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A hypothetical reality of Tarrawarra-like hydrologic response

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Abstract

The objective of this work was to develop a hypothetical reality of hydrologic response to be used as an error-free synthetic dataset in a larger ongoing study. The hypothetical reality was generated via rigorous simulation of a real system with a comprehensive physics-based model. The simulation was conducted with the Integrated Hydrology Model (InHM); the system is the Tarrawarra catchment located in southeastern Australia. Parameterization of the Tarrawarra boundary-value problem was based on the best available information, which, for example includes rainfall, discharge, and soil-water content data for the last six months of 1996. The InHM-simulated near-surface hydrologic response for the Tarrawarra boundary-value problem compares well (albeit not perfectly) with both the integrated and distributed observations from the catchment. The Tarrawarra-like hypothetical reality of wet season hydrologic response generated in this study is rich enough to be employed as an error-free synthetic dataset for quantitatively evaluating the capabilities/limitations of competing (underlying) modelling techniques. Copyright © 2009 John Wiley & Sons, Ltd.

Key Words Tarrawarra; integrated hydrology model; InHM; hydrologic response; synthetic data

Introduction

Distributed models of surface/near-surface hydrologic response have been available for many decades (see Loague and VanderKwaak, 2004). There is, however, no rigorously established protocol to determine how well these models are able to capture the internal dynamics of a given catchment/watershed under different conditions. Until such a protocol is available, it will not be possible to effectively employ distributed models (process-based or empirical), in a decision-management arena, to predict/forecast spatio-temporal hydrologic response. Error-free hydrologic-response (e.g., precipitation, soil-hydraulic property) data are necessary to develop the much needed protocol. Currently no single field-based data set has the spatial and/or temporal resolution needed to fully test all distributed hydrologic-response models. It is also (or should be) clear that field-based catchment- (let alone) watershed-scale datasets, of the type needed for comprehensive model testing, will not be available in the near future.

The effort reported here sets the foundation for a larger ongoing study designed to test how well distributed hydrologic-response models can simulate internal watershed processes. The objectives of the larger study are to: (i) generate an experimental framework for testing distributed hydrologic-response models, (ii) test a suite of distributed hydrologic-response models, and (iii) employ the testing framework to address particular measurement and modelling questions. The effort reported here was designed to develop the aforementioned experimental framework. A comprehensive physics-based model is used to simulate, as best as possible, the hydrologic response for a real catchment. The simulation, both the excitement (rainfall and potential evapotranspiration) and the response (integrated and distributed), is to be taken as an error-free hypothetical reality.

Objective

There are those who believe that hydrologic modelling can, at least historically, be reduced to the following seven steps: (i) going to the field,

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(ii) collecting some data, (iii) determining what happens at a given location, (iv) developing a model, (v) calibrating the model to reproduce the field observations, (vi) declaring victory, and (vii) moving on. It is our opinion that the efforts of many modellers (past and present), focused on understanding how hydrologic systems work (concept development), are not fairly represented by steps (vi) and (vii). It is important to establish at the outset that the objective of this effort was not to overfit a model to an event. The relative ease with which a given model can be made to fit, perhaps for the wrong reasons, a single rainfall-runoff event is well known (see Loague and Freeze, 1985). However, it is all but impossible to track (via simulation) every parcel of water within a real hydrologic system through time, regardless of model detail, due to information shortfalls that will not be met anytime soon. If one believes the physics upon which a physics-based model rests, then the generation of synthetic data with that model should be a reasonable supposition. The objective of the work described in this Scientific Briefing is to capture the generally dominant near-surface hydrologic response for a relatively simple hydrologic system with a comprehensive physics-based model. The model employed in this study is the Integrated Hydrology Model (InHM) (VanderKwaak, 1999); the real system is the Tarrawarra catchment (Western and Grayson, 1998).

Integrated Hydrology Model

InHM was designed to quantitatively simulate fully coupled 3D variably saturated flow in porous media, 2D flow over the surface/in open channels, and evapotranspiration. The mathematical underpinnings, as well as the important/innovative characteristics (e.g. no *a priori* assumption of a specific hydrologic-response mechanism), of InHM are fully developed by VanderKwaak (1999); VanderKwaak and Loague (2001); Loague and VanderKwaak (2004), and Loague *et al.* (2005, 2006). InHM has been successfully employed for several catchment/watershed-scale, event-based/continuous hydrologic-response simulations (VanderKwaak, 1999; VanderKwaak and Loague, 2001; Loague *et al.*, 2005, 2006; Pebesma *et al.*, 2005; Carr, 2006; Ebel and Loague, 2006, 2008; Heppner *et al.*, 2006, 2007; Jones *et al.*, 2006, 2008; Ran, 2006; BeVille, 2007; Ebel, 2007; Ebel *et al.*, 2007, 2008; Heppner, 2007; Mirus *et al.*, 2007; Ran *et al.*, 2007; Smerdon *et al.*, 2007; Heppner and Loague, 2008). The distributed physics-based pedigree, combined with its many successful applications, make InHM a suitable selection for the Tarrawarra simulations.

