j.booij@utwente.nl (M.J. Booij).

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natural randomness, uncertainty in data, models and parameters, and uncertainty about scenarios and measures. Scenarios are exogenous processes, which cannot be influenced by stakeholders (e.g. farmers, government) within the socio-economic or natural system (e.g. price development, population growth, climate change). Measures are technical or non-technical adaptations to the water system in order to achieve certain policy objectives (e.g. dike heightening, reforestation, spatial planning policies). Due to the considerable uncertainties, it may be difficult to make a selection of measures relevant for a particular water management problem.

This paper therefore introduces a methodology for the ranking of measures in order to support policy makers to make a strategic selection between different measures in a DSS while taking uncertainty into account. The methodology is applied to a pilot DSS for flood control in the Red River basin in Vietnam and China. This pilot DSS has been developed as part of the EC-funded project FLOCODS (FLOod COntrol Decision Support). Section 2 considers the decision context of the DSS, Section 3 describes the DSS and the ranking methodology, Section 4 discusses the application of the DSS and in Section 5 conclusions are drawn.

2. Decision context: variables and objectives

The Red River basin is situated in China and Vietnam and has a surface area of about 169 000 km^2. The delta covers about 15 000 km^2 and starts near Hanoi, the capital of Vietnam. The average annual precipitation strongly varies over the area between 700 and 4800 mm. About 80% of the precipitation occurs in summer when the Southwest monsoon brings warm, moist air across in the Indo-Chinese peninsula. Most of the floods therefore occur in July and August. The average discharge of the Red River is about 3750 m^3/s (Nghia, 2000). Similar to elsewhere in Southeast Asia, a marked contrast exists between the isolated and sparsely populated mountains and the densely populated delta (over 1000 people per km^2). The delta is a low lying area mainly used for the cultivation of rice (about 88% of the area). The upstream, mountainous area has a larger proportion of forest (about 42% of the area) and grassland forms the transition zone between the forest and rice fields.

Flood disasters cause massive losses of human life and immense damage to the infrastructure and economic activities in the Red River basin in Vietnam and China (e.g. Nghia, 2000). These floods result not only from climatological circumstances, but are also caused by human development. The ecosystem has been seriously disrupted due to rapid population growth and the uncontrolled development of industrial and urban centres. This has led to deforestation and other changes in the ecosystem, which in turn have increased the flooding risk. The severity of the floods can be mitigated by adopting suitable measures for flood control that take into account the social, economical and ecological consequences. Short term measures include flood diversion, rescue actions and prevention of unexpected dyke breaks and inundation in important and densely populated urban and industrial zones.

Here, the emphasis is on the long term, with measures such as reforestation, the construction of reservoirs in upstream areas and a controlled development of urban and industrial centres. The management objective is to reduce the total flood damage (decision variable). This is achieved by selecting a suitable combination of flood control measures considering all important consequences, including mean impacts and related uncertainties. The developed DSS is used to evaluate the impacts on the total flood damage of a number of flood control measures (Section 3).

3. Description of DSS

3.1. Model environment choice

The DSS should support decisions concerning the selection of a suitable combination of flood control measures considering all important consequences. The model environment for the DSS needs to be carefully selected, taking into account the objectives and application of the DSS. Therefore, the requirements and possibilities for the DSS model environment have been compared with each other in order to find the most appropriate model environment. Important requirements for the model environment are the capability to model spatially and temporally and at different spatial and temporal scales. Moreover, the model environment should be flexible, universally available and user-friendly. The model environments which were considered are third generation programming languages (e.g. Fortran), fourth generation languages (e.g. Matlab), geographical information systems (GIS, e.g. ArcView), combinations of existing models (e.g. a combination of an existing hydrological model, hydraulic model and socio-economic model) and existing DSSs (e.g. RAMCO, see de Kok et al., 2001). Additionally, experts have been consulted for their opinions.

The comparison of requirements and possibilities did not yield one favourite model environment. However, it was concluded that three groups of model environments could be omitted: third generation languages (problems with flexibility, presentation, etc.), combinations of existing models (different scales, interacting processes, universality) and existing DSSs (different scales, flexibility, universality). The choice between a fourth generation language and a GIS was further explored based on the literature (e.g. Theobald and Gross, 1994; Sharifi, 1999) and expert judgement. Most experts recommended the use of a GIS as the model environment, in particular PCRaster (see e.g. Wesseling et al., 1996), because of its spatio-temporal character. Therefore, PCRaster has been chosen as the model environment for the DSS. The main advantages of this model environment are the spatio-temporal character, the built-in capabilities, the flexibility and the possibility to construct user interfaces appropriate for the model user. Van der Perk et al. (2001) describes a DSS built within the PCRaster environment.

3.2. System components

The main components of the DSS are the integrated model system, the objectives and related measures, the appropriate system scales, the database and the scenarios. In this preliminary assessment, scenarios will not be considered. The integrated model system, measures, appropriate system scales and database are described below.

