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Improving perceptual and conceptual hydrological models using data from small basins

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Abstract This paper demonstrates how data from a small experimental basin can be used to evaluate possible structures for a lumped hydrological model. Data collected at the Mahurangi experimental basin in New Zealand includes rainfall, streamflow and multi-depth soil moisture time-series data. We use this data to evaluate possible model representations of the soil zone available in the FUSE modular modelling framework. Upper and lower soil zone architecture choices are tested. The results provide substantial guidance for model structure choice.

Key words model structure; diagnostics; hypothesis testing; soil moisture; recession analysis

INTRODUCTION

One of the most difficult research challenges in hydrological modelling is to identify the most appropriate model structure for a given application. Any model is necessarily a simplification of the true complexity of the physical catchment, and choices must be made to identify a parsimonious model structure which captures the dominant hydrological processes and provides good predictive power. To progress towards this goal we must learn more about how model structure influences predictions of internal states and fluxes, and relate these to observed catchment behaviour.

This paper discusses research conducted as part of the Predictions in Ungauged Basins (PUB) initiative to build a national hydrological model for New Zealand. Currently, our hydrological model (TopNet) is based on a generic description of catchment processes that may or may not provide the best representation for New Zealand catchments. A key research priority is to use data from small experimental basins in New Zealand to evaluate our current model structure and recommend changes if necessary. In particular, this paper focuses on our experiences in interpreting multi-depth soil moisture time-series data in conjunction with streamflow measurements, to test possible representations of the soil zone in the Mahurangi catchment.

STUDY AREA

Mahurangi catchment is located in the North Island of New Zealand (Fig. 1(a)). The climate is generally warm and humid, with mean annual rainfall of 1628 mm and mean annual pan evaporation of 1315 mm. The Mahurangi River Variability Experiment (MARVEX; Woods *et al.*, 2001) ran from 1997 to 2001, and investigated the space–time variability of the catchment water balance. Data from 29 nested stream gauges and 13 raingauges was complemented by measurements of soil moisture, evaporation and tracer experiments. Within the Mahurangi catchment, Satellite Station is a 0.84 km^2 sub-basin monitored intensively for soil moisture (Fig. 1(b)). Data from the Satellite catchment is used in all the analyses that follow.

Satellite Station is part of a dairy farm and comprises predominantly pasture, with some small areas of scrub, on gently undulating terrain. The elevation range is 50–115 m a.s.l. Approximately 80% of the catchment is classified as “hillslopes” with silty clay loam soil. The remaining 20% represents lowland valleys with alluvial fill soil of a relatively deep profile and high clay