Tarrawarra

Several experimental catchments were considered for this study. Despite successful simulation efforts, with rich datasets from the CB1 (e.g., Ebel *et al.*, 2008) and R-5 (e.g., Heppner *et al.*, 2007) catchments, the experimental catchment known as Tarrawarra (Western and Grayson, 1998) was selected here to provide the best foundation for an InHM base case simulation, which will subsequently be employed, as part of the larger effort, for the generation of error-free (wet season) hypothetical realities. CB1 and R-5 were not acceptable for this study due to, respectively, insufficient information to parameterize InHM for fractured bedrock flow (see Ebel *et al.*, 2007) and known problems with the discharge records (see VanderKwaak and Loague, 2001). During the last decade, as a testament to the quality of the data, the literature associated with the Tarrawarra catchment has accumulated impressively (e.g. Grayson *et al.*, 1997; Grayson and Western, 1998; Tyndale-Biscoe *et al.*, 1998; Western and Grayson, 1998, 2000; Western *et al.*, 1998a,b, 1999a,b, 2001, 2004a,b; Western and Blöschl, 1999; Grayson and Blöschl, 2000; Thierfelder *et al.*, 2003; Park and van de Giesen, 2004; Wilson *et al.*, 2004; Teuling and Troch, 2005; Teuling *et al.*, 2006; Perry and Niemann, 2007, 2008).

The 10·5 ha, gently sloping Tarrawarra catchment (shown in Figure 1) is located in southeastern Australia. The land use at Tarrawarra is well managed grazing. The soils across Tarrawarra (overlying siltstone bedrock) are silty and silty-clay loams (Western and Grayson, 1998). Figure 2 shows an interpolated subsurface topography for the interface between the A and B soil horizons. The average annual precipitation at Tarrawarra is 820 mm (Western and Grayson, 1998). The Tarrawarra catchment was selected for this study because the hydrologic response is known to be relatively straightforward, dominated by Dunne overland flow. The observations of precipitation, temperature, solar radiation, soil-water content, and surface water discharge from Tarrawarra (see Figure 1) provide the data base for exciting/evaluating the InHM simulations.

The 1996 Tarrawarra wet season, from June through October, and the dry period extending to the end of the year, comprise the length of continuous near-surface hydrologic-response simulation in this study. As shown in Figure 3, six observed rainfall-runoff storm series were identified for the 1996 wet season. The six storm series each met the following three criteria: (i) the observed discharge rate was greater than zero for the entire period, (ii) the observed peak discharge rate was greater than 20 L s^{-1}, and (iii) breaks in observed rainfall were shorter than one day. The six labelled peak discharges

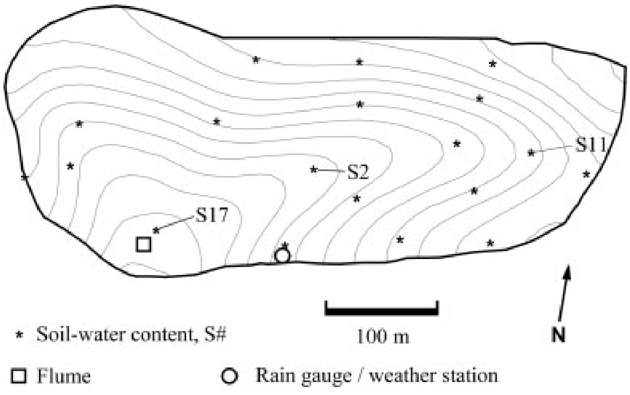

Figure 1. Tarrawarra catchment

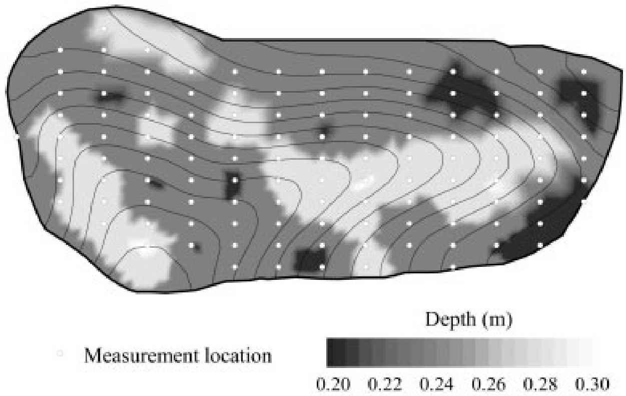

Figure 2. Subsurface topography at the contact between the A and B soil horizons. The measurement locations, from Western and Grayson (1998), are shown on the Kriged surface

in Figure 3 are, respectively, the highest discharge rates within each of the six storm series. Table I summarizes the characteristics of the six distinct rainfall-runoff storm series. Perusal of Table I shows the following:

- The total rainfall and runoff depths during the wet period are, respectively, 295 and 94 mm.
- The maximum, mean, and minimum rainfall depths for the six storm series are, respectively, 82, 35, and 11 mm.
- The maximum, mean, and minimum rainfall intensities (maximum) for the six storm series are, respectively, 4·4, 3·6, and 2·6 mm h^{-1}.
- The maximum, mean, and minimum runoff depths for the six storm series are, respectively, 34, 14, and 3 mm.
- The maximum, mean, and minimum peak discharges for the six storm series are, respectively, 54·3, 39·5, and 23·5 mm h^{-1}.