3.2.1. Integrated model system

The integrated model system is the representation of the natural and socio-economic system by proper hydrological, hydraulic and socio-economic models. This allows for a sensible evaluation of flood reducing measures. The complexities (processes, scales, formulations) of the different models should be balanced, i.e. it does not seem to be reasonable to combine a sophisticated hydrological–hydraulic model with a simple socio-economic model.

The hydrological model is based on the HBV model concepts (Bergström and Forsman, 1973). The considerations, which have led to the choice of HBV, are extensively described in Booij (2005). The HBV model is a conceptual hydrological model of river basin hydrology and simulates discharge using precipitation and potential evapotranspiration as input. In the DSS, the discharge is determined for each cell in the hydrological model and is dependent on several hydrological processes. These processes are modelled by several routines in the HBV model. The relevant routines for the Red River basin are the precipitation routine representing rainfall, the soil moisture routine determining actual evapotranspiration, overland flow and subsurface flow, the fast flow routine representing storm flow and the slow flow routine representing subsurface flow. The discharge of each model cell is routed down the river network using a digital elevation model. For a detailed description see e.g. Bergström (1995).

The simulated discharge serves as input into the hydraulic model. It is transformed into water depth using a stage–discharge relation derived from measured data. The water depth applies to the complete deltaic area. An additional water depth due to the tide is added to this water depth. The inundation depth in the flooded area is determined using this river water depth, the dike height and the elevation in the flooded area. A certain decrease in the inundation depth is assumed when the flood wave is in its falling stage.

The socio-economic model determines with linear functions the flood damage and incomes for different economic sectors. The flood damage is dependent on the simulated inundation pattern and the land use type, while the incomes are dependent on the economic sector (through prices, costs, etc.) and the land use type. The decision variable is the total flood damage in the deltaic area of the Red River basin.

3.2.2. Flood control measures

The DSS can be used for the evaluation of impacts of policy measures (under different scenarios). Three different measures are considered, namely dike heightening, reforestation and the construction of a retention basin. The impacts of these measures will be compared with the impacts in the base situation. The measures are briefly described below.

The dike system is represented by a constant dike height relative to mean sea level, which obviously is a simplification of reality. Moreover, it is assumed that the dike system is of good quality, which may not hold in reality. For example, Nghia (2000) states that the overall dike system is outdated, poor in repair and vulnerable to erosion. The measure dike heightening is achieved by increasing the dike height by 1 m.

Reforestation is a sustainable flood control measure and supports retainment of water in the soil and prevents erosion. This is achieved by adapting the land use pattern in the DSS, which subsequently will change the soil moisture function in the hydrological model and the damage and income estimates in the socio-economic model. Forest is randomly attributed to areas in a certain elevation range and with the land use types rice field and grassland in the base situation.

The construction of a retention basin is based on an existing retention basin. The main functions of the basin are flood control and power production. The water storage and release are dependent on several factors such as the inflow, the actual storage in the reservoir, the minimum and maximum storage and the maximum outflow. More details about the implementation of the reservoir in the DSS can be found in de Kort (2003).

3.2.3. Appropriate system scales

Appropriate scales for the DSS are chosen, taking into account its objectives. In this respect the terms flooding, possible measures and decision variables are important. Appropriate scale refers to all aspects of the spatial and temporal scale triplet (Blöschl and Sivapalan, 1995). For example, for flooding, this implies a choice of the time step (temporal spacing scale), flood duration (temporal support scale), flood frequency (temporal extent scale), spatial resolution (spatial support/spacing scale) and research area (spatial extent scale). In the same way, scale aspects for measures and decision variables should be chosen.

A rough analysis showed that the DSS should fulfil at least the following scale requirements:

(a) temporal resolution: one day;
(b) temporal extent: years to take into account the frequencies of extreme floods;
(c) spatial resolution: may vary depending on the variability and importance of processes, e.g. the resolution in the downstream area should be finer than in the upstream one, because of the importance of economic activities and consequently the flood damage modelling in the downstream area;
(d) spatial extent: complete Red River basin in Vietnam and China.

Therefore, the DSS has a variable spatial resolution with a more coarse scale (5 km) for the complete Red River basin and a finer scale downstream (1 km), see Fig. 1. The hydrological model has a spatial resolution of 5 km for the complete river basin, the hydraulic model has a spatial resolution of 1 km for the deltaic part of the river basin and the socio-economic model has a spatial resolution of both 1 km and 5 km. Booij (2003a) has found an appropriate spatial scale of 10 km for a similar problem in a smaller river basin. The temporal resolution of the DSS is one day and the time period

