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Parsimonious Catchment and River Flow Modelling

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Abstract: It is increasingly the case that models are being developed as "evolving" products rather than one-off application tools, such that auditable modelling versus *ad hoc* treatment of models becomes a pivotal issue. Auditable modelling is particularly vital to "parsimonious modelling" aimed at meeting specific modelling requirements. This paper outlines various contributory factors and aims to seed proactively a research topic by inextricably linking value/risk management to parsimonious modelling. Value management in modelling may be implemented in terms of incorporating "enough detail" into a model so that the synergy among the constituent units of the model captures that of the real system. It is a problem of diminishing returns, since further reductions in the constituent units will create an unacceptable difference between the model and the real system; conversely, any further detail will add to the cost of modelling without returning any significant benefit. The paper also defines risk management in relation to modelling. It presents a qualitative framework for value/risk management towards parsimonious modelling by the categorisation of "modelling techniques" in terms of "control volume."

Keywords: value/risk management; uncertainty; parsimonious/detailed modelling, auditable modelling

1 INTRODUCTION

Modelling is one field of scientific activity which has developed the capability of delivering customised solutions through identifying a variety of arrangements or changes within a system to comply with both external and internal boundary conditions. The outcome is a set of highly developed mathematical capabilities and versatile software tools. As modellers have become able to investigate the performance of a system under a whole range of different internal and external conditions and system settings, "application areas" of modelling and the purpose of their applications have diversified, e.g. flood forecasting and management of low flows. It is a valid approach to develop either "detailed models" serving a wide range of modelling requirements, or "parsimonious models" meeting specific requirements. This paper focuses on issues inherent in parsimonious modelling in terms of value/risk management and other relevant issues.

Dale (1970) attributes to Pascal the expression that "error comes from exclusion." If parsimonious modelling is regarded as the simplest solution excluding many possible details, there is a risk of oversimplification with important factors being overlooked. Arguably, one way of remedying this is by value/risk management and a conscientious regard to application areas and objectives of modelling. Value management is defined in terms of the incorporation of "enough detail" into a model so that it captures the synergy among the constituent units of the system. It normally lacks a rigorous procedure and inevitably involves the identification of a range of performances and selecting a model most closely meeting a prescribed performance. The paper argues that value management should be complemented with risk management, where risk, as detailed later, is a product of hazard (due to model errors) and its likelihood.

While value/risk management is well developed in various areas of science and water engineering, it requires to be further developed in modelling through the formulation of new methodologies and working tools. Categorisation of "modelling techniques" can serve as a qualitative tool capable of playing a significant role in parsimonious modelling. For instance, it is widely thought that value management is a problem of "diminishing returns." Factors contributing to the diminishing return problem in, say, rainfall-runoff modelling are different to those encountered in, say, hydrodynamic modelling, and this can be revealed by categorisation.

Categorisation of “flow problems” and of modelling techniques requires further formalisation to be useful in value/risk management of parsimonious models. The main focus of this paper is to present parsimonious modelling in terms of a collective consideration of (**i**) categorising modelling techniques and application areas, (**ii**) value management and (**iii**) risk management. The paper presents the following supporting cases. (**i**) Selecting hydrodynamic modelling resolution is discussed for the diminishing return problem. (**ii**) The case of rainfall-runoff models is discussed to show that model performance is affected by both the form of process description used in the model and the adequacy of the rainfall distribution provided by weather radar or raingauges. (**iii**) Appropriate model detail and resolution are discussed for modelling impacts of climate change on river flooding.

The aim of this paper is to seed proactively a research topic that is felt to pose some fundamental issues: to stimulate the subject of model choice in the context of parsimonious catchment and river flow modelling. The term “modelling technique” is used to refer to each individual set of equations used for modelling the various river flow problems but “modelling approach” to a set or category of techniques all with similar properties. Thus, the term “empirical models,” as a category, refers to those employing abstract mathematical functions to express the flow processes, e.g. black box and neural network models and transfer functions.