Boundary-Value Problem

The 3D finite-element mesh for the Tarrawarra boundary-value problem is shown in Figure 4. The surface of the mesh was developed from a digital elevation model with 5 m resolution (Western and Grayson, 1998). The subsurface of the mesh is conceptualized as two soil horizons and the underlying sedimentary bedrock, with all

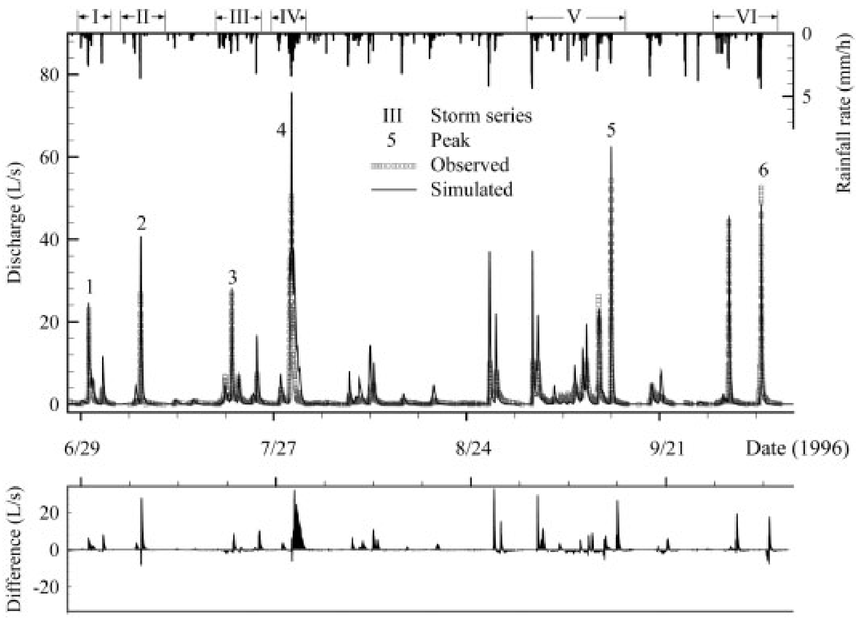

Figure 3. Observed versus InHM-simulated discharges for the 1996 Tarrawarra wet season. The difference shown in the lower panel is the InHM-simulated discharge minus the observed discharge

Table I. Rainfall-runoff characteristics from the 1996 Tarrawarra wet season

Storm series[a]	Date	Rainfall		Runoff	
		Depth [mm]	Maximum intensity [mm h^{-1}]	Depth [mm]	Peak discharge [L s^{-1}]
I—VI	June 28—October 8	295	4·4	94	54·3
I	June 28—July 3	16	2·6	6	23·5
II	July 6—July 11	11	3·6	3	27·2
III	July 19–27	22	3·2	11	27·5
IV	July 27–31	38	3·4	16	51·3
V	September 2–16	82	4·4	34	54·3
VI	September 29—October 8	38	4·4	12	52·9

[a] See Figure 3.

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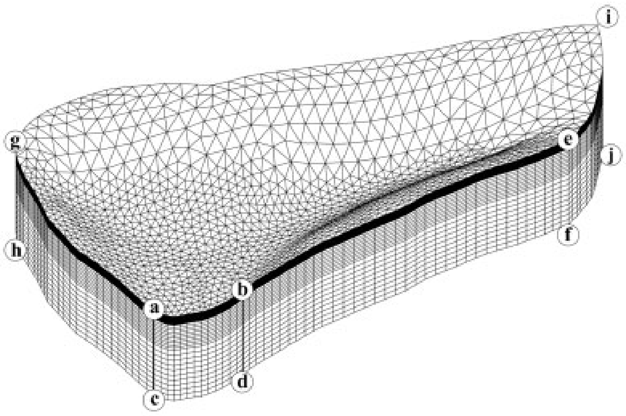

Figure 4. Finite-element mesh for the Tarrawarra boundary-value problem (note, labels (a) through (j) are employed in Table II)

three units being homogeneous and isotropic. The dimensions, nodal spacing, boundary conditions, and parameterization of the Tarrawarra boundary-value problem are summarized in Table II. Figure 4 shows that the vertical and horizontal nodal spacing is smallest, respectively, at the surface and in topographically convergent areas. The location associated with the simulated discharge (along a–b in Figure 4) was intentionally juxtaposed, relative to the flume location, due to the presence of a nearby access road. As the long-term objective of this study was to develop a relatively simple Tarrawarra-like hypothetical reality, the road was not considered. Parameterization of the Tarrawarra boundary-value problem for this study was based upon available data and the objectives of the long-term study. It is important to

Table II. Characteristics of the boundary-value problem used for the InHM simulation of the Tarrawarra catchment