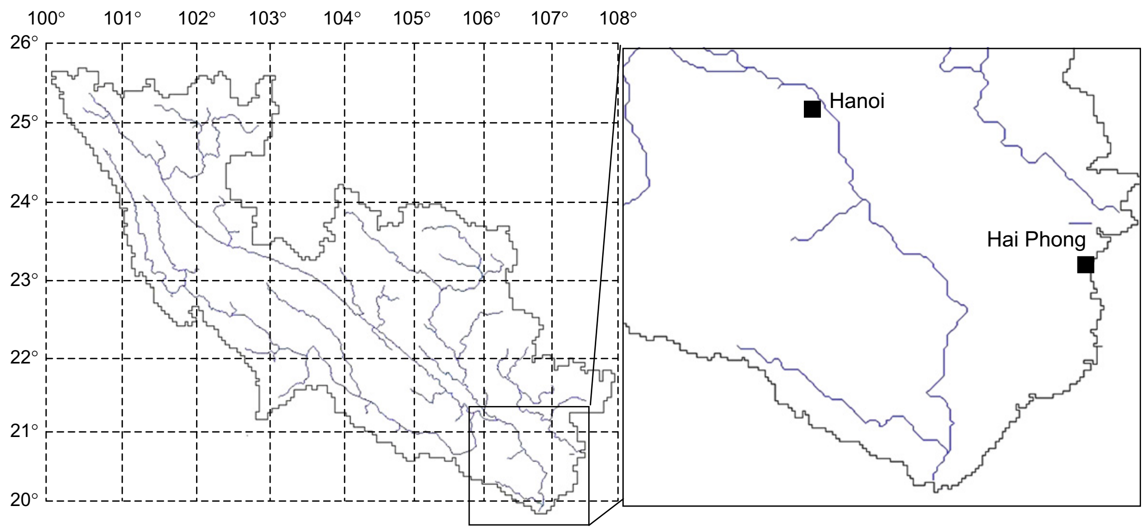

Fig. 1. Red River basin at a spatial resolution of 5 km between 20°N–26°N and 100°E–108°E (left, extent of area 770 km × 660 km) and delta of the Red River basin at a spatial resolution of 1 km (right, extent of area 154 km × 132 km).

considered is one year (1996). This year has been chosen, because it contains one of the major floods which have occurred in the river basin.

3.2.4. Database

Meteorological, hydrological, hydraulic and socio-economic data from several sources for the year 1996 were used (e.g. Vietnamese Hydrometeorological Forecasting Centre, Vietnamese Ministry of Agriculture and Rural Development, United States Geological Survey). Daily precipitation and evapotranspiration data from 15 stations and daily discharge data from five stations are included in the database. Furthermore, elevation data from a global digital elevation model and land use data from a global land cover database (based on surveys and remote sensing data) are employed. The spatial resolutions are 1 km for both the elevation and land use data. This spatial resolution for elevation is assumed to be appropriate for inundation modelling taking into account the flatness of the study area and the research objective. Socio-economic data include incomes, agricultural yields and flood damage in general at a provincial level and on an annual basis. Further information about the Red River basin and the data resources can be found in Booij (2003b) and de Kort (2003).

4. Measure ranking methodology

4.1. Concepts of ranking methodology

A methodology for the ranking of measures in a DSS has been developed in order to support policy makers to make a strategic selection between different measures while taking uncertainty into account. The methodology consists of an uncertainty analysis and a ranking procedure based on the significance of the difference between output distributions for different measures. These two steps are described below.

4.1.1. Uncertainty analysis

In an uncertainty analysis, the effect of different uncertainties (e.g. from data, models and parameters) on the output of interest (the decision variable) is determined. Two aspects are discussed, namely the type of uncertainty to be investigated and the choice of the uncertainty analysis method.

The uncertainty in the decision variable stems from natural randomness, uncertainty in data, models and parameters, and uncertainty about scenarios and measures. In principle, the most important uncertainty sources should be investigated, i.e. those uncertainties mostly affecting the decision variable. These uncertainty sources will be considered as random variables in the uncertainty analysis and all other sources are assumed to be deterministic. Methods to determine the importance of uncertainty sources include first-order uncertainty analysis (e.g. Melching et al., 1990), sensitivity analysis (see Morgan and Henrion, 1990) and the Morris screening method (Morris, 1991). However, in environmental modelling usually parameter uncertainty is investigated (e.g. Lei and Schilling, 1994; Seibert, 1997), because it is relatively easy to quantify. The effects of other uncertainties are more difficult to assess, in particular the effects of model structure uncertainty. This latter uncertainty can be assessed, for example, by model validation and intercomparison (e.g. Ye et al., 1997), including all kinds of events (dry–wet, smooth–peaky, etc.) in the calibration that trigger all relevant processes or including besides flux variables also state variables such as groundwater levels in the model calibration and validation (e.g. Lamb et al., 1999).

Uncertainty analysis methods often used in environmental modelling include first-order uncertainty analysis, Monte Carlo analysis (e.g. Seibert, 1997), Rosenblueth uncertainty analysis (e.g. Binley et al., 1991) and Bayesian uncertainty analysis (e.g. Tol and de Vos, 1998). The uncertainty analysis method to be used in the ranking methodology is chosen based on a multi-criteria analysis. Criteria for the selection are the nature of the model, research purpose, previous comparisons and available resources (e.g. Morgan and Henrion, 1990).