2 BASIS OF PARSIMONIOUS MODELLING

2.1 Categorisation of Modelling Techniques

The concept of control volume for categorising modelling techniques is depicted in Figure 1 and discussed further below. This categorisation, as originally outlined by Khatibi and Haywood (2002), features in an R&D project commissioned by the National Flood Warning Centre of the Environment Agency for England and Wales (EA, 2002).

Control volume is a microcosm of the whole system so that flow-state in the prototype system is rendered by replicating the control volumes side by side to describe the propagation of flood waves. It is composed of (**i**) a physical building block characterised by the selected spatio-temporal resolution, where resolution is the smallest level of detail, and (**ii**) a conceptual building block normally described by empirical relationships or by mathematical equations expressing conservation laws of nature.

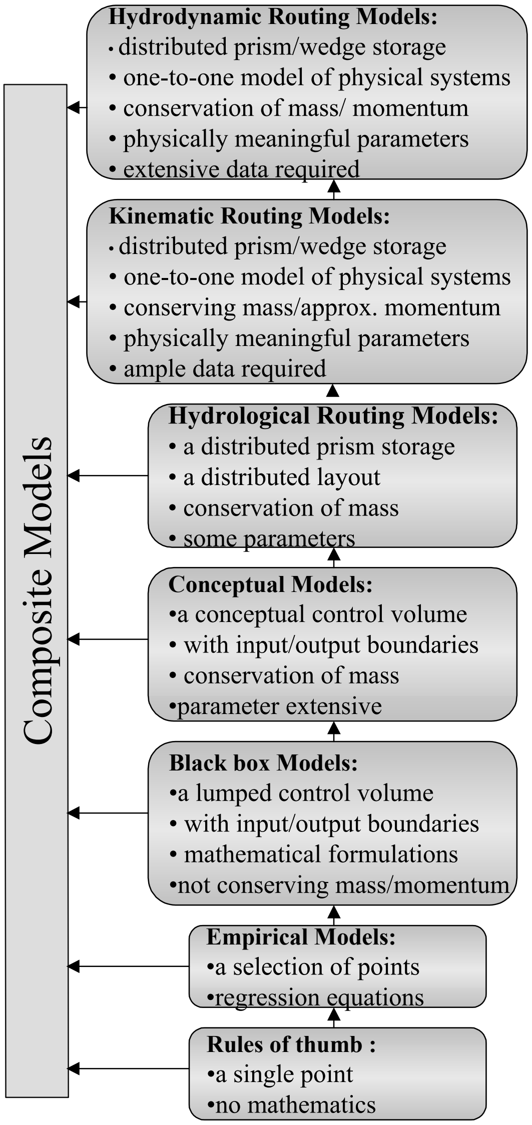

Figure 1 Categorising Modelling Techniques

The complexity of the mathematical equations and generic spatio-temporal resolutions go hand in hand. Thus, a selected spatial resolution as large as the physical system with sparse data would suit rules of thumb. Conversely, for a 2 m wide watercourse to be modelled by a hydrodynamic model would require a spatial resolution of the order of magnitude of 10-20 m.

Control volume is a fundamental building block in mathematical models of flow systems and uniquely suited to differentiate the generic steps in a whole range of modelling techniques. Figure 1 outlines the main generic steps in control volume identification in terms of spatial resolution, its physical layout, and application of conservation laws suiting the emerging regularity pattern at the selected resolution and data requirement. Each category is responsible for a modelling approach and has one subtle difference from the others, which is generic.

To illustrate the point, empirical, black box and conceptual models can be compared as follows.

- The choices of technique for correlation-type empirical techniques are much wider but they are suitable mainly for interpolation and may perform poorly for extrapolation.
- Black box models include the convolution theory, transfer functions and neural network modelling, which are described by a set of parameters whose values are not necessarily unique. For instance, unit hydrograph models depend on optimisation technique, their shape function, and loss model. If the assumptions of these models are satisfied, they can be used to extrapolate system behaviour.
- At the level of conceptual models, volume is conserved, although this volume may not be a one-to-one map of the physical volume. The volume conservation of these models is possibly achieved only at the expense of additional parameters and measurements.