Characteristic	Considered[a]	Final[b]	Confidence[c]
Dimensions [m][d]			
a–c, g–h, i–j, e–f, b–d	17–52	~17	—
a–b, c–d	—	~80	—
a–g, c–h	—	~250	—
g–i, h–j	—	~550	—
i–e, j–f	—	~160	—
e–b, f–d	—	~330	—
Number of nodes[d]			
Surface	—	1,335	—
Subsurface	58,740–80,100	73,425	—
Number of elements[d]			
Surface (triangles)	—	2,542	—
Subsurface (prisms)	111,848–149,978	137,268	—
Boundary conditions[d,e]			
Surface			
a–b	—	CD	M
a–g–i–e–b[f]	—	SF	M
Subsurface (faces)			
a–b–d–c, c–h–j–f–d	IP, SF, RF	RF	M
a–c–h–g, g–h–j–i, i–j–f–e, e–f–d–b	—	IP	M
Space increments [m][d]			
Horizontal (x, y)			
Hollow	—	~5	—
Upland	—	~15	—
Vertical (z)			
A-horizon[g]	—	Variable	—
B-horizon	0·04–0·10	0·05–0·07	—
Bedrock[h]	0·1–6·7	0·1–1·0	—
Layer thickness [m]			
A-horizon[i]	—	Variable	M
B-horizon	0·5–1·5	1·0	M
Bedrock	15–50	15	M
Saturated hydraulic conductivity [m s^{-1}]			
A-horizon[j]	10^{-6}–$10^{-5.2}$	$10^{-5.7}$	M
B-horizon[k]	$10^{-7.5}$–$10^{-6.5}$	10^{-7}	M
Bedrock[l]	10^{-9}–10^{-11}	$10^{-8.7}$	L
Porosity [m^3 m^{-3}]			
A-horizon[m]	0·40–0·55	0·48	M
B-horizon[n]	0·35–0·45	0·38	M
Bedrock[l]	—	0·20	L
Compressibility [m^2 N^{-1}][l]			
A-horizon	—	10^{-7}	M
B-horizon	—	10^{-7}	M
Bedrock	—	10^{-9}	M

Table II. (*Continued*)

Characteristic	Considered[a]	Final[b]	Confidence[c]
Characteristic curves[o]			
Alpha [m^{-1}]			
A-horizon	1·0–4·0	4·0	M
B-horizon	1·0–5·0	4·5	M
Bedrock	3·0–6·0	6·0	L
Beta [−]			
A-horizon	1·0–2·5	2·5	M
B-horizon	1·0–2·0	2·0	M
Bedrock	1·0–1·5	1·5	L
Surface roughness [−][p]	0·2–0·4	0·35	M
Depression storage [m][q]	—	0·01	L
Mobile water depth [m][r]	—	0·0001	L
Time step [s][s]	—	adaptive	—

[a] Within range (observed/reasonable) parameter adjustments.
[b] Values used to generate hypothetical reality.
[c] Confidence in final parameterization of boundary-value problem:
H, high; M, moderate; L, low.
[d] Finite-element mesh (see Figure 4).
[e] Boundary conditions: CD, critical depth; IP, impermeable; RS, regional sink; RF, radiation flux (employs a back-calculated gradient to determine a boundary flux); SF, specified flux (see Figure 4).
[f] Surface boundary condition, specified mixed flux of precipitation and evapotranspiration.
[g] Variable spacing between 0·02 m at the surface and 0·05 m at the contact between the A and B soil horizons.
[h] Variable spacing from 0·1 m at the soil bedrock interface to 1·0 m at the bottom boundary.
[i] Variable soil depths Kriged from 125 core measurements (Western and Grayson, 1998).
[j] Based upon 32 Guelph Permeameter measurements (Western and Grayson, 1998).
[k] Based upon ten Guelph Permeameter measurements (Western and Grayson, 1998).
[l] Freeze and Cherry (1979).
[m] Mean of the maximum neutron probe soil-water content values for the A-horizon (Western and Grayson, 1998).
[n] Mean of the maximum neutron probe soil-water content values for the B-horizon (Western and Grayson, 1998).
[o] Characteristic curves (hydraulic conductivity and soil-water content as functions of pressure head) for the unsaturated near-surface as represented by van Genuchten curve-shape parameters (van Genuchten, 1980).
[p] Surface roughness, represented by Manning's n values (Engman, 1985).
[q] VanderKwaak (1999).
[r] VanderKwaak (1999).
[s] Maximum time step ~100 000 s.
The values for gravitational acceleration, the density of water, and the dynamic viscosity of water were taken as 9·8 $m^2\ s^{-1}$, 1000 kg m^{-3}, and 0·001138 kg $m^{-1}\ s^{-1}$, respectively.

acknowledge that the Tarrawarra information, like all currently available datasets, is relatively sparse when compared with the data demands of a fully parameterized InHM.