The distribution type of the (dominant) random variables to be used in the uncertainty analysis method is dependent on the method itself and the amount of information available. The first-order method for example implicitly assumes that variables are normally distributed. When a limited amount of information about the random variables is available, uniform distributions should be preferably used. When information is available, statistical tests can be used to check whether a variable is e.g. normally distributed (see also Section 4.1.2). Furthermore, it should be checked whether the dominant variables are significantly correlated or not. When necessary, correlations should be taken into account in the uncertainty analysis, e.g. through covariances in the first-order method.

4.1.2. Ranking procedure

The ranking procedure is based on the significance of the difference between output distributions for different measures taking uncertainty into account. Therefore, first the distribution type needs to be determined and second, the significance of the differences is required as described below.

The hypothesis of output distributions being normally distributed is tested visually with quantile–quantile plots and quantitatively with the Kolmogorov–Smirnov test (see e.g. Zar, 1996). The nature of the output distribution (Gaussian or non-Gaussian) determines which test is used in the next step.

The significance is determined with the Student's test for Gaussian distributions and with the Wilcoxon test for non-Gaussian distributions. These tests are widely used and accepted for these two types of distributions (Helsel and Hirsch, 1992). The Student's test compares the means of two distributions, while taking the variance of both distributions into account. The specific Student's test to be used depends on the homogeneity of the variances from both distributions. The Wilcoxon signed rank test (see e.g. Zar, 1996), also known as the Mann–Whitney test, is a non-parametric test that detects differences in the distribution of two situations by ranking the output in both situations and comparing the resulting, standardised ranks.

4.2. Application of ranking methodology to DSS

For illustrative purposes, only the effect of parameter uncertainty on the total flood damage is taken into account. This uncertainty source is chosen because it may have large effects on the output, is relatively easy to quantify and is interesting in the context of the DSS. Only the uncertainty of six dominant parameters is considered. These dominant parameters are two parameters in the fast flow routine of the hydrological model, two parameters in the stage–discharge relation and one parameter in the inundation formulation of the hydraulic model, and one parameter in the flood damage function for rice of the socio-economic model. They have been selected on the basis of their contribution to the output uncertainty as determined by a first-order uncertainty analysis (see de Kort, 2003). First-order uncertainty analysis assumes linearity and independency of parameters, which is found to be reasonable taking into account the objective of the analysis. The uncertainties in the dominant parameters contributed to about 80% of the total output uncertainty.

Based on a multi-criteria analysis, the Monte Carlo uncertainty analysis method has been chosen. Monte Carlo analysis involves the random sampling of inputs and parameters and subsequently the determination of the model output. The quality of the probability distribution of the output obviously depends on the sampling number for which a generally valid value hardly can be given. The use of an efficient sampling technique can restrict the number of simulations needed. Therefore the Latin Hypercube Sampling (LHS) method is used. This method is a stratified sampling version of the Monte Carlo method and efficiently estimates the statistics of an output (Melching, 1995).

Only the six dominant parameters contributing considerably to the output uncertainty are sampled in the LHS uncertainty analysis. For all six parameters uniform distributions are assumed, because no data about uncertainty distributions were available and other studies (e.g. Yu et al., 2001) employed uniform distributions for similar analyses as well. Ranges of these uniform distributions are determined in different ways. Ranges for the two parameters in the fast flow routine of the hydrological model are based on values from other HBV studies taking into account differences in climatological and geographical conditions (Bergström and Graham, 1998) and are between −50 and +100% of the original value. Ranges for the two parameters in the stage–discharge relation are determined from the 90%-confidence interval of the measured stage–discharge relation and are between −15 and +10% of the original value. Ranges for the remaining two dominant variables are based on expert opinions (e.g. experts from the Vietnamese Hydrometeorological Forecasting Centre and the Vietnamese Ministry of Agriculture and Rural Development) and are between −60 and +60% of the original value.

The parameters are assumed to be independent from each other, which may result in a slight overestimation of the uncertainty. However, this overestimation may be compensated by contributions of the remaining parameters and processes to the output uncertainty. A total number of 100 samples of parameter sets have been used to generate 100 output values for each situation (base situation and three measures). This number of samples is arbitrarily chosen based on previous uncertainty analysis studies and the fact that this number corresponds to a reasonable number of about 1000 samples when employing Monte Carlo analysis (Yu et al., 2001).

