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Application of a fuzzy logic approach for linking hydro-ecological simulation output to decision support

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Abstract Riverine ecosystems are critical habitats for a variety of threatened species. They are under continuous threat of destruction and are bedevilled with complex hydro-environmental problems. Mathematical models can serve as powerful tools in solving water resources problems. Most of the models available for water management are crisp, deterministic and precise in character. However, most water-related problems are neither crisp nor deterministic. Solutions to such problems require a cocktail of models along with expert knowledge, which is formulated with words. This paper is expected to help bridge the gap between simulation output and policy formulation by proposing a framework for the integration of linguistic guidelines and indicators, developed *a priori*, into a purely numerical hydro-ecological system. The paper also discusses limitations in the use of traditional numerical models to aid decision support and initiate policy. Principles of the LiNK algorithm concept are illustrated with an example of the impact of a hydropower project on the habitat of endangered hippopotami in a protected park in Ghana, West Africa.

Key words computing with words (CW); fuzzy logic; Ghana; *Hippopotamus amphibius*; hydro-ecological modelling; hydropower; policy development

INTRODUCTION

The rate at which humans are altering the biosphere has increased dramatically in the past century (Reischauer & Fairbank, 1960; United Nations, 1997; Vitousek *et al.*, 1997). Computer-based numerical models have become indispensable tools in the management of our environment. The advent of the personal computer and the associated decrease in the cost of central processing unit (CPU) time means models are now ubiquitous and available for use by managers of the environment. The latter implies an increasing number of resource managers and policy makers rely either directly or indirectly on the information provided by these tools to guide their decisions. The last decade has seen rapid development in the science of model development and use, especially in multidisciplinary research projects.

Although models have been recognized as powerful tools in the quest for sound environmental management, their role and influence in the development of science based policy has received little or no attention in environmental science research and applications. In other words, there is a “disconnect” between the world of numerical model development and use and the practice / policy realm. The impact the gap creates in the optimum use of numerical models as tools for developing management strategies and sound policy is the basis for this paper.

SCIENCE POLICY GAP

Scientists and policymakers ought to be natural allies in efforts to promote more sustainable approaches to managing natural resources and the environment. Scientific results have to be translated into effective policies before they can affect the resource-using community. However, bringing science and policy-making together is a difficult procedure. The interface between the two establishments is often under-developed and/or most often functions poorly. A time-honoured model for the interaction between scientists and policy makers has been for scientists to maintain a “healthy distance” (Bush, 1945). The prevailing state of affairs between both communities can be attributed to a multitude of issues. Some political scientists argue that when scientists take on a role that affects policy outcomes, their independence ought to be limited, because democracy requires such trade-offs between freedom and political responsibility (Price, 1965). Some natural scientists view the bargain as Faustian, and caution colleagues that symbiotic relationships tend to switch between mutualism and parasitism as resource availability changes (Wagner, 2001). Others maintain that science is not the issue, and that the indecisiveness of policy makers reflects a shortfall of political willpower (Gelbspan, 1997). It is also worth noting that uncertainty continues to play a key role in the science–policy interface. For example, in the case of large-scale simulation models, constants and parameters contain assumptions and uncertainties that propagate in uncertain ways to produce uncertain output. For scientists, this is business as usual (Morgan & Henrion, 1990; Raynor & Malone, 1998). For society and its decision makers, however, such uncertainty may cast a shadow upon science itself (Shackley & Wynne, 1996). Bradshaw & Borchers (2000) identified three approaches that could potentially be used to bridge the gap between science and policy. The first and most familiar approach is to directly enhance public confidence by increasing communication (Dovers *et al.*, 1996). The second approach is to increase confidence by increasing the rate of scientific confirmation. The third approach preaches the realignment of the definition of scientific uncertainty as perceived by the public and policy makers with that of the science community. The work presented here contributes to the first approach.

STUDY AREA

Bui National Park is situated in the centre-west of Ghana; it is divided by the Black Volta River which separates it from the northern and Brong-Ahafo regions. The park covers an area of 1821 km^2. The vegetation of both sectors is predominantly savanna woodland, with areas of grassland and patches of riparian forest along the Black Volta River and other small rivers in the park. These riverine forests are the best-preserved of such forests remaining along the Black Volta and, probably, the only such forest left in the entire Volta system. Common tree species include *Butyrospermum paradoxum*, *Parkia clappertoniana*, *Daniella oliveri* and *Isoberlina doka* with the last three species dominant in savanna woodland. The park is, perhaps, the least developed in Ghana, although it has been in existence for three decades. The park contains the larger of only two *Hippopotamus amphibius* populations left in Ghana and probably in West Africa (Bennett & Basuglo, 1998). The planned Bui Hydropower project, expected to commence in the fourth quarter of 2007, will inundate slightly more than a third of the park. According to the International Union for the Conservation of Nature (IUCN), the hippopotamus is for the first time listed as species threatened with extinction (IUCN Report, 2006).