An hourly time step was used to enter both the rainfall and potential evapotranspiration rates, with no consideration for spatial variability within either. Potential evapotranspiration was estimated using the Penman Monteith equation (see Shuttleworth, 1993), driven by Tarrawarra data. Simulated evapotranspiration rates from the surface were saturation limited and decreased to zero when the soil-water content dropped below the wilting point (pressure head of −150 m).

Two constraints needed to be met to estimate the initial conditions for the Tarrawarra boundary-value problem: (i) generation of a perched water table resting on the permeability contact between the A and B soil horizons, and (ii) approximate, as closely as possible, the integrated response (discharge) for an event just prior to the simulation period. The following five steps were employed, in a month-long warm-up simulation (with InHM), to estimate the initial 3D pressure-head distribution: (i) hydraulic head values were set to 98% of the surface elevation across the entire domain at the start of the warm-up simulation, (ii) 3 h of unrestricted drainage, (iii) continued drainage with rain applied at 0·15 mm h^{-1} for 2 weeks, (iv) continued drainage with rain increased to 2·5 mm h^{-1} for 1·5 weeks, resulting in a fair match between observed and simulated discharges for the large event that precedes the simulation period by four days, and (v) drainage (without rainfall) continued for 4 days, until the start of the simulation period (27 June 1996). Draining the catchment (via the warm-up simulation) to estimate initial conditions provides a physics-based and internally valid estimate of the continuous head field (VanderKwaak and Loague, 2001). With the initial conditions in place, there were some within range (observed/reasonable) parameter adjustments, as summarized in Table II, for the Tarrawarra boundary-value problem.

Simulation Results

Integrated response

Figure 3 shows the observed versus InHM-simulated discharges for the 1996 wet season. Table III shows the observed versus InHM-simulated runoff depths and peaks for the six storm series (shown in Figure 3) for the 1996

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Table III. Observed versus InHM-simulated runoff characteristics for the 1996 Tarrawarra wet season

Storm series[a]	Observed		Simulated		EF[b]
	Depth (mm)	Peak discharge (L s^{-1})	Depth (mm)	Peak discharge (L s^{-1})	
I–VI	96	54·3	142	75·7	0·23
I	6	23·5	9	24·5	0·66
II	3	27·2	7	40·2	−1·57
III	11	27·5	12	28·1	0·61
IV	16	51·3	34	75·7	−0·02
V	34	54·3	38	62·6	0·33
VI	12	52·9	16	48·7	0·70

[a] See Table I and Figure 3.
[b] Model efficiency (EF), for the observed versus InHM-simulated discharge, is given by (Nash and Sutcliffe, 1970):

$$EF = \left[\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(S_i - O_i)^2\right] \Big/ \sum_{i=1}^{n}(O_i - \overline{O})^2$$

where S_i are the simulated values, O_i are the observed values, n is the number of samples, and $\overline{O}$ is the mean of the observed data. The EF statistic ranges from 1·0 to $-\infty$, with 1·0 indicating a perfect match between S_i and O_i. An EF of less than zero indicates that $\overline{O}$ is a better model than S_i for estimating O_i.

wet season. Table III also provides model performance results (i.e. EF values) for the InHM simulation shown in Figure 3. Perusal of Figure 3 and Table III leads to the following comments:

- The magnitude and timing of the observed versus simulated discharge appears to match (especially storm series I, III, and VI) reasonably well (Figure 3).
- The observed and simulated total runoff depths compare reasonable well at 96 and 142 mm, respectively (Table III).
- The simulated runoff depths for the six storm series are all larger than the observed depths; some slightly (e.g. a 9% difference for storm series III), some significantly (e.g. a 112% difference for storm series IV) (Table III and Figure 3).
- The simulated peak discharges for the six storm series are generally larger than the observed peaks (note, storm series VI is the only exception); some slightly (e.g. a 2% difference for storm series III), some significantly (e.g. a 48% difference for storm series IV) (Table III and Figure 3).
- The statistical characterization of model performance for the continuous simulation was relatively good with an EF value of 0·23 (Table III).
- The statistical characterization of model performance for the six storm series is very good (i.e. storm series I, III, and VI with EF values of, respectively, of 0·66, 0·61, and 0·70), fair (i.e. storm series V with an EF value of 0·33), and wretched (i.e. storm series II and IV with EF values of, respectively, of −1·57 and −0·02) (Table III).

Distributed response

Figure 5 shows the observed versus InHM-simulated soil-water contents at different locations for the entire simulation period. Figure 6 shows observed versus InHM-simulated snapshots of soil-water content. Perusal of Figures 5 and 6 lead to the following comments:

- The simulated soil-water contents compare well with the observed values at each of the three locations (both depths) during the wet and dry periods (Figures 1 and 5).
- The six simulated snapshots of soil-water content compare well, in both the wet and dry periods, with the corresponding observed snapshots (Figure 6).
- The patterns, which can be gleaned from the soil-water content snapshots, are similar to patterns within the subsurface topography map at the A and B soil horizon contact. It is worth pointing out that there is a stand of trees along the up-gradient (northern) side of the catchment, where the observed soil-water content is consistently lower, presumedly due to higher evapotranspiration rates that are not represented in the simulation (Figures 2 and 6).