5. Application of DSS: Red River basin

5.1. Results of DSS application

The observed and simulated daily discharge at Ta Bu (upstream area ca. 46 000 km^2) and Son Tay (upstream area ca. 144 000 km^2, 85% of Red River basin area) for a period around 1996 (1994–1998) is given in Fig. 2. Although no thorough calibration procedure has been done yet, the discharge at Ta Bu is reasonably simulated (Nash–Sutcliffe coefficient ca. 0.60, volume difference less than 5%). The discharge at Son Tay is less well simulated (Nash–Sutcliffe coefficient ca. 0.40, volume difference less than 5%) and in particular, peaks are

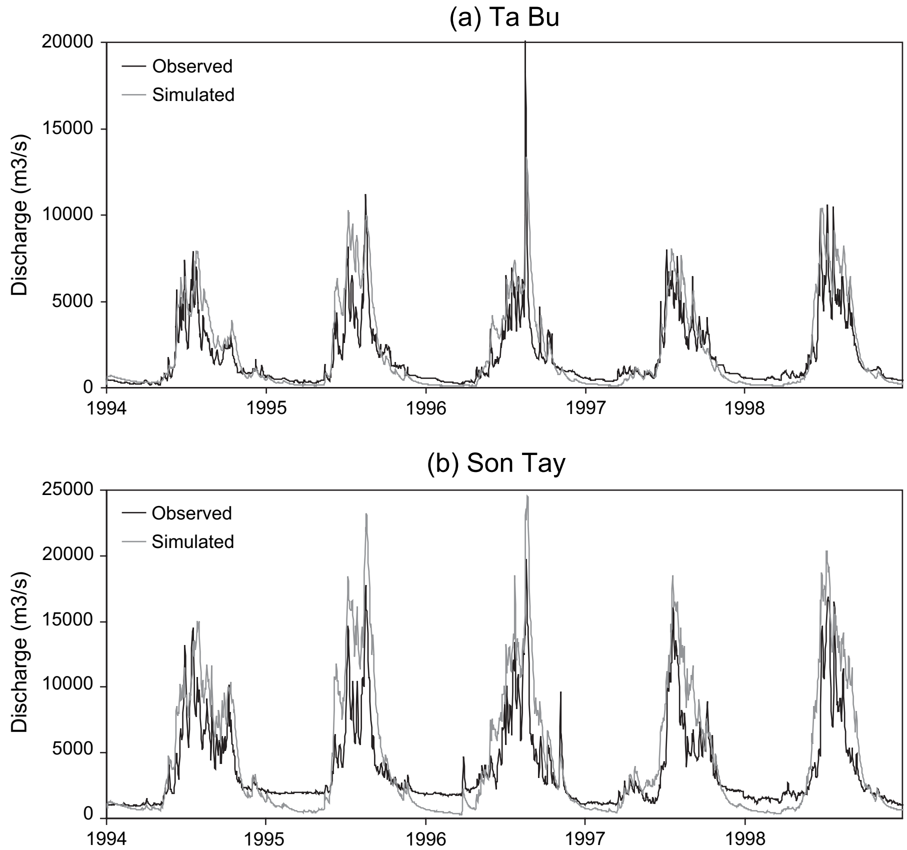

Fig. 2. Observed and simulated discharge at Ta Bu (a) and Son Tay (b) for period 1994–1998.

overestimated. However, in this preliminary stage the observed pattern is sufficiently represented by the simulated one. For other sub-basins similar results were obtained and a more extensive calibration will be performed in the near future, in particular by employing more data from the Chinese area.

The simulated inundated areas for the flood of 1996 in the downstream part of the Red River basin in combination with the elevation pattern are shown in Fig. 3. Unfortunately, observed maps with inundated areas are not available yet, but some may become available to check the simulated ones. The big 1996 flood event caused problems in the neighbourhood of the capital Hanoi. Besides flooding maps, more accurate information on dike height and quality are needed to improve this inundation simulation and hence the damage assessment. However, an accurate representation of inundation patterns in the DSS is not the aim of this paper, but rather the DSS is used to illustrate the ranking methodology including comparisons between damage values resulting from different flood control measures.

5.2. *Results of uncertainty analysis*

The results of the four sets of 100 LHS simulations are shown in Fig. 4. The simulated mean flood damage for the base situation corresponds well with the observed one (not shown here) of about 2.2 billion US$. It should be noted here that the flood of 1996 was one of the five major floods in the 20th century and thus the resulting damage was high. The measures reforestation, dike heightening and the construction of a retention basin reduce the simulated mean flood damage by about 5, 55 and 300 million US$, respectively. It should