PROBLEM DEFINITION

The Bui gorge, the location of an expected 400 MW hydropower plant is home to endangered hippopotamus species. Impact on the ecology and biodiversity of the gorge is expected to be two-fold: (1) during the construction phase of the project, and (2) after the completion of the project. To address both problems, a series of biophysical modelling exercises are being undertaken to firstly access the *status quo* and subsequently model the impact of the plant. The exercises include, among other things, assessment of the habitat needs and requirements of endemic hippopotamus species and development of a hydrological model to characterise mesoscale hydrological processes in the watershed of the Black Volta River.

Although the activities form part of the environmental impact assessment needs of the project, the ensemble of tools developed is also expected to form the basis for post construction management strategies and general policy formulation with respect to the management of anthropogenic impacts on watersheds in Ghana. The tool herein proposed is intended to function within a decision support platform.

The main decision support platform is expected to be achieved by an integration of a conceptual hydrological (HBV-IWS 2005) and a hippo habitat model (H-Mesoscale-CaSiMiR 2006). The proposed Linguistic Numerical transition Know-how LiNK concept (Fig. 1) is expected to make use of the output from the coupled hydro-ecological system for an interface with management strategy and future policy development.

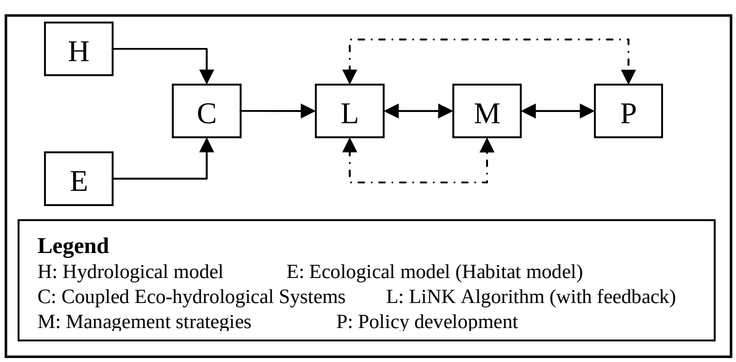

Fig. 1 Illustration of *a priori* numerical output into LiNK Algorithm (from biophysical modelling ensemble).

METHODS

For conventional dynamic systems modelled by differential equations, various concepts and methods for both system analysis and synthesis have been well developed and are widely used. However, for many large complex systems, due to the complexity involved and the intrinsic nature of information incompleteness, developing a conventional mathematical model to describe system behaviour in a meaningful way is either infeasible or impracticable (Wang, 2003). Fuzzy modelling (Zadeh, 1965) has proved to be an alternative to addressing the aforementioned problem. From a mathematical point of view, fuzzy systems are functions mapping their inputs to outputs (Ying, 1998). There are two major types of fuzzy systems: Mamdani fuzzy systems and Takagi–Sugeno (TS) fuzzy systems. Takagi-Sugeno (TS) fuzzy rules mainly differ from conventional fuzzy rules in that their conclusions are not fuzzy sets but (crisp) polynomial functions (Takagi & Sugeno, 1985).

Figure 3 illustrates the LiNK algorithm. Its inputs are composed of five system variables which are all dependent on the supply level (the water level in the Bui reservoir in metres). Hippo habitat and the riverine system can only be described as linguistic variables; the remaining three are numerically determined functions of supply level. The LiNK algorithm is achieved partially through the TS fuzzy rules for the two linguistic variables. The premise part of its rule is fuzzy membership functions. The consequent part of the TS rule is the system output represented as a composite profile ($P_{composite}$) which is a weighted average of each rule's output. The $P_{composite}$ is expected to help policy makers (and resource managers) to determine whether one specific policy (or management option) is suitable or not (the higher value of the composite profile, the more suitable the policy / management option). One can vary the input to analyze various scenarios and their corresponding outputs (the $P_{composite}$).

The following example is used to illustrate LiNK membership functions; three dam designs have been proposed for the Bui hydropower plant with full supply levels (FSL) of 198 m NLD, 183 m NLD and 152 m NLD, respectively. Their corresponding potential irreversible impact on the hippo habitat are high (fuzzy membership = 0.4), medium (0.7) and low (1.0), respectively. Figure 2 shows the potential impact on the hippo habitat at any supply level from 50 to 200 metres. Fuzzy membership functions can also be assigned to quantify the impact on the forest riverine system. The remaining variables are obtained through simulation results of various models at different supply levels. Determination of a fuzzy membership function of a variable requires input from expert knowledge in both quantitative and qualitative form. This procedure makes straddling between the linguistic and numerical world possible.