Overall assessment

In converging on the final parameterization for the Tarrawarra boundary-value problem (see Table II), the objective was to achieve the smallest residuals for all the observed versus InHM-simulated responses (e.g. discharge, soil-water content). In general, as shown in Table III, the simulations are better for most of the larger storm series than for the complete 1996 wet season (i.e. the small discharges are, comparatively, the least well simulated). A study of Figure 3 and Table III clearly shows, for the larger events, that the simulated discharges are greater than the observed discharges. As further evidence that the discharges were better simulated for the larger events it is worth noting that the EF value for the event associated with the largest peak within a storm series (see Figure 3) is generally better (four out of six) than the EF value (reported in Table III) for the storm series itself [i.e. 0·84 (1)/0·66 (I), −2·23 (2)/−1·57 (II), 0·76 (3)/0·61 (III), −0·45 (4)/−0·02 (IV), 0·62 (5)/0·33 (V), 0·73 (6)/0·70 (VI)].

Obviously, one could tweak, for example, the surface-saturated hydraulic conductivity (an effective value representation) to better fit the discharge (integrated response). However, in calibrating to the discharge, the simulated soil-water contents (distributed response), which are not mutually exclusive from the integrated response, are impacted. Although not the objective of this exercise, one can imagine endless parameter adjustments, with elements of equifinality (see Ebel and Loague, 2006), when attempting to improve model performance. Our relative confidence in the final parameterization of the Tarrawarra boundary-value problem is given in Table II.

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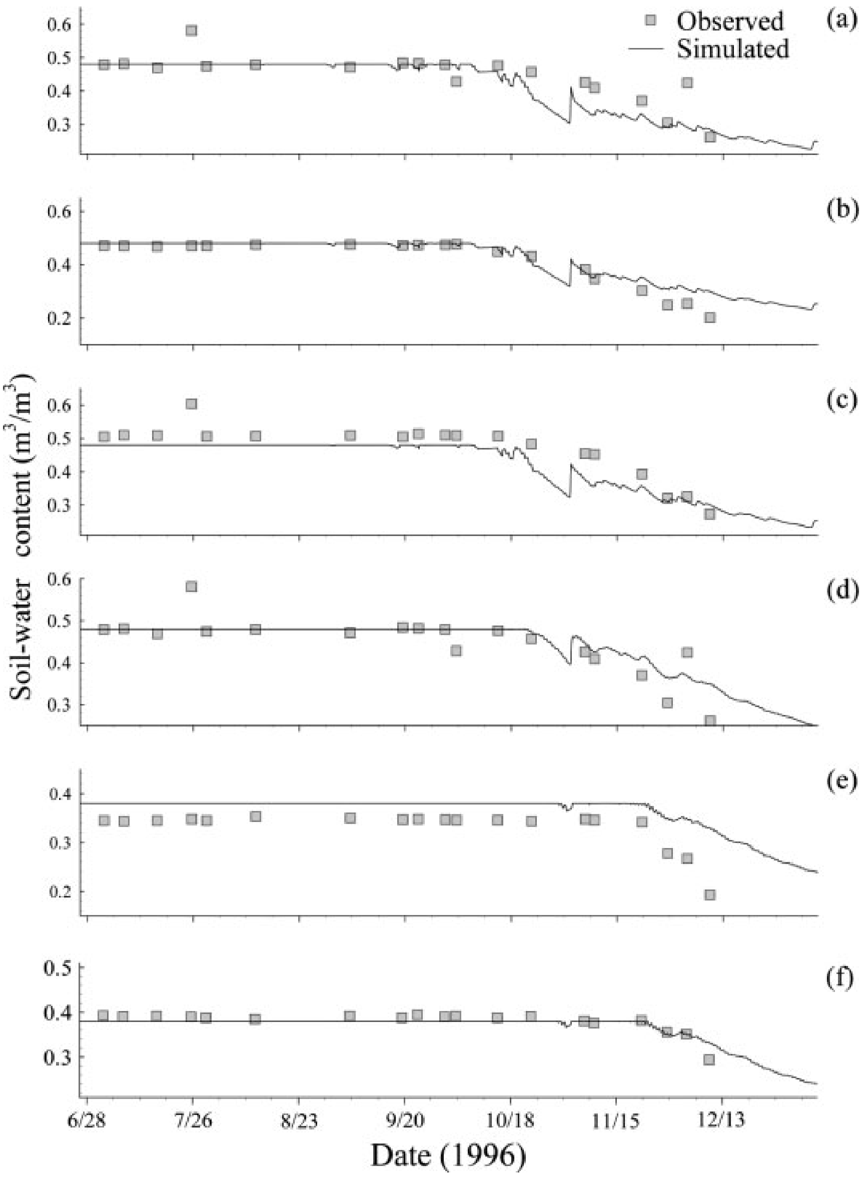