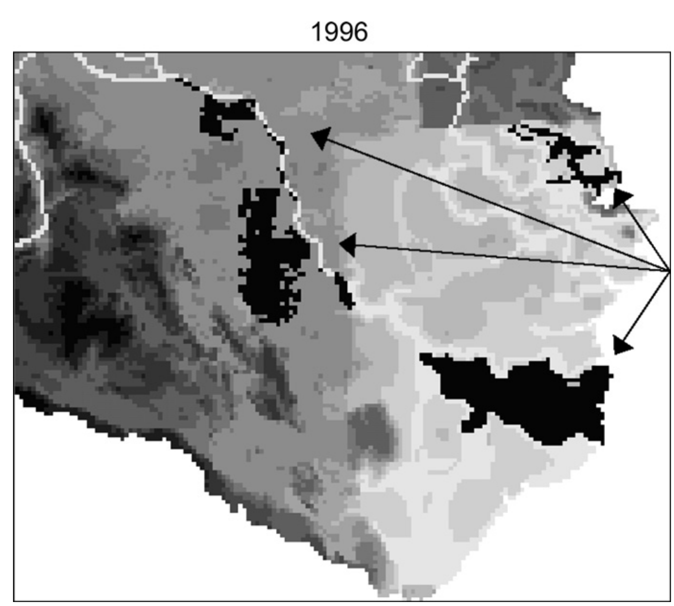

Fig. 3. Elevation pattern in downstream part of Red River basin and simulated inundated areas (black areas indicated with arrows) for 1996 flood.

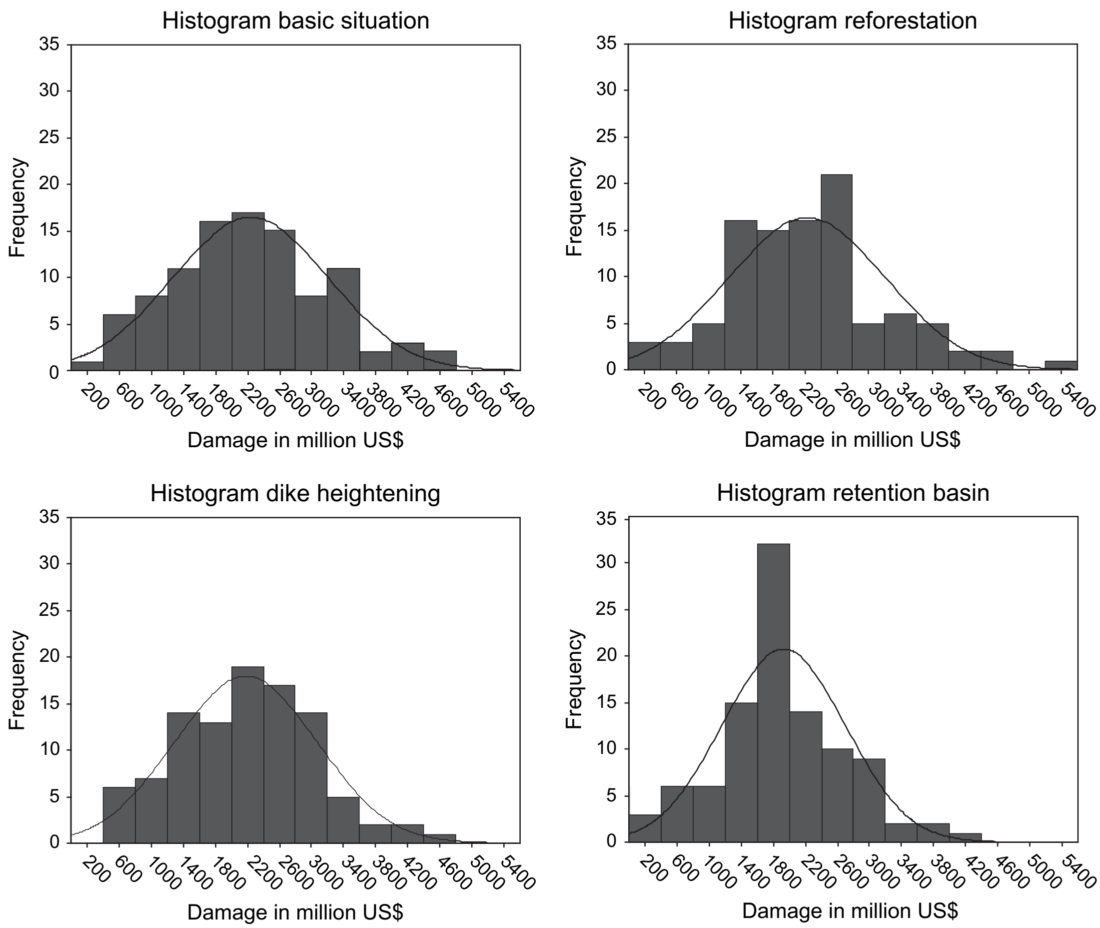

Fig. 4. Histograms and fitted Gaussian curves for base situation and three flood control measures.

be noted that the extent to which the flood damage is reduced depends highly on the dimensions and the location of the flood control measure. The small effect of reforestation on the flood damage may be due to the fact that erosion and sedimentation processes are not taken into account in the DSS. These processes probably play an important role in realising the flood control function of reforestation. Standard deviations for all four situations are high (up to 45% of the mean value) indicating large uncertainties in the estimation of the total flood damage. This is partly due to the assumption of independency of parameters done in the uncertainty analysis. Obviously, these large uncertainties result in large overlaps of the probability distributions are shown in Fig. 4.