The LiNK algorithm is expected to be operated in two modes; a forward and reverse mode for policy (or management strategy) development and analysis, respectively. Once the $P_{composite}$ is obtained, it will be defuzzified into a linguistic variable to allow policy analysis which will in turn be used as input to feed back the policy (or management strategy) formulation. The latter is achieved by computing with words techniques. The actual application is a comprehensive system that contains more variables and leads to a final composite profile. The case discussed in the paper adopts an extremely simplified system to verify and demonstrate the approach.

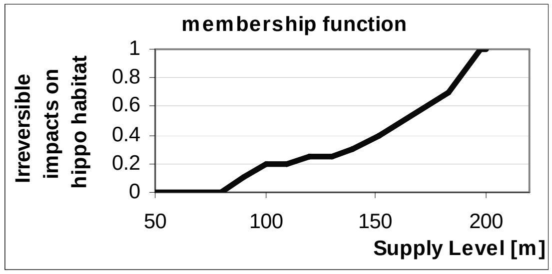

Fig. 2 Fuzzy membership function of irreversible impacts on the hippo habitat.

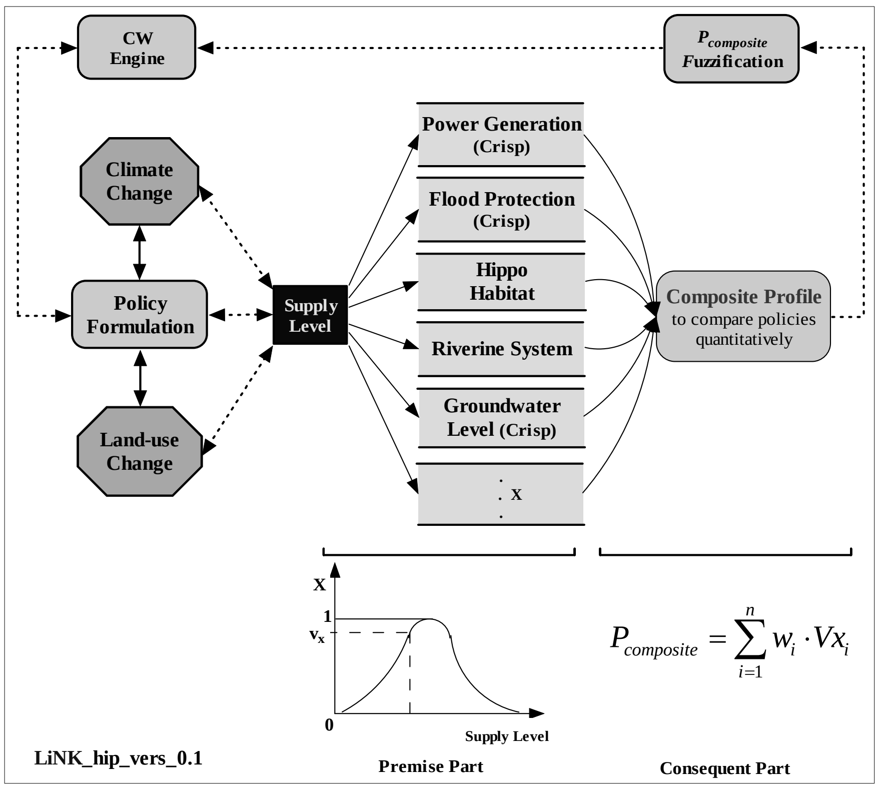

Fig. 3 The LiNK algorithm.

PRELIMINARY RESULTS AND DISCUSSION

The Bui hydropower project is a highly sensitive endeavour. The development of hydropower resources in a national wildlife park presents a unique challenge. The fact that the project is still going presents additional hurdles to the authors.

The second scenario (183m NLD) produces the highest $P_{composite}$. It corresponds to a fairly robust policy or management scenario grounded in dynamic mitigation strategies for biodiversity and ecosystem in the Bui Gorge. Initial results demonstrate the approach is feasible as an alternative policy or management strategy evaluation scheme. Unlike conventional methods where model results are used to contribute to policy or management discussions indirectly (resulting in time lag), the LiNK approach ensures an almost real-time convergence of all the components needed for policy dialogue or selection of management options. The LiNK approach invariably positions itself at the middle of the information supply chain from the integrated simulation output source to the policy options evaluation point, the sink most useful for managers and policy makers.

A follow-up piece is expected to report on the success and failure of the approach herein proposed.

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