Figure 5. Observed versus InHM-simulated soil-water contents for the 1996 Tarrawarra wet season and following dry period for (a) site 17 at 0·15 m, (b) site 11 at 0·15 m, (c) site 2 at 0·15 m, (d) site 17 at 0·30 m, and (e) site 11 at 0·45 m (f) site 2 at 0·45 m depths, respectively. See Figure 1 for the measurement (neutron probe) locations

It is not clear (without questioning the observations) why each of the large storm series were not equally well simulated. It is clear, however, that the Tarrawarra boundary-value problem is, relative to the actual (yet unknowable) variations in surface/near-surface parameters/variables, an approximation of the real catchment. For example, one can fairly assume that with spatially variable rainfall data, like from the 148 gages for the 860 m^2 CB1 (Ebel *et al*., 2007), and/or spatially variable surface-saturated hydraulic conductivity data, like from the 247 infiltration measurements for the 0·1 km^2 R-5 (Heppner *et al*., 2007), that the InHM-simulated response for Tarrawarra would be improved. Perhaps the biggest Netherland in parameterizing a model like InHM for simulations of the type reported here are the non-linear characteristic curves (i.e. hydraulic conductivity and soil-water content as functions of pressure head) that control hydrologic response in the unsaturated near-surface. For the Tarrawarra boundary-value problem, like almost all similar simulation efforts [see Ebel *et al*. (2007) for an exception], field measured characteristic curves were not available.

Epilogue and Beyond

First off, we are neither declaring victory nor moving on. The discrepancies between the InHM-simulation results and the Tarrawarra observations are taken to be a consequence of simplifications necessary to parameterize the boundary-value problem. Specifically, the discharge and soil-water content data are conservatively assumed to be correct. Furthermore, this effort should not be taken as yet another model application exercise facilitated by a good dataset. The work was designed to justify the generation of a synthetic (yet realistic) dataset that would be rich enough to test the full range of underlying

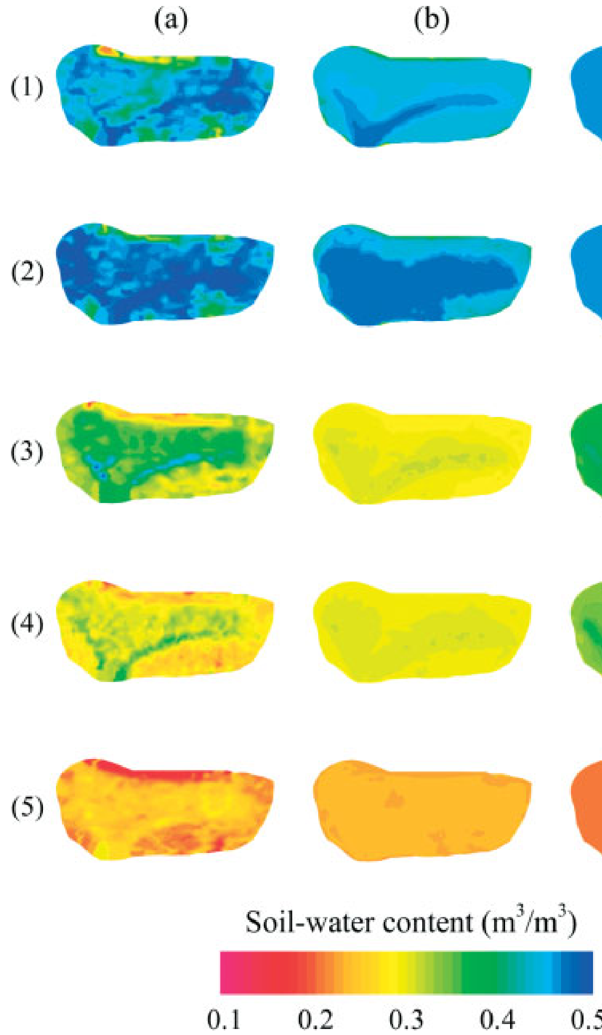

Figure 6. Snapshots of soil-water content for the Tarrawarra catchment on six occasions during 1996, (a) observed (Western and Grayson, 1998), (b) InHM-simulated (surface), and (c) InHM-simulated (mid-point of A-horizon): (1) July 3, (2) September 20, (3) October 25, (4) November 10/11, and (5) November 29. Each observed snapshot is based on approximately 500 TDR measurements (note, the wave guide length was 0·3 m)

(existing/future) modelling techniques. Clearly, when working with synthetic data there is no chance of being correct for the wrong reason, as there are no data-related uncertainties.

It is our opinion that the performance of InHM in capturing the observed 1996 wet season near-surface hydrologic response (both integrated and distributed) for the Tarrawarra catchment, does provide a foundation that is sufficient for establishing the boundary-value problem as a Tarrawarra-like hypothetical reality. In an ongoing study, this hypothetical reality is being employed as an error-free synthetic dataset to rigorously evaluate performance capabilities/limitations for a competing set of models. The idea of using synthetic hydrologic-response data to develop/refine concepts is not new. For example, Loague (1988) used the stochastic-conceptual model developed by Freeze (1980); Gan and Burges (1990) used the deterministic-conceptual model developed by Smith and Hebbert (1983). The Freeze (1980) and Smith and Hebbert (1983) models employ somewhat restrictive analytical solutions as operating algorithms. InHM, on the other hand, employs numerical methods to solve a comparatively complete set of coupled partial-differential equations. The biggest improvement between using the InHM simulations as a synthetic error-free dataset and the efforts of Loague (1988) and Gan and Burges (1990) is that the Tarrawarra boundary-value problem is based upon a well-characterized real system.