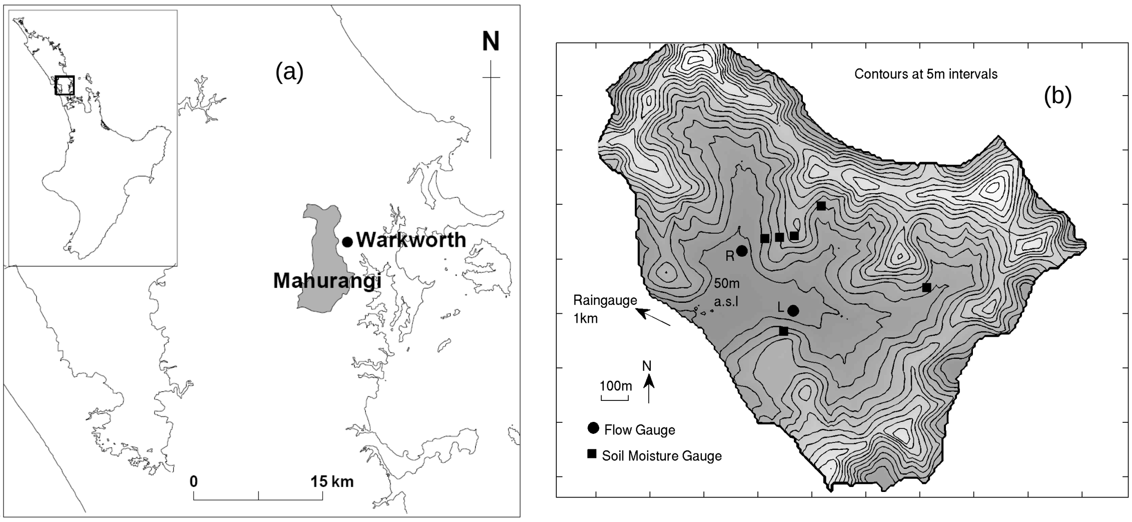

Fig. 1 (a) Location map for Mahurangi catchment in North Island of New Zealand, and (b) detailed map of Satellite sub-catchment, lying at the Eastern point of Mahurangi catchment, showing flow gauges and soil moisture measurement sites.

content. Both soil types are subject to cracking during dry periods. The catchment is drained by two streams, splitting it into Satellite Right (0.32 km^2) and Satellite Left (0.51 km^2).

Soil moisture was measured at six locations in Satellite Station, including three aligned on a hillslope transect in Satellite Right (Wilson *et al.*, 2003; Western *et al.*, 2004). Measurements were made at 30-minute intervals for 34 months, at two soil depths: 0–30 cm and 30–60 cm. Both Satellite Right and Left streams were gauged with v-notch weirs; data were recorded at 5-minute intervals. Tipping bucket rainfall measurements are available 1 km northwest of Satellite Station.

MODELLING DECISIONS

Our research aims to use experimental data collected at Mahurangi to inform the structure of a lumped model for this catchment, and hence to demonstrate how field data might be used to suggest appropriate structure(s) for a national hydrological model for New Zealand. In this paper we focus our attention on the model soil zone representation. To guide our choice of structure, we use the FUSE modular modelling framework developed by Clark *et al.* (2008) which allows a "mix-and-match" approach in which model elements are selected from any of four popular hydrological models (Fig. 2). The parent models are as follows: the US Geological Survey's Precipitation–Runoff Modelling System (PRMS) (Leavesley *et al.*, 1983), the NWS Sacramento model (Burnash, 1995), TOPMODEL (Beven & Kirkby, 1979) and the Variable Infiltration Capacity (ARNO/VIC) model (Liang *et al.*, 1994; Todini, 1996). The structural modelling decisions considered include: upper zone architecture, lower zone architecture, ET-available water, and production mechanisms for saturation excess, interflow and baseflow. Computer experiments showed that all 78 module combinations tested could, when optimised, produce good simulations as judged by the Nash-Sutcliffe criterion. However, we wish to identify those structures which give "the right answers for the rights reasons". We therefore begin by accepting all model combinations as multiple working hypotheses to describe the hydrological behaviour of Satellite catchment, and ask whether an analysis of the experimental data available can lead us to accept or reject some subset of these model structures. This method echoes the "hypothesis testing" approach to model evaluation (Beck, 1987; Beven, 2000). By formulating our hypothesis in terms of the modelling decisions in the FUSE framework, we aim for results which are directly relevant for standard hydrological modelling applications, avoiding the tempting response to suggest a unique conceptual model tailored to our catchment but with weaker applicability elsewhere.