2.2 Categories of Application Areas

It is outside the scope of this paper to categorise rigorously **flow problems** and **application areas** of river modelling. However, flow problems can be categorised based on conical sections into potential flow (elliptic), groundwater (parabolic) and wave (hyperbolic) problems. Wave problems are governed by hyperbolic equations for which water level cannot be decoupled from discharge. Governing equations describe the flow-state of the system and offer a spatially distributed process-based prediction capability. In brief, the other processes include (**i**) boundary processes, (**ii**) local processes imposing a relationship between discharge and depth as in bridges, weirs, sluices, spills and reservoirs.

The application areas in catchment and river modelling are diverse and include (**i**) flood forecasting, (**ii**) management of low water levels, (**iii**) water quality, (**iv**) water resources, (**v**) operations (navigation, maintenance requirements and scheduling of canalised rivers), (**vi**) climate change impact assessment, and (**vii**) erosion and sediment transport. An issue of relevance to parsimonious modelling is applying the same base model across a combination of the above application areas.

2.3 Value Management

Value management in modelling would reveal that a further reduction in the constituent units would create an unacceptable difference between the model and the real system. This would lead to an appropriate level of detail, where any further details would add to the cost of modelling without returning any significant benefit. This is a diminishing return problem. Value management seen in these terms is a tacit knowledge of many modellers, who often practise it in one way or another.

Quantitative value management may not be practised in one-off models, often because these may be developed without a long-term view on reuse or without regard for them as "evolving" products. Models need to be placed in a framework providing a clear definition of the objective(s), performance and cost-benefit measures, as well as providing a strategic view on detailed and parsimonious modelling.

The categorisation of modelling techniques is used in this paper as a qualitative framework for value management towards parsimonious modelling. Each modelling approach is associated with characteristic features so that capturing them in the models is essential to the particular modelling approach. These are outlined in Table 1.

Table 1 Main Features in Value Management

Modelling Approach	Value Management Features
Black box models	• The validity of the inherent assumptions over the catchment
Conceptual models	• The significant storage units in the model description of the catchment
Hydrologic routing	• Characteristic length of the river over which kinematic waves prevail
Kinematic routing	• Characteristic zone of the catchment where kinematic waves prevail • Selecting space and time-step
Hydro-dynamic routing	• Selecting space and time-step • Identifying a whole range of significant hydraulic units, such as control structures, afflux due to constrictions, abstractions/inflows, storage reservoirs, floodplains, perched main rivers, significant tributaries, bifurcation and loops

2.4 Risk Management

While deterministic models have emerged as explanatory and prediction tools for studying system behaviours in their performance mode, there is an increasing realisation that their outputs sometime may lead to failure. An understanding of failures is emerging and a framework may be established in terms of the study of errors or risks. Risk is a product of hazard and its likelihood. Hazard in modelling may be defined in terms of the impacts of errors instigated when models omit non-value adding units; or include imperfect units; or describe the system through an inappropriate set of equations. Hazard may also be instigated by errors due to modelling assumptions, erroneous data, and imprecision/approximations associated with governing equations. Estimates of the likelihood of hazard are not discussed here but ensemble modelling or similar techniques can be used.

Qualitative risk management, as a complement to value management, can also be used as a tool to guide parsimonious modelling. Value management for each modelling approach is normally associated with characteristic risk features. These are presented in Table 2.

Table 2 Main Hazard in Risk Analysis

Modelling Approach	Hazard
Black box models	• Violation of modelling assumptions • Parameter values may not hold outside their calibrated events • Volume may not be conserved
Conceptual models	• Violation of modelling assumptions • Parameter values may not hold outside their calibrated events • Parameter identification vulnerable to multiple optima and other problems
Hydrologic routing	• Violation of modelling assumptions • Parameter values may not hold outside their calibrated events • Calibrated characteristic wave length can be event-dependent
Kinematic routing	• Violation of modelling assumptions • Extrapolation of calibrated events • Wave shape may change • Routing through reaches with looped rating curves
Hydro-dynamic routing	• Violation of modelling assumptions • Parameter values may not hold outside their calibrated events • Risks of tempting to incorporate many insignificant features

Violation of modelling assumptions poses risk to any modelling technique. This problem is often overlooked, even though there is a wealth of tacit knowledge on the subject. Its articulation through hard evidence can make a significant contribution to modelling practices. Also, the nature of risk management can change according to the stage of modelling. For instance, Khatibi (2001) outlines such risks associated with different stages of hydrodynamic modelling.

