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A review of 40 years of hydrological science and practice in southern Africa using the Pitman rainfall-runoff model

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SUMMARY

The 40th anniversary of the initial development of the Pitman rainfall-runoff (developed in South Africa and widely applied throughout southern Africa) approximately coincides with the end of the IAHS PUB programme and the start of a new decade focussing on hydrological change (Panta Rhei) and society. The paper reviews the developments and applications of the Pitman model in the context of the appropriate outcomes of PUB and the proposed future directions of Panta Rhei. The focus of development of the Pitman model has been dominated by practical applications, while PUB was largely dominated by science issues. While some of the PUB principles have been applied with the Pitman model, there are others that are deemed inappropriate for practical modelling and others that would almost certainly benefit the Pitman model applications in the future. The paper includes discussions of the model structure, input data, parameters and output evaluations – all in the context of uncertainty. The capabilities of the model to address societal development impacts are also discussed and a brief example of an uncertainty approach to applying the model is provided. The conclusions are that some developments of the Pitman model anticipated more recent international developments, while others have not been ignored even if further efforts are required to effectively implement them. Perhaps the largest gap in applying uncertainty principles in practice is how to use them in water resources decision making.

1. Introduction

The end of the IAHS (International Association of Hydrological Sciences) decade on Predictions in Ungauged Basins (PUB – Blöschl et al., 2013; Hrachowitz et al., 2013) approximately coincides with the end of 4 decades of development and application of the Pitman (1973) rainfall-runoff model. Over this 40 year period the model has become one of the most widely used hydrological models in southern Africa (Hughes, 1997; Hughes and Metzler, 1998; Mazvimavi et al., 2005; Hughes et al., 2006; Tsheko, 2006; Tshimanga et al., 2011) and has also been successfully applied in other parts of the world (Wilk and Hughes, 2002). In its various forms it has been used for research purposes as well as for practical water resources assessments and has formed the foundation of some national water resources development strategies (SMEC, 1991; Bailey and Pitman, 2005). It is therefore appropriate to review the developments that have occurred in both the Pitman model itself and the way in which it is applied in the context of the original PUB objectives (Sivapalan et al., 2003) and the changes in the approaches to hydrological modelling that have resulted from the PUB decade.

Arguably, there can be little doubt that the Pitman model has contributed enormously to the practice of water resources assessment within southern Africa, and particularly within South Africa (Pitman et al., 1981; Midgley et al., 1994; Bailey and Pitman 2005), and in that respect it has certainly achieved its original objective (Pitman, 1973). However, it can also be argued that the methods used in practical water resources assessments are often far removed from scientific developments in the field of hydrological modelling as reflected in the vast amount of international research that was the outcome of the PUB decade (Blöschl et al., 2013; Hrachowitz et al., 2013). One of the objectives of this paper is to critically examine whether such a gap exists, in the context of the Pitman model, and to assess the extent to which the developments in the model and its use have been aligned with the PUB outcomes. The extent to which the Pitman model can contribute to the objectives of the new scientific decade of the IAHS (Panta Rhei – Montanari et al., 2013) is also discussed at the end of the paper. It is acknowledged at the outset that there are other hydrological models that have been in use for as long, or longer, than the Pitman model (Linsley, 1982), as well as models that can be considered to have bridged the gap between research and practice (Boughton, 2004; Young, 2006; Arheimer et al., 2011). While the observations made in this paper are specific to the Pitman model and the southern Africa region, they should also be of relevance to other models and other regions.

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Hrachowitz et al. (2013) thoroughly summarise the key achievements of the PUB decade and identify many of the reasons why PUB was necessary to improve the science of hydrological modelling. Blöschl et al. (2013) contains many detailed examples (and further references) of the advances made during the PUB programme and some examples of how these have been applied. Many of the philosophical issues associated with the science underlying the development and use of hydrological models have also been recently highlighted by Beven (2012). It is therefore unnecessary for this paper to repeat the details of either the issues or the achievements. However, from a southern Africa perspective, it is necessary to interpret some of the points raised by Hrachowitz et al. (2013) and Beven (2012) in the context of the Pitman model and its history of use, as well as in the context of a large and relatively data scarce region. Perhaps the most important general question to be asked is whether models are mainly intended to be elaborate tools for scientific investigations, or whether they are ultimately meant to be useful for addressing the many societal problems associated with managing water resources, particularly under changing conditions (Montanari et al., 2013)? These two broad objectives are not always compatible and there is little doubt that the PUB decade largely concentrated on the science issues, despite the addition of a 'PUB in Practice' theme towards the end of the decade. An example is the reference in Hrachowitz et al. (2013) to the recognition during PUB that the concept of "one size fits all" is not appropriate and that model structures should be tailored to fit individual catchment hydrological response characteristics. While this may be an appropriate science conclusion, it is certainly not appropriate from a practical perspective (Le Moine et al., 2007). The concept that every time a hydrological modelling consultant wishes to determine the water resources availability of a region they should build a new model is completely impractical. This might be possible for ungauged catchments in a research setting (Winsemius et al., 2009), but not by model users who are not model developers. The alternative is to develop a robust model that includes components to represent (at the catchment scale) all hydrological processes expected to dominate across the region of intended application (Le Moine et al., 2007). The individuality of the model in specific catchments is then represented through its parameter set, which may be quantified in such a way that some model processes are excluded and others emphasised. The practical advantages are that experience of the use of the same model can be shared across many different users. As Linsley (1982) noted more than 30 years previously, "a new model for every application would eliminate the opportunity for learning that comes with repeated applications of the same model." While the author considers that this statement is still valid from a practical perspective, it is also true that flexible modelling approaches can help to identify dominant processes – an important outcome of PUB (Fenicia et al., 2011).