Figure 7 shows seven snapshots of InHM-simulated surface saturations for the Tarrawarra-like hypothetical reality. The period of interest from which the snapshots are taken, shown with the observed versus simulated discharge ($EF = 0{\cdot}84$), is the first event from storm series I (see Figure 3). The snapshots in Figure 7, similar to the field squish test saturation maps pioneered by Tom Dunne (see Dunne *et al.*, 1975), are taken here as error-free synthetic data at a level of spatio-temporal intensity not feasible with invasive sampling methods. The distributed response (surface saturation) synthetic data given in Figure 7 is the tip of the proverbial iceberg. For example, there are 73 425 subsurface and 1335 surface pressure-head values generated at every time step within a *Tarrawarra-like* simulation that can,

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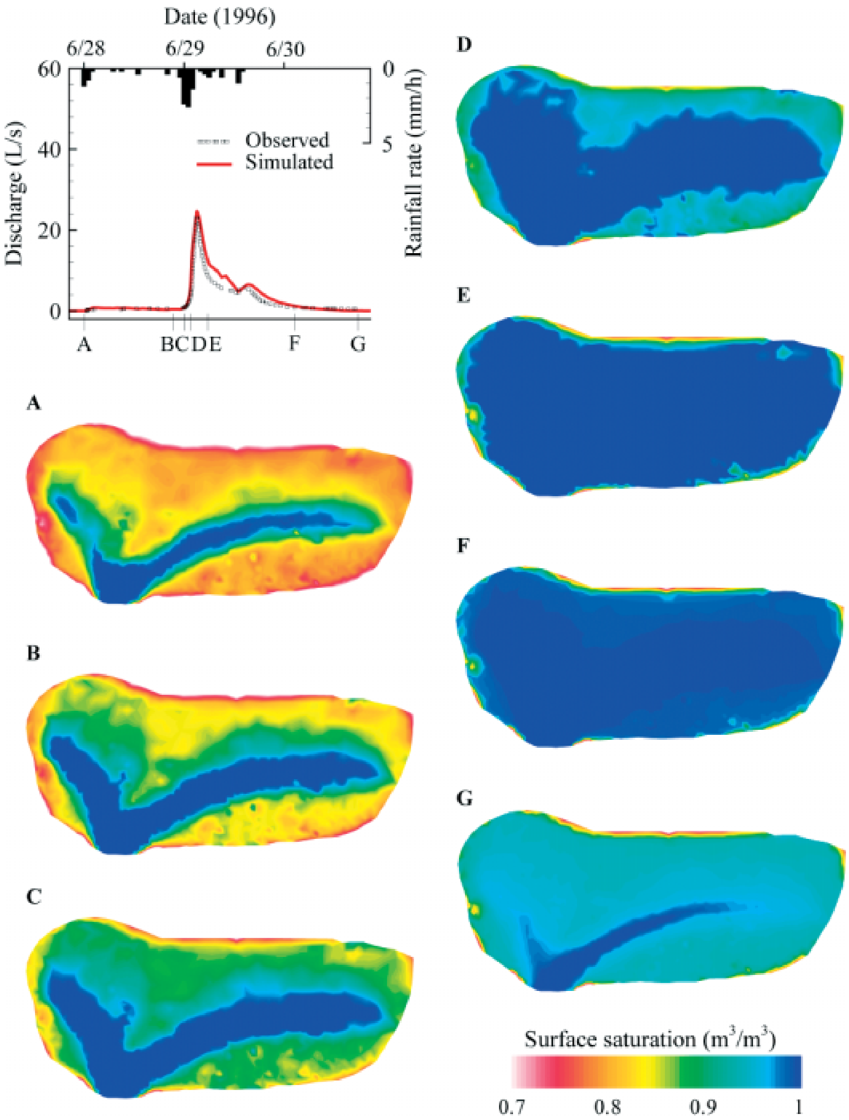

Figure 7. InHM-simulated discharge and surface saturation snapshots from the Tarrawarra-like hypothetical reality. The timing of snapshots A through G is given with the hydrograph in the upper left hand corner

in turn, be used to calculate: (i) water content and/or fluid pressure within the subsurface from a distributed perspective, (ii) depth and/or velocity at the surface from a distributed perspective, and (iii) surface and/or subsurface discharge from an integrated perspective. The physics-based InHM will also, with alternative storm characteristics and initial condition scenarios, be employed to generate new synthetic datasets that cover a wider range of hydrologic response for the Tarrawarra-like boundary-value problem. The new synthetic datasets to be developed from the Tarrawarra-like boundary-value problem will be available to the community at large.

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