There is no objective criterion for detecting failures instigated by modelling, but various quantitative approaches are emerging for the assessment of errors or risks associated with modelling. Examples include fuzzy logic (Bardossy and Duckstein, 1995), ensemble modelling and GLUE (Beven, 2000).

3 PARSIMONIOUS MODELLING - Cases

3.1 The Case on Hydrodynamic Modelling

There is a range of tacit knowledge associated with value management. Some of those associated with hydrodynamic modelling are outlined by Khatibi (2001) and include:

- fine resolution minimises numerical errors, but too fine a resolution increases costs and little improves the reliability of the results
- coarse resolution favours cost minimisation, but this can undermine accuracy by poorly representing the hydrodynamics of the system
- an out-of-bank urban flooding problem may involve unconventional flow paths (*e.g.* roads, alleys and back alleys), but allowances ought to be made for them if their contribution to system-wide flow balances is significant
- compromises on the scale defining water distribution in the system can significantly distort mass balance but satisfactory compromises may be sought in terms of space/time scale

3.2 The Case on Model Details

Bell and Moore (1998) implement a grid-based rainfall-runoff model, which is a clear example of matching the process description of a conceptual model to rainfall distribution data provided by weather radar or raingauges. The model has the following components:

- The topography of the catchment system, for which rainfall is to be transformed to runoff, is used for subdivision of the catchment into isochrone bands (delineating areas of equal time of travel to the basin outlet) for flow routing, using a Digital Terrain Model (DTM).
- The catchment is further sub-divided into grid squares coincident with those used by the weather radar to utilise distributed rainfall.
- Each grid square functions as a storage with a water budget comprising rainfall as input which is transformed into:

  - direct runoff when storage is full
  - infiltration into storage if the present storage is below its capacity
  - slow drainage from the storage if any storage is available, and
  - evaporation.
- The direct runoff and drainage are summed along isochrone bands contributing separately to fast and slow routing pathways respectively.
- These flows are then routed successively from one isochrone band to the next lower one using a discrete kinematic wave routing scheme.
- At the catchment outlet the routed flows from the fast and slow pathways are summed to give the modelled catchment flow. A number of alternative mathematical formulations are considered for the runoff production and routing units of the overall Grid Model.

The insight gained by this study has a bearing on parsimonious modelling, as follows:

- When errors dominate in the distributed rainfall estimates from radar, a simpler (lumped) model can provide a more robust forecasting scheme.
- When the distributed rainfall estimates can be relied on, provided the catchment response is spatially variable and/or rainfall is non-uniform in space, the distributed Grid Model can provide improved performance.

Improvement in performance is influenced if process description and the quality of the distributed data are commensurate. Thus, process description alone does not compensate for shortfalls in the data and vice versa.

3.3 The Case on Climate Change

Assessing the impacts of climate change on river flooding has remained a difficult modelling problem for the management of river basins. Spatial and temporal resolution of a model and the selection of the model details are two issues central to this assessment and closely related to parsimonious modelling.

This paper reflects on the procedure developed by Booij (2002) for determining appropriate model details using data for the River Meuse, Belgium, in the context of climate change impacts on river flooding. The model appropriateness procedure consists of three steps. (**i**) The dominant processes and associated key variables are identified. (**ii**) Statistical analyses with respect to the key variables are performed, which result in appropriate spatial and temporal scales for each key variable and relationships between key variable scales and the output variable. These latter relationships are used to combine the appropriate scales to one appropriate model scale. (**iii**) Mathematical description of processes in this study together with their scales is consistent with a kind of categorisation presented in this paper. These appropriate components have been implemented using a conceptual model (HBV model) to obtain the appropriate model, where HBV-1, HBV-15 and HBV-118 are an implementation of the HBV model with differing sub-basin units.