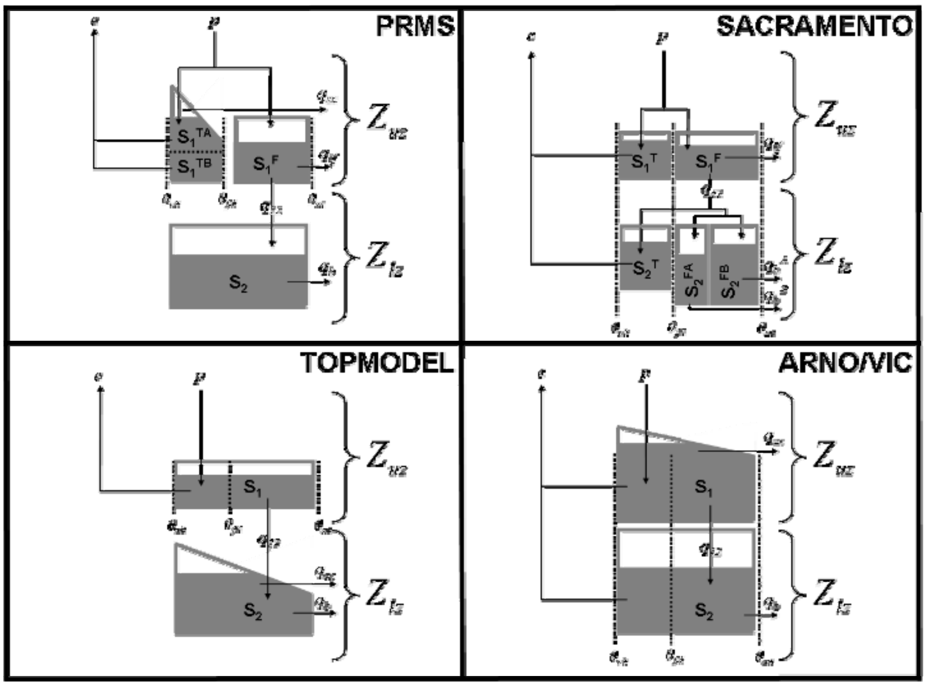

Fig. 2 Simplified diagrams for four popular hydrological models. Here Z_{uz} and Z_{lz} denote the depth of the upper and lower soil layers, and θ_{wlt}, θ_{fld}, and θ_{sat} denote the soil moisture at wilting point, field capacity, and saturation. Runoff is divided into q_{sx} (saturation excess), q_{if} (interflow) and q_b (baseflow). Figure reproduced from Clark *et al.* (2008).

TESTING LOWER SOIL ZONE REPRESENTATIONS: RECESSION ANALYSIS

Analysis of streamflow recessions can give insight into catchment storage–discharge behaviour, by examining the relationship between discharge and its time derivative: –dQ/dt = f(Q). Conversely, choosing the number and structure of lower-zone reservoirs in a hydrological model gives rise to a particular form of recession relationship, which can be compared against measured data. For example, Clark *et al.* (2009) demonstrate how the recession behaviour of the 41-ha Panola experimental watershed can be reproduced using three parallel linear resevoirs, without any requirement for nonlinear storage–discharge relationships. Recession analysis was carried out for Satellite catchment, and the results are illustrated in Fig. 3 for each season. Data was filtered to show only points on the recession limb of a hydrograph, when no precipitation was falling, and using the accumulated volume method of Rupp & Selker (2006) to remove noise at low flows.

Hypothesis 1: recession flows may be modelled using a single reservoir with nonlinear storage–discharge relationship

This hypothesis underlies the nonlinear storage function used to mimic the baseflow parameterization in ARNO/VIC, and the TOPMODEL power law parameterization (refer to Fig. 2). However, inspection of Fig. 3 leads us to reject this hypothesis, via the observation that there is no single Q *vs* dQ/dt relationship, and therefore no single Q *vs* storage relationship which is the behaviour which would result from a single storage reservoir. We infer instead that multiple storage reservoirs are required to represent catchment behaviour, whereby proportions of flow from each reservoir at the start of the recession may vary. Figure 3 suggests that time of year is an important control on these proportions, concurring with the proposition by Harman *et al.* (2009) that recession characteristics are sensitive to the recharge history of the catchment. This result also supports the finding of Chirico *et al.* (2003) who fitted a fully distributed model to the Mahurangi catchment and found that it was necessary to increase the complexity of the original power-law transmissivity formulation, effectively adding an additional flow pathway to the model.