5.3. Results of ranking procedure

The first step in the ranking procedure has been the determination of the distribution type. The quantile–quantile plots showed reasonable straight lines with only slight deviations from the expected normal value, even in the tails. This was confirmed quantitatively by the Kolmogorov–Smirnov test. Moreover, Large Lilliefors significance values ($\gg 0.05$) indicated that the output results can be considered as normally distributed. The four normal distributions (gray line is under black line) and their statistical notation are shown in Fig. 5.

The second step has been the assessment of the significance of the difference between output distributions for different measures taking parameter uncertainty into account. The Student's test is used for this purpose, because the model outputs were found to be normally distributed. According to this test, the construction of a retention basin is the only measure that significantly improves flood control for the Red River (two-tailed significance level <0.05 and a mean difference of about 300 million US$). The other two flood control measures result in a smaller mean flood damage than in the base situation, but do not significantly improve the situation. The final ranking of the flood control measures is therefore: (1) construction of a retention basin; (2) dike heightening; (3) reforestation.

6. Conclusions

A pilot DSS for flood control has been systematically developed and applied to the Red River basin in Vietnam and China. In order to take uncertainty in the DSS into account when evaluating different flood control measures, a methodology for the ranking of measures while taking uncertainty into account has been developed and applied to the DSS. The methodology consists of an uncertainty analysis and a ranking procedure based on the significance of the difference between output distributions for different measures.

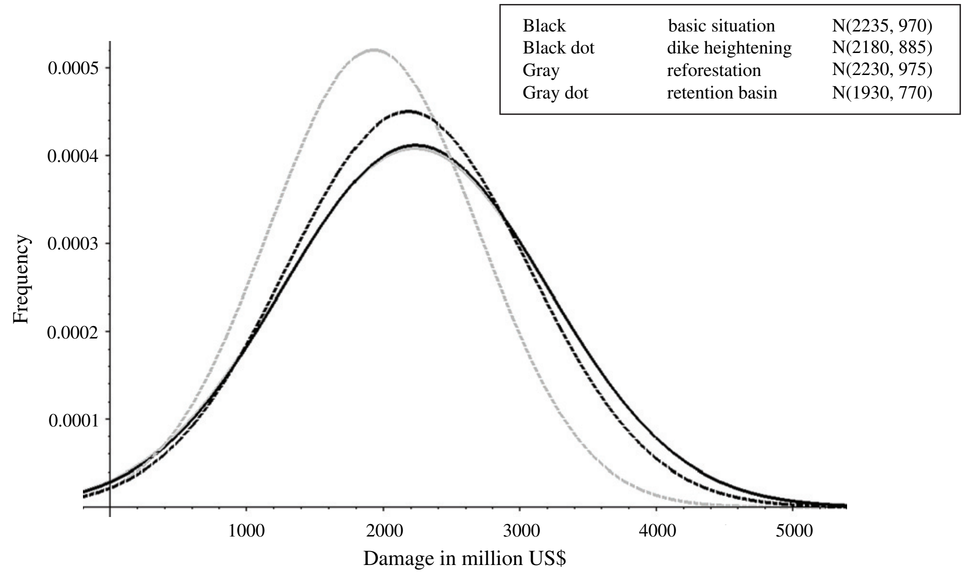

Fig. 5. Normal distribution for base situation and three flood control measures (gray line is under black line).

The mean flood damage in the base situation (without measures) is about 2.2 billion US$ for the year 1996 with a standard deviation due to parameter uncertainty of about 1 billion US$. The measures reforestation, dike heightening and the construction of a retention basin reduce the flood damage by about 5, 55 and 300 million US$, respectively. The construction of a retention basin significantly reduces flood damage in the Red River basin, while dike heightening and reforestation reduce flood damage, but not significantly.

Decision making on the basis of these results should be done with care. Several potentially important processes (e.g. erosion, sedimentation) are not taken into account yet, because of the pilot status of the DSS. Moreover, only six dominant parameters are considered in the uncertainty analysis. Other points which should be kept in mind are the dependency of the outcomes on the location and dimensions of the measures and the fact that implementation and maintenance costs of measures are not considered yet. However, the methodology proved to be suitable for the ranking of measures and may support decision makers when dealing with uncertainty.

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References

Andreu, J., Capilla, J., Sanchis, E., 1996. AQUATOOL, a generalized decision-support system for water-resources planning and operational management. Journal of Hydrology 177, 269–291.

Bergström, S., 1995. The HBV model. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colorado, pp. 443–476.

Bergström, S., Forsman, A., 1973. Development of a conceptual deterministic rainfall–runoff model. Nordic Hydrology 4, 147–170.

Bergström, S., Graham, L.P., 1998. On the scale problem in hydrological modelling. Journal of Hydrology 211, 253–265.