Developing a robust model that includes components to explicitly represent many different processes inevitably leads to a model with a large parameter set, even though it still falls into the conceptual (rather than fully physics-based) category. This potentially introduces many problems associated with equifinality (Beven, 2006) and parameter identifiability (Beven and Freer, 2001) and raises the question as to whether parsimonious models are better than more detailed representations of catchment hydrology (Jakeman and Hornberger, 1993; Perrin et al., 2001). Equifinality and lack of parameter identifiability can be readily perceived as problems from a mathematical perspective and contribute to arguments in favour of parsimonious models. However, they are also physically real problems (Hughes, 2010a) in that similar stream flow responses can be associated with different causative processes. From both scientific and practical perspectives, it is often desirable to be able to represent these different causes within a model. An example is whether the low flow regimes of rivers are derived from groundwater drainage or near-surface interflow processes (Hughes, 2010b). Increased groundwater abstractions would have a major impact on stream flows in the former case, but little impact in the latter case. Despite this potential advantage, it can also be argued that we rarely have enough information to fully resolve the physical equifinality when modelling natural systems (Beven, 2012) and therefore the extent to which model simulations are behavioural remains highly uncertain.

One of the major outcomes of the PUB decade was the enhanced recognition of uncertainty issues and specifically the need to quantify uncertainty and determine appropriate methods for reducing uncertainty under ungauged conditions (Yadav et al., 2007; Zhang et al., 2008; Winsemius et al., 2009; Wagener and Montanari, 2011; Kapangaziwiri et al., 2012). One of the relevant issues with respect to the Pitman model and its use for water resources assessments in southern Africa is the extent to which these methods have been taken up in practical modelling use (Pappenberger and Beven, 2006). The following four sections discuss the Pitman model structure, input data, parameter quantification and model output evaluation approaches that have been used, all in the context of uncertainty. The discussion is designed to review the evolution of the model and its use, and to identify how these four critical aspects of the model (indeed any model) are, or can be in the future, aligned with the approaches to modelling that emerged from the PUB decade. A section is included that refers to the capabilities of the model for simulating water resources development impacts. Some of the issues are illustrated using an example of the application of the Pitman model to a single catchment that is treated as ungauged.

2. Model structure and uncertainties

Fig. 1 provides a diagrammatic summary of the structure of the Pitman model, including some components (e.g. Hughes, 2004; DWA, 2008; Hughes et al., 2013c) that have been added since 1973. Despite the changes that have been made to some parts of the model, the basic structure remains largely the same as the original (Pitman, 1973). The objective of this section of the paper is not only to explain the structure, but also to relate the structure to real world hydrological processes, as far as possible, given the typical scale at which the model is applied (catchment areas of 10's to 1000's of square kilometres). It is a monthly time step model that operates on a sub-basin or nodal distribution scheme, each sub-basin having its own climate inputs and parameter sets. There have been many papers published before and during the PUB decade that have discussed the many different facets of model structure in relation to real world processes (Beven, 1989; Perrin et al., 2001; Kirchner, 2006; Fenicia et al., 2008a, 2008b, 2011 and many more included in the review by Hrachowitz et al., 2013). It is, however, instructive to return to some of the original design principles noted in Pitman (1973):

- "...only the principal components and relationships in the hydrological cycle must be selected so as to confine the model to an acceptable level of complexity."
- "The model should represent to an acceptable degree of accuracy the hydrologic regimes of a wide variety of catchments."
- "It should be easily applied with existing hydrologic data to different catchments."
- "The model should be physically relevant so that, in addition to streamflow, estimates of other useful features, such as actual evapotranspiration or soil moisture state, can be made."
- "The model should be applicable to ungauged areas."