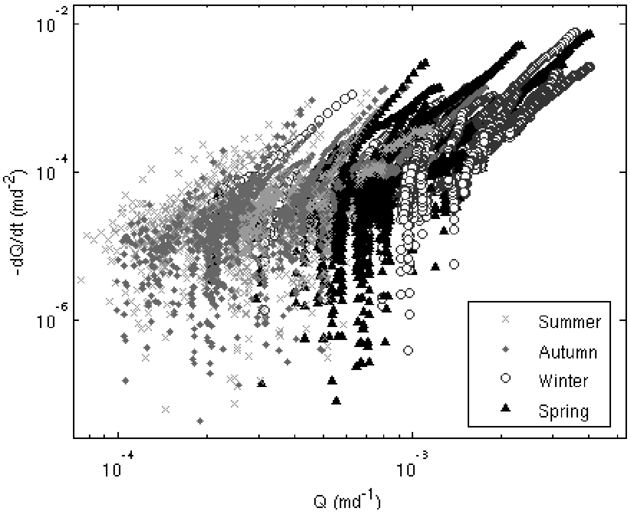

Fig. 3 Relationship between flow (Q) and flow time-derivative (dQ/dt) for Satellite Right, by season.

Hypothesis 2: recession flows may be modelled using a combination of linear reservoirs

Experimentation with synthetic recessions generated from conceptual models with different combinations of reservoirs leads to further conclusions. If only linear reservoirs are used in the model, a typical choice of time constants for two reservoirs might split the flow into quick-flow and slow-flow (e.g. Sacramento formulation). However, this implies that at the end of the recession when the slowflow dominates, the Q – dQ/dt plot has a gradient of unity in log-log space. This is not observed in the data (Fig. 3), and demonstrates that our model must either include multiple perennial reservoirs, or a nonlinear baseflow reservoir.

TESTING UNSATURATED ZONE REPRESENTATION: SOIL MOISTURE ANALYSIS

Hypothesis 3: interflow plays an important role in the Satellite catchment

The upper zone architecture in the PRMS and Sacramento models allows interflow; i.e. a runoff component originating from the unsaturated zone. Both models represent interflow as a linear function of free storage in the unsaturated zone. At Satellite catchment, direct measurements of soil moisture, in addition to inferred storage relationships from recession analysis, allow us to test hypotheses on interflow.

Where interflow dominates the initial phase of a recession, a strong relationship between the storage time-derivative and the quickflow component of runoff would be expected, as water is routed from free storage in the upper zone into the channel. To test this, recession analysis (above) was first used to partition the runoff by assuming that flow was derived from three linear storages (e.g. SACRAMENTO model), with storage time-constants fitted to the measured data. Flow from the fastest-responding storage was assumed to correspond to interflow (alternative slowflow reservoir combinations are possible, but unlikely to substantially affect the quickflow component).

The quickflow series showed no strong relationship with storage time-derivative (Fig. 4(a); correlation = 0.08), suggesting that shallow soil moisture stores do not directly contribute to flow. This is consistent with tracer studies suggesting that flow is controlled by a deeper reservoir with residence times of months to years (Bowden *et al.*, 2000). We conclude that interflow is not a dominant process in this catchment, and hence upper zone architecture choices without interflow (TOPMODEL, ARNOVIC) are preferred for model parsimony. An exception may occur where interflow substitutes for fast-responding groundwater flow not recognised in the model structure.

Notwithstanding the analysis above, we note the strong relationship between soil moisture at the start of an event and event runoff coefficient (Fig. 4(b); a rainfall event is defined as: minimum