Binley, A.M., Beven, K.J., Calver, A., Watts, L.G., 1991. Changing responses in hydrology: assessing the uncertainty in physically based model predictions. Water Resources Research 27, 1253–1261.

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling: a review. In: Kalma, J.D., Sivapalan, M. (Eds.), Scale Issues in Hydrological Modelling. Wiley, Chichester, pp. 9–48.

Booij, M.J., 2003a. Determination and integration of appropriate spatial scales for river basin modelling. Hydrological Processes 17, 2581–2598.

Booij, M.J., 2003b. Decision support system for flood control and ecosystem upgrading in Red River basin. In: Blöschl, G., Franks, S., Kumagai, M., Musiake, K., Rosbjerg, D. (Eds.), Water Resources Systems – Hydrological Risk, Management and Development. Proceedings of Symposium HS02b at IUGG 2003, Sapporo, Japan, IAHS Publ. no. 281, pp. 115–122.

Booij, M.J., 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. Journal of Hydrology 303, 176–198.

Helsel, D.R., Hirsch, R.M., 1992. Statistical Methods in Water Resources. Elsevier, Amsterdam.

de Kok, J.L., Engelen, G., White, R., Wind, H.G., 2001. Modeling land-use change in a decision-support system for coastal-zone management. Environmental Modeling and Assessment 6, 123–132.

de Kort, I.A.T., 2003. Decision making under uncertainty – ranking measures in a decision support system for flood control in the Red River in Vietnam while taking uncertainty into account. M.Sc. thesis, University of Twente, Enschede.

Lamb, R., Beven, K., Myraboe, S., 1999. Use of spatially distributed water table observations to constrain uncertainty in a rainfall–runoff model. Advances in Water Resources 22, 305–318.

Lei, J., Schilling, W., 1994. Parameter uncertainty propagation analysis for urban rainfall runoff modelling. Water Science and Technology 29, 145–154.

Melching, C.S., 1995. Reliability estimation. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Colorado.

Melching, C.S., Yen, B.C., Wenzel Jr., H.G., 1990. A reliability estimation in modeling watershed runoff with uncertainties. Water Resources Research 26, 2275–2286.

Morgan, M.G., Henrion, M., 1990. Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press, Cambridge.

Morris, M.D., 1991. Factorial sampling plans for preliminary computational experiments. Technometrics 33, 161–174.

Mysiak, J., Giupponi, C., Rosato, P., 2005. Towards the development of a decision support system for water resource management. Environmental Modelling and Software 20, 203–214.

Nghia, T., 2000. Flood control planning for Red River basin. In: Proceedings of International European–Asian Workshop Ecosystem & Flood, Hanoi, Vietnam, pp. 246–256.

Osmond, D.L., Gannon, R.W., Gale, J.A., Line, D.E., Knott, C.B., Philips, K.A., Turner, M.H., Foster, M.A., Lehning, D.E., Coffey, S.W., Spooner, J., 1997. WATERSHEDSS: a decision support system for watershed-scale nonpoint source water quality problems. Journal of the American Water Resources Association 33, 327–341.

Reichert, P., Borsuk, M.E., 2005. Does high forecast uncertainty preclude effective decision support? Environmental Modelling and Software 20, 991–1001.

Seibert, J., 1997. Estimation of parameter uncertainty in HBV model. Nordic Hydrology 28, 247–262.

Sharifi, M.A., 1999. Remote sensing and decision support systems. In: Stein, A., Van der Meer, F., Gorte, B. (Eds.), Spatial Statistics for Remote Sensing. Kluwer, Dordrecht (Chapter 14).

Theobald, D.M., Gross, M.D., 1994. EML: a modelling environment for exploring landscape dynamics. Computers, Environmental and Urban Systems 18, 193–204.

Tol, R.S.J., de Vos, A.F., 1998. A Bayesian statistical analysis of the enhanced greenhouse effect. Climatic Change 38, 87–112.

Van der Perk, M., Burema, J.R., Burrough, P.A., Gillett, A.G., Van der Meer, M.B., 2001. A GIS-based environmental decision support system to assess the transfer of long-lived radiocaesium through food chains in areas contaminated by the Chernobyl accident. International Journal of Geographical Information Sciences 15, 43–64.

Wesseling, C.G., Karssenberg, D.-J., Burrough, P.A., van Deurssen, W.P.A., 1996. Integrating dynamic environmental models in GIS: the development of a dynamical modelling language. Transactions in GIS 1, 40–48.

Ye, W., Bates, B.C., Viney, N.R., Sivapalan, M., Jakeman, A.J., 1997. Performance of conceptual rainfall–runoff models in low-yielding ephemeral catchments. Water Resources Research 33, 153–166.

Yu, P.-S., Yang, T.-C., Chen, S.-J., 2001. Comparison of uncertainty analysis methods for a distributed rainfall–runoff model. Journal of Hydrology 244, 43–59.

Zar, J.H., 1996. Biostatistical Analysis. Prentice Hall, Upper Saddle River, NJ.