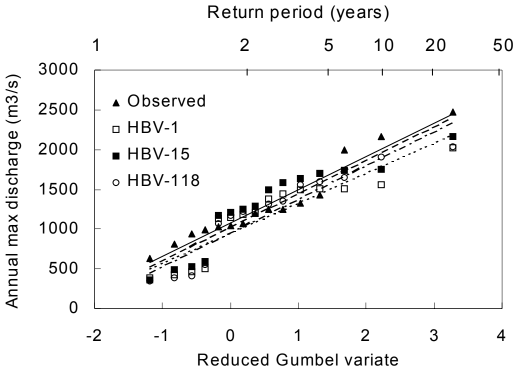

Figure 2 Annual Maximum Discharge for Different Conceptual Models

Two additional models were constructed to assess the sensitivity of the results to model complexity. The model details are presented by Booij (2002) and Fig. 2 shows an example of annual maximum discharges simulated by the different models in the calibration. The appropriate spatial model scale turned out to be around 10 km with a daily time-step. The model results became somewhat better with increasing model complexity. The appropriate model is complex enough, although the differences with the less complex models are small. It was found that the uncertainties in extreme discharges with climate change are large and that those due to precipitation and extrapolation errors are the most important ones.

4 DISCUSSION

Attention is drawn to the argument by Scholten *et al* (2000) that “Modelling … is not straightforward, but rather subjective, depending on the modelling team and its skills. Therefore one often refers to it as to the ‘art of modelling’. This artistic and creative label sounds as a positive designation, but it stresses the unscientific and ambiguous aspects of modelling. The major risks of modelling are related to the many choices that have to be made, the complexity of the problem and the object system at hand, …”. This paper argues that even though modelling is far from being a perfect tool, its shortfalls can be addressed significantly by auditable modelling practices. Categorisation of modelling technique together with value/risk management can go a long way towards replacing the creative art outlook of modelling with a sound scientific base. Other measures include categorising rigorously flow problems and application areas; Khatibi (2001) argues for formalising modelling procedures to this end. The authors are also currently working towards the modularisation of modelling procedures.

Two further issues are discussed here: (**i**) parsimonious modelling versus detailed modelling and (**ii**) the issue of uncertainty. Two main merits of detailed modelling include (**i**) meeting the requirements of a wide range of problems within the validity range of a particular modelling approach, and (**ii**) using such comprehensive models as a tool. However, detailed modelling can suffer from undue complexity in model building, calibration, verification and application. Parsimonious modelling, on the other hand, is simple but can suffer from uncertainties if implemented without conscious regard to the purpose of modelling, the field of application, and without value/risk analysis.

Concern for uncertainty is a topical issue and gaining prominence in workshops and conferences. However, sometimes uncertainty is taken as synonymous with errors or risks, restricted to discrepancies between modelled and observed values and their likelihood, but the issue is wider ranging. Sources contributing to uncertainty are diverse and include initial conditions and input data, imperfections in governing equations, errors of model schematisation, solution and calibration procedures, and others. Even when errors or risks are assigned to a source, assumptions have to be made about the statistical distribution of errors, which may include bias, covariance and inhomogeneity. There may be other unidentified error sources. Categorisation of modelling techniques offers additional scope in gaining an insight into uncertainty.

5 CONCLUSION

In a background where modelling can be implicated with art, in one way or another, parsimonious modelling poses the risk of oversimplifying the model so that either flow processes are reflected poorly or the reliance on the model has to be restricted to a narrow range. This risk can be mitigated by detailed modelling, although this has its own risks, albeit of a different nature, e.g. over-parameterisation. However, any art-base of modelling, detailed or parsimonious, has to be firmed up through an auditable procedure.

This paper argues that value/risk management together with categorisation of application areas of modelling and categorisation of modelling techniques in each field of application are effective steps towards selecting between detailed and parsimonious modelling. Improving knowledge of the subject and development of appropriate tools are called for. Refinement of distributed rainfall representation requires parallel effort in tailoring model process descriptions to realise benefits in model performance. When dealing with climate change impacts on river flows, involving large uncertainties in rainfall of low spatial resolution from regional climate models, the choice of level of detail of river basin model must recognise the limitations of the input data whilst achieving a sensible representation of process response.

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