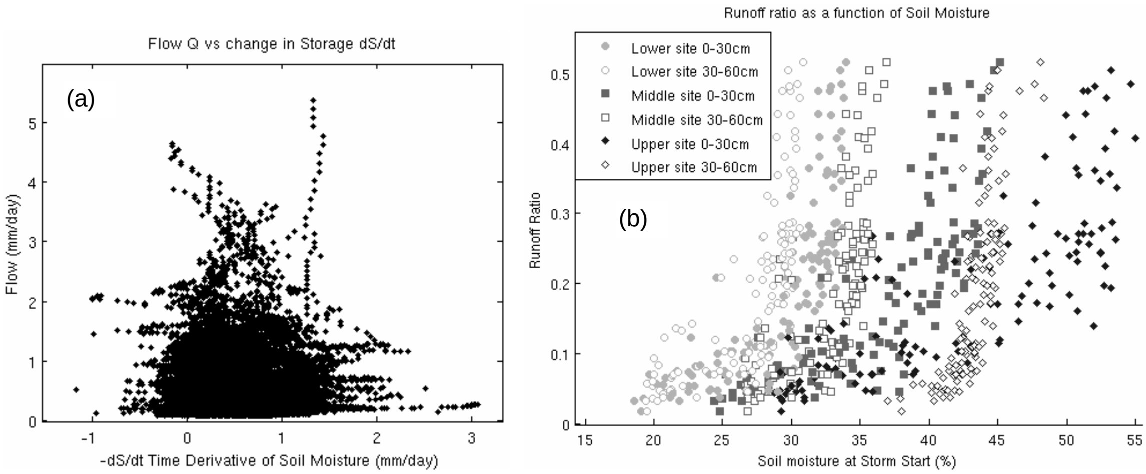

Fig. 4 (a) Relationship between flow and time-derivative of soil moisture, (b) runoff ratio as a function of soil moisture for each of the measurement sites.

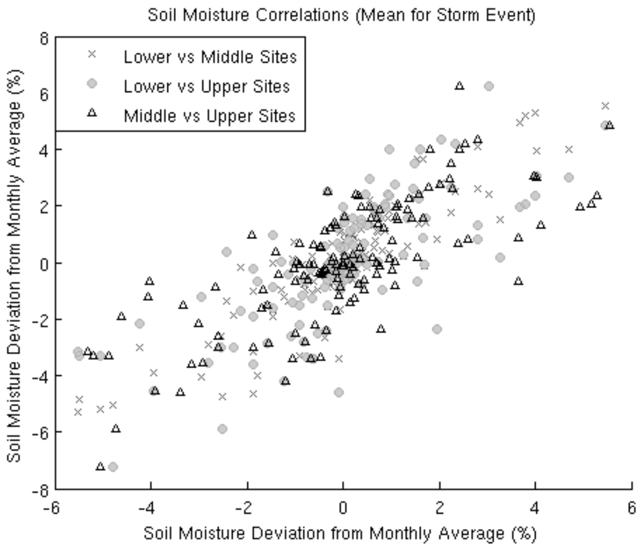

Fig. 5 Soil moisture correlations between sites at Satellite Right.

intensity 5 mm/day, minimum duration 1 hour, minimum time between events 6 hours. At all soil moisture measurement locations, the relationship displays a clear threshold nature, demonstrating the indirect control of soil moisture on flow despite lack of a direct interflow pathway.

TESTING LUMPED MODEL REPRESENTATION

Hypothesis 4: a lumped model of the soil zone adequately represents catchment behaviour

This hypothesis is assumed true in all the parent models of the FUSE framework: all are designed to operate as a lumped model at the scale of small experimental basins. The multi-site soil moisture data allow us to analyse the spatial variance of catchment wetness at time-scales affecting storm response. Detailed investigation of soil moisture patterns at Satellite catchment showed significant heterogeneity (Wilson *et al.*, 2003); however computing average soil moisture over storm events reveals strong connectivity across the hillslope. After removing seasonality effects, correlation coefficients between upper and lower soil layers are 0.77, 0.77 and 0.51 for lower, middle and upper elevations, respectively (not shown), and correlation between hillslope locations is also high: 0.90 between lower and middle elevations; 0.66 between lower and upper (Fig. 5).

This analysis suggests that at hillslope spatial scales and event time-scales, the soil layers at Satellite catchment act as a connected system, particularly at lower and middle elevations. The need for multiple reservoirs identified during recession analysis might therefore be interpreted as a representation of deeper aquifer systems. We suggest that a lumped soil zone model is suitable at these scales, with heterogeneity representation suited to a distribution function approach.

CONCLUSIONS

Our investigation shows that even relatively simple analysis of experimental data may be sufficient to provide substantial guidance for model structure choice. For example, we conclude that the TOPMODEL architecture previously used to model New Zealand catchments is unsuitable for the Satellite catchment, as it does not provide for multiple runoff-generating storage reservoirs. Further investigation is needed to ascertain whether this finding is replicated in other New Zealand catchments in different hydroclimatic zones.

By formulation of the hydrological modelling problem through a framework for testing multiple working hypotheses for model structure, this paper shows how a selection of structural diagnostic tests may be used. It is clear that other aspects of model structure might be tested in a similar way through innovative analysis of experimental data. In the same way that diagnostic signatures are increasingly being used to guide parameter identification, we suggest that a toolbox of simple structural diagnostics could be used to guide model structure choice.

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REFERENCES

Beck, M. B. (1987) Water quality modelling: a review of the analysis of uncertainty. *Water Resour. Res.* **23**(8), 1393–1442.

Beven, K. J. (2000) Uniqueness of place and process representations in hydrological modelling. *HESS* **4**(2), 203–213.

Beven, K. J. & Kirkby, M. J. (1979) A physically based, variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.* **24**, 43–69.

Bowden, B., Fahey, B., Basher, L., Stewart, M., Woods, R. & Bidwell, V. (2000) Sub-surface flow dynamics in a pasture hillslope, Mahurangi River. *Landcare Research* (unpublished abstract).

Burnash, R. J. C. (1995) *The NWS River Forecast System—Catchment modelling, in Computer Models of Watershed Hydrology* (ed. by V. P. Singh), 311–366. Water Resource Publications, Littleton, Colorado, USA.

Chirico, G. B., Grayson, R. B. & Western, A. W. (2003) A downward approach to identifying the structure and parameters of a process-based model for a small experimental catchment. *Hydrol. Processes* **17**, 2239–2258.

Clark, M. P., Slater, A. G., Rupp, D. E., Woods, R. A., Vrugt, J. A., Gupta, H. V., Wagener, T. & Hay, L. E. (2008) Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models, *Water Resour. Res*. **44**, W00B02, doi:10.1029/2007WR006735.

Clark, M. P, Rupp, D. E., Woods, R. A., Tromp-van Meerveld, H. J., Peters, N. E. & Freer, J. E. (2009) Consistency between hydrological models and field observations: linking processes at the hillslope scale to hydrological responses at the watershed scale. *Hydrol. Processes* **23**, 311–319.

Harman, C. J., Sivapalan, M. & Kumar, P. (2009) Apparent non-linearity in catchment-scale recession behaviour arising from spatial heterogeneity of linear small-scale dynamics. *Water Resour. Res.* (in press).

Leavesley, G. H., Lichty, R. W., Troutman, B. M. & Saindon, L. G. (1983) *Precipitation-runoff modelling system: User's manual.* US Geol. Survey Water Invest. Rep., 83-4238.

Liang, X., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. (1994) A simple hydrologically based model of land surface water and energy fluxes for general-circulation models. *J. Geophys. Res*. **99**(D7), 14,415–14,428, doi:10.1029/94JD00483.

Rupp, D. E. & Selker, J. S. (2006) Information, artifacts, and noise in dQ/dt—Q recession analysis. *Adv. Water Resour*. **29**, 154–160.

Todini, E. (1996) The ARNO rainfall-runoff model. *J. Hydrol*. **175**, 339–382, doi:10.1016/S0022-1694(96)80016-3.

Wilson, D. J., Western, A. W., Grayson, R. B., Berg, A. A., Lear, M. S., Rodell, M., Famiglietti, J. S., Woods, R. A. & McMahon, T. A. (2003) Spatial distribution of soil moisture over 6 and 30 cm depth, Mahurangi River catchment, New Zealand. *J. Hydrol.* **276**(1–4), 254–274.

Western, A. W., Zhou, S. L., Grayson, R. B., McMahon, T. A., Bloschl, G. & Wilson, D. J. (2004) Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. *J. Hydrol.* **286**, 113–134.

Woods, R. A., Grayson, R. B., Western, A. W., Duncan, M. J., Wilson, D. J., Young, R. I., Ibbitt, R. P., Henderson, R. D. & McMahon, T. A. (2001) Experimental design and initial results from the Mahurangi River variability experiment: MARVEX. In: *Observations and Modelling of Land Surface Hydrological Processes* (ed. by V. Lakshmi, J. D. Albertson, & J. Schaake), Water Resources Monographs. American Geophysical Union, Washington, DC, 201–213.